Investigation of nuclear forces in $d + p$ elastic and $p + d$ break-up reactions at intermediate energies
Mardanpour-Mollalar, Hossein

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5. Analysis of the $\bar{p} + d$ elastic reaction

5.1 Introduction

In this chapter, the experimental procedure to study the $\bar{p} + d$ reaction by BINA is presented. This reaction can lead to the following two channels: the elastic channel, $\bar{p} + d \rightarrow p + d$, and the break-up channel, $\bar{p} + d \rightarrow p + p + n$. For every reaction channel, differential cross-sections, and analyzing powers are observables of interest. The elastic channel of this reaction has been measured at KVI before [9, 10, 11]. For this experiment, the analysis of the elastic channel is necessary since, its analyzing power is used to extract the polarization of the proton beam, which was used in the analysis of the analyzing power in the break-up channel. In addition, the elastic channel is used for the energy calibration of the detectors of BINA. We explain the details of the analysis of the elastic channel in this chapter and the break-up channel in the next chapter.

Before going into the details of the data analysis, it is necessary to explain the scope of this chapter. For every given reaction, the kinematical phase space plays an important role in the data analysis. Therefore, we first explain which part of the two-body elastic-scattering phase space is studied in this experiment by BINA. Then, in order to calculate the experimental observables, we have to identify the reaction, which requires an energy calibration for every single scintillator. The calibration procedure will be presented in this chapter. After the energy calibration, we combine the data from all detectors. Then, the cross-section values are extracted for every center-of-mass angle, $\theta_{\text{c.m.}}$, after correcting for detection efficiencies, such as the MWPC efficiency.

BINA with its hodoscope-like geometry is capable of measuring the beam-polarization. These results can be compared to the polarization measurement with the IBP. The IBP can operate in parallel with the experiment and measures the beam polarization via $\bar{p} + p$ elastic-scattering reaction. The IBP analysis is presented at the end of this chapter and its results are compared with that of BINA to check the reliability of the polarization measurements.

5.2 Kinematical phase space and particle identification

The kinematics of the two-body elastic-scattering reaction has a simple analytical solution. For the proton-deuteron ($\bar{p} + d$) scattering, the number of parameters in the system is 6, namely the polar angle, $\theta$, the azimuthal angle, $\phi$, and the energy of both particles in the final state. The laws of energy and momentum conservation impose 4 relations between these parameters. Also, there is a symmetry for the $\phi$ of the reaction and it is redundant. Therefore, it is sufficient to measure one of the 6 parameters. The other parameters can be obtained analytically. In this experiment, we have a good angular resolution for the particles that pass through the MWPC. We, therefore, have chosen to use $(\theta, \phi)$, and derive the other parameters analytically. Figure 5.1 shows the angular range over which BINA can measure. The forward part covers scattering angles between $10^\circ < \theta < 35^\circ$.
Figure 5.1: Proton-deuteron scattering data measured with BINA. The scattering angle of particles at the backward detector, $\theta_{\text{ball}}$, is plotted versus the scattering angle of particles at the forward detector, $\theta_{\text{wall}}$. The kinematical curves from two possible elastic-scattering reactions, as explained in the text, are shown in the figure.

with an angular resolution of 0.7°. The backward ball detector, however, covers scattering angles between $35^\circ < \theta < 160^\circ$, but with a worse resolution of about 10°. The $\theta_{\text{ball}}$ value is chosen for the center of the detector elements in the ball part.

The elastic channel is divided into two groups:

1. The proton scatters to the forward wall and the deuteron scatters to the backward ball. This is marked as ($p_{\text{forw}} - d_{\text{back}}$) in Fig. 5.1.

2. The deuteron scatters to the forward wall and the proton scatters to the backward ball. This is marked as ($d_{\text{forw}} - p_{\text{back}}$) in Fig. 5.1.

The corresponding kinematical lines are plotted on top of the experimental data. In this graph, regardless of the type of the particles, the scattering angle of the backward-scattered particle, $\theta_{\text{ball}}$, is plotted versus the scattering angle of the forward-scattered particle, $\theta_{\text{wall}}$.

The data shown in Fig. 5.1 include events both from the elastic channel as well as those from the break-up channel. To reduce events from the break-up channel, additional conditions are applied. For the elastic channel, the azimuthal angle of the proton, $\phi_p$, differs by exactly $180^\circ$ from the azimuthal angle of the deuteron, $\phi_d$. The $\phi_d - \phi_p$ distribution for all data is shown in Fig. 5.2. The peaks at $-180^\circ$, and $180^\circ$ primarily contain events from the elastic-scattering. The width is due to the detector resolution and due to non-coplanar break-up events. Events for which $|\phi_d - \phi_p| = 180^\circ \pm 20^\circ$ are labeled as coplanar events.

The next step is to identify the elastic reaction by using the energy response of the forward-wall scintillators. The top panel in Fig. 5.3 shows the energy deposit of the forward-scattered particles in the $\Delta E$-scintillator versus its energy deposit in the $E$-scintillator for one of the hodoscope elements in the forward wall. The deposited energy in
5.2. Kinematical phase space and particle identification

Figure 5.2: The difference between azimuthal angles of a particle detected in the forward wall, \( \phi_{\text{wall}} \), and a particle detected in the backward ball, \( \phi_{\text{ball}} \). The peaks at \(-180^\circ\), and \(180^\circ\) are labeled as coplanar and primarily contain events from the elastic-scattering. The width is due to the detector resolution and due to non-coplanar break-up events.

The thin \( \Delta E \)-scintillator depends on the thickness of the scintillator and the atomic mass and the charge of the particle.

The elastically-scattered particles have a well-defined energy and are expected to be concentrated in the figure. This is in contrast to break-up events which can have a continuous energy spectrum. The deuterons from the elastic-scattering reaction can be clearly seen in the figure at \( E=1500 \) and \( \Delta E=400 \) (channel numbers). The \( E \)-detectors of BINA can stop protons up to an energy of 140 MeV. Therefore, particles with higher energies punch through the scintillator and part of their energy escapes from the system. To separate the elastic channel products from those of the break-up reaction, we use the coplanarity condition, \( |\phi_d - \phi_p| = 180^\circ \pm 20^\circ \). Using this condition, elastically-scattered protons and deuterons can be seen in the lower panel of Fig. 5.3. A large fraction of the break-up events are removed by applying the coplanarity condition. Note that the number of events which we labeled as deuterons is not reduced by applying a coplanarity condition as expected since deuterons can only stem from the elastic reaction. To conclude, with the coplanarity condition, we can bias the data to the elastic channel. However, this condition does not give exclusively the elastic channel, since part of the break-up events satisfies the coplanarity condition as well.

Since the deuteron can be identified unambiguously in the forward part, the phase space of the elastic channel for which the deuteron is scattered at forward angles and the corresponding proton toward backward angles has been chosen in the analysis of the elastic channel in this thesis.
5.3 Energy calibration

In this section, we focus on the energy calibration of the scintillators using the elastic reaction with deuterons scattered at forward angles. From the kinematics, the energy of forward-scattered deuterons for every \((\theta, \phi)\) can be calculated analytically. This is used to calibrate the energy response of the forward wall scintillators of BINA.

5.3.1 Energy calibration of the forward scintillators

The energy calibration procedure of the forward part of BINA for deuterons is illustrated in Fig. 5.4. As shown in the top-right panel of this figure, the response of the left PMT versus \(\theta\) gives a very complicated shape. The signals strength produced by the PMTs on the left and right part of the scintillator differs due to a different attenuation of the scintillator light. At small scattering angles, the energy response of the left PMT is well defined. At larger angles, however, one can observe two distinct loci. The top locus corresponds to deuterons which scatter close to the PMT, and the bottom one is due to deuterons which impinge on the scintillator on the other side, but still at the same polar angle. By multiplying the signal strength of the two PMTs connected to both sides of a scintillator, this problem can be avoided to a large extent; see the top left panel. In the lower-left panel, the value of \(\sqrt{L_{\text{chan}} \times R_{\text{chan}}}\) is divided by the value of the reconstructed
5.3. Energy calibration

Figure 5.4: The energy calibration procedure is illustrated in the forward part of BINA for deuterons. The top-right panel shows the response of the left PMT as a function of polar scattering angle. The top-left panel shows the product $\sqrt{L_{\text{chan}} \times R_{\text{chan}}}$. The lower-left panel, the value of $\sqrt{L_{\text{chan}} \times R_{\text{chan}}}$ is divided by the value of the reconstructed energy in MeV which is calculated from the elastic kinematics. The lower-right panel shows the calibrated energy, versus the deuteron scattering angle in the forward wall of BINA. The solid line shows the elastic scattering kinematics.

Figure 5.5 shows the calibrated energy, $E = \frac{\sqrt{L_{\text{chan}} \times R_{\text{chan}}}}{f(\theta_d)}$, versus the deuteron scattering angle in the forward wall of BINA for all the scintillators combined. As can be seen in this figure, the detectors are calibrated very well. Moreover, a slight contribution of the punch-through protons from the break-up reaction can be seen between 70-110 MeV. The background in this graph comes mostly from break-up events for which one particle scatters to the forward part and the second one to the backward ball. These background events satisfy the coplanarity condition. The deuteron peak can be clearly separated from a continuous background contribution after a cut of $E > 100$ MeV. The energy resolution
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5.3.2 Energy calibration of the backward ball of BINA

The procedure for calibrating the scintillators of the backward ball for protons is similar to that of the forward part. The calibration is performed by exploiting the precise coordinates of the forward-scattered particle. From the elastic-scattering kinematics, the coordinate information of the forward-scattered deuteron provides the energy and the coordinates of the corresponding backward-scattering proton. In this experiment, we divided the ball detectors into three groups in terms of their position:

1. $40^\circ < \theta < 80^\circ$, this region is dominated by deuterons from the elastic channel.

2. $80^\circ < \theta < 110^\circ$, this region can, in principle, be calibrated using the elastic protons. However, because of the shadow of the target holder, two groups of particles are detected in these scintillators. The first group comes from protons that pass through the target holder material and lose part of their energy and the second group is due to particles that do not hit the target shield. Due to lack of time, we decided not to use this region for the data analysis.

3. $\theta > 110^\circ$, this region is calibrated by the elastically scattered protons.

The calibration of backward-ball detectors in the third region is the easiest. Figure 5.6 shows the calibration procedure for this part of the phase space. For example, for a selected deuteron angle of $\theta_d = 20^\circ \pm 1^\circ$, we expect detectors at $\theta_p = 125^\circ \pm 3^\circ$ to detect

Figure 5.5: The calibrated energy, $E = \frac{\sqrt{E_{\text{lab}}^2 - p_{\text{chan}}^2}}{f(\theta_d)}$, versus the deuteron scattering angle is shown in the forward wall of BINA for all the scintillators. The locus shows the reconstructed energy from the elastic-scattering kinematics. The background contribution comes from coincident events in which one particle scatters to the forward and the second one to the backward part. These background events satisfy the coplanarity condition.

of the forward detectors is around $\sim 5\%$. 

Figure 5.5
the coincidence proton. The left panel shows the deposited energy for one of the detectors for the backward-scattering particles (in channel units). The right panel shows the same spectrum after a calibration based on the expected deposited energy from the kinematics of the elastic reaction and the response of the detector modeled by a GEANT-3 simulation.

![Energy Calibration Plot](image)

**Figure 5.6:** The energy calibration for one of the ball detectors of region 3, $\theta > 110^\circ$, is shown. The left panel shows the energy deposit for the backward scattering particles (in channel units). The calibrated energy of the ball detector is shown in the right panel.

After calibrating all the detectors in region 3, i.e., in the backward part of the ball for protons, we can accumulate data from all detectors and check the quality of the calibration. Figure 5.7 shows the energy of the forward-scattered deuterons versus that of the backward-scattered protons. In this picture, the elastic-scattering region can be seen which is accompanied by background from the break-up reaction. The line shows the expected correlation based on the kinematics of the elastic-scattering reaction. The calibrated energy for the ball part agrees with the kinematical line only in the middle range of the ball energies and deviates at lower and higher energies. The deviation could be due to a failure of the approximation which we used to transform the deposited-energy to the thrown-energy (generated energy) in GEANT-3. The resolution (energy and granularity combined) of the ball detectors is around $\sim 20\%$ for protons in the energy range of 20-40 MeV.

### 5.4 The MWPC efficiency

In this section, we describe the procedure to obtain the detection efficiency of the MWPC. These efficiencies are needed for extracting the cross sections. The MWPC inefficiency comes from charged particles which induce a signal above the required threshold. In case an event is registered in the $E, \Delta E$ part and not in the MWPC, that can be taken as an inefficiency of MWPC.

Since, the $E$- and $\Delta E$-detectors are used as the reference for calculating the MWPC efficiency, the surface of the MWPC is divided into areas corresponding to hodoscopes of $E$ and $\Delta E$. Every hodoscope is composed of a horizontal $E$-bar with a vertical $\Delta E$-bar. The efficiency for every hodoscope is defined as follows: if an incoming particle is registered in
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Figure 5.7: The energy of backward-scattered particles is shown versus that of forward-scattered particles for $\theta > 110^\circ$ with the coplanarity condition. The elastic-scattering region is shown at $E_{wall} \simeq 160$ MeV together with the expected correlation (solid) based on the elastic-scattering kinematics. The background from break-up reaction can be seen as a continuous spectrum in the picture.

In this experiment the X-plane of the MWPC failed due to a technical problem. Therefore, we used the Y- and U-plane information to calculate the X-position of the events. Consequently, events which have more than one hit in the MWPC cannot be analyzed unless the information from the $E, \Delta E$ scintillators is taken into account. So, we choose single hits for the calculation of MWPC efficiency in which there is a one-to-one correspondence between the MWPC and $E-\Delta E$ hodoscope.

For determining the elastic-scattering cross section, we need to measure the efficiency of the MWPC for deuterons. The deuterons are selected according to the procedure described before. The left panel in Fig. 5.8 shows the efficiency of the MWPC for deuterons. The detection efficiencies for deuterons are around 99%. The break-up cross section will be corrected for the efficiency of MWPC for protons in the energy range $20 < E_p < 160$ MeV. We expect that the MWPC efficiency depends on the energy of the proton. The efficiency for a proton is shown in the right panel of Fig. 5.8. The detection efficiencies for protons are around 97%. However, we observe that the efficiency for low-energy protons is slightly larger than that for high-energy protons by about 1%. We uses energy and position-dependent efficiencies for the cross section determination as presented in the next chapter.
5.5 The elastic-scattering cross section

The elastic-scattering cross section is obtained by counting the number of the elastically-scattered particles, \( N_d \), into a given \( \theta_{\text{c.m.}} \) bin and taking into account the corresponding solid angle \( \Delta \Omega \) with all known efficiencies, \( \epsilon \):

\[
\frac{d\sigma}{d\Omega} = \frac{N_d}{Q/Z} \cdot \frac{1}{t} \cdot \frac{1}{\Delta \Omega},
\]

where \( Q \) is the total integrated charge, \( Z \) is the charge per projectile, \( t \) is the number of the scattering centers, and \( \epsilon \) stands for all efficiencies in the system namely: MWPC efficiency and the hadronic reaction efficiency. Figure 5.9 shows the elastically-scattered deuterons for \( \theta_{\text{lab}} = 25^\circ \pm 1^\circ \) together with background from the break-up channel and events which undergoing a hadronic interaction in the scintillator. The hadronic efficiency is calculated using the GEANT-3 simulation. The details of this calculation is presented in the next chapter. The number of elastic-scattering counts are extracted by performing a fit through the data using a second-order polynomial, representing the background, together with a Gaussian function, representing the signal, which gives a reduced chi-square of \( \chi^2 \sim 1 \). The number of counts underneath the Gaussian function is taken as events coming from elastic scattering. This figures is obtained by requiring a coincidence with the backward ball and with the coplanarity conditions. More specifically, the following conditions were applied:

1. \(|\phi_{\text{wall}} - \phi_{\text{ball}}| = 180^\circ \pm 20^\circ \) (coplanarity condition).
2. \( \theta_{\text{ball}} > 80^\circ \), selects events in which the deuteron scatters to the forward-wall and the proton scatters to the backward-ball.
3. \( E_{\text{forw}} > 100 \text{ MeV} \), cuts the low-lying background which comes from break-up and protons in the forward part.

In principle, deuterons inside a ring of \( \theta_{\text{lab}} \pm 1^\circ \) for different \( \phi \)s should be distributed uniformly. But for some cases the distribution is not uniform. This happens if one of the...
coincidence products hits a dead detector or is scattered to a region where no detector exists. For this case, the coincidence trigger will be inefficient. In BINA, the target holder placed at $\theta_{ball} = 100^\circ \pm 15^\circ$, $\phi_{ball} = 90^\circ \pm 15^\circ$ and dead detectors in the ball part cause inefficiencies in the azimuthal distribution of the products of the elastic-scattering reaction. Figure 5.10 shows the simulated distribution for the protons in BINA. In the picture, the position of the missing detectors in the ball part, $\theta_p > 40$, and the target holder position can be seen. These dead areas in the backward ball cause inefficiencies in the distribution of forward-scattered deuterons, which need to be corrected for or partly excluded from the analysis. As an example, Fig. 5.11 shows the $\phi$ distribution for a ring at $\theta = 25^\circ \pm 1^\circ$. The inefficiency around $\phi_{wall} = 270^\circ$ is due to elastically-scattered protons which hit the target holder. The other inefficiency around $\phi = 130^\circ$ stems from a noisy detector in the ball part which is excluded from the analysis. We decided to calculate the cross section based on the data from the flat part of the $\phi$ distributions. In the data analysis, we cut the data into small runs. For each run, the number of counts at each angle is obtained by cutting the azimuthal distribution into small sectors, $\Delta \phi = \pm 5^\circ$, and fitting the peak and background in the same manner as in Fig. 5.9.

To monitor the fluctuations of the data during the experiment, the experimental data are divided into small time bins. The values of the elastic-scattering cross section for every hour and at different scattering angles are obtained as explained above, using the nominal parameters of the experiment such as the target thickness, the beam current, and taking into account the efficiencies. Figure 5.12 shows the cross section for several angles as a function of run number for the entire experiment. The fluctuation of the cross section in the course of the experiment is within the error bars. A zero-th order polynomial fit gives a reasonable $\chi^2/d.o.f.$ for each angle.
Figure 5.10: The simulated distribution of protons for the whole reaction phase space. In BINA, the target holder at $\theta_{\text{ball}} = 100^\circ \pm 15^\circ$, $\phi_{\text{ball}} = 90^\circ \pm 15^\circ$ and dead detectors in the ball part cause inefficiencies in the azimuthal distribution of the elastic-scattering events.

Figure 5.11: The distribution of deuterons in a ring in the forward wall with the corresponding proton in coincidence with the backward-ball. The ideal distribution is flat.

Figure 5.13 shows the cross section as a function of $\theta_{\text{c.m.}}$ for one of the runs as an example. The data points in this center-of-mass angular range correspond to $15^\circ < \theta_d < 30^\circ$ in the laboratory system. The cross section from this run is compared with the previous measurements at KVI and Adelberger and Brown [75] at 198 MeV. Also, the theoretical predictions for the cross sections from the Hannover-Lisbon group are included in the picture.
Figure 5.12: The elastic-scattering cross section as a function of run number for different angles. By fitting a constant line, an average cross section value for each angle is extracted.

5.6 Vector-analyzing power in elastic $\vec{p} + d$ scattering

The second experimental observable from the interaction of a polarized proton beam with a deuterium target is the analyzing power [54]. For a measurement of the analyzing power, we compare the distribution of the elastically-scattered particles at different azimuthal angles for two polarization states, and the unpolarized beam in the following way. The $\phi$-distribution obtained with the polarized beam is normalized to that obtained with an unpolarized beam. With this normalization, the geometrical asymmetries and inefficiencies are eliminated. Using Eq. 2.50, the reaction asymmetry, $(\sigma_1/\sigma_0)$ can be calculated as a
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The cross section as a function of $\theta_{\text{c.m.}}$ for one of the runs. The line indicates the theoretical predictions for the cross sections from the Hannover-Lisbon group including the effects of three-body force. Up-triangles show previous measurements at KVI \[11\] and filled diamonds are from the measurement at 198 MeV \[75\].

The obtained distribution is fitted with the function $A(1 + B \cos \phi)$ where $A$ is the offset and $B$ is the amplitude of the periodic function. The fitted amplitude, $B$, corresponds to $A_y p_Z$. Figure 5.14 shows a typical example of a measured asymmetry together with the fit.

The amplitude of the fit, $A_y p_Z$, can be exploited to obtain the analyzing power, $A_y$ if the beam polarization is known or can be used to obtain the beam polarization, $p_Z$, provided that the analyzing power is known. Here, by exploiting the value of analyzing power from other KVI measurements \[11\], we extract the beam polarization. The observed polarization at different angles should be the same. Therefore, after a positive check on statistical consistency of different angles, the weighted average was obtained as a function of time for all 3 polarization modes. Figure 5.15 shows the measured polarization by BINA as a function of run number for three polarization modes: $\uparrow$, $\downarrow$, and Off. In this graph, the measurements of BINA and IBP, which will be explained in the following section, are included for comparison. For every run number, the measured polarization states by BINA are shown by the blue filled circles, squares, and empty diamonds which represent the down-mode ($\downarrow$), up-mode ($\uparrow$), and the off-mode, respectively. The red symbols represent the same polarization modes for the IBP. In this experiment, the distribution of the polarized modes, down-mode and up-mode, is normalized to the off-mode (obtained by using an unpolarized beam) to get the value of the asymmetry. However, from the
previous measurements at KVI [72], it has been shown that the off-mode produced by POLIS for a proton beam has an offset polarization of $\sim +7\%$. This correction has been, accordingly, implemented in the polarization results of BINA.

### 5.7 Analysis of the IBP data

The IBP detector was used during the experiment to measure the polarization of the proton beam using proton-proton elastic scattering. BINA is capable of measuring the beam polarization in the same manner as IBP. Since this is the first polarization measurement with BINA, the comparison of polarization results from IBP and those of BINA can be a good check for the reliability of the BINA results. Unfortunately, we cannot measure the beam polarization with the IBP and BINA simultaneously, since the quality of the beam at the position of BINA is affected due to scattering of the particles at the IBP target. Also the IBP operates with a much higher beam current on the order of nA, whereas BINA uses beam currents of $\sim 10$ pA. Therefore, measurements with IBP were done independent of BINA. After an IBP measurement, the IBP target was taken out of the beam. We switched the beam between these two detectors frequently and the IBP has recorded the beam polarization a few times during the experiment.

In the following, first the particle identification of IBP scintillators are explained after which the reaction asymmetries for different azimuthal angles are shown. Finally, results of the polarization measurement are shown as a function of time. The results are compared with the polarization measurements obtained with BINA.
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Figure 5.15: The average polarization values for all polarization states are shown as a function of run number. The measurements from BINA and IBP are shown together to compare the measurements from both instruments. For every run number, the polarization states are shown by filled circles and squares and empty diamond which represent the down-mode ($\downarrow$), up-mode ($\uparrow$), and the off-mode, respectively. For more information, see text.

5.7.1 Particle identification in the IBP detector

The phoswich scintillators of IBP are made of two parts (see Chap. 4): a fast thin plastic scintillator ($\Delta E$), and a slow part ($E$), see Table 4.2 for details. The signal from each detector is read out using two different charge integration gates in the IBP acquisition system: a long gate of $\sim400$ ns which integrates the whole signal and covers the $E + \Delta E$ signal, and a short gate of $\sim40$ ns which covers almost the complete $\Delta E$ part of the signal. The type of particle can be identified by using the information from the short and long gates.

Figure 5.16 shows the products of the $^{12}\text{C}(\vec{p}, p)p$ reaction in the IBP scintillators. The spectrum depicts the short-gate integration versus the long-gate integration, and includes all events under the condition that at least two kinematically correlated IBP detectors gave a signal above the CFD threshold. In this picture, the desired particles are elastically-scattered protons of the $\vec{p} + p$ reaction. By gating the region corresponding to protons in one detector, the coincidence protons in the corresponding detector are selected. In detector 1 ($\theta_1(\text{lab}) = 19^\circ$), the energy of the proton is rather large ($\sim160$ MeV), therefore, the proton leaves most of its energy in the long gate. The energy of the proton in detector 2 ($\theta_2(\text{lab}) = 70^\circ$) is lower ($\sim50$ MeV) and, therefore, relatively more energy is deposited in the thin part of the scintillator. The other regions correspond to low-energy protons,
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Figure 5.16: The products of the H($\vec{p}, p$) reaction in the IBP scintillators are shown. The spectrum is a plot of the short-gate integration ($\Delta E$) versus the long-gate integration in the ADC. Detector 1, left panel, has $\theta_{1(\text{lab})} = 19^\circ$. At this angle the energy of one proton is rather large ($\sim$160 MeV). In the right panel, the energy of the proton in detector 2, $\theta_{2(\text{lab})} = 70^\circ$, is lower ($\sim$50 MeV). The regions corresponding to protons, deuterons, tritons, $\gamma$s, and neutrons are shown.

deuterons, tritons, $\gamma$s, neutrons, etc. coming from the proton-carbon reaction.

The reaction asymmetry is obtained using the number of counts measured at different azimuthal angles and different polarization states, as was described in the last section. The measured asymmetry, $\frac{\sigma(\theta, \phi)}{\sigma(0, \phi)}$, is shown in Fig. 5.17. The obtained distribution is again fitted with the function $A(1 + B \cos \phi)$ where $A$ is the offset and $B$ is the amplitude of the periodic function. The fitted amplitude, $B$, corresponds to $A_y p_Z$. The beam polarization, $p_Z$, is obtained by using the known value for the analyzing power, which for this reaction and angle is $A_y(\theta_{c.m.} = 141^\circ) = -0.289$. All the polarizations are calculated by normalizing the spectra obtained in a run with a polarized beam to those obtained in a run in which the hexapoles were turned off, producing a beam with a zero polarization.

Figure 5.15 shows results of the polarization measurements by the IBP as a function of time. The polarization states are shown by red filled circles, squares, and empty diamonds which represent the up-mode ($\uparrow$), down-mode ($\downarrow$), and the off-mode, respectively. The average polarization values are: for the up-mode ($\uparrow$) $\sim$45%, the down-mode ($\downarrow$) $\sim$−50%, and the off-mode $\sim$7%.
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Figure 5.17: The reaction asymmetry is defined as \( \frac{\sigma(\theta, \phi)}{\sigma_0(\theta, \phi)} \). The obtained distribution is fitted with the function \( A(1 + B \cos \phi) \) where \( A \) is the offset and \( B \) is the amplitude of the periodic function. The fitted amplitude, \( B \), corresponds to \( A_y p_z \).

\[ P_z = -0.50 \pm 0.03, \; A_y = -0.289, \chi^2 = 0.77 \]
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