PISA – an experiment for fragment spectroscopy at the Internal Beam of COSY: application of an Axial Ionization Chamber

R. Barna\textsuperscript{a}, V. Bollini\textsuperscript{b}, A. Bubak\textsuperscript{b,c}, A. Budzanowski\textsuperscript{c}, D. De Pasquale\textsuperscript{a}, D. Filges\textsuperscript{b}, S.V. Förtsch\textsuperscript{d}, F. Goldenbaum\textsuperscript{b}, A. Heczko\textsuperscript{e}, H. Hodde\textsuperscript{f}, A. Italiano\textsuperscript{a}, L. Jarczyk\textsuperscript{e}, B. Kamys\textsuperscript{e}, J. Kisiel\textsuperscript{g}, M. Kistryn\textsuperscript{c}, St. Kistryn\textsuperscript{c}, St. Kliczewski\textsuperscript{c}, A. Kowalczyk\textsuperscript{e}, P. Kulessa\textsuperscript{b,c}, H. Machner\textsuperscript{b}, A. Magiera\textsuperscript{e}, J. Majewski\textsuperscript{b,e}, W. Migda\textsuperscript{e}, H. Ohm\textsuperscript{b}, N. Paul\textsuperscript{b}, B. Piskor-Ignatowicz\textsuperscript{e}, K. Pysz\textsuperscript{b,c}* Z. Rudy\textsuperscript{a}, H. Schaaf\textsuperscript{b}, R. Siudak\textsuperscript{c,f}, E. Stephan\textsuperscript{g}, G.F. Steyn\textsuperscript{d}, R. Sworst\textsuperscript{e}, T. Thovhogi\textsuperscript{d}, M. Wojciechowski\textsuperscript{e}, W. Zipper\textsuperscript{g}

\textsuperscript{a}Institute of Physics, Messina University, Italy
\textsuperscript{b}Institut für Kernphysik, Forschungszentrum Jülich GmbH, Germany
\textsuperscript{c}H. Niewodniczański Institute of Nuclear Physics, Kraków, Poland
\textsuperscript{d}iThemba LABS, Somerset West, South Africa
\textsuperscript{e}M. Smoluchowski Institute of Physics, Jagellonian University, Kraków, Poland
\textsuperscript{f}Institut für Strahlen- und Kernphysik, Bonn University, Germany
\textsuperscript{g}Institute of Physics, University of Silesia, Katowice, Poland

Received 22 April 2003; received in revised form 7 October 2003; accepted 7 October 2003

Abstract

The Proton-Induced SpAllation (PISA) experiment performed at the internal beam facility of the COSY storage ring in Jülich, Germany, which is aimed at the precise measurement of double differential cross-sections over a broad range of energies and angles for spallation reactions induced by protons of 200–2500 MeV energy in various targets, is presented. In this paper the emphasis is put on the design, principles of operation and performance of a Bragg Curve Detector (BCD) optimized for internal beam experiments at storage rings. Very clean and distinct product identification (with $Z$ up to $B_{14}$) from reactions, in which a Ni target was bombarded with a 1 GeV circulating proton beam, is obtained. The individual elements are resolved for emission energies higher than 0.5 MeV/nucleon. Moreover, due to the detector read-out achieved by coupling a specially designed current sensitive preamplifier directly to a sampling ADC, the shape analysis of the signals from the BCD allows the isotope identification of light particles with $A$ up to $B_{11}$. It is also found that the BCD can be used efficiently as a thin $\Delta E$ detector for the telescope consisting of the BCD and a series of silicon detectors.

$^*Corresponding author.
E-mail address: krzysztof.pysz@ifj.edu.pl (K. Pysz).

2003 Elsevier B.V. All rights reserved.
PACS: 29.40.C; 25.40.S; 29.20.D
Keywords: Bragg curve detector; Spallation; Mass and charge spectroscopy; $\Delta E$-$E$ Technique; Storage ring

0168-9002/$-see front matter $\copyright$ 2003 Elsevier B.V. All rights reserved.
1. Introduction

The basic problem of the disintegration of a nucleus when its stability is disturbed by the energy-momentum transfer from an energetic projectile is still not fully understood and, moreover, there is even a severe lack of sufficiently reliable models or parameterizations capable of describing larger sets of experimental data. Various terminologies used for such decay processes include: break-up, spallation, fragmentation, multifragmentation. In the low incident energy range, where the involved interactions are not very violent, the processes are commonly referred to as “spallation” reactions in order to describe the nature of the phenomenon.

The existing reaction models attempt to reproduce the measured observables, like the yields of various ejectiles, their energy and angular distributions, the emission time sequence, the excitation energy of the emitting source and the distributions of the residua of the reactions, by taking into account the amount of the transferred energy, the composition and structure of the nucleus, the propagation modes of the excitation amongst the constituents of the nucleus, the interaction time, etc. The complexity of the interacting many-body system at present excludes a purely quantum-mechanical treatment of the problem. Instead, semi-classical approaches are being applied. The most popular approach is to simulate the first phase of the reaction by means of the so-called intra-nuclear cascade (INC) model followed by the evaporation from the energetically equilibrated system [1]. More sophisticated approaches utilize the method based on Boltzmann–Uehling–Uhlenbeck (BUU) or Vlasov–Uehling–Uhlenbeck (VUU) equations or use the Quantum Molecular Dynamics (QMD) model [2,3]. In this regard a relatively simple parameterization was proposed in Ref. [4].

The development of theoretical models or even the invention of parameterizations possessing strong predictive power is however retarded by the lack of sufficiently complete and precise experimental data. The Proton Induced SpAllation (PISA) collaboration has started an experimental program, which will supply precise and extensive experimental data sets, especially in areas where the experimental knowledge about the spallation process is rather sparse. The collected data will facilitate the more reliable modeling of nuclide production in nucleon–nucleus collisions over a broad range of incident proton energies and targets what is of great importance in many applications, both for fundamental studies in nuclear physics and astrophysics as well as in applied physics (material damage and radiation protection, radiation therapy, spallation neutron sources and transmutation of nuclear waste, accelerator driven energy amplifier, etc.).

In the next section the idea behind the fragment spectroscopy in the PISA experiment is described, while Section 3 deals with the design, construction and performance of the axial ionization chambers (Bragg curve detectors (BCD)) used as the main detectors in the experiment. A summary and perspectives of the experimental development are presented in Section 4.

2. PISA – a new experiment for spallation studies

The PISA experiment [5] is devoted to measure double differential cross-sections for spallation products coming from various targets (C, N, O, Si, Fe, Ni, Au, U), which are bombarded by protons of energies in the range from 200 MeV up to 2.5 GeV. In order to obtain undistorted information about the mechanism of the primary reactions, the use of thin targets (~100 µg/cm²) is an important prerequisite. To compensate for the low reaction rate due to the use of such thin targets the experiment is performed using the internal beam of the COoler SYnchrotron (COSY) at Forschungszentrum Jülich, Germany. The circulating proton beam has an intensity of about 5 × 10¹⁰ protons. In average each proton can pass through the target about 10⁵ times before the beam is used up as a result of the interactions with the target. Then the storage ring is filled again. The length of the duty cycle can be easily adjusted in order to obtain the optimal counting rate. In the PISA experiment this cycle lasts typically for several seconds. In effect, the achievable beam-target luminosity is some orders of magnitude
higher than that of conventional external beam facilities.

The purpose of the PISA detection system (Fig. 1) is to register charged reaction products over the broadest possible range of energies and masses with special emphasis on detection and precise identification of low-energy particles. This is done at eight fixed angles in the laboratory system where independent detection devices (so-called detection arms) are installed in the reaction plane. Two of them—at 15° and 120° laboratory angles—contain telescopes for time-of-flight (TOF) measurements (two microchannel plate (MCP)-based detectors with carbon foils of 15 μg/cm² thickness working as electron emitters) followed by a BCD detector. Directly behind the BCD, still inside its housing, a telescope of three silicon detectors is installed. These detection arms are ended with a phoswich detector. Detector telescopes each consisting of four silicon detectors are used at the detection angles of 35° and 100°. These telescopes are cooled down to a temperature of −10°C. The cooled Si-detector telescopes are also followed by phoswich detectors. Four additional phoswich detectors are installed at angles of 20°, 50°, 65° and 80° with respect to the beam direction. All phoswich detectors are separated from the vacuum by 50 μm thick stainless-steel windows. With the fully equipped detection arm (telescope for TOF measurement, BCD, Si-detector telescope and phoswich detector) the identification of elements is possible from $Z = 1$ to $Z \approx 20$, whereas the isotopes can be separated for $A \leq 20$. The detection energy ranges from 0.5 MeV/nucleon (for $Z = 2$) up to 150 MeV/nucleon (including also the hydrogen isotopes). Two semiconductor detector telescopes installed near the target are used as beam luminosity monitors, which count the δ-electrons ejected from the target. In order to achieve as small as possible forward detection angles the target is shifted from the geometrical centre of the scattering chamber upstream along the beam axis.

The scattering chamber is equipped with a movable target holder, a pincer grip and a target magazine, which can store up to eight targets. This setup allows targets to be exchanged during the experiment without disturbing the ultra-high vacuum (UHV) conditions in the chamber and in the COSY ring. The targets are foil strips or wires stretched horizontally across the target frames, which have a fork-like shape. During acceleration the injected beam passes underneath the target, and as soon as the required energy is obtained, the beam is shifted onto the target by steering magnets.

In order to avoid a deterioration of the UHV in the COSY ring due to continuous percolation of gas through the detector window an additional 1.1 μm thick Mylar foil is installed in front of the BCDs, which separates the UHV region and a separately pumped high vacuum volume closest to the BCD. The detection arms, which contain the ionization chambers, can be quickly separated.
from the scattering chamber by emergency valves. In the case of any deterioration of the vacuum conditions either in the arms or in the ring these valves close automatically.

It is intended to increase the efficiency of the present setup by equipping also the other detection arms of the PISA detection system with the full detector array allowing for the registration and identification of the reaction products in the whole energy and mass range of interest over a wider angular range.

3. Application of Bragg curve spectroscopy to the \((Z,A)\)-identification of spallation products

3.1. Description of the method

After first successful attempts to use the so-called Bragg Curve Spectroscopy (BCS) to identify highly ionizing particles \([6,7]\) several detectors exploiting characteristic features of the Bragg curve were built and used for various applications, proving their broad flexibility and usefulness \([8–15]\). Attractive features of such detectors are especially: very good atomic number resolution, up to \(Z \sim 20\), energy resolution of the order of 1\%, possibility to cover large solid angles, resistance to radiation damage and the adjustable energy range of the detected particles (by varying the gas pressure).

A Bragg curve detector is a relatively simple axial ionization chamber with a Frisch grid (FG), working typically at pressures of a few hundred millibar and allowing to mirror the gradual energy losses of charged particles passing through the gas volume of the detector in the time dependence of the anode signal. For a charged particle its specific energy loss, \(\text{d}E/\text{d}x\), in a given medium is described by the Bethe–Bloch formula (see e.g. Ref. \([16]\)). Since the energy loss per single collision is small, \(\text{d}E/\text{d}x\) increases slowly along the particle’s path. Only when the remaining energy is smaller than 1 MeV/nucleon the value of \(\text{d}E/\text{d}x\) increases rapidly forming the so-called Bragg Peak (BP). The amplitude of this peak depends solely on the particle’s charge and thus allows identification of the particle’s atomic number. The integral of \(\text{d}E/\text{d}x\) over the particle’s range gives the kinetic energy of the stopped particle. The principle of Bragg curve spectroscopy is illustrated in Fig. 2 where a typical output signal from a BCD is presented together with a set of relevant physical information contained within this signal.

A classical method of readout of the BCD was to use a charge sensitive preamplifier followed by two spectroscopy amplifiers in parallel, each with different time shaping constants \(\tau\). The amplifier with a short \(\tau\) (\(\sim 0.3\) \(\mu\)s) gives an output signal with amplitude, which corresponds to the area under the BP. Integrating the charge with a long time constant (\(\sim 8\) \(\mu\)s, depending on particular detector dimensions) gives a signal with the amplitude being proportional to the particle energy. Although with this method the exact shape of the Bragg curve cannot be reproduced, the identification of the atomic numbers of the particles was nevertheless found to be satisfactory \([7,8]\). A later technique of sampling the ionization

![Fig. 2. Typical output signal from a BCD as sampled by a flash ADC. The maximum of the curve gives the so-called Bragg peak (BP) which is dependent on the charge of the particle. The integral over the whole length of the signal reflects the kinetic energy \(E\) of the particle. Other parameters like range of the particle in the detector medium, \(R\), or partial energy losses \(\Delta E\) can be also extracted from the shape of the curve (see Section 3.4). The sampling frequency of the used flash ADC results in a length of a single sample of 0.1 \(\mu\)s.](image)
density over the particle’s path with the use of a sampling (flash) ADC provided new possibilities of extracting additional parameters (particle range $R$, or partial energy losses, $\Delta E$) during the off-line analysis of the recorded data [14].

3.2. BCD design for spallation studies in internal storage ring experiments

As a device, which permits the registration and the identification of particles with a very low-energy threshold and in a broad mass range, the BCD is a crucial component of the PISA detection setup. Since the PISA experiment is performed at an internal beam facility the construction and operation of the BCDs requires special care in order to preserve the UHV conditions, which are typical for internal storage ring experiments. The BCD volumes containing gas at a pressure of 300 mbar are separated only by a very thin Mylar foil from the scattering chamber, where UHV conditions of the COSY accelerator have to be met. For this reason an additional Mylar foil of 1.1 $\mu$m thickness was installed at a distance of about 10 cm from the front of the BCD window in order to create an intermediate vacuum region pumped continuously.

The detector (cf. Fig. 3) is constructed as a cylinder limited by a cathode (being simultaneously the entrance window) and by an anode spaced from the cathode by 22 cm. Both electrodes are made of 3.5 $\mu$m thick Mylar foils, which are metalized on one side. Between these electrodes the Frisch grid is positioned at a distance of 2 cm from the anode. It is a mesh made of 20 $\mu$m diameter tungsten wires, which are gold-plated. The distance between the neighbouring wires of the mesh is 1 mm. The electric field homogeneity between the cathode and FG is maintained by several stainless-steel rings spaced by 1 cm. The internal diameter of the detector is 5 cm. All internal parts are mounted to an isolating skeleton made of Plexiglass. Such a design of the detector permits easy exchange of defect parts and a simple modification of all intrinsic distances if necessary. The detector housing, gas in- and outlets as well as electrical feedthroughs are standard vacuum parts commercially available, e.g., from the Leybold Company [17]. In order to keep the entrance window (cathode) flat, it is supported on the outside by a mesh woven from tungsten wires with 50 $\mu$m diameter, spaced by 5 mm both in $X$ as well as $Y$ direction. The window foil is glued to an exchangeable frame with an epoxy glue. Earlier tests revealed that the foil fixed and supported in such a way is able to withstand an absolute pressure difference of 1 bar without damage. For normal working conditions of such a detector, with gas pressures not exceeding 300 mbar, the present safety factor is high enough to satisfy the

![Fig. 3. Schematic drawing of a BCD used for spallation studies at the internal accelerator beam facility. For details see text.](image-url)
COSY vacuum requirements. However, when operating such a detector in less stringent safety conditions the window thickness could be reduced. The tightness of the window ensures that the vacuum level of $10^{-6}$ mbar in front of the window is maintained when the gas pressure inside the BCD is increased from 1 to 400 mbar.

Various configurations of the voltage distribution were checked during the testing phase of the detectors. The simplest and most convenient solution with the cathode kept at negative and the anode at positive potential while the FG is grounded, allowed easy control and adjusting of the electric field strengths according to the current gas pressure. However, it was decided that in order to decrease the probability of electrical discharges in the vicinity of the entrance window, the cathode is grounded to the detector housing. In such a case both the FG as well as the anode have to be supplied with high positive potentials. The mesh supporting the entrance window is electrically connected to the cathode in order to avoid undesirable charge collection near the window. The voltages for the field shaping rings between the cathode and the FG are reduced by means of voltage dividers made of high precision $1 \times 10^6$ Ohm resistors. The anode and the FG are supplied from two separate HV channels through RC filters in order to eliminate the influence of voltage ripples.

### 3.3. BCD operation characteristics

The main problem, which a designer of an ionization chamber must deal with, is the small amount of charge produced by the detected particles since no charge multiplication process occurs in the detector. However, for the detected fast heavy ions the number of secondary electrons released by ionization in the counting gas isobutane is still $4.3 \times 10^4$ per MeV energy loss, with several MeV to tenths of MeV being lost in the active BCD volume and a fraction of these electrons defining the Bragg peak (cf. Figs. 2, 8, 9). These electrons must drift over the substantial detector length with little recombination and at the end form an output signal substantially higher than any ambient noise. Therefore the detector geometry, the gas used, its pressure as well as the applied voltages have to be carefully selected. With the P10 gas mixture (90% argon and 10% methane) used at the beginning of our tests we experienced problems with obtaining reasonable signals before reaching the discharge limit. These problems extended over a broad range of gas pressures. We therefore decided later to use isobutane, which is characterized by a 12% lower mean energy needed for electron-ion pair production than in the P10 mixture [18,19], increasing the number of released electrons. In fact, by using isobutane both the output signal amplitude as well as the discharge limit increased.

In order to avoid problems with sparking we have taken special care about the internal construction of the detectors: materials, electrical components, cables, connectors were carefully selected and positioned, considering also possible gas contaminations—see below. In effect we obtained a discharge free mode of operation with the voltages up to 3 kV for isobutane pressures from 100 to 300 mbar.

The area of the anode and its distance to the FG defines the capacity of the detector section, in which the output signal is created. Since the current of primary electrons is very small, it is required to keep the electrical capacity of this volume as small as possible in order to obtain the best signal to noise ratio. Unfortunately, by increasing the grid–anode distance also the minimal energy of particles, which can be detected in the detector, is increased [20]. As a reasonable compromise, on the basis of tests performed, we have chosen the anode-FG distance to be equal to 2 cm, which proved to be an optimal solution in the present design.

A crucial aspect for proper performance of the detector is a reliable gas flow control system. We experienced that effects of gas ageing can significantly reduce the detection efficiency of the BCD. When the gas is not refreshed continuously, after a short time the detection efficiency drops significantly, eventually even to zero. This is caused by the admixture into isobutane remnants of electronegative gases (generally O$_2$ and vapors of water), attached initially to the vessel walls and hidden in the pores of various parts of the detector. Even a trace amount of such pollutants
may capture a significant part of the drifting free electrons, making the detection impossible. It is for this reason that all internal parts of the detector have to be maintained extremely clean and their walls have to be polished. The detector volume itself should be pumped out to low pressure well before use. Effects described above practically exclude using BCDs with a static gas volume. Instead, a system, which allows permanent gas refreshing, has to be applied. In the case of our BCDs the gas flow is sustained by a membrane pump connected via a hand-operated fine valve to the gas outlet of the detector. Gas is supplied from a bottle containing high purity (99.95\%) isobutane through a stable pressure reducer connected with a hand-operated fine valve and followed by an electromagnetic dosage valve. The pressure in the detector is kept stable (with an accuracy better than 1\%) by an electronic unit [21], which according to the readout of a pressure sensor controls the opening fraction of the electromagnetic valve. The apertures of both hand-operated valves have to be found experimentally.

Due to the potential danger, which is created by the use of BCDs in terms of the strict vacuum conditions inside the COSY ring, the gas pressure control unit reacts to any deviation from the narrow tolerance window by immediately shutting off the gas inlet to the detector. In such a case the high-voltage supply of the electrodes of the detector is also instantly ramped down.

In order to obtain undistorted information about the energy losses of the detected particles the anode must be effectively screened from the positive ion current flowing between the FG and the cathode. The FG quality is described by its screening efficiency. The formula for calculating the screening inefficiency is given by Bunemann et al. [22]. In the case of our BCD, the grid screening efficiency amounts to about 98\%, which—as the results show—is sufficient for satisfactory detector performance.

The effectiveness of charge collection depends on the used gas and on the reduced electric field strength $\varepsilon/p$ (where $\varepsilon$ and $p$ are the strength of the electric field and the gas pressure, respectively), which enters in form of the parameter $\rho$:

$$\rho = \frac{\varepsilon_{\text{anode-FG}}}{\varepsilon_{\text{cathode-FG}}} / p$$

In practice, for a given gas pressure the voltages of the anode and the FG are increased until the amplitude of the output signal saturates and the signal length is close to a minimum. This indicates that the recombination of the electrons traveling through the detector is minimal and that all of them are passing through the FG and are collected at the anode. Values of $\rho$ between 2.0 and 2.5 were maintained in the present work. For the construction of our BCD this ensures that all drifting electrons will pass through the FG [22]. Depending on the gas pressure the maximal collection of electrons were obtained for values of $\varepsilon_{\text{cathode-FG}}/p$ in the range of 0.4–1.3 V/cm mbar.

### 3.4. Signal readout and analysis

The aim of the signal processing in the readout of BCDs is to record the $(dE/dx)(x)$ function as undistorted as possible in order to be able to perform a detailed shape analysis of the registered Bragg curves. For this purpose the anode signal is read out into a specially constructed, high sensitivity current preamplifier (see Fig. 4), from which a 40 MHz, 12-bit sampling ADC is fed via a voltage amplifier stage and an output buffer (CAEN, module V729A; in order to reduce the amount of recorded data, the 10 MHz frequency of the FADC was selected). The amplitude distributions of the samples reflect the particle’s stopping curve. The current preamplifier feeds also a charge integrator creating an output signal proportional to the total charge released by the detected particle. In this way we have direct information related to the kinetic energies of the stopped particles and, moreover, a separate channel allowing the discrimination of the signals. From the output buffers of both channels positive as well as negative signals are obtained in order to make the front-end electronics more flexible for the use with various discriminators and ADCs. The gain factor of 10 of the voltage amplifier allowed to feed the output signal from the preamplifier directly to the sampling ADC. In this
In the way we avoided an additional shaping amplifier, which would obviously distort the shape of the recorded Bragg curve. The typical shape of a registered Bragg curve is presented in Fig. 2. The rise and fall times of the preamplifier and of the voltage amplifier have been adapted to the integration through the drift time of about $0.4 - 0.5 \mu s$ in the 2 cm deep FG-anode gap in order to obtain an as little as possible distorted shape of the particle’s energy-loss function. We learned, however, that the performance of the preamplifier is limited by a reasonable choice of its sensitivity. While using a too sensitive preamplifier we obtained output signals contaminated with a very large noise superimposed on the recorded curve. In effect both the atomic number as well as the energy resolution were significantly reduced.

Advantages of recording the shape of the Bragg curve are described in Ref. [14]. Here we would like to remind that by analyzing certain parameters, particle identification is improved significantly. These are: total kinetic energy of the particle, amplitude of the Bragg peak, range of the particle in the detector and partial energy loss values, which could be selected over any range of the whole particle path. Also other parameters like the Bragg peak width or the initial energy of the particle might be examined in order to obtain better isotope separation (cf. Ref. [20]).

### 3.5. Detector performance

Results which are presented here were obtained during a test run of the PISA experiment in October 2002. A 150 $\mu g/cm^2$ thick Ni target was bombarded with the circulating COSY proton beam of 1.9 GeV energy. The working pressure of isobutane in both BCD detectors was 200 mbar and the applied voltages were $HV_{FG} = 2400$ V and $HV_{anode} = 2900$ V for the FG and anode, respectively. Fig. 5 presents an example of the obtained data. A scatter plot of the BP amplitude versus energy of the detected particles is shown in the upper part of the figure. The kinetic energy of a particle is proportional to the sum over the recorded FADC samples in the area of the signal. In order to increase the accuracy in determining the BP amplitude the five samples closest to the BP are added together (cf. Fig. 2). The energy calibration was done by comparing the experimental spectra with simulated ones. The simulations were performed with the use of the Geant4 code [23], taking into account the exact experimental geometry, composition and thicknesses of all parts of the detection system. The projection of events contained in the indicated gate onto the vertical axis is presented in the lower part of Fig. 5. The plot shows a very clean charge separation for particles with atomic numbers from 2 up to 14.
Only due to poorer statistics the ions of the higher atomic numbers are not so well represented. Furthermore, since the $^8\text{Be}$ isotopes decay in flight before reaching the BCD, the events corresponding to $^7\text{Be}$ and other Be isotopes, respectively, are well separated. Another characteristic property of the BP amplitude versus energy plot is the presence of clear “punch through” events corresponding to light ions with higher energy, which are not stopped in the BCD. The lowest energy, where individual elements can be identified, is about 0.5 MeV/nucleon and is common for all the detected $Z$ (cf. Fig. 6b).

In Fig. 5a the linear part of the BP amplitude versus energy $E$ curves does not remain completely horizontal for each atomic number $Z$, i.e. the amplitude of the Bragg peak increases gradually as the energy of the stopped particles increases. This phenomenon was quoted in earlier works describing the general features of Bragg curve spectroscopy (e.g. Ref. [14]) and it seems to be unavoidable. This effect is caused by partial recombination of drifting electrons. For the ionization induced by particles with low kinetic energies and stopping well in front of the FG the probability of recombination of electrons is higher than when the main stream of electrons is released near the FG and they have only a short path to travel. By recording the shapes of the signals the described effect can however be compensated for, which allows to improve the energy resolution.

In order to obtain charge identification spectra for events over the full energy range where the particles can be identified (i.e. $0.5 \text{ MeV/nucleon} \leq E \leq E_{\text{max}}$, with $E_{\text{max}}$ being the maximum energy of particles stopped before the FG) the histogramming was applied along the lines fitted to the centres of gravity of each distribution (cf. Fig. 6a and b). The projection of the in this way linearized distributions onto the Bragg-peak axis is presented in Fig. 7. Because the widths of the distributions along the fitted lines are not constant and increasing with energy, the resulting histograms have no Gaussian shapes. Thus, in order to evaluate the element resolution, $\Delta Z$, the standard deviations were calculated for each of the individual $Z$ lines. The such estimated $\Delta Z$ have values between 10% and 12% of one charge unit for peaks where isotopes are not resolved, and 14% for beryllium where the isotopical structure is visible.
The dependence of the ranges of the particles on their energies may give an indication of the particles’ mass. However, in contrast to Ref. [14] our analysis of particles’ ranges within the detector volume did not provide any new information other than we already obtained from Figs. 5 and 7. This could be due to difficulties in determining the beginning of the particle’s trajectory accurately enough since the ionization at this point is relatively small.

Much better results were obtained when the classical $\Delta E$-$E$ method was applied. Fig. 8 shows the resolved isotopes of $^6$Li and $^7$Li, $^7$Be, $^9$Be and $^{10}$Be, and $^{10}$B, $^{11}$B. The total kinetic energy is again derived from the integrated area under the signal curve. It was found that the resolving power of the method strongly depends on the part of the Bragg

![Image](image-url)
The region close to the entrance window is biased by relatively high uncertainties due to small ionization and the effect of electron recombination as discussed above. Optimal resolution is achieved when a rather big area of about 40 samples is considered for $\Delta E$, what causes however an increase of the energy threshold above which the isotopes can be resolved. This region is marked in Fig. 2 as $\Delta E$. The obtained results are very promising and show that the identification of the isotopes for the particles with mass numbers up to $A = 11$ could be achieved.

Using a BCD as an integral part of a telescope comprising other detectors, allows to check whether the entire BCD can be operated as a $\Delta E$ detector, too. By selecting the energy loss curves of the particles, which did not stop inside the BCD’s volume and which subsequently produce signals in the following silicon detector telescopes, one is able to plot the $\Delta E$-$E$ distributions as presented in Fig. 9. In the upper part the energy deposited in the BCD is shown versus the energy loss in the first 100 $\mu$m thick Si detector, whereas in the lower part the energy signals of two silicon detectors with a total thickness of about 400 $\mu$m are added together. In spite of the relatively small energy deposit of the particles which punch through the BCD this creates a possibility to identify not only elements, but also the isotopes of the light reaction products. In effect the particles, which are not stopped in the BCD but only in the subsequent silicon detector, can also be identified.

4. Summary

An axial ionization chamber (BCD) was applied to register spallation products in the PISA experiment performed at the internal beam facility of the COSY accelerator in Jülich, Germany. The construction and rigorous control of the detector operation allows to meet the strict vacuum safety conditions, which are typically required for experiments using an internal target station of a storage ring. By employing a specially designed current preamplifier and a flash ADC not only excellent charge resolution is achieved, but also very clean isotopic resolution for light ions up to boron is observed. Further optimization of the read-out system is envisaged in order to distinguish isotopes of even heavier elements. Information on the energy of the particles deposited in the BCD is applied also for the mass identification using both the time-of-flight technique (together with MCPs) as well as the $\Delta E$-$E$ method (together with silicon detectors). This enables us to obtain mass identification by using three different methods: TOF and BCD, BCD by itself and BCD combined with a Si-telescope. These methods certainly improve the identification of ejectiles which are stopped in the BCD, decrease their detection energy threshold as well as assist in the $(A, Z)$-identification of those particles which pass through the BCD. The values of the minimum kinetic energies of an unambiguously identified particle are found to be: 0.5 MeV/nucleon for $Z$-identification regarding only the BCD data, 1 MeV/nucleon for $A$-identification on the basis of using the TOF combined with the BCD results and larger than

Fig. 8. Isotopic resolution obtained in the Bragg curve detector with a method similar to the classical $\Delta E$-$E$ method. Within a limited dynamic range the identification of isotopes of Li, Be, and B is possible. The region where the energy losses were taken from is indicated in Fig. 2 by “$\Delta E$”.

The curve which is taken for calculating the $\Delta E$ value.
This study has shown that the BCD is a powerful and effective detector for spallation product identification. Further development of the PISA detection system, which includes to equip additional detection arms with axial ionization chambers, is in progress.

**Acknowledgements**

We would like to express our gratitude to the staff of Heavy Ion Laboratory of the Warsaw University in Poland and the staff of INFN LNS in Catania, Italy for providing us with various ion beams during the test phase of our apparatus. We acknowledge especially support from Dr. F. Ferrera and Dr. E. De Filippo from INFN LNS and their significant help with incorporating our readout system into the data acquisition system in Catania. We wish to thank also Mr. L. Conin, Dr. U. Bechstedt and Mr. N. Dolfus from the Research Centre Jülich for their fruitful collaboration in preparing the vacuum control system for the PISA experiment. The PISA project is supported partially by DLR/BMBF Grant no. POL01/090, the EU-HINDAS project FIS5-1999-00150, and EU TMR project ERB-FMRX-CT98-0244. We acknowledge the support of the European Community—“Access to Research Infrastructure Action of the Improving Human Potential Programme”—LIFE, contract HPRI-CT-1999-00027.

**References**