Meson Photoproduction at GRAAL and BGO-OD Experiments

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Introduction

The excitation spectrum of the nucleon is the most important ground where to test our understanding of QCD in the strong-coupling regime and the study of baryon resonances plays the same role for understanding the nucleon structure as the nuclear spectroscopy played for the investigation of the nucleus structure. There are major experimental, theoretical and computational efforts that aim to explore both the spectrum and the structure of excited nucleons. The dominant decay channel of nucleon resonances is the hadronic decay via meson emission. Photoproduction of mesons, which carries information on strong and electromagnetic decay properties, therefore provides a very valuable tool for their study. Polarization degrees of freedom in photoproduction processes play a crucial role, offering a complementary approach with respect to pion scattering. They are particularly important as they are very sensitive to the details of the interaction, via an interference mechanism allowing to access resonance properties that are difficult to extract from differential cross section measurements where a single contribution often dominates the transition amplitude[1–4]. The detailed description of the photon-nucleon interaction requires a complete data set containing, at least, eight independent observables: the cross section, the three single polarization observables (beam, target and recoil nucleon) and four, appropriately chosen, double polarization observables[5]. The properties of the resonances can then be extracted from the photoproduction data via partial wave analysis and multipole decomposition, in the framework of different approaches[3, 6] and the comparison of the calculated observables with the experimental data becomes a strong constraint to the theoretical models[4, 7] determining the role and the properties of the included resonances.

Dedicated experimental programs exist to perform accurate measurements of meson photo- and electro-production off the nucleon in order to discover its excitations, and determine its internal structure. A new generation of electron accelerators equipped with tagged photon facilities have opened the way to meson photoproduction experiments of high sensitivity and precision [9].

The experiments are centered at high duty electron beams, in particular at the GRAAL facility at the ESRF in Grenoble, at the ELSA accelerator in Bonn, at CEBAF at Jlab in Newport News, at the MAMI accelerator in Mainz, at SPring-8 in Osaka and at LNS at Tohoku University in Sendai. The GRAAL and BGO-OD experiments will be object of discussion in this thesis. The GRAAL experiment
is based on the use of a tagged and polarized photon beam obtained through the Compton back-scattering of laser light off the 6.03GeV electrons circulating in the ESRF storage ring. The coupling of the GRAAL beam with a large acceptance detector covering 0.95-4π solid angle with cylindrical symmetry (LACGrANγE) is the ideal tool in order to measure polarization degrees of freedom, in particular Σ beam asymmetries.

The first measurement of the beam asymmetry Σ for η’ photoproduction off proton in the threshold region using the GRAAL data will be presented in the chapter three.

In fact, the data on η’ photoproduction is scarce. Up to now only η’ cross section data on the proton and, recently, on the deuteron are available. The energy region from threshold (1.447 GeV) up to 2.84 GeV was explored and total and differential cross section data were produced. The photoproduction of η’ meson offers the distinct advantage of serving as an isospin filter for the spectrum of nucleon resonances and thus simplifies data interpretation and theoretical efforts to predict the excited states contributing to these reactions. In fact, since the η’ meson has isospin I=0, the Nη’ final states can only originate from intermediate I=1/2 nucleon states [10].

The extraction of the η’ Σ beam asymmetry is one of the goals of the new BGO-OD experiment. The BGO-OD experiment at the ELSA facility in Bonn involves the use of a Bremsstrahlung tagged and polarized photon beam of energy between 0.7 and 3.2 GeV, a large solid angle high resolution BGO calorimeter and the Open Dipole spectrometer equipped with tracking detectors. This apparatus will be used to measure polarization observables and cross sections in the photoproduction of pseudo-scalar and vector mesons off an hydrogen or deuterium target. The results obtained at the BGO-OD experiment with the BGO calorimeter, equipped with the new electronic readout based on sampling ADCs, during the tests performed with the beam time will be presented in the chapter five. The proper functioning of the apparatus has allowed the reconstruction of the pseudo-scalar mesons π⁰ and η invariant masses. The characteristics of the BGO crystals in combination with the new ADC modules have been studied, concerning both the linearity and resolution in the energy reconstruction and the performances in the time response to a monochromatic tunable source of high energy electrons available at the BTF (Beam Test Facility) of the LNF-INFN in Frascati (Rome, Italy) and are reported in chapter six.
Chapter 1

Quark model and meson photoproduction

1.1 History

After the Rutherford experiment, indicating how compact is the atomic nucleus, and the discovery of the neutron by Chadwick, it became necessary to understand how the nucleus is built out of protons and neutrons[8]. The mechanism of Yukawa with the exchange of a massive boson turned out successful with the discovery of the pion at Bristol in 1947 [11]. However, several complications occurred almost simultaneously.

First, the Yukawa picture of nuclear forces was very efficient for the long-range part, but not at shorter distances.

Second, the interaction of pions with nucleons was shown to produce new particles, nucleon resonances, in particular the $\Delta(1232)$, which has isospin 3/2, i.e., exists in four possible electric charges. Similarly, proton-nucleon or proton-nucleus scattering, or proton-antiproton annihilation were able to produce several new mesons, the ones desired to improve the theory of nuclear forces, and others. These hadrons are not stable, with for instance $\Delta \rightarrow N + \pi$, but were named hadrons as well, baryons or mesons.

Third, a new quantum number, strangeness $S$, was introduced to summarise the properties of the new particles (hyperons and K mesons) observed in the 50s and 60s. Murray Gell-Mann and Yuval Neeman succeeded in describing the new particles in a symmetry scheme based on the group SU(3)[12]. The baryons were
classified in octets and decuplets, the mesons in octets and singlets. In 1964, Gell-Mann and Feynman’s PhD student George Zweig proposed that the baryons and mesons were bound states of the hypothetical triplet particles. Gell-Mann called the triplet particles ”quarks”, using a word that had been introduced by James Joyce in his novel Finnegans Wake.

1.2 The quarks quantum numbers

Quantum chromodynamics (QCD) is the theory of the strong interactions. QCD is a quantum field theory and its constituents are a set of fermions, the quarks, and gauge bosons, the gluons. The quarks participate in strong interactions because they carry color charges. The color charges are similar to the electric charge in Quantum Electrodynamics (QED), but with important differences. Unlike electric charge, which is a scalar quantity in the sense that the total charge of an electric system is simply the algebraic sum of individual charges, the color charge is a quantum vector charge, a concept similar to angular momentum in quantum mechanics. The total color charge of a system must be obtained by combining the individual charges of the constituents according to group theoretic rules analogous to those for combining angular momenta in quantum mechanics. The quarks have three basic color-charge states, which can be labeled as $i = 1, 2, 3$, or red, green, and blue, mimicking three fundamental colors (see fig.1.1). Three color states form a basis in a 3-dimensional complex vector space. A general color state of a quark is then a vector in this space. The color state can be rotated by $3 \times 3$ unitary matrices. The 3-dimensional color space forms a fundamental representation of SU(3).

The gluons are responsible of the interaction of the quarks. A simple way to understand this is that the gluons in strong interactions play the role of photons in QED, which mediate electromagnetic interactions between charged currents. Like photons, gluons are massless, spin-1 particles with two polarization states (left-handed and right-handed).

The description of hadronic properties which strongly emphasizes the role of the minimum-quark-content part of the wave function of a hadron is generically called the quark model[13]. This model is not perfect. It provides no explanation for confinement, doesn’t make absolute mass and rate predictions for decays. However, it does make a rather large number of very good predictions. In fact, it provides
a very natural framework within which to classify mesons. It is a good means to address issues such as structure and decays, and even makes some rather good predictions for relative decay rates[14].

The quarks are the fundamental objects participating in strong interactions. Like the electrons, they are simple structureless (as far as we know) with spin-1/2 particles and, by convention, positive parity. Antiquarks have negative parity. The color charge of an antiquark is denoted \( \bar{3} \), which is a representation space of SU(3) where the vectors are transformed according to the complex conjugate of an SU(3) matrix.

Quarks have the additive baryon number 1/3, antiquarks -1/3. Table 1.1 gives the other additive quantum numbers for the three generations of quarks. They are related to the charge \( Q \) (in units of the elementary charge \( e \)) through the generalized Gell-Mann-Nishijima formula:

\[
Q = I_z + \frac{(B + S + C + B + T)}{2} \tag{1.1}
\]

where \( B \) is the baryon number.

**Table 1.1: Additive quantum numbers of the quarks.[13]**

<table>
<thead>
<tr>
<th></th>
<th>d</th>
<th>u</th>
<th>s</th>
<th>c</th>
<th>b</th>
<th>t</th>
</tr>
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<td>(-\frac{1}{3})</td>
<td>(+\frac{2}{3})</td>
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<td>+\frac{1}{2}</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S-strangeness</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C-charm</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B-bottomness</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>T-topness</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
</tr>
</tbody>
</table>

The convention is that the flavor of a quark (\( I_z \), S, C, B, or T) has the same sign as its charge \( Q \). With this convention, any flavor carried by a charged meson has the same sign as its charge, e.g., the strangeness of the \( K^+ \) is +1, the bottomness of the \( B^+ \) is +1 etc.. while the antiquarks have the opposite flavor signs[13].
1.3 Particles classification

Free quarks do not exist; they exist only in bound states. The reason lies in the
distance dependence of the strong force between coloured objects. The potential
between color charged objects rises approximately linearly at larger distances,
while the potentials of all other interactions asymptotically approach a constant
value. This means that the separation of two quarks would require an infinite
amount of energy. In practice, if one tries to remove a quark from a hadron (e.g.
with deep inelastic scattering) the result is a jet of mesons and baryons from the
production of quark-antiquark pairs which combine to form color neutral hadrons.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{The quark colours (left) and anticolours (right) combine to be colorless.}
\end{figure}

Color neutral objects are called "white". There are two ways of obtaining a
"white" charge: the combination of charge and anti-charge (e.g. "red" + "anti-
red"="white") or the combination of all three charges:"red"+"blue"+"green"="white".
Two different types of "white" hadrons are known: hadrons made of quark-
antiquark pairs are called mesons, hadrons consisting of three quarks are called
baryons.

1.3.1 Mesons

The mesons have baryon number $B = 0$. They are $q\bar{q}'$ bound states of quarks $q$
and antiquarks $q'$ (see fig.1.2) where the flavors of $q$ and $q'$ may be different. If the
orbital angular momentum of the $q\bar{q}$ state is $\ell$, then the parity $P$ is $(-1)^{\ell+1}$. The
total angular momentum $J$ results from the coupling of the spin $s$ of the quarks
and their orbital momentum $\ell$ with $|\ell - s| \leq J \leq |\ell + s|$, where $s$ is 0 (antiparallel
quark spins) or 1 (parallel quark spins).

The charge conjugation, or C-parity $C = (-1)^{\ell+s}$, is defined only for the $q\bar{q}$ states
made of quarks and their own antiquarks. The C-parity can be generalized to
the $G$-parity $G = (-1)^{I+\ell+s}$ for mesons made of quarks and their own antiquarks (isospin $I_z = 0$), and for the charged $u\bar{d}$ and $d\bar{u}$ states (isospin $I = 1$). The mesons are classified in $J^{PC}$ multiplets. The states can be written in spectroscopic notation as $2s+1\ell J$ and are shown in table 1.2. The $\ell = 0$ states are the pseudoscalars ($0^{--}$) and the vectors ($1^{--}$). The orbital excitations $\ell = 1$ are the scalars ($0^{++}$), the axial vectors ($1^{++}$) and ($1^{+-}$), and the tensors ($2^{++}$)[13]. Some sets of quantum numbers are absent. In fact, the states in the natural spin-parity series $P = (-1)^J$ must, according to the above, have $s = 1$ and hence, $CP = +1$. Thus, the mesons with natural spin-parity and $CP = 1$ ($0^{+-}, 1^{-+}, 2^{++}, 3^{-+}$, etc.) are forbidden in the $q\bar{q}'$ model. The $J^{PC} = 0^{--}$ state is forbidden as well. These latter quantum numbers are known as explicitly exotic quantum numbers. These mesons may exist, but would lie outside the $q\bar{q}'$ model. In the low mass energy region, we have three quarks, $u$, $d$ and $s$ which can be combined with three antiquarks. This leads to nine possible $q\bar{q}'$ combinations with the same $J^{PC}$. If we now assume that the three quarks are flavor symmetric, then we can use the $SU(3)$ -flavor group to build up the nominal nine mesons (a nonet).

$$3 \otimes \bar{3} = 1 \oplus 8$$ (1.2)

The nine members of the nonet combine into two groups, eight members of an octet, $|8\rangle$ and a single member of a singlet $|1\rangle$. Under the $SU(3)$ symmetry, all the members of the octet have the same basic coupling constants to similar reactions, while the singlet member could have a different coupling. The $q\bar{q}'$ combinations for the pseudoscalar mesons are shown in fig. 1.3.
A fourth quark such as charm $c$ can be included by extending $SU(3)$ to $SU(4)$. However, $SU(4)$ is badly broken owing to the much heavier $c$ quark mass. Nevertheless, in an $SU(4)$ classification, the sixteen mesons are grouped into a 15-plet and a singlet:

$$4 \otimes \bar{4} = 15 \oplus 1$$

The weight diagrams for the ground-state pseudoscalar $0^{-+}$ and vector $1^{--}$ mesons are depicted in fig. 1.4[13].

Isoscalar states with the same $J^{PC}$ will mix, but mixing between the two light quark isoscalar mesons, and the much heavier charmonium or bottomonium states, are generally assumed to be negligible. In the following, we shall use the generic names $a$ for the $I = 1$, $K$ for the $I = 1/2$, and $f$ and $f'$ for the $I = 0$ members of the light quark nonets. Thus, the physical isoscalars are mixtures of the $SU(3)$ wave function $\psi_8$ and $\psi_1$:

$$f' = \psi_8 \cos \theta - \psi_1 \sin \theta$$

$$f = \psi_8 \sin \theta + \psi_1 \cos \theta$$

where $\theta$ is the nonet mixing angle and:

$$\psi_8 = \frac{1}{\sqrt{6}} (u\bar{u} + d\bar{d} - 2s\bar{s})$$

Figure 1.3: SU(3) weight diagram for the $J^{PC} = 0^{-+}$ - pseudoscalar nonet (a) and $J^{PC} = 1^{--}$ - vector nonet (b).
Figure 1.4: SU(4) weight diagram showing the 16-plets for the pseudoscalar (a) and vector mesons (b) made of the u, d, s, and c quarks as a function of isospin $I$, charm $C$, and hypercharge $Y = S + B - \frac{C}{3}$. The nonets of light mesons occupy the central planes to which the $c\bar{c}$ states have been added.\[13\]

$$\psi_1 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}).$$ \hspace{1cm} (1.7)

In this scheme, the ideal mixing occurs for the choice of $\theta = 35.26^\circ$, $(\cos\theta = \sqrt{\frac{2}{3}}$, $\sin\theta = \sqrt{\frac{1}{3}})$. Under this assumption, the physical states have the quark content as in equation 1.8.

$$f' = \sqrt{\frac{1}{2}}(u\bar{u} + d\bar{d})\cos\alpha - s\bar{s}\sin\alpha$$ \hspace{1cm} (1.8)

It is possible to simply relate these two parameterizations, and can be easily shown that they are the same if $\vartheta = 90^\circ - \theta$.

The pseudo-scalar mesons are often written in a different mixing scheme; a way to understand this is to imagine that the $\eta$ and the $\eta'$ are interchanged. In fact, in terms of the pseudo-scalar mixing angle, $\theta_p$, their mixing is given as in the equations 1.9 and 1.10.

$$\eta' = \psi_8 \cos\theta - \psi_1 \sin\theta$$ \hspace{1cm} (1.9)
\[ \eta = \psi_8 \sin \theta + \psi_1 \cos \theta \]  

(1.10)

The pseudoscalar mixing angle \( \theta_P \) can also be measured by comparing the partial widths for radiative \( J/\psi \) decay into a vector and a pseudoscalar, radiative \( \phi(1020) \) decay into \( \eta \) and \( \eta' \), or \( \bar{p}p \) annihilation at rest into a pair of vector and pseudoscalar or into two pseudoscalars. One obtains a mixing angle between \(-10^\circ\) and \(-20^\circ\)\[13\].

Finally, it is possible to use these \( SU(3) \) wave functions to predict mass relations between members of a meson nonet. For a pure nonet, one can derive a generalized linear mass formula, (equation 1.11). This formula is useful in predicting the masses of nonet members, and also verifying that a set of states can actually form a nonet\[15]\:

\[ (m_f + m_{f'}) (4m_K - m_a) - 3m_fm_{f'} = 8m_K^2 - 8m_K m_a + 3m_a^2. \]  

(1.11)

In addition to the linear mass formula, it is also possible to predict the nonet mixing angle, \( \theta \) purely from the masses. Equation 1.12 can be used to determine the mixing angles.

\[ \tan^2 \theta = \frac{3m_{f'} - 4m_K + m_a}{4m_K - m_a - 3m_f} \]  

(1.12)

1.3.2 Baryons

The baryons are states of three quarks (qqq), see figure 1.5. They have non-integral spin and are thus fermions with baryon number \( B = 1 \). The wave function of the baryons can be written as:

\[ |qqq\rangle = |color\rangle_A \times |space, spin, flavor\rangle_S \]  

(1.13)

Figure 1.5: Baryons (qqq).
where the subscripts $S$ and $A$ indicate symmetry or antisymmetry under interchange of any two equal-mass quarks. For all ground state baryons, the product of flavor and spin part is symmetric. But, since quarks are fermions, the total wave function must be antisymmetric, which is only possible if the color part is completely antisymmetric. This leaves two possibilities: baryons with $J^P = 3/2^+$ with symmetric spin and symmetric flavor part and baryons with $J^P = 1/2^+$ and mixed symmetry in the spin and flavor parts. The $J^P = 3/2^+$ states are arranged in one SU(3) decuplet and the $J^P = 1/2^+$ states in one SU(3) octet, see fig. 1.6.

Figure 1.6: The baryon octet (left) and decuplet (right). In the octet ($J^P = 1/2^+$) there are the proton, $p$, and the neutron $n$ made of $u$, $d$ quarks. The other components of the octet contain also the strange quark $s$.

The lowest mass baryons are made up of $u$, $d$, and $s$ quarks. The three flavors imply an approximate flavor SU(3), which requires that baryons made of these quarks belong to the multiplets on the right side of

$$3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A.$$  \hspace{1cm} (1.14)

Here the subscripts indicate symmetric, mixed-symmetry, or antisymmetric states under interchange of any two quarks. The 1 is a $uds$ state ($\Lambda 1$), and the octet contains a similar state ($\Lambda 8$). If these have the same spin and parity, they can mix. The mechanism is the same as for the (see above). In the ground state multiplet, the SU(3) flavor singlet $\Lambda 1$ is forbidden by Fermi statistics[13]. The addition of the $c$ quark to the light quarks extends the flavor symmetry to SU(4). However, due to the large mass of the $c$ quark, this symmetry is much more strongly broken than the SU(3) of the three light quarks. Figures 14.4(a) and 14.4(b) show the SU(4) baryon multiplets that have as their bottom levels an SU(3) octet, such as the octet that includes the nucleon, or an SU(3) decuplet, such as the decuplet that includes the $\Delta(1232)$. All particles in a given SU(4) multiplet have the same
spin and parity. The addition of a $b$ quark extends the flavor symmetry to SU(5). For the "ordinary" baryons (no $c$ or $b$ quark), flavor and spin may be combined in an approximate flavor-spin SU(6), in which the six basic states are $d \uparrow$, $d \downarrow$, ..., $s \downarrow$ ($\uparrow$, $\downarrow$ = spin up, down). Then the baryons belong to the multiplets on the right side of:

$$6 \otimes 6 \otimes 6 = 56_S \oplus 70_M \oplus 70_M \oplus 20_A.$$  \hfill (1.15)

where:

$56_S = 10 \oplus 2 \otimes 2$ made of a decuplet of spin $s = 3/2$ and multiplicity $2S + 1 = 4$ and an octet with $s = 1/2$ and multiplicity 2;

$70_M = 2 \otimes 4 \oplus 2 \otimes 8 \oplus 2 \otimes 2$ made of a decuplet of spin $s = 1/2$ and multiplicity 2, an octet with $s = 3/2$ and multiplicity 4, an octet with $s = 1/2$ and multiplicity 2 and a singlet with $s = 1/2$ and multiplicity 2;

$20_A = 1 \otimes 2 \otimes 2$ made of a singlet of spin $s = 3/2$ and multiplicity $2S + 1 = 4$ and an octet with $s = 1/2$ and multiplicity 2.

**Figure 1.7:** SU(4) multiplets of baryons made of $u$, $d$, $s$ and $c$ quarks. (a) The 20-plet with an SU(3) octet; (b) The 20-plet with an SU(3) decuplet.
Usually the baryons are classified into bands that have the same number \( N \) of quanta of excitation. Each band consists of a number of supermultiplets, specified by \((D, L^P_N)\), where \( D \) is the dimensionality of the SU(6) representation, \( L \) is the total quark orbital angular momentum, and \( P \) is the total parity. The \( N = 0 \) band, which contains the nucleon and \( \Delta(1232) \), consists only of the \((56,0^+_N)\) supermultiplet. The \( N = 1 \) band consists only of the \((70,1^+_N)\) multiplet and contains the negative-parity baryons with masses below about 1.9 GeV. The \( N = 2 \) band contains five supermultiplets: \((56,0^+_N), (70,0^+_N), (56,2^+_N), (70,2^+_N), \) and \((20,1^+_N)\).

Table 1.3: Quark-model assignments for some of the known baryons in terms of a flavor-spin SU(6) basis. Only the dominant representation is listed. Assignments for several states, especially for the \( \Lambda(1810), \Lambda(2350), \Xi(1820), \) and \( \Xi(2030) \), are merely educated guesses. † recent suggestions for assignments and re-assignments from ref. [16]

<table>
<thead>
<tr>
<th>( J^P )</th>
<th>((D, L^P_N))</th>
<th>\emph{Octet members}</th>
<th>\emph{Singlets}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2(^+)</td>
<td>((56,0^+_N))</td>
<td>1/2(N(939))</td>
<td>(\Lambda(1116))</td>
</tr>
<tr>
<td>1/2(^+)</td>
<td>((56,0^+_N))</td>
<td>1/2(N(1140))</td>
<td>(\Lambda(1600))</td>
</tr>
<tr>
<td>1/2(^-)</td>
<td>((70,1^-_N))</td>
<td>1/2(N(1535))</td>
<td>(\Lambda(1670))</td>
</tr>
<tr>
<td>3/2(^-)</td>
<td>((70,1^-_N))</td>
<td>1/2(N(1520))</td>
<td>(\Lambda(1690))</td>
</tr>
<tr>
<td>1/2(^-)</td>
<td>((70,1^-_N))</td>
<td>3/2(N(1650))</td>
<td>(\Lambda(1800))</td>
</tr>
<tr>
<td>3/2(^-)</td>
<td>((70,1^-_N))</td>
<td>3/2(N(1700))</td>
<td>(\Lambda(?))</td>
</tr>
<tr>
<td>5/2(^-)</td>
<td>((70,1^-_N))</td>
<td>3/2(N(1675))</td>
<td>(\Lambda(1830))</td>
</tr>
<tr>
<td>1/2(^+)</td>
<td>((70,0^+_N))</td>
<td>1/2(N(1710))</td>
<td>(\Lambda(1810))</td>
</tr>
<tr>
<td>3/2(^+)</td>
<td>((56,2^+_N))</td>
<td>1/2(N(1720))</td>
<td>(\Lambda(1890))</td>
</tr>
<tr>
<td>5/2(^+)</td>
<td>((56,2^+_N))</td>
<td>1/2(N(1680))</td>
<td>(\Lambda(1820))</td>
</tr>
<tr>
<td>7/2(^\pm)</td>
<td>((70,3^-_N))</td>
<td>3/2(N(2250))</td>
<td>(\Lambda(?))</td>
</tr>
<tr>
<td>9/2(^\pm)</td>
<td>((70,3^-_N))</td>
<td>3/2(N(2250))</td>
<td>(\Lambda(?))</td>
</tr>
<tr>
<td>9/2(^\pm)</td>
<td>((56,4^+_N))</td>
<td>1/2(N(2220))</td>
<td>(\Lambda(2350))</td>
</tr>
</tbody>
</table>

**Decuplet members**

<table>
<thead>
<tr>
<th>( J^P )</th>
<th>((D, L^P_N))</th>
<th>\emph{Octet members}</th>
<th>\emph{Singlets}</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/2(^+)</td>
<td>((56,0^+_N))</td>
<td>3/2(\Delta(1232))</td>
<td>(\Sigma(1385))</td>
</tr>
<tr>
<td>3/2(^+)</td>
<td>((56,0^+_N))</td>
<td>3/2(\Delta(1600))</td>
<td>(\Sigma(1690)) †</td>
</tr>
<tr>
<td>1/2(^+)</td>
<td>((70,1^-_N))</td>
<td>1/2(\Delta(1620))</td>
<td>(\Sigma(1750)) †</td>
</tr>
<tr>
<td>3/2(^-)</td>
<td>((70,1^-_N))</td>
<td>1/2(\Delta(1700))</td>
<td>(\Sigma(?))</td>
</tr>
<tr>
<td>5/2(^-)</td>
<td>((56,2^+_N))</td>
<td>3/2(\Delta(1905))</td>
<td>(\Sigma(?))</td>
</tr>
<tr>
<td>7/2(^+)</td>
<td>((56,2^+_N))</td>
<td>3/2(\Delta(1950))</td>
<td>(\Sigma(2030))</td>
</tr>
<tr>
<td>11/2(^-)</td>
<td>((56,4^+_N))</td>
<td>3/2(\Delta(2420))</td>
<td>(\Sigma(?))</td>
</tr>
</tbody>
</table>

Table 1.3 lists the established baryon resonances and their dominant quark-model assignments within a flavor-spin SU(6) basis. The question marks in this table represent the "missing states".


1.4 The non-relativistic harmonic oscillator and the Isgur-Karl models

The literature contains a large number quark-model predictions for the baryon spectrum\[17–26\]. Most of models start from three equivalent constituent quarks in a collective potential. The masses of the up and down constituent quarks range from 220 MeV for relativistic models to 330 MeV for non-relativistic models. Here, the quarks are not point-like but have electric and strong form factors. The potential is generated by a confining interaction, for example the potential of the harmonic oscillator, by a short range residual interaction. This fine structure interaction, usually taken as color magnetic dipole-dipole interaction mediated via one-gluon exchange (OGE), is responsible for the spin-spin and spin-orbit dependent terms\[9\].

Isgur and Karl solve the Schroedinger equation \( H\Psi = E\Psi \) for the three valence-quark system baryon energies and wave functions, with a Hamiltonian:

\[
H = \sum_i (m_i + \frac{\vec{p}_i^2}{2m_i}) + \sum_{i<j} (V^{ij} + H^{ij}_{hyp}),
\]

(1.16)

where the spin-independent potential \( V^{ij} \) has the form \( V^{ij} = C_{qqq} + br_{ij} - 2\alpha_S/3r_{ij} \) with \( r_{ij} = |\vec{r}_i - \vec{r}_j| \). In practice, \( V^{ij} \) is written as a harmonic-oscillator potential \( Kr_{ij}^2/2 \) plus an unspecified anharmonicity \( U_{ij} \), which is treated as a perturbation. The hyperfine interaction \( H^{ij}_{hyp} \) is the sum

\[
H^{ij}_{hyp} = \frac{2\alpha_s}{3m_im_j} \left\{ \frac{8\pi}{3} \vec{S}_i \cdot \vec{S}_j \delta^3(\vec{r}_{ij}) + \frac{1}{r_{ij}^3} \left[ \frac{3(\vec{S}_i \cdot \vec{r}_{ij})(\vec{S}_j \cdot \vec{r}_{ij})}{r_{ij}^2} - \vec{S}_i \cdot \vec{S}_j \right] \right\}
\]

(1.17)

of contact and tensor terms arising from the color magnetic dipole-magnetic dipole interaction. In this model the spin-orbit forces which arise from one-gluon exchange and from Thomas precession of the quark spins in the confining potential are deliberately neglected; their inclusion spoils the agreement with the spectrum, since the resulting splittings tend to be too large.
In zero-th order in the anharmonic perturbation $U$ and hyperfine perturbation $H_{hyp}$, the spatial wave functions $\psi$ are the harmonic-oscillator eigenfunctions $\psi_{NLM}(\rho, \lambda)$ where:

$$\rho = \frac{(\vec{r}_1 - \vec{r}_2)}{\sqrt{2}}, \lambda = \frac{1}{\sqrt{6}}(\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)$$  \hspace{1cm} (1.18)

are the Jacobi coordinates which separate the Hamiltonian in Eq. (1.16) into two independent three-dimensional oscillators when $U = H_{hyp} = 0$. The $\psi_{NLM}(\rho, \lambda)$ can then be conveniently written as sums of products of three-dimensional harmonic oscillator eigenstates with quantum numbers $(n, l, m)$, where $n$ is the number of radial nodes and $|l, m\rangle$ is the orbital angular momentum, and where the zero-th order energies are $E = (N + \frac{3}{2})\omega = (2n + l + \frac{3}{2})\omega$, with $\omega^2 = 3K/m$.

For nonstrange states these sums are arranged so that the resulting $\psi_{NLM}$ have their orbital angular momenta coupled to $\vec{L} = \vec{l}_\rho + \vec{l}_\lambda$, and so that the result represents the permutation group SU(3). The resulting combined six-dimensional oscillator state has energy $E = (N + 3)/\hbar\omega$, where $N = 2(n_\rho + n_\lambda) + l_\rho + l_\lambda$, and parity $P = (-1)^{|l_\rho - l_\lambda|} \hspace{1cm} [27]$.

The $N = 0$ oscillator band describes positive-parity ground-state baryons (including the $N(939)$ and $\Delta(1232)$), the $N = 1$ band describes the lowest negative-parity states, the $N = 2$ band describes the first positive-parity excited states, etc.

The eigenstates have the following structure:

$$\Psi_{N L t} = \tilde{N} P_N(\rho, \lambda)e^{-\frac{\alpha^2}{2}(\rho^2 + \lambda^2)}Y_{l_\rho}(\Omega_\rho)Y_{l_\lambda}(\Omega_\lambda)$$ \hspace{1cm} (1.19)

where:

$\tilde{N}$ is the normalization factor ;

$P_N$ is the polynomial of degree $N$;

$\vec{L}$ is given by the sum $\vec{l}_\rho + \vec{l}_\lambda$ with $|l_\rho - l_\lambda| \leq L \leq l_\rho + l_\lambda$;

$t$ is referred to the different kind of symmetry ($A$ Antisymmetric, $S$ Symmetric, $M$ Mixed);

$Y_{l_\rho}$ and $Y_{l_\lambda}$ are the spherical harmonic functions;
However, some states appear degenerate in the quantum number $N$ as the $\psi_{20S}$ state. This is evident from the table 1.4.

Table 1.4: Eigenstates $\psi_{nLt}$ of the harmonic oscillator.

<table>
<thead>
<tr>
<th>$\psi_{nLt}$</th>
<th>N</th>
<th>$n_\rho$</th>
<th>$n_\lambda$</th>
<th>$l_\rho$</th>
<th>$l_\lambda$</th>
<th>L</th>
<th>P</th>
<th>$N/J_2$</th>
<th>$P_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi_{00S}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\psi_{11M}^\rho$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-</td>
<td>$\alpha\sqrt{2}$</td>
<td>$\rho$</td>
</tr>
<tr>
<td>$\psi_{11M}^\lambda$</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-</td>
<td>$\alpha\sqrt{2}$</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>$\psi_{20S}$</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>$\frac{1}{\sqrt{2}}\alpha^2(\rho^2 + \lambda^2) - 3$</td>
<td></td>
</tr>
<tr>
<td>$\psi_{20M}$</td>
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<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>$\frac{\alpha^2}{\sqrt{3}}\rho^2 - \lambda^2$</td>
<td></td>
</tr>
<tr>
<td>$\psi_{22S/22M}$</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>+</td>
<td>$\frac{2\alpha^2}{\sqrt{15}}\rho^2$</td>
<td></td>
</tr>
<tr>
<td>$\psi_{22S/22M}$</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>+</td>
<td>$\frac{2\alpha^2}{\sqrt{15}}\lambda^2$</td>
<td></td>
</tr>
<tr>
<td>$\psi_{20M}$</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>+</td>
<td>$\frac{2\alpha^2}{\sqrt{3}}\rho\lambda$</td>
<td></td>
</tr>
<tr>
<td>$\psi_{21A}$</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>+</td>
<td>$\frac{2\alpha^2}{\sqrt{3}}\rho\lambda$</td>
<td></td>
</tr>
<tr>
<td>$\psi_{22M}$</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>+</td>
<td>$\frac{2\alpha^2}{\sqrt{3}}\rho\lambda$</td>
<td></td>
</tr>
</tbody>
</table>

The consequence of the anharmonic term $U$ in the eq. 1.16 is to remove the degeneracy of the level $N$ of the harmonic oscillator; the term of the hyperfine coupling ($H_{hyp}$) is used essentially to separate the degeneracy in mass between the proton $p(939)$ and the $\Delta(1232)$:

$$M_\Delta - M_N = \delta = \frac{4\alpha_S\alpha^3}{3m_q^2\sqrt{2\pi}}$$

(1.20)

where:

$$\alpha^2 = \sqrt{3km}$$

$$m_q = \frac{1}{3}m_N$$

$\delta$ = "hyperfine splitting":is adjusted to produce the correct mass difference observed between the nucleon and the $\Delta$. This results in the separation of the $\psi_{00S}$ state in:

$$\psi_{00S}\frac{1}{\sqrt{2}}(\Phi_{MAXMA} + \Phi_{MSXMS})$$

which represents the octet with $s = 1/2$ (proton,neutron etc.)

$$\psi_{00S}\Phi_{SXS}$$

which represents the decuplet with $s = 3/2$ ($\Delta$ etc.).

The theory is able to reproduce the trend of the experimental levels quite satisfactorily, considering the reduced number of free parameters that must be provided.
by the experiment. However, the number of expected resonances is higher than the observed ones.

Figure 1.8: Effective degrees-of-freedom in quark models: three equivalent constituent quarks, quark-diquark structure and flux tubes.

Alternative concepts are not a priori ruled out. In fact, models have been proposed which are based on other degrees of freedom, see fig. 1.8. One group of models describes the nucleon structure in terms of a quark-diquark \((q-q^2)\) cluster (see ref.[28]). If the diquark is sufficiently strongly bound, low lying excitations of the nucleon will not include excitations of the diquark. Therefore, these models predict fewer low exciting states of the nucleon than the conventional quark model. On the other hand, the number of states would be increased in an algebraic model proposed by Bijker et al.(ref.[29, 30]). The model is based on collective excitations of string-like objects carrying the quantum numbers of the quarks. Radial excitations arise from the rotations and vibrations of these strings. Alternative models are available not only in view of the ”constituents” but also in view of the residual interaction. In the conventional models, this interaction is due to OGE. Meanwhile, Glozman and Riska (see ref.[31]) have developed a model where the residual interaction is due to the exchange of the Goldstone bosons, taken to be the pseudo-scalar octet mesons. This is a radically different picture since in this case gluons do not contribute at all to the nucleon structure[32].

1.5 Nucleon resonances and meson photoproduction

The excitation spectrum of the nucleon is the most important ground where to test our understanding of QCD in the strong-coupling regime and the study of hadronic resonances plays the same role for understanding the nucleon structure as the nuclear spectroscopy played for the investigation of the nucleus structure.

The number of excited states with definite quantum numbers follows directly from the number of effective degrees-of-freedom and their quantum numbers in the
models. Consequently, a comparison of the experimentally determined excitation spectrum and the transition amplitudes to the model predictions should allow the determination of the number of degrees-of-freedom.

In the case of atomic or nuclear physics the excited states decay by photon emission which are the bosons of the electromagnetic field. Similarly, the hadronic resonances decay via meson emission.

\[ \gamma N \to N_{em}^* \to N \gamma \quad \pi N \to N_{had}^* \to N \pi \]

Thus, the lifetimes of excited states are typical for the strong interaction \((\tau \approx 10^{-24}s)\) with corresponding widths of about 100 MeV. The spacing of resonances is often no more than 10 MeV such that the overlap is large. This makes difficult to identify and investigate individual states, as demonstrated in fig 1.10 that shows the total photoabsorption cross section for the reaction \(\gamma N \to NX\) on the proton and neutron. The trend of the cross section with the energy can be expressed by a development in partial waves:

\[
\sigma = \frac{\pi \hbar^2}{p_{cm}^2} \sum_l (2l + 1) |1 - a_l|^2
\]

where:

- \(p_{cm}\) is the momentum in the center of mass of the reaction;
- \(a_l\) are the amplitudes of the partial waves \(\Rightarrow a_l = \eta_l e^{i\delta l}\).

In the case of elastic diffusion \(\eta_l = 1\); when a resonance mass \(m\) is excited, the cross section has a maximum for \(\delta_l = \pi/2\) and the dependence from the energy is characterized by the excitation curve:

\[
\sigma(pT \to N_j^*) = \frac{4\pi \hbar^2}{p_{cm}^2} \frac{2J + 1}{(2S_p + 1) \times (2S_T + 1)} \cdot \frac{(\Gamma/2)^2}{(E - E_R)^2 + (\Gamma/2)^2}
\]

where:

- \(p\) is the projectile particle;
- \(T\) is the target particle;
Chapter 1. *Quark model and meson photoproduction*

- $\Gamma$ is the half height amplitude of the Breit-Wigner function; the width of the resonance is strictly linked to the time of life of resonance, $\tau$, by the relation $\tau = \frac{\hbar}{\Gamma}$;

- $p_{cm}$ is the momentum of the projectile in the center of mass;

- $S_p$ is the spin of the projectile;

- $S_T$ is the spin of the target;

- $E_R$ is the central energy of the resonance peak.

The baryon resonances are baryon excited states with non-integral spin characterized by the quantum numbers, electric charge, spin, isospin, parity and charge conjugation.

There are two possibilities to reach a resonance state; the first is given by excitation in the elastic diffusion (*formation process*), the second consists in the production of a final state with defined mass and quantum numbers (*production process*).

![Figure 1.9: Excitation (left part) and production (right part) of the $\Delta$ resonance](image)

In the left part of the picture 1.9 is represented the formation process for the $\Delta$ resonance. In this case the projectile ($\pi$) and the target ($N = \text{nucleon}$) have the quantum number and the energy necessary to the formation of that resonance, thus the particles in the final states are the decay products of the reaction.

The resonance is produced with kinetic energy that can be deduced from the following expressions, in the laboratory system:

\[
(p_\pi + p_N)^2 = (M^*)^2 \rightarrow (E_\pi + m_N)^2 - p_\pi^2 = (M^*)^2
\]

\[
E_\pi^2 + m_N^2 + 2E_\pi m_N - p_\pi^2 = (M^*)^2
\]

\[
E_\pi^2 - p_\pi^2 = m_\pi^2 \rightarrow m_\pi^2 + m_N^2 + 2E_\pi m_N = (M^*)^2
\]
It gives:

$$E_\pi = \frac{(M^*)^2 - m_\pi^2 - m_N^2}{2m_N}$$

Thus, the kinetic energy necessary to produce the resonance is:

$$T_{LAB} = E_\pi - m_\pi = \frac{(M^*)^2 - m_\pi^2 - m_N^2}{2m_N} - m_\pi = \frac{(M^*)^2 - m_\pi^2 - m_N^2 - 2m_\pi m_N}{2m_N}$$

In the right part of the fig.1.9 the production process of the $\Delta$ resonance is reported. The interaction between the projectile and the target produces, in the final state, the resonance ($\Delta$ or $N^*$) and a pion. Then it decays in one or more pions and a nucleon; in this case the resonance is produced as a real particle not as an intermediate state.

**Figure 1.10:** Cross section for total photoabsorption on the proton (left part) and the neutron (right part). The points represent the measured data; the curves correspond to the fit of Breit-Wigner shapes of nucleon resonances ($P_{33}(1232), P_{11}(1440), D_{13}(1520), S_{11}(1535), F_{15}(1680)$ (only for the proton), and $F_{37}(1950)$) and a smoothly varying background[33].

The baryon resonances are usually indicated with the notation $L_{2I2J}(W)$ where $W$ is the mass, $L = 0, 1, 2, ..$ the angular momentum for the decay into the $N\pi$ - channel given in the spectroscopic notation as S,P,D,... and $I,J$ are the isospin and the spin of the resonances, respectively.

In the table 1.5 the list of $N^*(I = 1/2)$ and $\Delta^*(I = 3/2)$ resonances (using the spectroscopic notation) provided from the constituent quark-model is represented. The number of stars indicates the status of knowledge of the resonances.
Table 1.5: Classification of the $N^*(I = 1/2)$ and $\Delta(I = 3/2)$ resonances provided from the constituent quark-model. The degree of knowledge of the resonances is indicated by the number of stars; no stars means that the resonance is not yet observed ("missing resonances" problem)[8].

<table>
<thead>
<tr>
<th>$N^*$</th>
<th>Status</th>
<th>$SU(6) \times O(3)$</th>
<th>Parity</th>
<th>$\Delta^*$</th>
<th>Status</th>
<th>$SU(6) \times O(3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{11}(938)$</td>
<td>****</td>
<td>(56, 0$^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{11}(1535)$</td>
<td>****</td>
<td>(70, 1$^-$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{11}(1650)$</td>
<td>****</td>
<td>(70, 1$^-$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_{13}(1520)$</td>
<td>****</td>
<td>(70, 1$^-$)</td>
<td></td>
<td>$S_{31}(1620)$</td>
<td>****</td>
<td>(70, 1$^-$)</td>
</tr>
<tr>
<td>$D_{13}(1700)$</td>
<td>***</td>
<td>(70, 1$^-$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D_{15}(1675)$</td>
<td>****</td>
<td>(70, 1$^-$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{11}(1520)$</td>
<td>****</td>
<td>(56, 0$^+$)</td>
<td></td>
<td>$P_{31}(1875)$</td>
<td>****</td>
<td>(56, 2$^+$)</td>
</tr>
<tr>
<td>$P_{11}(1710)$</td>
<td>***</td>
<td>(70, 0$^+$)</td>
<td></td>
<td>$P_{31}(1835)$</td>
<td>(70, 0$^+$)</td>
<td></td>
</tr>
<tr>
<td>$P_{11}(1880)$</td>
<td>(70, 2$^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{11}(1975)$</td>
<td>(20, 1$^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{33}(1720)$</td>
<td>****</td>
<td>(56, 2$^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{13}(1870)$</td>
<td>*</td>
<td>(70, 0$^+$)</td>
<td></td>
<td>$P_{33}(1920)$</td>
<td>****</td>
<td>(56, 2$^+$)</td>
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<tr>
<td>$P_{13}(1910)$</td>
<td>*</td>
<td>(70, 2$^+$)</td>
<td></td>
<td>$P_{33}(1985)$</td>
<td>(70, 2$^+$)</td>
<td></td>
</tr>
<tr>
<td>$P_{13}(1950)$</td>
<td>(70, 2$^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{13}(2030)$</td>
<td>(20, 1$^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{15}(1680)$</td>
<td>****</td>
<td>(56, 2$^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{15}(2000)$</td>
<td>**</td>
<td>(70, 2$^+$)</td>
<td></td>
<td>$F_{35}(1905)$</td>
<td>****</td>
<td>(56, 2$^+$)</td>
</tr>
<tr>
<td>$F_{15}(1995)$</td>
<td>(70, 2$^+$)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$F_{17}(1990)$</td>
<td>**</td>
<td>(70, 2$^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{35}(1950)$</td>
<td>****</td>
<td>(56, 2$^+$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most nucleon resonances have been identified in pion scattering reactions which profit from the large hadronic cross-sections. However, the investigation of nucleon resonances only in the $N\pi$-channel has two obvious disadvantages: no use is made of the rich information connected to electromagnetic transition amplitudes and experimental bias may arise for nucleon resonances that couple only weakly to the $N\pi$-channel, which could be partially responsible of the "missing resonance" problem.

Meson photoproduction, where the nucleon is excited electromagnetically into the resonant state, which subsequently decays hadronically via the emission of mesons, is the ideal complementary tool. Historically, the first extended resonance studies used charged pions which due to their long lifetime and their charge are fairly easy
to detect. However, more recently neutral meson photoproduction moved into the center of interest. In fact, the reactions that involve neutral mesons have the advantage that non-resonant background contributions are much less important, because the incident photon couples only to charged mesons (fig.1.11).

![Figure 1.11: Example of the excitation function, i.e. the total cross section as function of the incident photon energy for photoproduction of charged and neutral pions from the proton is shown in the figure. In the energy region from 2 - 5 MeV the neutral channel shows a very clean signal for the excitation of the $P_{33}(1232)$ resonance. The charged channel on the other hand has a lot of background from other reaction mechanisms, e.g. the pion pole term. This background is particularly visible close to production threshold where the contribution from the Delta-resonance is still small.](image)

In particular, the investigation of meson photoproduction reactions requires two major components: a beam of high energy, quasimonochromatic photons and a device for the detection and identification of the produced mesons.

The production of the photons is almost entirely based on two different techniques: bremsstrahlung or laser backscattering (fig.1.12). In the bremsstrahlung facilities an electron beam is accelerated and directed into a converter target (usually a thin metal foil). In this target some of the electrons produce bremsstrahlung photons which are then used as photon beam.

In the laser backscattering facilities, low energy photons from a laser are shot on high energy electrons circling in a storage ring. A certain advantage of this technique is that the polarization degrees of freedom are transferred from the laser photons to the Compton back-scattered high energy photons. On the other hand, beam intensities are limited since high intensity laser beams reduce the lifetime of the stored electron beams[9].
Both techniques produce photon spectra with a continuous energy distribution. Thus, it is necessary in both cases to measure event-by-event the energy of the individual photons. This is done by the so-called "tagging" method.

The energy of the incident electron is known (fixed by the accelerator) and the energy of the scattered electrons is measured usually by means of magnetic momentum analysis. The photon energy is then the difference of the initial and final electron energies.

The GRAAL and the BGO-OD experiments that are the objects of the following chapters are experiments based, respectively, on the laser backscattering and bremsstrahlung techniques.

1.6 Polarization observables

Polarization observables play a central role in the identification of the baryon resonances; in fact polarization asymmetries are an essential ingredient in the interpretation of various meson production reactions in terms of the various resonances that contribute to the processes as real or virtual intermediate states [36].
The most general expression of the amplitude for the scalar meson photoproduction from the nucleon can be written in the Chew-Goldberger-Low-Nambu (CGLN) parametrization [37]:

$$ F = i F_1 \cdot \vec{\sigma} \cdot \vec{\epsilon} + F_2 \cdot (\vec{\sigma} \cdot \vec{q})(\vec{\sigma} \cdot (\vec{k} \times \vec{\epsilon})) + i F_3 (\vec{\sigma} \cdot \vec{k})(\vec{q} \cdot \vec{\epsilon}) + i F_4 (\vec{\sigma} \cdot \vec{q})(\vec{q} \cdot \vec{\epsilon}) \quad (1.24) $$

where $\vec{k}, \vec{q}$ are momentum unit vectors of the photon and meson, $\vec{\epsilon}$ is the polarization vector for a real photon of helicity $\lambda_{\gamma} = \pm 1$, and $\sigma$ are the nucleon’s spin matrices (fig.1.13).

The differential cross section in the center of momentum (cm) frame for an unpolarized target and an unpolarized photon beam is given in terms of the CGLN-amplitudes by:

$$ \frac{k^*}{q^*} \frac{d\sigma}{d\Omega} = \left[ |F_1|^2 + |F_2|^2 + \frac{1}{2} |F_3|^2 + \frac{1}{2} |F_4|^2 + Re(F_1 F_3^*) \right] + Re(F_3 F_4^*) - 2 Re(F_1 F_2^*) \cos(\Theta^*) - \right. $$

$$ \left. + \left[ |F_3|^2 + \frac{1}{2} |F_4|^2 + Re(F_1 F_4^*) + Re(F_2 F_3^*) \right] \cos^2(\Theta^*) - \right. $$

$$ \left. + \left[ Re(F_3 F_4^*) \right] \cos^3(\Theta^*) \right) \quad (1.25) $$

where $q^*, k^*$ are meson and photon cm momenta, respectively, and $\Theta^*$ is the cm polar angle of the meson. Four complex amplitudes are required to describe the process. Since one phase will always remain ambiguous, this means that seven quantities are required at each kinematic point. The differential cross section provides information only on the sum of the absolute squares of these amplitudes.
Instead, polarization observables allow extraction of more information, including phases \cite{36}.

In fact, a "complete" experiment does not only require the measurement of the differential cross section \(d\sigma/d\Omega\), the photon beam asymmetry \(\Sigma\), the target asymmetry \(T\) and the recoil nucleon polarization \(R\). In addition, several double polarization observables which are characterized as \(BT\)– (beam-target), \(BR\)– (beam-recoil), \(TR\)– (target-recoil) type have to be determined, in total at least eight polarization observables must be determined\cite{9}.

A different parametrization of the amplitude exists in terms of the helicities of the initial and final state particles. In the reaction \(\gamma N \rightarrow N'M\) (where \(M\) is a pseudoscalar meson) the following values of helicity are possible:

- \(\lambda_\gamma = \pm 1\) for the real photon;
- \(\nu_i = \pm \frac{1}{2}\) for the initial state nucleons;
- \(\nu_f = \pm \frac{1}{2}\) for the final state nucleons;

Therefore, eight matrix elements \(H = \langle \nu_f | T | \lambda_\gamma \rangle\) can be considered. They are reduced by parity conservation to the four independent helicity amplitudes \(H_1 \div H_4\), defined as follows:

\[
H_1 = H_{+1/2,+3/2} = +H_{-1/2,-3/2} \quad H_2 = H_{+1/2,+1/2} = -H_{-1/2,-1/2}
\]

\[
H_3 = H_{-1/2,+3/2} = -H_{+1/2,-3/2} \quad H_4 = H_{+1/2,-1/2} = +H_{-1/2,-1/2}
\]

The physical observables can be expressed in terms of helicity amplitudes \cite{38} as follows:

\[
\frac{d\sigma}{d\Omega} = \frac{1}{2} \frac{q^*}{k^*} (|H_1|^2 + |H_2|^2 + |H_3|^2 + |H_4|^2) \quad (1.28)
\]

\[
\Sigma = \frac{q^*}{k^*} \text{Re}(H_4^*H_1 - H_3^*H_2) \frac{d\sigma}{d\Omega} \quad (1.29)
\]
where \( q^* \), \( k^* \) are the cm momenta of meson and photon, and \( \Sigma, R, T \) are the photon beam asymmetry, recoil polarization and target asymmetry.

In general it is impractical to do the "complete" experiment. Therefore, the analysis of meson photoproduction data often relies on reaction models.

### 1.6.1 Multipoles

Since we are interested in the photoproduction of mesons via intermediate excitation of resonances, it is convenient to decompose the helicity amplitudes into multipole components because the intermediate resonance has definite parity and angular momentum.

For a definite orbital angular momentum \( \ell \) of the finale state composed of the meson-nucleon system, the possible multipoles are the following:

- \( E_{\ell \pm} \) that is referred to the electric multipole \( EL \) with \( L = \ell \pm 1 \)
- \( M_{l\ell \pm} \) that is referred to the magnetic multipole \( ML \) with \( L = \ell \)

where \( \ell \pm \) indicates that the intermediate resonance has total angular momentum \( J_R = \ell \pm \frac{1}{2} \) and parity \( P_R = (-1)^{\ell \pm 1} \).

In the initial state the photon couples electromagnetically to the nucleon to produce the resonance state. Then, the resonant state decays by strong interaction to the nucleon ground state via emission of the meson in the final state. The parity
and the angular momentum in the initial, resonant and final state must be the same. From the parity and angular momentum conservation laws the selection rules, on the resonance which can contribute to the process, can be derived:

1) Final state: \( J = \ell + \frac{1}{2} \Rightarrow \ell = J - \frac{1}{2} \)

\( \Pi_f = (-1)^{\ell + 1} ; \)

-Initial state:

a) \( L = J + \frac{1}{2} = \ell + \frac{1}{2} + \frac{1}{2} = \ell + 1 \)

\( \Pi_i = \Pi_f = (-1)^{\ell + 1} = (-1)^L \Rightarrow Electric \text{ multipoles } E_{i+}(EL) \)

b) \( L = J - \frac{1}{2} = \ell + \frac{1}{2} - \frac{1}{2} = \ell \)

\( \Pi_i = \Pi_f = (-1)^{\ell + 1} = (-1)^{L+1} \Rightarrow Magnetic \text{ multipole } M_{i+}(ML) \)

2) Final state: \( J = \ell - \frac{1}{2} \Rightarrow \ell = J + \frac{1}{2} \)

\( \Pi_f = (-1)^{\ell + 1} ; \)

-Initial state:

a) \( L = J + \frac{1}{2} = \ell - \frac{1}{2} + \frac{1}{2} = \ell \)

\( \Pi_i = \Pi_f = (-1)^{\ell + 1} = (-1)^{L+1} \Rightarrow Magnetic \text{ multipole } M_{i-}(ML) \)

b) \( L = J - \frac{1}{2} = \ell - \frac{1}{2} - \frac{1}{2} = \ell - 1 \)

\( \Pi_i = \Pi_f = (-1)^{\ell + 1} = (-1)^{L+2} \Rightarrow Electric \text{ multipole } E_{i-}(EL) \)

Each resonance can be excited by two multipoles, one electric and one magnetic, except for the resonant states with \( J = \frac{1}{2} \) that can be excited only by one multipole (\( E_{0+} \) for the states with negative parity and \( M_{1-} \) for states with positive parity.)

The multipole expansions of the helicity amplitude discussed before is given by [38]:

\[
H_1 \propto \sum_{\ell=0}^{\infty} [B_{\ell+} - B_{(\ell+1)-}] [P^\prime_{\ell} (\cos \theta^*) - P^\prime_{\ell+1} (\cos \theta^*)] \\
H_2 \propto \sum_{\ell=0}^{\infty} [A_{\ell+} - A_{(\ell+1)-}] [P^{\prime \prime}_{\ell} (\cos \theta^*) - P^{\prime \prime}_{\ell+1} (\cos \theta^*)] \\
H_3 \propto \sum_{\ell=0}^{\infty} [B_{\ell+} - B_{(\ell+1)-}] [P^{\prime \prime}_{\ell} (\cos \theta^*) + P^{\prime \prime}_{\ell+1} (\cos \theta^*)] \\
H_4 \propto \sum_{\ell=0}^{\infty} [A_{\ell+} - A_{(\ell+1)-}] [P^\prime_{\ell} (\cos \theta^*) + P^\prime_{\ell+1} (\cos \theta^*)] \\
(1.32)
\]
where $P'_\ell$, $P''_\ell$ are derivatives of Legendre polynomials; $B_{\ell \pm}$ and $A_{\ell \pm}$ are the following linear combinations of the $E_{\ell \pm}$ and $M_{\ell \pm}$ multipoles:

\[
A_{\ell+} = \frac{1}{2}[(\ell + 2)E_{\ell+} + \ell M_{\ell+}] \\
B_{\ell+} = E_{\ell+} - M_{\ell+}
\]

\[
A_{(\ell+1)-} = \frac{1}{2}[-\ell E_{(\ell+1)-} + (\ell + 2)M_{(\ell+1)-}] \\
B_{(\ell+1)-} = E_{(\ell+1)-} - M_{(\ell+1)-}
\]

Since the helicity amplitudes (or CGLN) can be expanded in a series of multipoles, it is possible also for the physical observables, which can be expressed as a function of the helicity amplitudes. In particular, the angular distribution of the cross section linked to each single resonance is different. In fact, the angular distributions reflect the quantum numbers of the excited state when the cross section is dominated by a resonance.

An example is the excitation of the $P_{33}(1232)$-resonance ($\Delta$-resonance) via the $M_{1+}$-multipole which exhibits the characteristic $(5 - 3\cos^2(\Theta^*))$ angular distribution.

Therefore, the analysis of resonance contributions uses a parametrization of the cross section in terms of multipole amplitudes. However, the differential cross-sections by themselves do not allow a unique extraction of the multipoles. They depend on the combination of the spin of the resonance and the order of the photon multipole but not on the combination of the parities of resonance and multipole. For example, the excitation of a $5/2^+$ resonance by an electric quadrupole has the same angular dependence as the excitation of a $5/2^-$ resonance by a magnetic quadrupole. This problem can be solved with the polarization observables. This
can very clearly be seen in the case of the $\eta$ meson photoproduction that is reported below.

### 1.6.2 An example: the $\eta$ photoproduction

The unpolarized differential cross section for the $\eta$ photoproduction in terms of the multipoles is given by (at the lowest order in the multipoles):

$$
\left( \frac{d\sigma}{d\Omega} \right)_{UNP}^{\eta} = \frac{q_{cm}}{2k_{cm}} \left\{ |E_{0^+}|^2 - \text{Re}[E_{0^+}^* (E_2 - 3M_{2^-})] + 2 \cos \theta \text{Re}[E_{0^+}^* (3E_{1^+} + M_{1^+} - M_{1^-})] + 3 \cos^2 \theta \text{Re}[E_{0^+}^* (E_{2^-} - 3M_{2^-})] \right\}. \tag{1.33}
$$

Since the multipole $E_{0^+}$ is dominant in the threshold region, it is very difficult to discern the contributions of the other resonant states. This ambiguity can be solved considering the beam asymmetry. In this case, other resonances become evident by the interference with the dominant multipole $E_{0^+}$:

$$
\Sigma = -\frac{q_{cm}}{2k_{cm}} \left( \frac{d\sigma}{d\Omega} \right)_{UNP}^{\eta} 3 \sin^2 \theta \text{Re}[E_{0^+}^* (E_{2^-} - M_{2^-})]. \tag{1.34}
$$

### 1.6.3 Isospin decomposition

Up to now the complication due to the isospin has not yet been considered. In fact, the isospin must be conserved at the hadronic vertex of the meson photoproduction reaction. For this reason, in the case of the $\eta, \eta'$ photoproduction that have isospin value $I_{\eta, \eta'} = 0$, the intermediate state must have $I_R = 1/2$ (since the nucleon isospin $I_N = 1/2$, see fig.1.16). As a consequence, the $\eta, \eta'$ photoproduction is an *isospin filter* because it allows to produce only $N^*(I = 1/2)$ resonances, that usually are hidden from the $\Delta(I = 3/2)$ resonances.

Instead, pion photoproduction allows the access to both intermediate states with $I = 1/2$ ($N^*$) and with $I = 3/2$ ($\Delta$)(fig.1.17).
Figure 1.16: The meson photoproduction with $I = 0$ allows the access to the intermediate resonances with $I = 1/2$ ($N^*(I = 1/2)$ resonances).

Figure 1.17: In the pion photoproduction reaction can be produced both intermediate states with $I = 1/2$ ($N^*$) and with $I = 3/2$ ($\Delta$).

However, in the electromagnetic vertex the isospin can be violated, thus on this vertex both the isoscalar ($\Delta I = 0$) and isovector ($\Delta I = 0, \pm 1$) components of the electromagnetic current must be considered. Each multipole amplitude has to be reconstructed from the various isospin contributions. In the case of the isovector meson photoproduction, as the pion, three independent matrix elements must be defined [39]:

\[
A^{IS} = \langle I_f = \frac{1}{2}, I_{f,3} = \pm \frac{1}{2} | \hat{S} | I_i = \frac{1}{2}, I_{i,3} = \pm \frac{1}{2} \rangle
\]

\[
\mp A^{IV} = \langle I_f = \frac{1}{2}, I_{f,3} = \pm \frac{1}{2} | \hat{V} | I_i = \frac{1}{2}, I_{i,3} = \pm \frac{1}{2} \rangle
\]

\[
A^{V3} = \langle I_f = \frac{3}{2}, I_{f,3} = \pm \frac{1}{2} | \hat{V} | I_i = \frac{1}{2}, I_{i,3} = \pm \frac{1}{2} \rangle
\]

where $S$ and $V$ are the isoscalar and isovector parts of the transition operator.

The four possible pion photoproduction reactions off proton and neutron are not independent each other; they can be expressed in terms of the combination of the three isospin amplitudes:

\[
A(\gamma p \rightarrow \pi^+ n) = -\sqrt{\frac{1}{3}} A^{V3} + \sqrt{\frac{2}{3}} (A^{IV} - A^{IS}) \quad A(\gamma p \rightarrow \pi^0 p) = \sqrt{\frac{2}{3}} A^{V3} + \sqrt{\frac{1}{3}} (A^{IV} - A^{IS})
\]

\[
A(\gamma n \rightarrow \pi^- p) = \sqrt{\frac{1}{3}} A^{V3} - \sqrt{\frac{2}{3}} (A^{IV} + A^{IS}) \quad A(\gamma n \rightarrow \pi^0 n) = \sqrt{\frac{2}{3}} A^{V3} + \sqrt{\frac{1}{3}} (A^{IV} + A^{IS})
\]
For the $\eta$ photoproduction which is an isoscalar particle, for example, the relations are more simple:

$$A(\gamma p \rightarrow \eta p) = (A^{IS} + A^{IV})$$
$$A(\gamma n \rightarrow \eta n) = (A^{IS} - A^{IV})$$ (1.38)

The complication of isospin amplitude means that a complete characterization of the photoproduction amplitudes for isovector as well as for isoscalar mesons requires also measurements off the neutron which must rely on meson photoproduction from light nuclei. In principle, two possibilities exist to learn about the isospin composition via production from nuclei. Photoproduction from bound nucleons in quasifree kinematics can be used to extract the production cross section on the neutron. Here, the meson is produced on one nucleon which is subsequently knocked out of the nucleus. The other nucleons act only as spectator. Additional information can be obtained from coherent meson photoproduction, where the reaction amplitudes from all nucleons add coherently and the nucleus remains in its ground state. Nuclei with different ground state quantum numbers may be used as spin/isospin filters of the production amplitudes.
Chapter 2

The GRAAL experiment

2.1 Introduction

The Graal experiment (GRenoble Anneau Accelerateur Laser) has aimed at a more detailed knowledge of the baryon spectrum via the precise measurement of cross sections and polarisation observables in photo-induced reactions on the nucleon. The GRAAL facility has been located at the European Synchrotron Radiation Facility (ESRF) in Grenoble (fig.2.1). It provided a polarised and tagged photon beam by the backward Compton scattering of laser light on the high energy electrons (6.03GeV) circulating in the ESRF storage ring (844 m circumference), over a 6.5 m long straight section (the interaction region).

![Figure 2.1: ESRF storage ring (Grenoble, France.)](image)

The GRAAL experiment has been dismantled at the end of 2008 after a long activity of 16 years. Many results have been extracted for the first time in the
energy range $E_\gamma = 0.5 \div 1.5$ GeV in a wide angular range with very high precision due to the excellent performances of the beam (high polarization degree) and of the detector, providing strong constraints on models. The Graal data have allowed, among the various results, the extraction of the width of the $S_{11}$ resonance ($\Gamma = 180$ MeV) [40].

![Figure 2.2: Estimated total cross-section for the reaction $\gamma p \rightarrow \eta p$. The GRAAL results (closed circles) are compared with CLAS (open squares), CBELSA (open stars) and LNS-GeV-$\gamma$ (open crosses) data[40].](image)

The precise determinations of the resonance properties, like the estimation of the branching ratio of the $D_{13}(1520)$ and $F_{15}(1680)$ resonances in the $\eta N$ channel have been also achieved [41].

For the first time in the same experiment the beam asymmetry of the four photoproduction channels of pions off proton and neutron have simultaneously been measured [42],[43],[44],[45].

1. $\gamma p \rightarrow \pi^0 p$
2. $\gamma p \rightarrow \pi^+ n$
3. $\gamma n \rightarrow \pi^0 n$
4. $\gamma n \rightarrow \pi^- p$
In fact, as reported in chapter 1, the four reactions are not independent since they can be described in terms of the three reaction amplitudes (eq. 1.35).

The GRAAL setup consisted of a tagged and linearly polarized photon beam, a liquid Hydrogen or Deuterium target and a large acceptance detector (LAGRAN$\gamma$$E$). The backscattered photons of useful energies are emitted in a narrow cone and impinge on the liquid-Hydrogen target placed at 41.5 m from the center of the interaction region, while the scattered electrons are detected in an internal tagging system. The beam size at the target is $\approx 2 \times 1 cm^2$. A primary collimator followed by a sweeping magnet is used only to cut the low-energy tails of the beam. Two secondary collimators placed under vacuum eliminate the multitude of low-energy photons produced by showers in the main collimator and are essential to get a reduced electromagnetic background in the detector[46].

### 2.2 The $\vec{\gamma}$ beam at GRAAL

In the case of Compton scattering of low-energy photons off ultra-relativistic electrons, the energy dependence of the scattered photon versus angle in the laboratory frame reduces to:

$$E_\gamma = \frac{4\gamma^2 E_L}{1 + \frac{4\gamma E_L}{m_e} + \theta^2 \gamma^2},$$  \hspace{1cm} (2.1)

where $\theta$ is the angle between the scattered photon and the incident direction of the electron, $\gamma$ is the Lorentz factor of the electron ($\approx 12000$ for the 6 GeV ESRF beam), $E_L$ is the energy of the incident photon and $m_e$ is the mass of the electron (fig.2.3).

![Figure 2.3: Definition of Compton-scattering kinematical variables.](image)

The $\phi$ angle between the incoming photon and the electron beam axis cannot exceed $1^\circ$ given the geometry of the set-up and has no measurable influence. The
maximum photon energy (Compton edge) depends on the laser wavelength. The Compton scattering generates a beam shape which depends strongly on energy and polarization. By contrast to Bremsstrahlung beams, the energy spectrum is rather flat and the low-energy photons can be suppressed by collimation before they reach the target (fig. 2.4) [46].

The $\gamma$-ray beam polarization is calculated with the help of the Klein-Nishina formula and was first derived for such asymmetric collisions by Arutyunian et al. [49]. Its energy dependence is displayed in fig. 2.5 for two of the used wavelengths (514 nm, 351 nm) and in the case of a 100% linearly polarized laser beam.

The $\gamma$-ray polarization is close to 1 at the Compton edge (98% for green and 96% for UV) and decreases smoothly with energy down to a minimum of $\approx 20\%$ at our energy threshold ($E_\gamma \approx 550$ MeV). Polarization of backscattered photons is proportional to the incident laser light polarization. Before each period of data taking, the laser polarization was measured into the laser hutch, after all optical elements. In order to avoid any distortion during the beam transport, a special viewport was used to minimize mechanical stress on the window.

The laser polarization was evaluated as:

$$P_L = 98 \pm 2\%.$$
Figure 2.5: Theoretical linear polarization of the $\gamma$-ray beam for two laser lines: $\lambda = 514$ nm (green line) and $\lambda = 351$ nm (UV line). The energy threshold (550 MeV) introduced by the tagging system is shown.[46]

Polarization calculation at a given energy or equivalently at a given scattering angle $\theta$ results from an integration over the azimuthal angle of all photons emitted at the same $\theta$:

$$P(\theta) = \frac{\int P(\theta, \phi) \frac{d\sigma}{d\Omega}(\theta, \phi) d\phi}{\int \frac{d\sigma}{d\Omega}(\theta, \phi) d\phi}$$  \hspace{1cm} (2.2)

Due to the scattering of electrons on the residual vacuum over the 6.5 m long interaction region, unpolarized Bremsstrahlung photons contaminate the Compton beam and affect the average degree of polarization. Thanks to an excellent vacuum in the ring, the fraction of Bremsstrahlung photons $F_{\text{Brems}}/F_{\text{Compton}}$ remained of the order of 0.1% over the entire experiment. In summary, the expression used to calculate the beam polarization and its associated error is given by:

$$P_\gamma = P_L P_{\gamma}^{th} \left( 1 - \frac{F_{\text{Brems}}}{F_{\text{Compton}} + F_{\text{Brems}}} \right),$$ \hspace{1cm} (2.3)

$$\frac{\delta P_\gamma}{P_\gamma} = \sqrt{\left( \frac{\delta P_L}{P_L} \right)^2 + \left( \frac{\delta P_{\gamma}^{th}}{P_{\gamma}^{th}} \right)^2 + \left( \frac{\delta F_{\text{Brems}}}{F_{\text{Compton}} + F_{\text{Brems}}} \right)^2},$$ \hspace{1cm} (2.4)

where $P_{\gamma}^{th}$ is the calculated polarization. The only significant source of error came from the laser beam polarization:
\[ \frac{\delta P_\gamma}{P_\gamma} = \frac{\delta P_L}{P_L} = 0.02. \]  

(2.5)

2.3 GRAAL apparatus

The detection system includes three main parts.

- At forward angles \( \theta_{lab} \leq 25^\circ \) there are two planar wire chambers, a time-of-flight (TOF) hodoscope made up of 26 horizontal and 26 vertical plastic scintillator bars, each 3 cm thick, and a TOF shower wall. The latter is an assembly of 16 modules, each being a sandwich of four converter-plus-scintillator layers.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{graal_setup.png}
\caption{General layout of the GRAAL set-up (the drawing is out of the scale).}
\end{figure}
- At central angles from 25° to 155°, the target is surrounded by two cylindrical multi wire chambers, a 5 mm thick scintillator $\Delta E$ barrel, and a ball made up of 480 crystals, each of 21 radiation lengths.

- At backward angles $\theta_{\text{lab}} \geq 155^\circ$ there are two plastic scintillator disks separated by a 1 cm lead converter for veto purposes.

The apparatus provides the detection and identification of all types of final state particles in an almost $4\pi$ solid angle and has cylindrical symmetry, making it suitable for measurements of the beam asymmetry $\Sigma$ [50].

### 2.3.1 Beam detectors

The monitoring of the gamma beam was performed by using:

- two detectors to determine the flux of the photons in the experimental area;
- the tagging system to measure the photon energy and give the start signal of each photo-nuclear event.

#### 2.3.1.1 Flux detectors

The $\gamma$-ray beam intensity has been measured by means of a low efficiency thin monitor. It was used to avoid pile-up problems at high counting rate. It consists of three plastic scintillators ($5 \times 5 \times 0.5 \text{cm}^3$), the first one acting as a veto, the two others being in coincidence, and a thin $\text{Al}$ converter (2 mm) placed after the veto. The efficiency measured is equal to $(2.68\% \pm 0.03)$[46]. It has been obtained by the comparison with the SPACAL absorber at low rate. It is a lead/scintillating fiber calorimeter with efficiency of 100%. It takes into account the $\gamma$-ray conversion in the Al converter and it is found experimentally independent of the $\gamma$-ray energy in the covered range[47]. The typical flux during the experiment was $10^6 \gamma/sec$.

#### 2.3.1.2 Tagger

The photon energy is provided by an internal tagging system (fig. 2.7) located right after the exit dipole of the interaction region (fig.2.6). The position of the scattered electron is measured by a silicon microstrip detector (128 strips with
a pitch of 300 $\mu m$ and 1000 $\mu m$ thick). Two long plastic scintillators covering most of the focal plane (38.4 mm) and eight additional small ones (6.8 mm long) are situated behind the microstrip detector. The small scintillators overlap each of the neighbouring ones by 2 mm along the direction of the incoming electron beam. The signal rise time of the plastic scintillators is less than 1.8 ns and a custom made electronics, based on GaAs technology, provides the synchronization of the discriminated signal of one of the long scintillators with the RF signal of the electron beam. The final logical signal has a total time jitter less than 100 ps with respect to the timing of the electron beam and is capable of separating two electrons of adjacent bunches (2.8 ns). This signal drives a triple coincidence (called ”TAG” hereafter) with the second long scintillator and any of the small plastic scintillators that provides an excellent global start signal for all Time-of-Flight (ToF) measurements and enters in the different triggers of the experiment [46].

The whole system is shielded against the huge X-ray background by a 4$\pi$ box made of stainless steel and tungsten and having a total thickness equivalent to 8 mm of lead. The thickness of this box and the minimum distance allowed between its wall and the electron beam determines our threshold of 550 MeV. The experimental energy resolution can be directly extracted from the fit of the Compton edge with an error function. The measured resolution of 16 MeV (FWHM) is in agreement with the estimated one extracted from the simulation and is dominated by the energy spread of the electrons in the storage ring (FWHM = 14 MeV). The relation between the $\gamma$-ray energy $E_\gamma$ and the distance, $x_e$, of the scattered electron from the beam axis can be approximated by the following expression:
\[ E_\gamma = E_e \frac{x_e}{a_0 + x_e} \]  

(2.6)

where \( E_e \) is the electron beam energy and \( a_0 \) is a geometrical factor, constant to an excellent approximation over the tagged energy range \( (da_0/a_0 = 5 \cdot 10^{-4}) \). The beam energy value provided by the ESRF machine group, based on an \( \int Bdl \) measurement over the ring, was:

\[ E_{eESRF} = 6040 \pm 20 \text{ MeV}. \]  

(2.7)

The geometrical factor \( a_0 \) depends on the radius of curvature in the dipole and on the longitudinal position of the microstrip detector. Its value can be inferred from the distance between Compton edges associated with different laser lines. We have obtained:

\[ a_0 = 159.92 \pm 0.3 \text{mm} \]

Finally, the distance \( x_e \) of the scattered electron to the beam axis is:

\[ x_e = (n_{\mu strip} - 0.5)\Delta x + x_0 \]  

(2.8)

where \( n_{\mu strip} \) is the number of the hit microstrip, \( \Delta x \) the pitch (300 \( \mu \text{m} \)) and \( x_0 \) the distance of the first microstrip to the stored electron beam. This latter parameter is deduced from the fit of the position of the Compton edge run by run. Taking into account all possible sources of uncertainties, we estimate that the absolute error on the photon energy calibration does not exceed \( \approx 2 \text{ MeV} \) over the whole tagged range.

### 2.3.2 The target

The target cell is an aluminum hollow cylinder of 4 cm in diameter closed by thin mylar windows (100 \( \mu \text{m} \)) at both ends. It can be filled with liquid Hydrogen (\( H_2 \)) or Deuterium (\( D_2 \)). To satisfy different experimental requirements (resolution versus counting rates), three different lengths (3, 6 and 11 cm) have been used over
the data taking periods. When filled with hydrogen, the working temperature is 18 K, giving a density $\rho \approx 7 \cdot 10^{-2} \text{g/cm}^3$.

![Longitudinal target profile reconstructed from the vertex distribution of the $\rho\pi^+\pi^-$ reaction in the case of a 6 cm long target.](image)

**FIGURE 2.8:** Longitudinal target profile reconstructed from the vertex distribution of the $\rho\pi^+\pi^-$ reaction in the case of a 6 cm long target.

The longitudinal position of the target is a crucial parameter for the control of the acceptance. The target profile displayed in fig. 2.8 corresponds to the vertex distribution (along the beam axis) of the three charged particles reaction $\rho\pi^+\pi^-$, provided by the central tracking detector. From this distribution, the exact target position could be extracted. It should be noted that the profile shape reflects the geometrical acceptance of the central part of the detector for the selected events [46].

### 2.3.3 The LAGrAN$\gamma$E apparatus

The $4\pi$ LAGrAN$\gamma$E (Large Acceptance Graal Apparatus for Nuclear $\gamma$ Experiment) detector (fig.2.9) has been designed to detect both neutral and charged particles produced in photoproduction reactions on light nuclei with total center-of-mass energy $W \leq 2$ GeV. The apparatus is composed of two main parts: a central one ($25^\circ \leq \theta \leq 155^\circ$) and a forward one ($\theta \leq 25^\circ$).

#### 2.3.3.1 Central detectors

The central detectors consist of the BGO electromagnetic calorimeter, the scintillator barrel and the Multi-Wire-Proportional-Chambers (MWPC). The BGO detector is shown in detail in fig. 2.10. The electromagnetic calorimeter is made
of 480 BGO crystals (Bismuth germanate, $Bi_4Ge_3O_{12}$). It is designed to measure energies and angles of gammas and low-energy protons up to 300MeV/c, as well as the angles and $\Delta E$ response for charged pions\cite{51–53}.

![Figure 2.9: Sketch of the LAGrAN$\gamma$E detection system.](image)

The mechanical support structure of the BGO calorimeter consists of 24 baskets of carbon fiber composite material supported by an external steel frame. Each basket is divided into 20 cells with very thin walls, 0.38mm for the inner and 0.54mm for the outer walls, to keep the crystals optically and mechanically separated. The support frame is divided into two halves which can be taken apart by 1.5m to allow the access to the target and to the central detector region. When closed, the structure leaves a 20cm - diameter hole along the beam-line for the insertion of the target, the cylindrical wire chambers and the plastic scintillator barrel.

![Figure 2.10: BGO detector. In the picture also the target system and TOF wall are visible.](image)
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Figure 2.11: A sketch of the BGO calorimeter showing the carbon fiber baskets mounted on the external support frame separable into two halves.

The crystals are of eight different dimensions and are shaped like truncated pyramidal sectors with trapezoidal basis. They define 15 angular regions in the plane containing the beam axis and 32 regions in the plane orthogonal to the beam axis. The 480 crystals have all the same length of 24 cm (corresponding to 21 r.l.). Each crystal is wrapped up in a thin (30 µm) aluminized mylar reflector and its back side is optically coupled to a photomultiplier (see fig.2.12).

![Figure 2.12: One BGO crystal.](image)

Decay time and scintillation light efficiency of BGO are known to be strongly dependent on temperature especially in the range of room temperatures; unfortunately this related temperature behaviour is not precisely known and seems to depend rather strongly on crystals construction procedure and on intrinsic crystal properties (shape, dimensions, concentration of impurities and of air bubbles, trapping centers, etc.).
The energy dependence of the BGO energy resolution of photons is presented in fig. 2.13. The energy resolution was parameterized in the usual way:

\[
\Gamma(\%) = \sqrt{a^2 + \left(\frac{b}{E_\gamma}\right)^2 + \left(\frac{c}{\sqrt{E_\gamma}}\right)^2}
\]  

(2.9)

where \(a\) represents the constant term that gives the asymptotic behavior, \(b\) is the noise term generally negligible at high energies (but not in our case), and \(c\) is the statistical term containing sampling and fluctuations of all kinds. The energy resolution (FWHM) results \(\simeq 3\%\) for \(E_\gamma = 1\text{GeV}\).

In the chapter six, will be presented the measurement of the BGO resolution performed at the BTF (Beam Test Facility) of Frascati. We made new tests of the BGO crystals in order to study their characteristics in combination with the new electronics readout currently used at the BGO-OD experiment at the ELSA facility in Bonn.

- A cylinder of 32 bars of plastic scintillator (NE110A) is installed between the cylindrical chambers and the calorimeter. Each bar is 43.4 cm long, with a trapezoidal section \((h = 18\text{mm}, H = 19\text{mm})\). The bars are housed, four by four, in a carbon fiber structure 0.5 mm thick. Each bar covers an azimuthal section of the calorimeter. The internal diameter of the barrel is 9.4 cm. The scintillators are 5 mm thick and they allow neutral and charged discrimination and charged particle identification by energy loss measurement in combination with the measurement of the energy released in the BGO.

- The Multi Wire Proportional Chambers (MWPC) are used to measure the direction of the charged particles which leave the target after a nuclear reaction. The
two chambers, which are cylindrically symmetric, surrounding the target along
the axis $z$ are placed one inside the other. They cover a polar angle between $25^\circ$
and $160^\circ$, the inner and outer diameters of the chambers are respectively 10 cm
and 17 cm, their length is 40 cm and 50.5 cm. The center of both chambers is
movable in the forward direction with respect to the center of the target in order
to increase the detection efficiency of charged particles that tend to be emitted in
the forward direction in the laboratory system due to the Lorentz boost[54].

![Image of the cylindrical chamber: the wires and the internal
cathode of the internal chamber are shown. The second cathode (not present)
is superimposed with opposite helicity.](image1)

**Figure 2.14:** Image of the cylindrical chamber: the wires and the internal
cathode of the internal chamber are shown. The second cathode (not present)
is superimposed with opposite helicity.

![Scheme of the Multi Wire Proportional Chambers.](image2)

**Figure 2.15:** Scheme of the Multi Wire Proportional Chambers.

For each chamber the anodes consist of gilt tungsten wires ($20 \ \mu m$ diameter)
stretched along the cylinder axis (corresponding to the beam one). The wires are
surrounded by two cathodes planes made of strips as shown in fig.2.15. The gap
between wires and strips is 4mm. The cathodes are made of copper deposited
on kapton sheets which are glued on a shell of polymetacrilate foam. The two
cathodes of one chamber are structured in adjacent strips (3.5 mm wide, 0.5 mm
between two strips) wrapped as spirals around the beam axis (see fig.2.14 ) and
with opposite helicity with respect to the beam ($z$) axis. The gas of the chamber
is an argon-ethan (85% and 15% respectively) mixture.

The azimuthal position of a given particle is directly deduced from the hit wire and
the position along the chamber axis (z coordinate) is calculated from the charge distribution on the cathode strips.

### 2.3.3.2 Forward detectors

They are composed by the two planar multiwire chambers (MWPCs), a double layer scintillator hodoscope and a shower detector.

- The plane chambers are composed of two planes of wires (3mm distance between the two wires) with perpendicular directions. The first chamber has the wires oriented in the x, y direction while the second in the u, v direction (at 45°) with respect to the x, y plane) in order to resolve the ambiguities when more than one particle goes through the chambers. The chambers are respectively 93.2 and 133.2 cm far from the target center. Each plane is composed of gilt tungsten wires, placed between aluminized mylar cathodes. The space within each catode (10mm) is filled in with an Argon-Ethane mixture (85 and 15%, respectively). A 2400V voltage is applied to the wires. Under these conditions the efficiency is close to 100% for the detection of one particle and the position resolution is comparable to the wire distance. The angular limit of the plane chambers is $\theta < 21^\circ$. Since the lower limit of the cylindrical chambers is $\theta > 25^\circ$, there is a small angular region that is not covered by the detectors [54].

- A $3 \times 3 m^2$ plastic scintillators wall identifies charged particles in the forward direction. The wall is made up by two series of 26 scintillator bars, respectively vertically and horizontally oriented. This detector gives an angular resolution of $2^\circ$ and it measures the time of flight with a resolution $F_{TOF} = 600 ps$ for the charged particle identification and energy measurement for protons[34]. The detection efficiency is 100% if the particle energy is greater than few MeV.

- The shower detector is an assembly of 16 modules, mounted with their long axes in the vertical direction and covering all together a sensitive area of $3 \times 3 m^2$ with position resolution of 11-18 cm and a time-of-flight resolution of 600 ps for photons and charged particles and 700-800 ps (FWHM) for neutrons. The modules are attached to a strong mechanical arch, aligned relatively to the beam and permanently fixed in the experimental hall at 3.3m from the target. Two central modules have half-circle holes, which form a 9 cm diameter hole for the beam passage. Each module is a composition of four $4 \times 19 \times 300 cm^3$ scintillator
bars, separated by three layers of 3 mm thick lead converter. The scintillator bars have been manufactured in the Kharkov Institute for Single Crystals and are made of polystyrene polymer with scintillating additives. This material was chosen because of its radiation and aging hardinesses, fast light decay and relatively low price. The bars for each module were machined together from the same bulk, in order to obtain identical sizes and properties, and then they have been hand-polished[48].

The main functions of the shower detector are:

1. Detection of photons, emitted at forward angles from short-life particle decays as ($\pi^0 \rightarrow 2\gamma$), ($\eta \rightarrow 2\gamma$), ($\Sigma \rightarrow \gamma\Lambda$), their discrimination from neutrons and the determination of their angles from the hit positions in the wall;

2. Detection of neutrons produced in photon induced reactions on the proton and the neutron, determination of their momenta by means of the measured TOF and the hit position;

3. TOF and position measurement for charged particles, complementing the information from the preceding MWPCs and the scintillator hodoscope.

### 2.4 Acquisition system

The GRAAL experiment scheme of the acquisition system (called SAGA, *Sisteme Acquisition Graal Asic*) is a hardware event builder which associates compact and programmable ASIC type electronics and standard electronics read by a FERA bus. ASIC circuits permit analog to digital signal processing for many types of particle detectors, such as anode wires and cathode strips of the MWPCs, photomultipliers and drift chambers. The electronics is directly placed on boards and connected to the detector, in order to reduce the number of interconnections and, therefore, the risk of failure due to connectors. The data transfer is performed by a 32 bit ECL bus, linking all the detectors. A SUN workstation controls all the detectors settings by the ASIC bus. Once the buffer is transferred in the shared SUN memory, it can be recorded on tapes or processed by the spectra building program, running on the workstation[35].

Six of the twelve detectors are controlled by the FERA electronic system. Their calibration and their monitoring is performed by a traditional CAMAC system.
on a Alpha station, operating with the VMS. The FERA bus is read by the ASIC bus through the FASIC module (thresholds, delays, amplitudes, widths, channel connection on a oscilloscope, etc.) located on the different boards. It runs on the SUN station with a powerful graphical interface called SL-GMS. The data acquisition time depends on the largest conversion time (4 $\mu$s for the audio converter), on the bus speed (5 ns/m) multiplied by two VME periods (125 ns). For about 100 events this time amounts at 17.5 $\mu$s, giving, this way, a transfer rate of about 23 Mbytes/s, that has to be compared to the ETHERNET transfer limit (600 Kbytes/s). The trigger frequency being about 200 Hz, the number of lost events is thus negligible [54].

### 2.4.1 Trigger system

The acquisition system is composed of different triggers, which come from either physical or beam events. All of them are in coincidence with the Tagging detector. An energy deposition in the BGO larger than 200 MeV, in coincidence with an electron in the Tagging detector, triggers the data acquisition for the physical events. This energy threshold eliminates almost all the electromagnetic background. This trigger is used for the photoproduction of mesons that decays into photons. Channels with three charged particles are triggered by the following condition: at least two particles in the forward hodoscope and at least one particle in the central barrel. This trigger allows to study the photoproduction of strange mesons ($K\Lambda$ and $K\Sigma$) as well as the charged decay of other mesons ($\eta, \omega$). Two other triggers rule the beam acquisition: the first is the coincidence between the second and the third scintillators of the thin monitor in anticoincidence with the first one and in coincidence with an electron in the Tagging detector. The second is an energy threshold on the SPACAL, always in coincidence with an electron in the Tagging detector. These triggers allow to calculate the monitor efficiency and the beam flux [54].

### 2.4.2 Data taking

Each period of data taking is divided into runs. The run length is approximately four hours long, depending on the trigger and on the intensity of the laser line. During each run the two laser states are alternated with the bremsstrahlung mode.
For each trigger and each polarization or Bremsstrahlung state the acquisition records on a module of scales the total number of events. In particular the monitor, the SPACAL and the time scales are read to calculate the beam flux for each polarization and Bremsstrahlung state. The maximum flux is limited by the ESRF. In fact, the loss of electron beam life time due to Compton backscattering may never exceed 20% of the electron time of life.

2.5 Data preanalysis

The fig. 2.16 displays the flow chart of the programs used to process simulated and real data. The structure was designed in order to have the same type of analysis (starting from the program prean) for both real and simulated data.

The prean program receives digital output (ADC, TDC, signals from MWPCs...) and transforms them into physical quantities. The number of charged tracks in the MWPCs is calculated together with their energy loss in the hodoscope or barrel and any energy released in the calorimeters (shower or BGO). Neutral particles are classified with their angles and energies measured by the calorimeter[54].

The analysis program eta prime reads the output of prean. At the same time the monitoring program reads the beam triggers from the thin monitor, the SPACAL and the scales to calculate the photon flux. This is necessary to achieve the calculation of polarization observables (asymmetry) after the selection of the kinematical variables (at merge level).
Figure 2.16: Flow chart of the program used for the treatment of simulated and real data.
Chapter 3

The $\eta'$ photoproduction at GRAAL

3.1 Introduction

In this chapter, the first measurement of the beam asymmetry of the $\eta'$ meson, using the GRAAL data, will be presented. Up to now there are not results from other experiments in this energy region. The importance of the study of the $\gamma p \rightarrow \eta'p$ reaction will be discussed below.

3.2 The $\eta'$ photoproduction

Understanding the structure of the proton and its excited states is one of the key questions in hadronic physics. Without precise data from many decay channels, it will be difficult or even impossible to accurately determine the properties of well established resonances, or to confirm or rule out the existence of weakly established resonances or new, so-far not observed states. Of particular importance are well-chosen decay channels which can help isolate contributions from individual excited states and clarify their importance. Photoproduction of $\eta$ and $\eta'$ mesons offers the distinct advantage of serving as an isospin filter for the spectrum of nucleon resonances and thus simplifies data interpretation and theoretical efforts to predict the excited states contributing to these reactions. In fact, the $\eta$ and $\eta'$ mesons
have isospin I=0, the N\(\eta\) and N\(\eta'\) final states can only originate from intermediate I=1/2 nucleon states [10].

The \(\eta\) and \(\eta'\) were discovered in 1961 and 1964. These mesons belong to the light pseudoscalar meson family as also \(\pi\) or \(K\). Some properties are still barely known, such as the \(p - \eta\) scattering length which is assumed to be located between 0.2 fm and 1.05 fm. The wave functions of \(\eta\) and \(\eta'\) can be expressed as a linear combination of the wave functions \(\psi_1\) and \(\psi_8\). The mixing angle in this linear combination is determined to have a value around 15.5°. In addition, the mass of \(\eta\) is 547 MeV/c\(^2\) while the mass of \(\eta'\) is 958 MeV/c\(^2\). This represents a big difference of a factor of 1.75.

The observation of \(\eta\) and \(\eta'\) decays is ideal for studying symmetries and symmetry violation in QCD. The \(\eta \rightarrow 3\pi\) and \(\eta' \rightarrow 3\pi\) decays are sensitive to isospin symmetry breaking due to light quark mass differences of the quarks u and d. Decays of \(\eta \rightarrow 2\gamma\), \(\eta' \rightarrow 2\gamma\), \(\eta \rightarrow \pi^+\pi^-\gamma\), \(\eta' \rightarrow \pi^+\pi^-\gamma\) can be used to probe chiral anomalies of QCD. In addition forbidden or suppressed decay modes can be verified in the large variety of possible strong and electromagnetic decay branches of \(\eta\) and \(\eta'\) [56].

Data on \(\eta\) photoproduction off the free proton were obtained and studied in many different laboratories over a wide kinematical range [57–66].

In literature total and differential cross section data of \(\eta'\) photoproduction off proton are largely present while measurements of polarization observables are totally absent. Analyses published before 2005 observed fewer than 300 \(\eta'\) events [67–69] and an interpretation in terms of resonance contributions was difficult. Data from Jefferson Laboratory significantly improved the world database [70]. They observed 2105 \(\eta'\) events, which allowed the extraction of differential cross sections. Though more precise than previous measurements, the CLAS data are still limited in their angular coverage. The CLAS acceptance limited the measurement of the \(\gamma p \rightarrow p\eta'\) reaction to photon energies above 1.527 GeV (\(W = 1.94\) GeV) and \(\eta'\) center-of-mass scattering angles c.m. in the range \(-0.8 \leq \cos \theta^\eta_{c.m.} \leq 0.8\).

The differential cross sections for \(\eta'\) photoproduction obtained at CLAS are shown in figs. 3.1 and 3.2. In general, the angular distributions, while flat at threshold, show a continuing increase in slope at forward angles with increasing photon energy. At the highest energies, growth at backward angles is also observed. These general features are suggestive of coupling to a s-channel resonance near threshold,
with increasing contributions of t- and u-channel exchange as the energy above threshold increases. The SAPHIR measurements [69] are shown for comparison in fig. 3.1. The CLAS data, with much smaller error bars and smaller photon energy bins (SAPHIR has energy bins of 100 MeV for energies below 1.84 GeV and 200 MeV wide bins above), generally agree with the SAPHIR results within the very large error bars of the latter, but the CLAS values are nonetheless systematically lower.

In fig. 3.2 are reported the results (shown as red, green, and blue lines) representing a consistent analysis of the reactions $\gamma p \rightarrow p\eta'$ and $pp \rightarrow pp\eta'$ by Nakayama and Haberzettl (NH). The NH analysis is based upon a relativistic meson-exchange model of hadronic interactions including coupled-production mechanisms [70]. In the model by Nakayama and Haberzettl ([70] and ref. [71] therein), the $N\eta'$ final state couples to $N(1535)S_{11}$ and $N(1710)P_{11}$. The authors claim the importance of $J = 3/2$ states ($N(1940)P_{13}$, $N(1780)D_{13}$, $N(2090)D_{13}$) in the process, which are useful to obtain the correct shape of the differential cross sections for energies from 1.728 GeV to 1.879 GeV.

The black lines are referred to the calculations performed using a relativistic
meson-exchange model by A. Sibirtsev et al. [75] as a recipe. For both models, allowed processes include s-, t- and u-channel contributions.

The analysis of the data with two different models of the process suggests for the first time contributions from both the S11(1535) and P11(1710) nucleon resonances to the \( \eta' N \) channel in photoproduction, the two resonances previously identified as strongly coupling to the \( \eta N \) channel [76].

The fig. 3.3 shows the differential cross section for the reaction \( \gamma p \rightarrow p\eta' \rightarrow p2\pi^0\eta \) measured with the CBELSA/TAPS detector at an electron beam energy of \( E_{e^-} = 3.18 \text{ GeV} \). A rather flat angular distribution is again observed at low energies suggesting s-channel resonance production near threshold. The data set also shows a continue increase in slope at forward angles, which becomes more prominent at higher energies. This forward peak is most likely due to t-channel exchange mechanisms. Above 2 GeV in photon energy, growth at backward angles could be indicative of u-channel contributions. The overall agreement between the CBELSA/TAPS and CLAS data is good at threshold to fair above \( E_\gamma = 1800 \) MeV.
Chapter 3. The $\eta'$ photoproduction at GRAAL

Figure 3.3: Differential cross sections $\gamma p \rightarrow p\eta' \rightarrow p2\pi^0\eta \rightarrow p\rho\gamma$ (dark grey squares) using 50-MeV wide energy bins and $\cos\theta^p_{\text{c.m.}}$ bins of width 0.2. The data cover the full angular range; energies are given in MeV. For comparison, data are shown from SAPHIR [69] (gray stars) and CLAS [70] (gray triangles). The SAPHIR data are based on only 250 events and thus, have large error bars. The dashed line represents the SAID model [72].

Figure 3.4: Differential cross section on the reaction $\gamma p \rightarrow p\eta' \rightarrow p2\pi^0\eta \rightarrow p\rho\gamma$ close to the reaction threshold, obtained at CBELSA (dark grey squares) determined for individual tagger channels using 5 $\cos\theta^p_{\text{c.m.}}$, c.m. bins of width 0.4. Energies in the plots are given in MeV. Though limited in statistics, all angular distributions appear to be flat indicating s-wave behavior of the reaction at threshold.

The s-wave behavior of the reaction close to the reaction threshold is visible from the experimental data. Fig. 3.4 shows the differential cross sections for $\gamma p \rightarrow p\eta'$ [10] from CBELSA. The differential cross sections shown in fig. 3.4 have been used to determine the total $\eta'$ cross section and to study the energy dependence.

In fig. 3.5, the total cross section for $\eta'$ photoproduction obtained from the CBELSA/TAPS Collaboration is displayed [10]. At 2 GeV in the invariant mass spectrum and above, the cross section for the $\eta'$ production is dominated by the $\rho$ and $\omega$ exchange resonances.
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3.3 Analysis

3.3.1 Event selection

The $\pi^+\pi^-\eta$ (BR 43.4%), $\pi^0\pi^0\eta$ (BR 21.6%) and $\gamma\gamma$ (BR 2.14%) $\eta'$ decay modes were analyzed with the LAGRAN$\gamma$E detector of GRAAL experiment.

In the $\gamma\gamma$ analysis, we require to detect at least two photons in the BGO calorimeter, a proton in the forward direction ($\theta_p < 25^\circ$) and no other particles in the apparatus. All the performed analysis look for a forward proton. In fact, the study of the kinematics $\eta'$ photoproduction off proton at 50 MeV over the threshold showed that for such energy interval the maximum values of the proton polar angle do not overcome the value of $16^\circ$. In the case of $\pi^0\pi^0\eta$ decay mode, we ask to detect at least six neutral particles in the calorimeter and no charged particles. Instead, for the $\pi^+\pi^-\eta$ decay channel we look for at least two neutral particles in the BGO and two charged pions in the whole apparatus.
The information from the BGO crystals is analyzed by reconstructing the clusters with the border method: each cluster is composed of adjacent crystals. The number of crystals can vary as a function of the applied energy threshold on each crystal, because cluster belonging to different particles can overlap. This effect is valued by using the simulation.

The center of gravity of the cluster provides the polar and azimuthal coordinates of the particles with respect to the origin (which is assumed to be target centre). The ADC signal from each crystal is converted into energy and a correction constant is applied in order to include non-linearity effects, which are relevant at higher energies.

About the information coming from the barrel detector, the ADC signal of each scintillator bar is read and only the bar ADC signals above a fixed threshold are converted in energy after an off-line calibration of the barrel. The conversion factor is estimated from the comparison between the simulated and real distributions of the protons energy in the $\pi^0$ photoproduction.

Once the number of tracks detected by the cylindrical MWPCs is also reconstructed, the identification of the number of neutral and charged particles is divided in to two steps. First of all we checked the association between the cylindrical MWPCs, the BGO and the barrel; if it is successful the cluster is classified as a charged particle. Also the anticoincidence between the BGO and barrel classifies the clusters into charged or neutrals; in fact if the association between the two detectors is successful, the cluster is classified as a charged particle, if not as a neutral particle.

The number of neutral particles is thus equal to the number of neutral clusters.

A proton detected in the forward region gives a signal either in the MWPC’s, hodoscope and shower detector, or in the first two if it has a sufficiently low energy to stop in the hodoscope. The planar MWPCs give the best information about the emission angles ($\theta, \phi$) with a resolution of $1.5^\circ$ and $2^\circ$ for the polar and azimuthal angle, respectively; the hodoscope about their energy loss and the time of flight. The neutron can only give a signal in the shower detector.

In the energy region in which we work, protons are not relativistic, but pions are minimum ionizing particles (M.I.P.). This means that, in principle, they could be discriminated by looking at the plot of the energy loss by the particle in the scintillator as a function of:
the energy released in the BGO (for the particles in the central detectors) (panel a of the fig.3.6)

• the particle TOF measured in the hodoscope (for the particles in the forward detectors) (panel b of the fig.3.6).

Figure 3.6: Part a): energy loss in the barrel vs. measured energy by the BGO; part b): energy lost vs. TOF measured by the plastic scintillator wall.

Nevertheless, we have decided to accept as candidates of possible proton all charged particles; protons are discriminated from background pions in a second step only on the basis of kinematics criteria. In principle, we cannot discriminate the photons and neutrons with the BGO calorimeter, we can distinguish them only by an appropriate analysis procedure. Although neutrons in the forward direction are clearly discriminated from photons through their TOF (see fig.3.7), this is not possible in the BGO detector.

The response of the BGO detector to neutrons has been simulated by using the FLUKA package [55] for hadron interactions. The simulation showed that, at the energies that are typical of this experiment, a neutron can interact in the BGO detector with only a small number of crystals. Unfortunately, low energy photons can also produce low-multiplicity clusters and therefore a criterion based on counting the number of crystals in a cluster can only provide a first preliminary particle selection.

The information gathered from direct measurements in the apparatus is the following:
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**Figure 3.7**: Identification of the neutral particles by using the energy released in the shower detector vs. the particle TOF measured in the same detector.

**Figure 3.8**: The cluster multiplicity in the BGO detector: (a) cluster multiplicity for a gamma; (b) cluster multiplicity for two gammas; (c) cluster multiplicity for neutrons; (d) cluster multiplicity for protons.

- \( E_{\gamma} \), the energy of the incident photon;
- \( E_{\eta'}^{\text{meas}} \), \( \theta_{\eta'}^{\text{meas}} \), \( \phi_{\eta'}^{\text{meas}} \), the candidate \( \eta' \) energy and angles in the case of the \( \gamma\gamma \) analysis, otherwise we measure \( E_{\eta}^{\text{meas}} \), \( \theta_{\eta}^{\text{meas}} \), \( \phi_{\eta}^{\text{meas}} \) and \( E_{\pi^0}^{\text{meas}} \), \( \theta_{\pi^0}^{\text{meas}} \), \( \phi_{\pi^0}^{\text{meas}} \);
- \( \theta_{N}^{\text{meas}} \) and \( \phi_{N}^{\text{meas}} \), the candidate proton angles.

If a two-body kinematics is assumed, this information provides an overdetermined set of constraints. For this reason, all kinematical variables can also be calculated.
by means of only a subset of the other measured ones. A possible choice is given by the $M_X$ the mass of the recoil particle, calculated from $E_\gamma$ and from the proton measured energy and angles from the reaction $\gamma p \rightarrow pX$.

### 3.3.2 Kinematical cuts

In the following, the reconstruction of the invariant mass ($m_{inv}$) and missing mass of proton ($m_{miss}$) is reported. The first is calculated from the products of the $\eta'$ decay, while the second is determined by the proton detection (via the polar angle). For example, if we consider the following $\eta'$ decay channel:

$$\eta' \rightarrow \gamma \gamma$$

for each photon $\gamma_1$ and $\gamma_2$ we measure the energy $E_{\gamma_1}$ and $E_{\gamma_2}$ and the polar and azimuthal angles $\theta$ and $\phi$. The equations of the energy and momentum conservation laws are solved in order to calculate the components of the $\eta'$ momentum:

$$P_{x\eta'} = E_{\gamma_1} \sin \theta_{\gamma_1} \cos \phi_{\gamma_1} + E_{\gamma_2} \sin \theta_{\gamma_2} \cos \phi_{\gamma_2}$$

$$P_{y\eta'} = E_{\gamma_1} \sin \theta_{\gamma_1} \sin \phi_{\gamma_1} + E_{\gamma_2} \sin \theta_{\gamma_2} \sin \phi_{\gamma_2}$$

$$P_{z\eta'} = E_{\gamma_1} \cos \theta_{\gamma_1} + E_{\gamma_2} \cos \theta_{\gamma_2}$$

The energy value is given by:

$$E'_{\eta'} = E_{\gamma_1} + E_{\gamma_2}$$

Thus, the invariant mass results:

$$m_{inv} = \sqrt{E'_{\eta'}^2 - (P_{\eta',x}^2 + P_{\eta',y}^2 + P_{\eta',z}^2)}$$

The missing mass is calculated from the equations:

$$m_{miss} = \sqrt{(E_\gamma + m_p - E_p)^2 - (P_p^2 + E_\gamma^2 - 2P_p E_\gamma \cos \theta_p)}.$$
where:

- $E_\gamma$ is the energy of the incident photon;

- $m_p$ and $E_p$ are respectively the mass of the target proton and the energy of the detected proton;

- $P_p$ is given by:

$$P_p = \sqrt{p_{p,x}^{\text{meas}} + p_{p,y}^{\text{meas}} + p_{p,z}^{\text{meas}}}$$

with:

- $p_{p,x}^{\text{meas}} = -(|P| \sin \theta_p \cos \phi_p)$
- $p_{p,y}^{\text{meas}} = -(|P| \sin \theta_p \sin \phi_p)$
- $p_{p,z}^{\text{meas}} = E_\gamma - |P| \cos \theta_p$.

The simulation has been used to determine the best selection criteria and to optimize the kinematical cuts. In the fig.3.9 the ratio between the proton energy and the proton momentum is reported. As said before, the protons are not relativistic in our energy region ($\beta < 0.4$).

![Figure 3.9: Ratio between the proton energy and the proton momentum.](image)

The measurements related to the proton have a good resolution: about 1% for energy by using the TOF information from hodoscope, lower than 1% for angles measured by the planar MWPCs. In fig.3.10 the ratio between the difference of the reconstructed momentum and the generated momentum and the reconstructed momentum is represented showing a proton momentum resolution of about 2.5%.
Figure 3.10: Ratio between the difference of the reconstructed momentum and the generated momentum and the reconstructed momentum obtained from the simulation.

In the fig. 3.11 the invariant mass and the proton missing mass for the $\eta'$ channel are shown. The $\eta'$ mass is properly reconstructed in both cases but the extraction of the beam asymmetry has been possible only using the missing mass in order to have enough statistics, including the $\pi^+\pi^-\eta$ channel.

Figure 3.11: (a) Invariant mass before (black line) and after the kinematic cuts, (b) missing mass for the $\eta'$ photoproduction before cuts (dashed red line) and after cut on the $\eta'$ threshold energy (dotted black line) and the application of the cut of the proton polar angle ($\theta_p$) vs the energy $E_\gamma$ (solid blue line).

A strong background suppression is entailed by cuts in the bidimensional distribution of the polar angle of the proton ($\theta_p$) as a function of the energy $E_\gamma$ (shown in the fig. 3.12).

It is clear from the fig. 3.13 that the background events coming from the other competing channels are strongly cleaned up by the applied kinematical cuts. In blue is reported the proton missing mass ($\gamma p \to pX$) after the application of the
bidimensional cut. It was possible also to identify the different \( \eta' \) decay modes putting some conditions on the final state particles of the \( \eta' \) decay. The result is represented in the fig. 3.14. To identify the \( \eta' \) decay channel \( \eta' \rightarrow \pi^+\pi^-\eta \) we require to have the number of neutral tracks in the central detectors and the number of the photons in the forward detectors equal at least to two with the condition on the number of charged pions in the central and forward part of the apparatus greater than zero and lower than three (see panel a) of fig.3.14). The identification of the \( \eta' \) decay channel \( \eta' \rightarrow \gamma\gamma \) is obtained in a similar way but with the request on the number of charged pions equal to zero (panel b) of fig.3.14). The last decay channel reported in the fig. 3.14 panel c) is selected by the restriction on the number of neutral tracks in the central detectors and the number of the photons in the forward detectors greater or equal than six and, as in the first case, with the number of the neutral pions greater than zero and the charged pions equal to zero.
3.3.3 Preliminary results: the $\eta'$ beam asymmetry in threshold region

The experimental beam asymmetry $\Sigma$ can be derived from the polarized differential cross section:

$$\frac{d\sigma}{d\Omega}(\pm,0,0) = \frac{d\sigma}{d\Omega}(0,0,0) [1 + \Sigma \cdot P_S]$$

(3.7)

where:

- $\pm$ superscript indicates the choice for the photon polarization;

- $(0,0,0)$ means the unpolarized differential cross section; the indexes are referred, respectively, to the beam polarization asymmetry, to the target polarization asymmetry and to the recoil polarization asymmetry.

- $P_S$ is the Stokes vector which gives the direction and degree of polarization of the photon as determined by the experimental set-up.

The Graal photon beam is linearly polarised. The two possible states $\phi = 0(\parallel)$ and $\phi = \frac{\pi}{2}(\perp)$ are eigenstates of the matrix $P$ and, thus, the equation simplifies:

$$\frac{d\sigma}{d\Omega}(\pm,0,0) = \frac{d\sigma}{d\Omega}(0,0,0) [1 \pm P \Sigma \cos 2\phi].$$

(3.8)

where $P$ is the experimental degree of the linear polarization.
If we measure the number of events selected for a given channel and for each polarization state, \( N_\parallel \) and \( N_\perp \), with an efficiency \( \epsilon \) and their relative fluxes, \( F_\parallel \) and \( F_\perp \) we obtain:

\[
\frac{N_\parallel}{F_\parallel} = \epsilon \frac{d\sigma}{d\Omega} (\parallel, 0, 0) = \frac{d\sigma}{d\Omega} (0, 0, 0) [1 - P\Sigma \cos 2\phi] \epsilon \tag{3.9}
\]

\[
\frac{N_\perp}{F_\perp} = \epsilon \frac{d\sigma}{d\Omega} (\perp, 0, 0) = \frac{d\sigma}{d\Omega} (0, 0, 0) [1 + P\Sigma \cos 2\phi] \epsilon \tag{3.10}
\]

The efficiency \( \epsilon \) can be a function of the angles of the meson in the c.m. system, \( \theta_{\text{c.m.}} \) and of the photon energy, \( E_\gamma \).

However, the equations 3.9 and 3.10 are calculated for fixed values of \( \theta_{\text{c.m.}}, E_\gamma \) thus in this case \( \epsilon \) can be considered as a constant.

A slight dependence of \( \epsilon \) on the azimuthal angle can originate from small asymmetries in \( \phi \) of the detector response, but, as this dependence is the same for both polarisation states, it is possible to cancel this efficiency in the formulas that provide the experimental asymmetry \( \Sigma \). We can therefore add equations 3.9 and 3.10 to calculate the unpolarised cross section:

\[
\frac{d\sigma}{d\Omega} (0, 0, 0) = \frac{N_\parallel}{F_\parallel} + \frac{N_\perp}{F_\perp} \tag{3.11}
\]

The unpolarised cross section can thus be replaced in equations 3.9 and 3.10 to obtain two equations, where the only unknown is \( P\Sigma \):

\[
\frac{N_\parallel}{F_\parallel} = \frac{1}{2} \left( 1 - P\Sigma \cos 2\phi \right) \tag{3.12}
\]

\[
\frac{N_\perp}{F_\perp} = \frac{1}{2} \left( 1 + P\Sigma \cos 2\phi \right) \tag{3.13}
\]

A third equation can also be used to extract the beam asymmetry and it is obtained by the difference between 3.10 and 3.9 divided by 3.11:
\[
\frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} = P\Sigma \cos 2\phi 
\]

The number of events, \( N_\perp \) and \( N_\parallel \), are the result of kinematical selections, while \( F_\parallel \) and \( F_\perp \) are the number of total incident photons, measured by the flux detectors. Selected events have been grouped together in bins with fixed values of \( E_\gamma \), \( \theta_{\eta'}^{c.m.} \), and \( \phi_{\eta'} \) (where \( E_\gamma \) is the \( \gamma \) energy, and \( \theta_{\eta'}^{c.m.} \) and \( \phi_{\eta'} \) are the polar and azimuthal angles in the c.m. respectively). The beam asymmetry, \( \Sigma(E_\gamma, \theta_{\eta'}^{c.m.}) \) has been extracted by fitting the azimuthal behaviour of the ratio defined in the equation 3.13, in fixed bins of \( (E_\gamma, \theta_{\eta'}^{c.m.}) \).

The detection efficiency cancels out in the ratio between the two polarization states, so that the extraction of the asymmetry is free from systematic errors from the determination of the absolute efficiency. The azimuthal distribution (eq.3.13) has been fitted for each bin of \( E_\gamma \) and \( \theta_{\eta'}^{c.m.} \) as is shown in fig.3.15, where the bin with \( E_\gamma = 1.475 GeV \) and \( \theta_{\eta'}^{c.m.} = 74.75^\circ \) is reported as an example.

![Figure 3.15: The azimuthal distribution of the ratio of eq.3.13 for data on proton for the value on \( E_\gamma = 1.475 GeV \) and \( \theta_{\eta'}^{c.m.} = 74.75^\circ \).](image)

From the fit the product of \( P\Sigma \) is obtained, and from it \( \Sigma \) is computed from the knowledge of \( P(E_\gamma) \) (see par.2.2).

The result of the beam asymmetry \( \Sigma \) of the \( \eta' \) photoproduction on the proton is plotted as a function of the polar angle in the center-of-mass of system (using seven bins in the \( \theta_{c.m.} \)) in the fig. 3.16. The errors bars are statistical only.

The averaged degree of polarization of the beam in the considered energy bin is
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96%.

As check of the result, a comparison between the beam asymmetry obtained by using two independent samples of $\eta'$ events (selecting the neutral and charged particle decays) was made and it is reported in the fig. 3.17. In blue the values of the $\Sigma$ asymmetry extracted, when only the neutral $\eta'$ decay is selected, is shown; in red the values extracted, when only the charged $\eta'$ decay is selected, is reported.

As it is possible to see, the extracted values of $\Sigma$ asymmetry are in good agreement in the two cases.

To verify the accuracy of the analysis procedure a sample of events with flat asymmetry equal to 0.5 has been used. The extracted beam asymmetries are equal to $0.5 \pm 0.01$ (see fig. 3.18). The analysis software chain gives an uncertainty of $\sim 1%$. 

![Figure 3.16: Beam asymmetry $\Sigma$ in $\eta'$ photoproduction on proton. The energy value indicated in the plot is referred to the mean value of the bin for the free protons.]

![Figure 3.17: Check on the beam asymmetry $\Sigma$ in $\eta'$ photoproduction on proton. In blue the values of the $\Sigma$ extracted, when only the neutral $\eta'$ decay is selected, is shown; in red the values extracted when only the charged $\eta'$ decay is selected is shown.]

![Figure 3.18: Sample of events with flat asymmetry equal to 0.5. The extracted beam asymmetries are equal to $0.5 \pm 0.01$.]
We have presented the result of the beam asymmetry $\Sigma$ of the $\eta'$ photoproduction off proton in the threshold region. It is the first measurement of $\Sigma$ for the $\eta'$ photoproduction. Up to now, only $\eta'$ cross-section data are available in literature. We found that the trend of the beam asymmetry is in average zero confirming the dominant role of the s-wave function\cite{90, 91}. However, for $\theta_{c.m.}$ value lower than 90°, it become higher than zero. A possible explanation is given by the interference of the S(1535) and P(1710) nucleon resonances as suggested in the ref. \cite{63}.

**Figure 3.18:** Check of the analysis procedure on the beam asymmetry extraction using a simulated sample of events which give a flat asymmetry. The plot shows the validity of the analysis procedure.
Chapter 4

The BGO-OD experiment

4.1 Physics motivations

The BGO-OD experiment at the ELSA facility in Bonn (see Figure 4.2) involves the use of a Bremsstrahlung tagged and polarized photon beam of energy between 0.7 and 3.2 GeV, a large solid angle high energy resolution BGO calorimeter and the Open Dipole spectrometer equipped with tracking detectors. This apparatus will be used to measure polarisation observables and cross sections in the photoproduction of pseudo-scalar and vector mesons off an Hydrogen or Deuterium target.

The BGO-OD set-up is ideal to study the $\eta$ and $\eta'$ photoproduction, in particular for the measurement of both, charged and neutral, decay channels (thanks to the combination of the BGO calorimeter with the magnetic spectrometer):

- $\eta \rightarrow \gamma \gamma$; $\eta' \rightarrow \gamma \gamma$
- $\eta \rightarrow \pi^0 \pi^0 \pi^0$; $\eta' \rightarrow \pi^0 \pi^0$
- $\eta \rightarrow \pi^+ \pi^- \pi^0$; $\eta' \rightarrow \eta \pi^+ \pi^-$

The $\eta$ meson has been the object of extensive studies at the GRAAL experiment (determination of the amplitude $\Gamma$ of the $S_{11}(1535)$ resonance[40], the branching ratios (BR) of the $D_{13}$ (1520) and $F_{15}$ (1680) resonances for the $\gamma p \rightarrow \eta p$ reaction[41], mixing angles of $D_{13}$ (1520 and 1700) and $S_{11}$ (1535 and 1650). However, at the BGO-OD experiment the extension to higher energy it is possible.
In the case of the $\eta'$ photoproduction, only cross section data are available in literature. The first measurement of the beam asymmetry (only in the threshold region) has been presented in the chapter two by using the GRAAL data. The CLAS and CBELSA/TAPS experiments have produced a rich amount of cross section data for $\eta'$ photoproduction on the proton [70, 90, 91] and on the deuteron [92], covering the energy region from threshold (1.447 GeV) up to 2.84 GeV. However, the cross section data alone are insufficient to pin down the resonances parameters, while beam and/or target asymmetries could be very helpful to better determine the partial wave contributions in this reaction, and impose stricter constraints on the parameter values.

A crucial channel for the problem of the "missing" or poorly established resonances that couple strongly to strange decay channels is the $\gamma p \rightarrow K^+\Lambda$ process. Differential cross section data with high statistics have been measured with the SAPHIR detector [77, 78] at ELSA and the CLAS detector [79, 80] at Jefferson Lab. However, the discrepancies between these data lead to a important differences in the partial wave analysis and leave ambiguities to the contributing s-channel resonances, with the most notable difference around the structure at $\sqrt{s} = 1.9$ GeV. The LEPS collaboration [81] measured the $K^+\Lambda$ differential cross section for center of mass energies 1.945-2.28 GeV (photon beam energy of 1.5-2.4 GeV) and forward angular range (centre of mass $K^+$ polar angle of $0 - 60^\circ$). The data was consistent with the CLAS data in the energy overlap region and partially reproduces the peak structure at $\sqrt{s} = 1.9$ GeV, however this is at the lower limit of the energy range.

The measurement of the $\gamma p \rightarrow K^+\Lambda$ differential cross section, and polarisation observables $\Sigma$, $C_X$, $C_Z$, $O_X$ and $O_Z$ are planned at the BGO-OD experiment. The data will cover the overlap region between CLAS and LEPS, and provide important statistics at the observed structure at $W = 1.9$ GeV. The disagreement of either Regge model [82] at forward angles in fig.4.1 and above $W = 2$ GeV suggests that there is still significant s-channel contributions in this region, and a reggeisation of only t-channel contributions cannot describe this data.

The study of the s-channel resonance excitations contributing to the $\gamma p \rightarrow K^+\Lambda$ spectrum is complicated by large t-channel contributions. As explained in reference [85], the $K^0$ photoproduction offers the advantage of the absence of t-channel exchange from the production process. Charged and neutral strangeness channels, and the associated hadronic coupling constants are linked via SU(3) symmetry.
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Figure 4.1: Differential cross sections for $\gamma p \rightarrow K^+\Lambda$. Closed circles, open squares and open triangles represent LEPS [81], SAPHIR [78] and CLAS [79, 83] data respectively. The dotted and dash-dotted curves are Regge models with only $K^*$ exchange, and $K^*$ and $K^+$ exchange respectively, from Guidal et al. [82]. The solid line is the isobar plus Regge model of Mart and Bennhold [84].

Cross sections and polarisation observable data for $\gamma n \rightarrow K^0\Lambda$, for example, provide important constraints upon the $\gamma p \rightarrow K^+\Lambda$ reaction mechanism. Despite these advantages, there is limited data for the $\gamma n \rightarrow K^0\Lambda$ channel.

The BGO-OD experiment will measure differential cross sections and polarisation observables for the $\gamma n \rightarrow K^0\Lambda$ channel, vastly improving the limited data set. In fact, the BGO-OD detector is able to reconstruct $K^0$ via both neutral and charged pion decay modes. Recoil polarisation, $P$, will be measured from the self analysing $\Lambda$ weak decay. A linearly polarised beam will be used to measure the beam asymmetry, $\Sigma$, and the double beam-recoil polarisation observables, $O_X$ and $O_Z$. With a circularly polarised beam, the beam-recoil polarisation observables, $C_X$ and $C_Z$ will be extracted from threshold to a beam energy of approximately 1.7 GeV. Polarisation observables for $\gamma n \rightarrow K^0\Sigma^0$ will also be extracted from the same data set. The BGO-OD experiment will study also the channel $\gamma p \rightarrow K^0\Sigma^+[86]$.

A great interest is direct also on the excited hyperon photoproduction. The classical constituent quark models are based on the assumption of three constituent quark models inside each baryon. They are very successful for the spatial ground state of baryons, but have serious problems for the prediction of the baryon excited states[93].

The lowest spatial excited baryon is expected to be a $(uud)$ $N^*$ state with one quark in orbital angular momentum $L = 1$ state, and hence should have negative parity. Experimentally, the lowest negative parity $N^*$ resonance is found to be $N^*$ (1535), which is heavier than two other spatial excited baryons: $\Lambda^*(1405)$.
and $N^*(1440)$[94]. These mass differences however can be described using unquenched quark models with five components. These can either be interpreted as a meson cloud or a pentaquark molecule with di-quark structure. The $N(1535)$ for example can be described as a bound $K\Lambda - K\Sigma$ system and $\Lambda(1405)$ as a dynamically generated $KN - \Sigma\pi$ resonance. Alternatively within a penta-quark description, $N(1535)$ can be described as $[ud][ud]\bar{d}$ and $\Lambda(1405)$ as $[ud][sq]\bar{q}$ with $q\bar{q} = (u\bar{u} + d\bar{d})/\sqrt{2}$. These descriptions have important implications for the entire spectrum of hyperon resonances.

Due to the limited data on excited hyperons and the ambiguity as to their structure, a detailed search with the BGO-OD experiment is proposed. $\Sigma^*$ resonances close in mass to $\Lambda(1405)$ can be identified via $\Sigma^* \rightarrow \pi\Lambda$, and avoid misidentified background from $\Lambda(1405)$. Differential cross sections, and polarisation observables, $\Sigma$, $P$, $C_X$ and $C_Z$ will be used to disentangle reaction mechanisms. Resonant structures can be studied via the photoproduction of $K^*$, $K^+\Lambda$ and $K^0$. The reaction $\gamma p \rightarrow K^+\Lambda(1520)$ will also be studied to constrain potential $\Sigma^*_{1/2}$ resonances close to $\Sigma(1385)$, and provide differential cross section data up to 2.8 GeV. The BGO-OD experiment will identify all three $\Lambda(1405)$ decay modes, providing differential cross section, and t dependence data for each. The experimental setup is ideal to identify all particles in the final state for the decay $\Lambda(1405) \rightarrow \Sigma^0\pi^0$, the only decay channel with no background from $\Sigma(1385)$ (isospin forbidden)[86]. Another aim of the BGO-OD experiment consists in the photoproduction of the vector mesons ($\omega$, $\phi$, $\rho$). Also these reactions are very useful to investigate the problem of the ”missing resonances”. The $\omega$ photoproduction is interesting for different reasons: first, there is no well established nucleon resonance decaying by $\omega$ emission; second, the threshold of $\omega$-photoproduction lies in the third resonance region, which is less explored than the first two ones; third, from the sparse data in the literature and a new generation experiment, evidence for resonance excitations in $\gamma p \rightarrow \omega p$ is still not obvious. Due to the fact that the $\omega$ meson is isoscalar ($I = 0$), the $s$ channel production of this meson is only associated with the decay of $N^*(I = 1/2)$ states and not the decay of $\Delta^*(I = 3/2)$ states, which greatly simplifies the contributing excitation spectrum. However, the vector meson character of the $\omega$ implies that at least 23 observables have to be measured to disentangle all contributing resonances, instead of the 8 which are required in the pseudoscalar case. It can be hoped that fewer than 23 observables already provide significant constraints. In any case, the measurement of polarization observables will provide important information about the ”production mechanism” of the $\omega$ meson[98].
At BGO-OD, the $\omega$ meson will be identified by both, the $\omega \rightarrow \pi^+\pi^0\pi^-$ (B.R.: 89.2 \%) and the radiative $\omega \rightarrow \pi^0\gamma$ (B.R.: 8.3 \%) decays thanks to the high momentum resolution in the forward direction combined with charged particle tracking and photon spectroscopy with BGO Ball and cylindrical MWPCs in the central angular region.

The $\phi$ meson will be identified by its $\phi \rightarrow K^+K^-$ decay (B.R.: 48.9 \%). The BGO-OD setup allows also a more detailed study about the $\rho$-meson. Its main decay modes (to almost 100\%) proceed via $\rho^0 \rightarrow \pi^+\pi^-$, $\rho^+ \rightarrow \pi^+\pi^0$ and $\rho^- \rightarrow \pi^-\pi^0$.

In particular, the last two decays that derive from the “twins” reactions $\gamma p \rightarrow \rho^+n$ and $\gamma n \rightarrow \rho^-p$ may be confused in case of the proton inefficiency combined with neutral noise and for this reason the BGO - spectrometer combination is crucial.

### 4.2 Experimental set-up

A schematic view of the experimental apparatus located at the S-beamline of Bonn is shown in Figure 4.4. The Electron Stretcher Accelerator (ELSA, see Figure 4.2) consists of three stages (injector LINAC, booster synchrotron and stretcher ring) and provides a beam of polarized and unpolarized electrons with a tunable energy up to 3.5 GeV. The extracted bunched electron beam impinges on a radiator in the S-beamline. Scattered electrons produce coherent and incoherent bremsstrahlung photons. Coherent bremsstrahlung is used to produce linearly polarized photons, while circular polarization is obtained via bremsstrahlung of longitudinally polarized electrons.

The flux of the photons in the experimental area is monitored using two detectors: the GIM (Gamma Intensity Monitor) that measures, at low rate, the total number of photons and the FluMo (Flux Monitor) for the measurement of the flux at higher rates. The GIM is made of lead glass and uses the Cherenkov effect to detect charged particles from the shower generated by an incoming photon. It is built of just one single lead glass block and one 2" phototube (Hamamatsu R2083). The FluMo detector is built of three scintillators and copper foil between the first and second scintillator. A fixed percentage of incoming photons will convert into electron-positron pairs within the copper foil. These charged particles will then be detected by the two following scintillators. To not count charged particles not coming from the converter, there is a veto scintillator in front of it[95].
The BGO-OD detector setup is a combination of a central detector system and a forward spectrometer for charged particles, completed by a photon tagging system. The resolution of the tagger is about $1\% \div 2\%$ of the incident electron beam.

### 4.2.1 Tagging system

The tagging system includes 120 scintillators. The tagger hodoscope, due to the geometrical constraints, is split into a horizontal part (54 scintillators) which mainly lies in the focal plane and a vertical part, out of plane (66 scintillators). The scintillators are placed such that a tagging range of about $10\% E_0 - 90\% E_0$ is covered with variable resolution ($10 \div 40$ MeV).

Only clusters of 2 or 3 adjacent scintillators are occupied, so that the resolution of the tagger is than defined by the overlapping areas of the scintillators. The overlap of the scintillators is 55%.
4.2.2 Central detector system

4.2.2.1 BGO Rugby ball

The central detector of the experimental setup is the high energy resolution and large solid angle \((0.9 \cdot 4\pi)\) BGO electromagnetic calorimeter of the former GRAAL experiment.

The design of the calorimeter has been performed in order to have a constant thickness in every direction and a central hole of radius 100 mm for the passage of the beam, target and inner detector housing. The resulting structure is made of
480 truncated pyramidal crystals of 240 mm length (corresponding to 21 radiation lengths), arranged in a $15 \times 32$ matrix, covering the polar angles from $25^\circ$ to $155^\circ$ and the whole azimuthal angles, corresponding to a total solid angle $\Delta \Omega$ of 11.3 sr. The mechanical structure consists of 24 carbon fiber baskets, each containing 20 crystals, and supported by an external steel frame. The baskets are divided into cells to keep the crystals mechanically and optically separated (see chapter two for the details of the detector).

### 4.2.2.2 Barrel scintillator

A cylinder of 32 plastic scintillator bars, for the measurement of the $\Delta E$ of charged particles, allows in combination with the energy released in the calorimeter, and, in anticoincidence with it, the identification of charged particles (protons and pions) (see chapter two).

### 4.2.2.3 Multi wire proportional chambers (MWPCs)

Two cylindrical multi wire proportional chambers (MWPCs), under construction, will be used for the reconstruction of trajectories from charged particles. Each chamber is made of two coaxial cylindrical cathodes which are segmented into strips, helically wound in opposite directions. The anode array consists of equally spaced wires stretched parallel to the cylinder axis in the middle of the active area (gas gap $\sim 8 \text{ mm}$). The geometrical parameters are tuned to fit inside the carbon structure of the BGO and around the target nose. The front end electronics (preamplifiers), is not integrated in the chambers, but will be positioned very close (cable length about 150 cm) to one end of the chambers[86].

The 2 mm pitch of the wires, which have a diameter of 20 $\mu m$, results in an expected azimuthal angular resolution of $\Delta \Phi \approx 2^\circ$. The resolution along the longitudinal coordinate is determined by the strip width and the crossing angle between internal and external strips. The minimum resolution can be achieved at a relative angle of 90 degrees of the strips. The expected resolution is $\Delta z \approx 300 \mu m$ by using a strip width of 4.5 mm. Finally, the resolution in the polar angle $\theta$, which depends on $\Delta z$ and the relative radii of the two chambers, is expected to
be $\theta \approx 1^\circ$ with the planned geometry. The outer dimension of the full chamber set-up is length = 690 mm (active length = 520 mm), inner diameter 84.4 mm and outer diameter 187 mm.

The readout electronics after the preamplifiers is based on different VME modules for the wires and the strips. The wire hits are registered via VFB2 modules from ELB21 with a self-developed TDC firmware and the strip signals are measured via Sampling ADC modules from Wiener. The chamber gas is mixed from three components, 70% Argon, 29.5% Ethane, 0.5% Halocarbon 14 ($CF_4$) inside a dedicated gas mixer in the vicinity of the detector.

### 4.2.3 Target system

The target cell and the cryogenic system are located directly behind the beam dump along the beam direction. The cell is contained in a vacuum pipe, which guarantees the thermal insulation and is surrounded hermetically by the central detectors. The target cell is a 4 $cm$ diameter Aluminum cylinder, closed by thin mylar windows at the two sides for the passage of the beam. Two different lengths of the cell are available (6 and 11 $cm$) in order to fulfill different experimental requirements. The target cell can be filled either with liquid Hydrogen ($H_2$) or Deuterium ($D_2$).

### 4.2.4 Multi-gap Resistive Plate Chamber (MRPC)

To cover the forward angular region between $\theta_{lab} = 25^\circ$ and $\theta_{lab} = 8^\circ$ an azimuthally-symmetric Multi-gap Resistive Plate Chamber detector (MRPC) will be installed between the BGO and the MOMO detector.
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Figure 4.7: Acceptance for the proton recoil in the case of the $\eta$, $\omega$ and $\eta'$ photoproduction[87].

The importance of the covered angular region is clearly visible in the fig.4.7. The acceptance for the proton recoil is very important, especially in the proximity of the threshold and especially in photoproduction channels, $\eta$, $\omega$ and $\eta'$ channels that are of greatest scientific interest for us.

The detector is divided into 16 phi sectors and each of the sectors is divided into 15 pad in the polar angle, corresponding to 480 channels in total. Each sector in the azimuthal angle consists of four stacks. The expected spatial resolution $\sigma_s$ is 1 cm$^2$ and the time resolution $\sigma_t$ is about 50 ps. A scheme of the detector is shown in the following (see fig.4.8).

Each sector is housed in a box with walls in alveolate paper (b) and covered by a copper foil (a)(see fig.4.8, panel (a)). This material has low density but it provides an excellent rigidity and mechanical resistance.

The system of the readout of the signal is realized as printed circuit (c). The printed circuits are separated from the first glass of the stack by a mylar foil (d) that is highly insulating. The remaining part of the detector is composed by many thin foils (about 0.40 mm) (f) and nylon wires (0.25 mm) (g). In the space between a glass and the following the gas mixture (96%$C_2F_4H_2$ (tetrafluoroethane),3%$C_4H_{10}$ (isobuthane), 1%$SF_6$ (sulfur hexafluoride)) is fluxed[87]. The mixing and flushing
of the gas is controlled by an electronically controlled system. The external face of the glass stack, which borders with the mylar, is covered by a resistive layer of a special paint which allows the application of the high voltage on the glass itself. The readout system will be instrumented with 16 modules of 32 channel multihit TDC (CAEN V1290A) with a 25 ps resolution (LSB).

### 4.2.5 The forward spectrometer

The polar angular region of forward angles (θ < 12°) is covered by the B1-magnetic field spectrometer that uses a dipolar field of about 0.5 T for the separation, identification and measurement of the momentum (3% resolution) of charged particles emitted in the photoproduction processes.

For this purpose, the spectrometer is equipped with MOMO and SciFi2 detectors, eight double layer drift chambers (DCs) and a time-of-flight (TOF) detector.
4.2.5.1 MOMO detector

The MOMO detector (MONitor of Mesonic Observables) consists of 672 scintillating fibers, of circular profile with diameters of 2.5 mm, arranged in three planes inclined at 60° with respect to each other. The fibers are individually read out by 16-channel Hamamatsu R4760 phototubes. The sensitive area is circular with a diameter of 44 cm. A 4 cm diameter central hole allows the passage of the beam [88],[89].

![Front view to the MOMO vertex detector](image)

**Figure 4.9:** Front view to the MOMO vertex detector. The beam passes through the central hole. The numbers denote the different layers and the three boxes at the end of each read-out symbolize the phototubes. The support stand is visible in the lower part of the figure.

This detector was originally built for the MOMO experiment at COSY and was successfully used there for the detection of pion and kaon pairs in proton and deuteron induced two meson production reactions.

Originally the PMTs were shielded against magnetic fields by 1 mm thick mu-metal cylinders wrapped around the 16-channel tubes. However, this was not sufficient for the rather strong magnetic field (> 0.1T) present at its position at BGO-OD about 1 m from the magnet. So additional shielding was added. 1 mm thick Permenorm cylinders were placed around the tubes mounts. Permenorm is a shielding material, that has about twice the magnetic saturation density than mu-metal. Tests showed, that this combination of mu-metal and Permenorm is sufficient for the operation of the detector at maximum magnetic field. MOMO is fully operational.
4.2.5.2 SciFi2 Detector

The SciFi2 detector is shown in fig. 4.10. An active area of $66\,cm \times 51\,cm$ is obtained using 640 scintillating fibers with a diameter of 3mm. The planar detector covers an angular range of $\pm 10^\circ$ in the $x$-direction and $\pm 8^\circ$ in the $y$-direction. A central hole ($4\,cm \times 4\,cm$) allows the beam to pass through. Groups of 16 fibers are glued together to form a so-called module. The profile of one module is shown in fig. 4.10. The design guarantees a minimum path length (about 2mm) for particles traversing the circular fibers. The modules are arranged in two layers twisted by $90^\circ$. The signals from each module are read out by 16-channel photomultipliers (Hamamatsu H6568).

![Figure 4.10: In the upper part the design of the SciFi2 detector is shown; in the down part the profile of one of the module is reported.](image)

The analogue signals from the phototubes of both detectors are fed to 16-channel leading edge discriminators. The threshold for each channel can be programmed individually via a serial bus. The discriminator outputs then feed multihit TDC modules via a standard LVDS signal format. The timing resolution of the detectors is about 2 ns (FWHM).

4.2.5.3 Drift Chambers (DC)

Tracking of charged particles behind the spectrometer magnet is performed with eight horizontal drift chambers (DCs), which have been built at the PNPI of Gatchina. To cover the necessary angular range each DC has a sensitive area of at least $2456\,mm \times 1232\,mm$. 
The distance of the chambers from the target ranges from 3.7m for the first chamber up to 4.7m for the last. For accurate positioning and simplified handling the chambers hang from two support bars attached to the magnet.

The chambers are arranged in four different orientations, the vertical wires to measure the x-coordinate, the horizontal ones to measure the y-coordinate, and tilted by $\pm 9^\circ$ from vertical for u- and v-coordinate measurement. The layer drift cell geometry is identical for all chambers. To create a nearly symmetric electrical field additional field wires are introduced on both sides of the drift cell layers. The spacing between two anode wires of the same layer is 17mm [96].

High voltage is supplied to the chambers from a CAEN SY2527 crate via specially designed chamber mounted fuse boards, that split the HV supply to several channels per chamber. This fuse boards allow to monitor the current for each sector of 32 sense wires of a chamber individually, and protect the chamber by switching off the HV supply if one sector exceeds the current limit. Interfacing to this cards is done via an optically isolated USB interface, with full integration into the experiments slow control. The photon beam has to penetrate the DCs. To avoid counting overload by secondary $e^+e^-$, pairs insensitivity spots of $5 \times 5cm^2$ are realized at the centre of the chambers by anodizing 6 of the sense wires with gold, thus increasing the total diameter to 100$\mu$m in the desired area. The effect of this procedure has been successfully tested at PNPI.

The chambers are operated with a mixture of 70% Argon and 30% CO$_2$. After mixing, the gas is distributed to the chambers individually and vented after passing the chamber.

The readout of the chambers is done with the CROS-3 (Coordinate Read Out System, third generation) developed by PNPI Gatchina. It consists of four different types of cards:

- CSB - CROS-3 system buffer
- CCB16 - CROS-3 16-channel concentrator board
- CCB10 - CROS-3 10-channel concentrator board
- AD16 - 16-channel amplifier/discriminator card

The AD16 amplifier/discriminator boards are directly attached to the drift chambers. The digitized signals of the frontend boards are sent via an LVDS link to the CCB10 concentrators. The CCB10 concentrators transmit their signal to the
single CCB16 card. Finally an optical fiber connects the readout system to CSB system buffer implemented as a PCI-card [86].

4.2.5.4 Time-of-flight detector (TOF)

The time-of-flight (TOF) detector is an essential component for particle identification, because it provides time of flight measurements for charged particles. It covers the region $\theta < 8^\circ$ and $\theta < 12^\circ$ in the vertical and in the horizontal directions, respectively, at a distance of $5\,m$ downstream the target [86].

The ToF detector consists of 4 walls. Each one is composed of 14 NE110 bars 300 cm long, 20 cm high and 5 cm thick. The readout of each bar is performed at both the ends by a light guide and a PM (Hamamatsu R2083), corresponding to 28 read-out channels. One bar of insensitive material is located at the center of each wall, in correspondence of the beam position. Two walls are installed in the area: one with horizontal and one with vertical bars, wall3 and wall4, respectively. Wall3 is located in front of wall4, with respect to the beam direction [99]. The time resolution is $\sigma_t \pm 500\,ps$ and the efficiency for neutron detection $\epsilon_n \simeq 15\%$. Overall, a $\Delta p/p \approx 2\%$ momentum resolution for charged particles is expected.
Chapter 5

BGO calibration and preliminary results at BGO-OD

5.1 Introduction

In this chapter, a detailed description of the new electronic readout of the BGO calorimeter, based on the Wiener Sampling ADC modules and the equalization/calibration procedures, that we performed at the BGO-OD experiment, will be presented. The preliminary results obtained by the Members of the BGO-OD collaboration, during the test beam time, as proof of the very good status of the detector, have been reported.

5.2 BGO readout system

The BGO acquisition is performed by using thirty Wiener Sampling ADC modules. The modules allow the extraction of the total deposited energy and of the starting time of the signal. The ADC modules AVM16-Mambo operate with a sampling frequency of 160 MHz (corresponding to 6.25 ns interval between two samples) with 12 bit resolution (i.e. 4096 channels) and a system timer resolution of 1.5625 ns. The signal is sampled inside a time interval defined by the user, that can start after or before the trigger signal. The baseline is evaluated in periods free of trigger and pulses on a basis of 32 consecutive samples for every channel, which must not differ more than ±1 (in channel units). In order to exploit almost completely
the full 12 bit ADC measurement range for negative pulses, the baseline for each channel can be shifted upwards or downwards by means of a DAC.

![Diagram](image1)

**Figure 5.1**: Trigger scheme (a); Printed circuit board of AVM16 (b). Here are visible the DIP-switches for the address setting, the reference clock synchronization and the trigger connector.

The AVM16 modules have 16 channels and one trigger input (lowermost LEMO connector) but these modules are provided also of an internal trigger (level trigger). In the internal trigger case, the trigger issue is fired when a signal exceeds the threshold fixed by the user. They can be operated in stand alone mode or synchronized with other AVM16s with an external trigger. All cards that have to be synchronized in one crate can be connected with a flat band cable on the front panel I/O connectors, so that a LVDS bus with jumper terminations in the first and last cards can be established. The figure 5.1 shows a master crate with a card configured as Local Master (LM), receiving the external trigger signal.

The control module works as the Local Master (LM). This module has the same trigger sources as in stand alone mode, but it distributes the trigger to all the other modules, working in “Slave“ configuration. When the slave modules receive
a trigger, they issue their busy signal and only when all modules are ready a new trigger signal can be processed.

All data corresponding to a trigger event get the same event number assigned. After recognition of a trigger signal, the corresponding time stamp is sent to all ADC FPGAs. This time determines the "trigger window" and the corresponding data from the DPRAM are read and analysed. The latency time can be set to a maximum of $\pm 6.4 \, \mu s$. The trigger window can be up to $6.4 \, \mu s$ long.

![Figure 5.2: Trigger Window.](image)

Feature extraction algorithms, implemented in the AVM16 modules, allow to extract the main parameters of the pulse, such as total and partial integrals of the signal, amplitude and time of relative maxima and minima, start time of the signal. For each channel independently, the user can choose that only the main features of the signal are transmitted or also the raw data samples. All time measurements are relative to the trigger. Time measurements before the trigger are positive, after the trigger are negative.

In figure 5.3 is illustrated an example of the main features for a signal with pile-up events: the window start point ($P_0$), which represents the user defined latency time; amplitude and time of minima ($P_i$, $P_{pi}$, ...) and maxima ($P_a$, $P_{pa}$, ...), extracted when a rising slope is detected; the pulse start time ($P_z$, $P_{pz}$, ...), extrapolated from the crossing of the slope and the pedestal value (or the current pedestal value for pile-up signals) and the total and partial charge integrals ($P_q$, $P_{pq}$).
The values of the individual samples can be reported in a histogram, such as that shown in the figure 5.4, where a typical temporal trend of the signal of a crystal of BGO is shown. In this case, the time window acquisition chosen was of 600 ns. The very fast rise time of the signal (about 20 ns) is clearly visible. The falling edge of the signal is of exponential shape with a relation:

\[ N(t_i) = N_0 e^{-t_i/\tau} \]  

(5.1)

where:

- \( N(t_i) \) is the height of the sampled signal at the time \( t_i \);
- \( N_0 \) is the initial height of the signal;
- \( \tau \) is the time of the slow decay of the BGO (300 ns).

\[ \text{Figure 5.4: Example of a sampling of a signal of BGO crystal.} \]

### 5.2.1 ADC’s saturation

The ADC modules, as we mentioned before, have a resolution on the single sample (included the baseline) of 12 bit that corresponds to the maximum sampling value of 4096. Up to now, the baseline’s value is set at half of the scale, providing a 11 bit resolution (2048 channels). In order to avoid the ADC saturation, the first maximum of each signal must be lower than the end-scale (2048). We can evaluate the maximum energy measured by the ADC (i.e. the energy corresponding to the end-scale), making the approximation that the integral of the rising edge can be neglected:
\[ Q_{\text{tot}} = \sum_{i=1}^{n_{\text{sample,max}}} N_0 \exp\left(-\frac{t_i}{\tau}\right) = N_0 \left(1 - \exp\left(-\frac{t_f}{\tau}\right)\right) \]

where:

\( \tau_{\text{sample}} = 6.25\,\text{ns} \) is the time interval between two samplings;

\( \tau = 300\,\text{ns} \) is the decay time of the BGO;

\( Q_{\text{tot}} \) is the total charge of the signal (in channel units);

\( t_i \) is the time related to the i-th sampling;

\( t_f = 600\,\text{ns} \) is the integration time of the signal;

\( N_0 \) is the first maximum amplitude of the signal. The ratio between the end-scale value and \( N_0 \) allows us to calculate the maximum energy explored by the ADC module (without attenuation). In case of the equalization channel equal to 60, \( N_0 \) results \( \sim 11.6 \). This result multiplied by the energy of second peak of the source (1.275 MeV) provides the max energy that can be explored (\( \sim 200\,\text{MeV} \)) before the saturation of the ADC occurs.

### 5.3 BGO calibration procedure

The absolute calibration of the Bgo Rugby Ball is obtained using the 1.275 MeV photons (\( E_{\text{source}} \)) emitted by three \( ^{22}\text{Na} \) sources located inside the BGO cylindrical hole.

In Figure 5.5 a three-dimensional mapping of the BGO Ball with the number of hits is represented. x and y coordinates are the number of the crown (\( \theta \)) and the azimuthal distribution (\( \phi \)) of crystals of the same crown, respectively. Here, the number of hits with energy threshold \( > 1.0\,\text{MeV} \) is shown where the three sources of \( ^{22}\text{Na} \) appear clearly.

The response of the 480 crystals is equalized using a procedure that sets all the photomultiplier (PM) gains, varying their high voltages. The equalization is strictly
Figure 5.5: The number of hits with energy threshold $> 1.0 \text{MeV}$ is shown. Here, the three sources of $^{22}\text{Na}$ appear clearly.

necessary, because a threshold on the hardware sum of the energy released in the BGO is used as a trigger for the experiment. After the equalization, for the same energy released, the response of the PM associated to each crystal will be located at the same ADC channel. For the calibration procedure an internal trigger which is provided by the ADC, when a signal overcomes a certain threshold, was used; it was chosen in order to guarantee the same statistics on all the crystals, which a global trigger on the hardware sum of the energies of all the crystals could not insure. In Figure 5.6 a schematic representation of the experimental chain of calibration is shown: the output signal from the phototube, coupled to the crystal, is sent to a mixer that delays, eventually attenuates, splits the signals into two parts, one sent to the ADC for the readout and the other to the sum over the signals.

Figure 5.6: Scheme of the experimental calibration chain.

To obtain the calibration constants for each channel, we fix the PM voltages so that the response to the energy of the second peak of the source is located at the channel 60 of the ADCs. The channel is fixed within a tolerance of $\pm 3\%$, which, in
any case, does not affect the calibration of the data, since the calibration constant of each crystal is registered and used for the offline energy conversion\cite{97}.

The calibration procedure enables us to monitor the position of the peaks during the time (without changing the HV, just recording their position). It requires that the attenuators of the mixers and the beam are switched off.

The calibration constant of each crystal may change during time due to two principal reasons: variation in the crystal light output due to temperature effects and variation in the PM gain. Gain variations of the photomultipliers may occur as a consequence of the following effects:

- photocathode temperature variation;
-instability in the high voltage power supply;

-aging of the cathode and dynode materials;

-voltage dividers instability [52].

In Figure 5.7 the azimuthal distribution ($\phi = 1 \div 32$) of the values of the calibration constants for six BGO crowns ($\theta = 1, 2, 7, 8, 14, 15$) related to different set of calibrations is shown. The blue squares refer to the equalization on February 15th, 2012; it is possible to see that all the responses are set within a maximum dispersion of $\pm 3\%$ (except for crystal $\theta = 2, \phi = 14$, whose PM had low gain). For the calibration constants on March 1st and March 5th, the fluctuations of the position of the second peak is about 1-2 channels which means a variation of about 1.6%-3.2% of the calibration constants. More fluctuations occur in the case of the comparison between the calibration constants obtained on February 15th and March 1st. The position of the second peak changes of about six channels corresponding to a variation of 9.8%. When a new calibration procedure is performed at a certain time and new calibration constants are recorded, these can be used for the correct conversion channels-energy at that time. But if strong differences with respect to the previous calibration occur, we can only infer that an uncertainty in the energy conversion arose in the period in-between. For this reason it is necessary to repeat the calibration procedure often in order to reduce the uncertainty in the behaviour of the calibration constants between two consecutive calibrations[97].

In figure 5.8, some examples of BGO calibration spectra are illustrated, where both the peaks of the $^{22}\text{Na}$ source are visible. They refer, respectively, to the calibration data of March 1st, 2012 for $\theta = 1$ (from $\phi=1$ up $\phi=8$) at the beginning of data taking without magnetic field and to the ones of March 5th, 2012 for the same theta value, in the same experimental conditions but at the end of the data taking.

Making the calibration procedure in presence of the magnetic field, we observed a deviation of the calibration constants from the equalization channel (60) which increases with the intensity of the field. In the next paragraph, we report the results of the tests made with the magnetic field on in order to monitor its impact on the response of the crystals.
Figure 5.8: (a) Calibration spectra obtained with the $^{22}\text{Na}$ sources at $\theta = 1$ (2012,01 March) at the beginning of data taking without magnetic field. (b) Calibration spectra (2012,05 March) at $\theta = 1$ without magnetic field at the end of data taking.

5.4 Tests with the magnetic field

Each photomultiplier (coupled to the crystal) is equipped with an internal cylindrical shielding in Permalloy-C, a Ni-Fe alloy with high magnetic permeability (10000), which is suited for the shielding of low magnetic fields. Each photomultiplier is located inside a PVC tube.

Figure 5.9: Internal scheme of the photomultipliers in use with the BGO crystals, models n. R329-02 and R580 Hamamatsu.

The photomultipliers in use are linear-focusing devices, with the trajectory of the photoelectrons drifting towards the first dynode almost parallel to the axis of the tube (see fig.5.9). The dependence of the impact of the magnetic field on the azimuthal angle is also convoluted with the fact that the behaviour of the tubes with
the field is not symmetric in x and y, depending on the position of the dynodes. This effect is completely random, due to the rotation of the tubes with respect to the crystal and cannot easily be de-convoluted.
The position of the source peaks has been monitored with the magnetic field of intensity equal 0.168T and 0.338T. As one can see by the comparison with the calibration spectra acquired in absence of magnetic field (see fig. 5.8), the two peaks are yet good visible with a magnetic field of 0.168T; the signals are reduced of about 20%-30% of the original. However, with the higher intensity, their reconstruction is done only in few cases and for most of the crystals both peaks disappeared completely.

In the figure 5.11, the behaviour of the peak channel of the calibration as a function of the azimuthal angle at fixed theta is shown. We compare the calibration constants of the equalization of February 15th, 2012 (without magnetic field) with the calibrations of the March 2nd, 2012 (with the magnetic field of lower intensity). The general behaviour for the first theta angles shows a worsening of the response as the azimuthal angle increases, especially for the \( \phi \) value from 5 to 15. The effect is much less visible for \( \theta \geq 6 \).
The impact of the magnetic field can be seen also in the picture 5.12 where the event rate in the BGO is shown. The number of hits for each energy threshold value decreases drastically for the values of \( \phi \) above mentioned in particular for the field of intensity equal to 0.338T.
The solution for the screening of the BGO is in progress.

5.5 Preliminary results of the beam time tests

The beam time tests were performed with the following experimental conditions: electron beam energy 2.5 GeV, two different BGO trigger conditions (the threshold of the energy sum of all the 15 crowns higher than 400 MeV and with a BGO-trigger where the threshold of the energy sum of the first 13 crowns was higher than 200 MeV), the target filled of liquid Hydrogen \( H_2 \), and the totally equipped BGO electronic readout.
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Figure 5.10: (a) Calibration spectra at $\theta = 1$ (2012,02 March) with a magnetic field of intensity equal to 0.168T. (b) Calibration spectra (2012,02 March) at $\theta = 1$ with a magnetic field of 0.338T.

In Figures 5.13 and 5.14 (indexes from $1 \div 240$ and from $241 \div 480$ correspond to the two halves of the BGO, left and right respectively, with respect to the incident beam), we show the energy and time distributions per index of crystals, respectively.

As one can see, there is a strong global difference between the time measured in the two halves, which is trivially due to differences in the cable lengths, but also a little difference can be observed between the forward or backward crowns (indexes 1-48 and 192-240 for the left part; indexes 241-248 and 432-480 for the right part) which is probably due to the different electron transit time in the phototubes of different sizes (37-48ns).

In fig.5.15, the time distribution of one crystal ($\theta = 1$, $\phi = 4$) and its zoom are illustrated. A rough estimate of the time resolution provides about 4 ns (RMS). The analysis\(^1\) was performed with the Explora code [100] using the calibrated energy and time information of the deposited energy in the BGO crystals. To reconstruct the energy and position of incident particles in the BGO, the first

\(^{1}\)The analysis has been performed by the Member of the BGO-OD Collaboration T.Jude.
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(a) (b) (c) (d)

Figure 5.11: The dependence of the crystal response to the magnetic field on the azimuthal angle; the blue squares represent the calibration constants of the calibration of February 15th, 2012; the pink squares to the calibration of March 2nd, 2012 with a magnetic field of 0.168T.

The step was the identification of photons from 'clusters' of adjacent crystals due to electromagnetic showers from bremsstrahlung and pair production.

To identify the detected particles, without the charged particle identification (the scintillator barrel was still not in operation during the beam time), the size of reconstructed clusters within the BGO was used. The fig.5.16 shows the characteristics of the clusters reconstructed in the BGO. In the panels a) and b) the number of clusters identified per event in the BGO and the number of crystals contained within each cluster are shown, respectively; in the panel c) the sum of the energy of all the crystals within the cluster is reported. In particular, in the analysis is required that each proton candidate had to have at least 40 MeV energy deposit (panel c)) because there is a lot of low energy clusters which would be unlikely to be protons. Finally in the last two panels d) and e) the number of protons and photons identified per event.
Figure 5.12: Bgo matrix in the case of no field (a); magnetic field of 0.338T (b); magnetic field of 0.168T (c). The threshold for each crystal is 1MeV (left part) and 20MeV (right part).

A cluster of three or more crystals was assumed to be a candidate photon, a cluster with only one crystal is a possible candidate proton or a charged pion (see fig.5.16)[101]. This criterion causes, unfortunately, a strong rejection of events, when one of the two photons has low energy and hence low multiplicity, but guarantees a clean selection of good events.

Particularly, we observed that when the total energy deposit is below about 300 MeV there is much low energy background to discern any structure in the spectrum. However above approximately 400 MeV there is a concentration of events with the invariant mass close to the expected $\pi^0$ mass, and a smaller shoulder above 500 MeV is consistent with the mass of the $\eta$ meson.
5.6 First tests with linearly polarized photon beam

The excellent status of the BGO calorimeter has allowed also a preliminary estimation of polarization degree of the beam supposing known the $\pi^0$ beam asymmetry. The results on the analysis\(^2\) of the first runs acquired with linearly polarized photons for the reaction $\gamma p \rightarrow \pi^0 p$ are presented in the following.

\(^2\)The analysis has been performed by the Members of the BGO-OD Collaboration J.Hannappel and V.Vegna.
Figure 5.15: Start time distribution of crystal $\theta = 1, \phi = 4$ (left panel) and the zoom of the distribution with a rough estimate of the time resolution (right panel).

Figure 5.16: Cluster reconstruction within the BGO Ball (only using one data file) (a) The number of clusters identified per event in the BGO Ball. (b) The number of crystals contained within each cluster. (c) The cluster energy (summed energy of all crystals within the cluster). (d) The energy of clusters containing only one crystal. These are assumed to be protons if the energy exceeds 40 MeV. (e) The number of protons identified per event. The value at zero extends to approximately 300k. (f) The number of photons identified per event (clusters containing at least 3 crystals)[101].

The scintillator barrel is not used during the test beam time, so only the data from the BGO calorimeter and the tagging detector are used in the analysis. Thus, the discrimination between photons and other particles in the BGO is made, again, by considering the size of each cluster.

Only the events with two photons and one proton in the BGO are considered. The proton and the $\pi^0$ must satisfy the condition of coplanarity:

$$170^\circ < |\phi_{\pi^0} - \phi_p| < 190^\circ.$$
Figure 5.17: Invariant mass when the two photons energy is greater than 400 MeV. A Gaussian distribution is used to fit to the peak at the expected $\pi^0$ mass[101].

Figure 5.18: Invariant mass distribution of the final state photons for events which satisfies the coplanarity condition [102].

In fig. 5.18, the invariant mass distribution of the two final state photons is shown for the selected events [102].

The measurement of the $\pi^0$ beam asymmetry ($\Sigma(E_\gamma)$) is performed by using the following formula:

$$\frac{N_{\text{pol}}(E_\gamma)}{N_{\text{unpol}}(E_\gamma)} = \frac{\sigma_{\text{pol}}(E_\gamma) \times F_{\text{pol}}(E_\gamma) \times N_{SC} \times \epsilon}{\sigma_{\text{unpol}}(E_\gamma) \times F_{\text{unpol}}(E_\gamma) \times N_{SC} \times \epsilon} =$$

$$\frac{\sigma_{\text{unpol}}(E_\gamma)(1 - P(E_\gamma)\Sigma(E_\gamma) \times \cos(2\phi_{\text{pol}})) \times F_{\text{pol}}(E_\gamma)}{\sigma_{\text{unpol}}(E_\gamma) \times F_{\text{unpol}}(E_\gamma)}$$

(5.3)

where $N_{\text{pol}}$ and $N_{\text{unpol}}$ is the number of the polarized and unpolarized counts, respectively; $\sigma_{\text{pol}}(E_\gamma)$ and $\sigma_{\text{unpol}}(E_\gamma)$ are the polarized and unpolarized cross sections; $N_{SC}$ is number of scattering centers in the target, $\epsilon$ is the detection efficiency,
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$p(E_\gamma)$ is the polarization degree of the photon beam, $\phi^{pol}$ the azimuthal angle between the reaction plane and the photon beam polarization and $F^{pol}(E_\gamma)$ and $F^{unpol}(E_\gamma)$ are the unpolarized and polarized flux of photons [102].

The eq. 3.3 can be written as:

$$\frac{N^{pol}(E_\gamma)}{N^{unpol}(E_\gamma)} = (1 - p(E_\gamma)\Sigma(E_\gamma) \times \cos(2\phi^{pol})) \frac{F^{pol}(E_\gamma)}{F^{unpol}(E_\gamma)}.$$  \hspace{1cm} (5.4)

The polarization degree as a function of the incoming photon energy extracted from simulation is shown in the fig. 5.19.

![Figure 5.19: Polarization degree of the beam as a function of the incoming photon Energy. The vertical lines show the ranges of the three energy regions investigated. The polarization degree is maximum in the second energy range (between 250 MeV and 400 MeV).][102]

The azimuthal distribution of the ratio in the eq. 5.4 has been measured in three energy regions and in 12 $\phi$ bins, each of them having a width of 30°:

- 170-250 MeV: the polarization degree increases from 10% to 35%
- 250-400 MeV: the polarization degree changes between 35% and 40%
- Over 400 MeV: there is a plateau of the polarization degree of about 12%.

The distributions (reported in the fig.5.20) are fitted using the following function:

$$p0 \times (1 + p1 \times \cos(2(\phi^{pol} + p2)))$$  \hspace{1cm} (5.5)

where:
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Figure 5.20: Azimuthal distribution of the ratio in eq.5.4 in the incoming photon energy range: 170-250 MeV, 250-400 MeV and 400-710 MeV.\cite{102}

\( p_0 \) corresponds to the ratio of the polarized flux and the unpolarized one, in the considered energy range; \((-1) \cdot p_1 \) corresponds to the half of the product between the polarization degree of the beam and the beam asymmetry, in the considered energy range; \( p_2 \) corresponds to a phase term to be added to \( \phi^{\pi^0} \) to consider the difference between \( \phi^{\pi^0} \) and \( \phi_{pol} \) (because \( \phi^{\pi^0} \) is referred to the \( \pi^0 \) azimuthal angle in the laboratory frame).

Higher statistics is necessary to perform more precise measurements but the experimental results clearly show the expected azimuthal behavior of the ratio in eq.5.4 \cite{102}. The observed distributions allow the extraction of the \( P\Sigma \) product in three energy regions and, supposing the beam asymmetry \( \Sigma \simeq 1 \), it is possible to extract the beam polarization. The resulting value of the beam polarization is consistent with the ones expected from the simulation.
Chapter 6

BGO Tests at the Beam Test Facility of Frascati

6.1 Introduction

The characteristics of the BGO crystals in combination with the new ADC modules actually installed in Bonn have been studied, concerning both the linearity and resolution in the energy reconstruction and the performances in the time response to a monocromatic tunable source of high energy electrons available at the BTF (Beam Test Facility) of the LNF-INFN in Frascati (Rome, Italy).

6.2 Experimental apparatus

The tests have been performed at the "Beam Test Facility" of the Laboratori Nazionali di Frascati (see fig.6.1) of the INFN. It is part of the $DAΦNE$ $Φ$-factory complex which includes a high current electron and positron LINAC, a 510 MeV $e^-$ and $e^+$ accumulator and two 510 MeV storage rings.

Before the high-intensity electron or positron beam pulses produced by the 60 m long LINAC are injected into the double storage ring, they can be extracted to a transfer line that is dedicated to the calibration of particle detectors (the BTF transfer line)[103]. Here, the number of particles can be reduced to a single electron per pulse by means of a variable thickness copper target. The particle momentum is then selected, with an accuracy better than 1%, using a dipole magnet and a
Figure 6.1: Schematic view of the DaΦne facility in Frascati

set of tungsten collimators.
Thus, the energy of the beam can be modulated in energy and intensity but also the multiplicity of the beam, allowing to have one, two or more electrons of the same energy simultaneously impinging on the crystals. This allows, although the maximum energy of an electron at the end-point of the Bremsstrahlung spectrum is \(\approx 510\) MeV, to reach higher energies in the matrix of the crystals due to the sum of several electrons (up to \(2.5 \div 3\) GeV).

We studied the response of the detector not only as a function of the energy but also as a function of the electron multiplicity at the same energy to see if differences can arise in the two cases.

Figure 6.2: Beam Test Facility in Frascati
We used a matrix of 7 crystals arranged inside a PVC basket with removable walls. The position of the walls could be adjusted with Aluminum screws (see fig. 6.3) in order to guarantee a better tightness among the crystals. No inert material was present between the crystals because they were not mechanically separated. The axis of the basket, located on a table and tilted by a wedge, corresponding to the axis of the central crystal of the matrix, was aligned along the direction of the electron beam. The height of the table could be regulated in order to align the center of the basket with the beam.

![Image](image_url)

**Figure 6.3:** Upper: the matrix of the seven BGO crystals arranged inside the PVC basket used for the tests. Down: the plastic scintillator (used for the coincidence) represented with the matrix of the crystals.

The trigger to the acquisition has been provided by a plastic scintillator plate, located in front of the crystals, when the signal is in coincidence with an over threshold deposited energy in the BGO crystals.
6.3 The electronics read-out

All the electronics read-out was located inside the experimental area, close to the detector. Access to the processor was provided via an ethernet connection. The signal from the PM of each crystal was split and (i) attenuated and sent to the ADC module for digitization, or (ii) sent to a linear Fan-In-Fan-out together with the signals coming from the other crystals for trigger purposes. The linear sum of the seven signals was amplified and sent to a threshold discriminator and then to a coincidence unit, together with the discriminated signal of the scintillator pad. A veto to the coincidence unit, to avoid further triggers during the dead time of the acquisition, is provided by a Dual Timer module activated by an output of the coincidence unit.

The reset of the Dual Timer is externally provided by the acquisition program via an I/O-Register. In figure 6.4 a scheme of the electronics read-out is shown. The acquisition is performed by using the W-ie-Ne-R sampling ADC AVM-16 modules, specifically modified by the Company on the basis of the requests of our collaboration. The module has 16 channels and a sampling frequency of 160 MHz (see chapter three). Each channel is equipped with an individual 12-bit Analog-to-Digital-Converter. Digitized data from the 16 channels are transmitted to 4 Spartan-3 FPGA circuits from Xilinx (each for a block of four channels), where they are continuously stored in a ring buffer memory (6÷4µs wide). The on-board feature extraction capabilities of the 4 Spartan FPGA circuits allow the compact readout of the sampled signal, reducing the amount of data to be transferred. An on-line analysis of the pulse implemented in the module allows the extraction of the main features of the signal, such as:

![Electronics Scheme](image)
1. amplitude and time of the first relative maximum of the signal and of all other maxima (and the same for the relative minima);

2. start time of the signal;

3. total integral of the signal and partial integrals in case of overlapping pulses.

For test and debugging purposes also raw samples can be transmitted for single channels. The signal can be reconstructed off-line using the transmitted main features. When an internal or external trigger is provided to the module, data are transmitted to a control VIRTEX-5 FPGA chip via four local data buses and then transferred over a VME bus. The trigger can be:

1. internal: every channel is provided with an internal leading edge discriminator with a programmable threshold; we use this option for calibration purposes;

2. external: it is provided via a NIM signal; since data are continuously stored in the ring buffer memories, the sampling window can start before or after the trigger arrival and no hardware delay is required for the timing between the analogic signal and the trigger; we use this option during data acquisition.

The monitoring and the recording of the pedestals is performed constantly for each channel separately during periods free of trigger and pulses, allowing, in this way the offline pedestal subtraction.

Signals produced by a BGO crystal and amplified by a linear device like a photomultiplier have a slow decay time (of the order of 300ns), but rather fast rising edge. With the sampling ADC, also the start time of the BGO signal has been extracted and time resolution has been measured. Good time performances have been measured, which can be used for background rejection in the analysis of the time correlation between the crystals belonging to the same cluster.

### 6.4 Calibration and data acquisition

The response of the seven crystals has been equalized by using the 1.275 MeV photons emitted by a $^{22}\text{Na}$ source, varying the high voltage applied to their photomultipliers. In the fig.6.5, an example of the spectrum of the $^{22}\text{Na}$ obtained
after the equalization procedure is shown. Here, the two peaks corresponding to the 0.511MeV and 1.275MeV photons, respectively are visible. We used the second peak of the source for the equalization because, due to the threshold of the internal trigger, the first one is cut towards the low energies. The two peaks are fitted with a gaussian plus a straight line (parameters of the fit for the peak at 1.275MeV are indicated in the box). Typical measured resolutions at 1.275MeV are of the order of 15% (FWHM).

![Typical spectrum from $^{22}$Na measured with one of the seven crystals (the two peaks corresponding to the 0.511MeV and 1.275MeV photons respectively are visible). Typical measured resolutions at this energy are of the order of 15% (FWHM).](image)

During the equalization procedure, signals from the source are not attenuated, since they have small amplitude (about 7mV).

The width of the sampling and the integration window must therefore be much smaller than the window used during the data acquisition, in order to avoid the integration of noise signals comparable with the signal of the source itself. To taking account of the different integration windows, we applied a correction on the calibrations constants.

We collected data at six different values of the beam energy. Data settings have been collected at the following energies of the single electron (in parenthesis also the number of electrons simultaneously entering in the area is indicated): 100MeV (4 peaks of multiplicity=1÷4), 150 (6 peaks), 200 (7 peaks), 300 (7 peaks), 400 (9 peaks) and 500MeV (4 peaks). For each event, we considered a cluster of all the crystals, summing up the energies deposited in all of them, since the e.m. shower spreads over several crystals.
Figure 6.6: Energy spectrum of the beam when the single electron has an energy of 100, 150, 200, 300 MeV. The visible peaks correspond to the events when a single electron or two, three, ..., n electrons entered in the area, depositing their energy in the detector.

As said before, also the multiplicity of the beam can be modulated, modifying the aperture of a system of slits located after the dipole with the help of another calorimeter available at the BTF and located behind our detector (while our detector was temporarily removed from the beamline lowering the table).

In figures 6.6 and 6.7, the energy spectrum of the beam is shown for all the energy
settings. The peaks correspond to the different value of multiplicity of electrons with the same energy. The peaks appear clearly separated at all energies and each peak has been fitted separately with a gaussian (plus a background approximated with a straight line), with mean value of the energy $E_{\text{meas}}$ and resolution $\sigma_{E_{\text{meas}}}$. As it is possible to see from the figures 6.6 and 6.7, for each energy setting ($E_{\text{NOM}} =$ nominal energy of the beam), several peaks of multiplicity are visible. They correspond to energies, which are multiple of $E_{\text{NOM}}$ ($E_{\text{NOM}}, 2E_{\text{NOM}}, \ldots nE_{\text{NOM}}$).

We extracted the linearity curve plotting the fitted vs. the nominal energy for the different energy values at a fixed multiplicity of electrons or viceversa for the different multiplicities at each energy setting.

Since the calorimeter is a linear device, we expect that if a single electron of energy $E_0$ deposits its energy in the detector or n electrons, each of energy $E_i = E_0/n$, i.e.:

$$E_0 = \sum_{i=1}^{N} E_i$$  \hspace{1cm} (6.1)
the response of the detector should be essentially the same in the two cases. Small
differences could arise due to the following effects:

- the longitudinal penetration (in terms of $t_{95\%}$) of the e.m. shower produced by a
  single electron of energy $E_0$ is slightly larger than the one of the showers produced
  by $n$ electrons of energy $E_0/n$. But at our energies, the penetration depth is
dominated by the terms independent from the energy. For example, in the case
of a single electron of energy 2 GeV, $t_{95\%} \simeq 20.9X_0$, while for five electrons of
energy 0.4 GeV, $t_{95\%} \simeq 19X_0$. In any case, the Molière radius of the BGO, which
describes the transverse energy containment, is about 2.3 cm and the e.m. is never
contained in a single crystal, thus reducing the possibility that a shower is not
longitudinally contained in the crystal;

- the higher the multiplicity of the incident electrons, the wider their transverse
  spatial distribution, which causes a spread of the deposited energies all over the
crystals of the matrix.

In figure 6.8 we reported the fitted values of the energy with the error coming from
the fitted resolution as a function of the nominal energy for all energy settings and
multiplicities. Points of the same colour refer to the data of the same energy
setting with increasing value of multiplicity. We compared the results obtained at
the same values of energy with different multiplicities and we found that they are
in good agreement. They follow a linear behaviour:

$$E_{meas} = p_0 + p_1 \times E_{nom}$$ \hspace{1cm} (6.2)

with

$p_0 = (-7.233 \pm 3.971)\text{MeV}$

$p_1 = -0.977 \pm 0.0055\text{MeV}$

and a satisfactory reduced $\chi^2_{red}$ value: $\chi^2_{red} = 0.4$. Only the three points at the
highest energies, 2400 MeV, 2800 MeV, and 3200 MeV (corresponding to 6, 7 or
8 electrons of energy 400 MeV each) are slightly higher than expected, probably
denoting small non-linearities in the PM of the central crystal of the matrix or of
the ADC module. Removing the three points, the fit provides:
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Figure 6.8: The linearity curve of the detector: the energy fitted from data is plotted as a function of the nominal energy. Error bars represent the fitted sigma of the gaussian fit. Points of the same colour represent the fit of the different peaks obtained when one, two or more electrons of the same energy entered in the area.

\[ p_0 = (-4.808 \pm 4.206)\text{MeV} \]

\[ p_1 = 0.971 \pm 0.007 \]

and a \( \chi^2_{\text{red}} = 0.34 \).

The linearity was tested also considering the results obtained at the same values of multiplicity with different energy values. They are compared and found in reasonable agreement.

Figure 6.9: The linearity curve of the detector: the energy fitted from data is plotted as a function of the nominal energy. Error bars represent the fitted sigma of the gaussian fit. Only data for multiplicities less or equal four are reported and points with the same colour represent data obtained at the same multiplicity.

In this case the fit provides:
\[ p_0 = (-1.868 \pm 4.845) \text{MeV} \]

\[ p_1 = 0.9628 \pm 0.01027 \]

and a \( \chi^2_{\text{red}} = 0.25 \).

The deviation of the energy released in all the BGO matrix (\( E_{\text{meas}} \)) from the nominal energy (\( E_{\text{nom}} \)) was also estimated, as before, for the same energy settings (fig. 6.10) and for the same multiplicity value (fig. 6.11). It was obtained from the following equation:

\[
\Delta E[\%] = \frac{E_{\text{meas}} - E_{\text{nom}}}{E_{\text{nom}}} \times 100. \tag{6.3}
\]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.10}
\caption{Deviation of the measured energy from the nominal energy. The same marker indicates the same energy setting (increasing the multiplicity).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.11}
\caption{Deviation of the measured energy from the nominal energy. The same marker indicates the same multiplicity value (increasing the energy setting).}
\end{figure}
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The BGO resolution in combination with the new ADC module, was extracted subtracting the BTF resolution, which is \( \simeq 1\% \text{(RMS)} \) at all the energies, from the measured resolution:

\[
(\Gamma_{BGO})^2 = (\Gamma_{\text{meas}})^2 - (\Gamma_{BTF})^2
\]  

(6.4)

In figure 6.13, we show the energy resolution, obtained from the the fit of the peaks for all settings for multiplicities between 1 and 4 simultaneously.

![Figure 6.12: The BGO energy resolution, extracted from the fit of the peaks with a gaussian distribution and subtracted of the BTF energy resolution, as a function of the nominal energy. Data for all energy settings and multiplicities are reported and points with the same colour represent data obtained at the same energy settings.](image)

As before, we have compared the energy resolutions concerning energies obtained in different ways (one single electron with energy \( E_0 \) or \( n \) electrons with energies \( E_0/n \)) and we found reasonable agreement between the different cases. Data of the same colour represent the results obtained at the same multiplicity for different energy settings. In this way, it is possible to compare the behaviour of data when two, three or more electrons have been impinging on the BGO crystals and deposited their energy. We have not observed clear difference with respect to the simplest case of one single electron. As we said also in the chapter two, a general parametrization of the energy resolution is the following:

\[
\Gamma(\%) = a_{\text{CONST}} \oplus \frac{a_{\text{STAT}}}{\sqrt{E_{\text{NOM}}}} \oplus \frac{a_{\text{NOISE}}}{E_{\text{NOM}}}
\]  

(6.5)
Figure 6.13: The BGO energy resolution, extracted from the fit of the peaks with a gaussian distribution and subtracted of the BTF energy resolution, as a function of the nominal energy. Only data for multiplicities less or equal four are reported and points with the same colour represent data obtained at the same multiplicity.

where the terms are summed in quadrature:

- $a_{\text{CONST}}$ is the constant term, that gives the asymptotic behavior. It is connected at the intercalibration precision, which are limited due to the equalization procedure, at the longitudinal non-uniformities ($\approx 0.3\%$) in the collection of the emitted light and to the temperature fluctuations, which can be neglected since the crystals have been monitored in calibration during the data collection.

- $a_{\text{STAT}}$ is the statistical term. It contains sampling and fluctuations of all kinds (i.e. fluctuations in the number of particles of the e.m. shower and in the number of photo-electrons emitted at the PM cathode). It results close to zero confirming that all the effects contributing to this term are negligible. It is in good agreement with results obtained for similar kind of detectors.

- $a_{\text{NOISE}}$ is connected to the electronic noise, generally negligible at high energies. This term is small as it could be expected from read-out devices such as the photomultipliers.

However, as it’s possible to see from the plot 6.12, the better fit is given from the energy setting of 400 MeV. It’s not a coincidence. In fact, studying the spot of the beam has been found that only in the case of this energy setting the beam was perfectly centred and above all, it has a spread lower than the other settings.
Figure 6.14: Bidimensional distribution of the \( x \) and \( y \) coordinates of the centroid for all the energy setting: (a) 100 MeV; (b) 150 MeV; (c) 200 MeV; (d) 300 MeV; (e) 400 MeV; (f) 500 MeV.

of energy. In the fig.6.14 the spatial distribution of the beam, overlapped to the matrix of the seven crystals, is shown for all the energy settings. To calculate the centroid, the center of the crystal number three was assumed as the impact point of the beam (since any experimental measurement was available). The coordinates of the centroid has been calculated as:

\[
x_B = \frac{\sum_{i=1}^{7} x_i \cdot q_{total}}{\sum_{i=1}^{7} q_{total}}; \quad y_B = \frac{\sum_{i=1}^{7} y_i \cdot q_{total}}{\sum_{i=1}^{7} q_{total}}
\]

where \( x_i \) and \( y_i \) are the crystals coordinates (see table 6.1) and \( q_{total} \) is the released charge, event by event, in each crystal.

The global resolution of the BGO, with the new of the Sampling ADC modules, is confirmed to be of the order of 3\% at 1 GeV, which is compatible with the requests at the BGO-OD experiment.
Table 6.1: Crystals coordinates.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>x[cm]</th>
<th>y[cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>-2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
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<tr>
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<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>-1</td>
<td>-2</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>-2</td>
</tr>
</tbody>
</table>

6.5 Time response of the detector

For the first time the time response of the detector has been studied with a test beam and its time resolution has been estimated. In figure 6.15, the distribution of the start time in the seven crystals is illustrated. As it is possible to see from the fig.6.15 for a central crystal (as the crystal number 3) we have a typical time resolution less than 2\(\text{ns}\); for a lateral crystal (as the crystal number 0) the measured resolution is about 6 – 7\(\text{ns}\), probably it is due to a spread in the propagation of the secondary products of the electromagnetic shower.

A difference in typical mean value is visible between the large and the small crystals: in the first case the \(t_{\text{trg}}\) is about \(-234\text{ns}\), instead in the second case the \(t_{\text{trg}}\) is about \(-222\text{ns}\) with a \(\Delta t \simeq 10 – 12\text{ns}\) and \(|t_{\text{trg}}| > |t_{\text{sm}}|\). The different electron transit time in the photomultipliers, maybe it is reason for the \(\Delta t\).
Figure 6.15: The start time distribution of the seven crystals of the matrix. Distributions has been fitted with a gaussian; the fit parameters are reported in the plot.
Chapter 7

Conclusions

Understanding the structure of the proton and its excited states is one of the key questions in hadronic physics. Without precise data from many decay channels, it will be difficult or even impossible to accurately determine the properties of well established resonances, or to confirm or rule out the existence of weakly established resonances or new, so-far not observed states. Of particular importance are well-chosen decay channels which can help isolate contributions from individual excited states and clarify their importance. Photoproduction of $\eta'$ meson offers the distinct advantage of serving as an isospin filter for the spectrum of nucleon resonances and thus simplifies data interpretations and theoretical efforts to predict the excited states contributing to these reactions. Since the $\eta'$ meson has isospin $I=0$, the $N\eta'$ final states can only originate from intermediate $I=1/2$ nucleon states.

In the past few years, the CLAS experiment at Jlab and the CB-ELSA-TAPS in Bonn have produced a rich amount of $\eta'$ cross section data on the proton and, very recently, on the deuteron. The energy region from threshold ($1.447$ GeV) up to $2.84$ GeV was measured and total and differential cross section data were produced. However, the cross section data alone are insufficient to pin down the resonances parameters, so it is crucial the role of the beam and/or target asymmetries.

We have presented the first estimation of the $\eta'$ beam asymmetry off proton in the threshold region, by using the GRAAL data. Up to now, neither results from other experiments are available. The trend of the beam asymmetry has been shown the possible presence of the $S(1535)$ and $P(1710)$ nucleon resonances as suggested in the ref.[63].
We have presented the new BGO-OD experiment at the ELSA facility in Bonn. This apparatus will be used to measure polarisation observables and cross sections in the photoproduction of pseudo-scalar and vector mesons off a Hydrogen or Deuterium target.

The BGO-OD set-up is ideal to study the $\eta$ and $\eta'$ photoproduction, in particular for the measurement of both, charged and neutral, decay channels (thanks to the combination BGO calorimeter and magnetic spectrometer).

We have reported the details of the BGO calorimeter calibration procedure that we used.

The excellent status of the BGO Ball has allowed to obtain promising results during the beam time tests, as the reconstruction of the $\pi^0$ and $\eta$ mesons invariant mass and the preliminary estimation of the polarization degree of the beam (supposing known the $\pi^0$ beam asymmetry), made by the Members of the BGO-OD Collaboration. In fact, a basic analysis of the reaction $\gamma p \rightarrow \pi^0 p$ has been performed looking for the final state particles in the BGO calorimeter.

We have studied the performances of the BGO crystals in combination with the new ADC modules, concerning both the linearity and resolution in the energy reconstruction. The global resolution of the BGO, with the new readout of the Sampling ADC modules, is confirmed to be of the order of 3% at 1 GeV, which is compatible with the requests at the BGO-OD experiment. For the first time, we have studied the time response of the detector with a test beam and we have estimated its time resolution ($\sim 2$ns (RMS) for a crystal hit centrally by the beam).
Bibliography


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[86] http://bgo-od.physik.uni-bonn.de


