KEK Preprint 95-66
June 1995
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SCAN-9507268

509534

Submitted to Nucl. Instrum. Meth., A.

APPLICATION OF BRAGG-CURVE COUNTERS TO A TARGET MULTIFRAGMENTATION MEASUREMENT

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Abstract

We have constructed Bragg-curve counters (BCCs) to detect the intermediate-mass fragments (IMFs) emitted during target multifragmentation induced by 12-GeV primary protons on Au, Ag targets. An energy resolution of $\sim 1.0\%$ and an atomic-number resolution of 2.0% have been achieved. Long-term stability of the output pulse-heights, which was necessary for actual IMF measurements, was realized by employing a continuous gas-flow system with a constant pressure.

1 Introduction

In the collision of a high-energy light particle with a heavy target nucleus intermediate-mass fragments (IMFs) with $6 \leq A < A_{\text{target}}/3$ are emitted from the target nucleus with energies of several MeV/nucleon, i.e. target multifragmentation, where A_{target} is the mass number of the target. This phenomenon makes a good probe for studying the property of highly excited nuclear matter.

Most of the studies of target multifragmentation have been based on inclusive measurements of the IMFs. Because both the IMF multiplicity and their correlations are not well known, exclusive measurements of IMFs have been desired in order to understand the reaction mechanism in detail. Exclusive measurements in light-particle induced target multifragmentation require the use of a 4π -counter system to detect the IMFs and the use of a coincidence method. Such a system must possess an ability to identify the atomic- (or mass-) number of the ions in the mass region of the IMFs,

and to measure with high accuracy the kinetic energy of heavy-ions as low as a few MeV/nucleon. In addition to these requirements, the system should be insensitive to the high-rate background radiation associated with the high-intensity primary beam, i.e. the beam halo.

Various kinds of counter systems have been constructed to observe IMFs in target multifragmentation. The time-of-flight spectrometers [16] at the FNAL and the BNL consist of micro-channel-plate detectors and a gas-semiconductor ionization chamber (or solid state detectors; SSD). The typical 4π -counter systems, e.g. Miniball [17], FASA [18] and ISIS [19], are combinations of CsI(Tl)-crystal scintillators and other appropriate devices. These counter systems avoid the problem of a beam halo by restricting the intensity of the primary beam to a low level. However, the low counting rate requires a long beam time to obtain good statistics.

Since we plan to study target multifragmentation using the high-intensity light-particle beams provided from the 12-GeV Proton Synchrotron of the National Laboratory for High Energy Physics (KEK-PS), we have adopted a Bragg-Curve Counter(BCC) as a device to construct a 4π -counter system. In our final plan, twelve BCCs are to be arranged in the reaction plane to observe the angular distributions and correlations of the IMFs, and eight BCCs are to be placed out of plane to obtain information on the IMF multiplicity of the reaction. As a first step, we constructed two typical prototype BCCs and investigated their performance using ^{241}Am α -particles and ^{19}F beams from tandem accelerators. In this paper we report on the performance of these prototype counters and their usefulness in experiments at the KEK-PS.

2 Bragg-Curve Counter

A Bragg-Curve Counter(BCC)[1]-[15] is a kind of ionization chamber with a Frisch-grid. Since the electric field in the counter is parallel to the incoming particle path, the electrons along the particle path drift to the anode of the BCC through the Frisch grid. Then, the output signal from the anode as a function of time is proportional to the energy-loss distribution of the particle along its path, i.e. the Bragg Curve [1]. We can, therefore, identify the atomic number of the incoming particle from the maximum pulse height of the anode signal, which corresponds to the Bragg peak, and the total kinetic energy of the particle from the integration of the total output signal. Up to now the BCC has realized the atomic-number identification of heavy ions ranging from $Z=2(\text{He})$ to $Z\approx 38(\text{Sr})$ [7] and their energy-measurements with a resolution of better than 1% . These capabilities are suitable to observe the IMFs

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emitted in target multifragmentation. In addition, the simple structure of the BCC is suitable to construct a 4π -counter system.

Furthermore, the BCC has an advantage of being resistant to radiation damage, and of being insensitive to minimum-ionizing particles. At around the primary beam line at the KEK-PS there is a very high flux of background radiation since the KEK-PS was designed to produce as many secondary particles as possible, and not for experiments with the direct use of primary beams. Therefore, in the very early stage of our project we found that solid detectors such as CsI(Tl) crystal, plastic scintillator and SSD could not be operated properly within 10cm from the beam axis because of the very high flux of beam-associated charged particles, i.e. the beam halo. Finally, we found that the BCC exhibits almost the best performance, even in a bad environment, as described above. Thus, our experiment at the KEK-PS to study multifragmentation has become possible. The excellent performance of BCCs against the beam halo enabled us to also perform experiments with a relatively high intensity of the primary-beam compared to any other existing counter system. We believe that the use of high intensity primaries is essential to shed new light on the reaction mechanisms of multifragmentation.

2.1 Counter construction

Two prototype BCCs were constructed. The first type (Fig.1), which is called 'four-in-one BCC', was designed for angular-distribution measurements. The other (Fig.2) was a BCC to be placed out of the reaction plane in order to estimate the IMF multiplicity. The latter was named 'large-acceptance BCC'. The common structure of the BCCs is given in the following subsections.

The counter consists of a Frisch grid, an anode and field-shaping electrodes (see Fig.1 and 2). The effective length, i.e. the distance between the entrance window and the Frisch grid, was chosen to be about 30cm in order to stop the IMFs of several MeV/nucleon within the gas volume at a pressure of 200-300 Torr. The Frisch grid was formed by stretching tungsten wires of $50\mu\text{m}$ in diameter with a spacing of 1mm (the geometric transparency is 95%). These wires were point-welded on a stainless-steel frame. The anode was a 1mm thick stainless-steel plate placed 10mm behind the Frisch grid. The Frisch grid and the field-shaping electrodes were supported by insulator pillars made of polyacetal resin (Delrin), and were connected to a voltage-dividing resistor chain (the total resistance of $\sim 15\text{M}\Omega$) in order to shape the electric field between the entrance window and the Frisch grid. The dimensions of the electrodes as well as the target-counter distance were so determined that the particles from 10mm wide region can not escape detection.

For the entrance window it is essential to reduce its thickness so as to be as thin as possible in order to minimize the energy loss of incoming IMFs. The window was made of a $1.8\mu\text{m}$ thick aramid film (MICTRON³) supported by a tungsten net (thickness of $50\mu\text{m}$, 30-mesh). The inside face of the window was coated with aluminum to make the window electrically conductive. The coated film was also used as a cathode so that a uniform electric field could be effectively achieved on the surface. The entrance window was confirmed to withstand an inner pressure of about 500Torr.

2.1.1 The 'four-in-one BCC'

In the 'four-in-one BCC', four sets of Frisch grids and anodes were placed in a gas volume to enable the independent extraction of four anode-signals. This counter was designed to measure the angular distributions of IMFs over an angular range of 80° at steps of 20° . This structure makes it possible to reduce the dead spaces between the adjacent anodes. Between four Frisch grids and the entrance windows, fourteen field-shaping electrodes were placed at intervals of 20mm to make a homogeneous electric field toward the target point (see Fig.1).

Four entrance-window foils were mounted on a common detachable frame, which was placed at the front face of the 'four-in-one BCC'. The window was concentric about the target center at a distance of 150mm, and the solid angles of four counters were defined to be identically 74msr by the frame of the window. The angular acceptance of each counter was set to be $\pm 7.6^\circ$.

2.1.2 The 'large-acceptance BCC'

The 'large-acceptance BCC' is a single counter having the shape of a frustum of an oct-angular pyramid, as shown in Fig.2. This shape is useful for placing many counters around the target with the smallest dead angles between the adjacent counters. The active area in the BCC has a conical shape to realize as large a solid angle as possible.

In order to avoid any distortion of the electric-field distribution near to the chamber wall, twenty-one field shaping electrodes are placed in the counter with different spacings, depending on the location, i.e. smaller spacing at closer positions to the window (see Fig.2). The field uniformity was checked by using the field calculation program POISSON[20] in cylindrical ordinates.

A stainless-steel collimator with a circular opening was placed in front of the window frame to define the solid angle. The target was mounted at a point 96mm away from

³This film was supplied by TORAY Co. Ltd., Japan

the collimator on the counter axis. The solid angle achieved was 114msr.

3 Operation

The basic parameters of BCC operation were determined by test measurements using an ^{241}Am - α source and ^{19}F -beams from the tandem accelerator at Kyushu University. Simple readout electronics (Fig.3) were prepared for testing the operation of the BCCs. The anode signal of the BCC was amplified by a charge-sensitive pre-amplifier, and was fed to two shaping amplifiers having different shaping time constants (τ_s and τ_l). The short time constants (τ_s) was selected to roughly be the electron drift-time from the Frisch grid to the anode, i.e. about 100ns; and the long time constants (τ_l) was that from the entrance window to the anode, i.e. about 10 μ s. We can therefore obtain the Bragg peak signal from a short-time-constant shaping amplifier and the energy signal from a long-time-constant shaping amplifier.

3.1 Gas Flow System

It is known that the counter gas in the BCC is deteriorated by the release of impurities from the chamber walls and the electrode surfaces, causing a degradation of the Bragg-peak pulse height. In order to keep this deterioration as small as possible, we paid attention to the following points concerning the counter construction. The chambers were made of stainless steel and the inner walls were electrolytic-polished to prevent impurities from being absorbed on the surfaces. The electrodes and insulators were washed in clean alcohol in an ultrasonic cleaning machine. In every screw used, a thin coaxial slot was made to let the gas out of the screw hole. For fixing the net and the film on the entrance-window frame, resins with small volatility (Araldite AY103⁴ or Torr-Seal⁵) were used.

In long-time measurements of the Bragg-peak pulse height using an ^{241}Am - α source, however, it was found that these treatments were not sufficient to keep the pulse height stable for more than 1 hour. This necessitated us to introduce a gas-flow system. The gas-flow system consisted of a needle-valve, a pressure gauge, a control valve, and a valve controller; fresh gas was fed to a counter at a constant pressure⁶. We operated the gas-flow system at a flow rate of about 500scm (standard cubic centimeters per minute) after purging the chamber from the contaminations by using some repetition of

gas-filling and -evacuation processes. By using this system it was found that the Bragg-peak pulse height was kept stable within 0.6% per hour. However, the dependence of the pulse height upon the temperature of the BCC was seen in a long-term measurement; it was necessary to maintain the atmospheric temperature so as to be constant.

3.2 Gas Mixture

An argon-methane gas mixture was usually used as a counter gas of the BCCs [1],[2],[6]-[9], [12],[13],[15]. Since the drift velocity of electrons in the gas depends upon the mixture rate, we compared the counter responses to the ^{19}F ions of 67MeV for the gases of P-10(90% Ar+10% CH₄) and P-3(97% Ar+3% CH₄). The elastic scattering of a ^{19}F -beam from the tandem accelerator in Kyushu University was used for the measurements.

Firstly, the electron drift velocity was measured from the rise time of the pre-amplifier output signal as a function of the grid bias. A grid bias at which the electron drift velocity was relatively insensitive to the fluctuations of the bias voltage was selected for each P-10 and P-3 gas. Secondly, the anode bias was set to be 100Volt higher than grid bias in order to keep the inefficiency of the grid as low as possible. Finally, the resolution of the Bragg-peak nd energy was measured for both P-10 and P-3.

No difference was observed in the Bragg-peak resolution for elastically scattered ^{19}F ions. In the case of the P-3 gas, however, it was found that the shaping time required for the BCC output signal to give reliable information on the kinetic energies exceeded 15 μ sec. In order to avoid the situation of a slow data-taking rate, we selected P-10 gas for the counter gas, which required a shaping time constant of 6 μ sec.

3.3 Bias Supply

In the measurement described above, the anode bias and the grid bias were obtained from two high-voltage power supplies. It turned out immediately that the signal from the BCCs was fairly sensitive to the ripples and noise on the high-voltage power supplies. In order to eliminate the ripples of both bias voltages, RC-integrators (low-pass filter) with time constant of 4.7msec were used at the outputs of the power supplies. From a comparison of the performances using dry batteries and power supply modules (FLUKE415B, Ortec556 and Ortec456) as high-voltage power supplies, it was found that ripples of <10mV peak-to-peak in the output voltage were required, especially for the grid bias. Ripples of the anode bias were relatively not so serious as hat of the grid bias.

⁴Product of CIBA-GEIGY (Japan) Ltd.

⁵Product of Varian Vacuum Products Co., U.S.A.

⁶Main parts of the gas flow system were supplied by MKS INSTRUMENTS Inc., U.S.A.

4 Counter tuning using ^{19}F ions

The introduction of the gas flow system, the gas mixture rate, and the ripple level of the counter bias supply were thus determined. Further tuning of the performances of the two BCCs was studied using ^{19}F -beams of 60, 70 and 80MeV, which were supplied by the tandem accelerator of the Tandem Accelerator Center, University of Tsukuba. The purpose of this test experiment was to fine tune of the time constants of the shaping amplifiers and to put the energy and atomic-number scales on the output signals.

The experimental setup was as follows. An Al target with a thickness of about $220\mu\text{g}/\text{cm}^2$ was bombarded by ^{19}F beams, and the scattered ^{19}F ions together with reaction products were detected by the BCC at $\theta(\text{lab.})=10^\circ$. A collimator having a small acceptance ($\sim 26\text{msr}$) was placed in front of the BCCs in order to reduce the kinetic-energy dispersion of the scattered ^{19}F incident on the counter. The particles were introduced along the central axis of the counter. The BCC was filled with the P-10 gas at a pressure of 200 or 300Torr using the gas-flow system. The gas pressure and ^{19}F -beam energy were adjusted so as to stop the elastically scattered ^{19}F just before the Frisch grid in order to obtain the best energy and atomic-number resolution.

4.1 Fine Tuning of Time Constants

The readout electronics that we employed were essentially the same as that shown in Fig.3. It is known regarding the atomic-number determination that the smaller is the time constant of the shaping amplifier, the wider is the energy region over which the pulse height of the Bragg peak is nearly independent of the energy, and the worse is the signal-to-noise ratio [7][10]. In order to optimize the time constants for our BCCs, the response of the amplifier output was studied for scattered ^{19}F . Figure 4 shows scatter plot, the energy versus the Bragg peak, obtained for $\tau_s=0.25, 0.10$ and $0.04\mu\text{sec}$ (Ortec460). As can be seen in this figure, the pulse heights for the Bragg peak are roughly constant for ion energies of above $\sim 30\text{MeV}$ in the cases of $\tau_s=0.04$ and $0.10\mu\text{sec}$, while $\sim 35\text{MeV}$ in the case of $\tau_s=0.25\mu\text{sec}$.

The resolution for the Bragg peak or energy was obtained by fitting the Gaussian-distribution function to the pulse-height distribution for the elastically scattered ^{19}F . The observed values of the Bragg-peak resolution (full width at half maximum: FWHM) are shown in Table 1. The value for $\tau_s=0.10\mu\text{sec}$ was slightly better than that for $0.04\mu\text{sec}$. In order to achieve a good atomic-number resolution for heavy ions over a wide range of their kinetic energy, we adopted a time constant (τ_s) of $0.1\mu\text{sec}$ for our BCCs.

The output signal of an amplifier with a larger time-constant (τ_l) gives the kinetic energy of the incoming particle. The time-constant (τ_l) should be roughly the total electron drift-time from the entrance window to the anode. We studied the pulse heights of the energy signals for time constants of 1, 6 and $10\mu\text{sec}$ (Ortec472A). It was found that the minimum time-constant to give saturated pulse height for an energy pulse was $6\mu\text{sec}$ for our BCCs.

The energy resolution (FWHM) for 70MeV ^{19}F elastic scattering was 0.86% for the ‘four-in-one BCC’ and 1.0% for the ‘large-acceptance BCC’. Energy-loss straggling in the Al target was estimated to be negligibly small ($<0.04\%$). The Bragg-peak resolution for the ^{19}F ions was 2.0% for both BCCs, irrespective of their energy. These energy and Bragg-peak resolutions are comparable to the best attained values of previously manufactured BCCs in the world [1]-[15].

4.2 Atomic-number identification and Energy calibration

The atomic numbers of heavy ions were identified using a scatter plot, the Bragg peak versus the energy, by referring to the locus formed by the scattered ^{19}F ($Z=9$) ions and that of the α -particles ($Z=2$) measured separately using an ^{241}Am - α source.

For the purpose of converting the channel numbers of the energy spectrum into the energies of heavy ions, the elastically scattered ^{19}F ions were used as reference standards. The energy value was estimated from kinematical calculations of the reactions together with estimations of the energy losses in the window-film and the Al-target. For other energy reference standards we used the α -particles produced in $^{19}\text{F}+\text{Al}$ reactions. As can be clearly seen in the scatter plot, there is a turning point in the α -particle locus. This turning point corresponds to α -particles that stop just at the anode of the BCC. We can then determine the α -particle energy from the range-energy relation in the P-10 gas. The conversion formula was, thus, made from these references, assuming a linear relation.

The turning point of each locus corresponding to the appropriate atomic number in the scatter plot can provide an extra reference of the energy by means of the range-energy relation. The relations between the atomic number and its energy, thus deduced, were consistent with one another.

5 BCC performance at KEK-PS

We carried out target multifragmentation experiments using the above-mentioned BCCs at the primary beam line of the 12-GeV Proton Synchrotron of the National

Laboratory for High Energy Physics (KEK-PS). The ‘large-acceptance BCC’ was set at $\theta(\text{lab.})=90^\circ$, and the ‘four-in-one BCC’ was placed on a turn table on the opposite side of the beam to the ‘large-acceptance BCC’ in the same reaction plane. A 12-GeV proton beam (intensity of $\sim 1.5 \times 10^9$ particles/spill) was transported onto Au and Ag targets with a thickness of about $800 \mu\text{g}/\text{cm}^2$. Prior to the experiment, the BCCs were kept in a vacuum ($\sim 2 \times 10^{-5}$ Torr) for one day. The BCCs were then filled with the P-10 gas at a pressure of 200Torr using the gas-flow system. The grid and anode bias that we employed was +1000 and +1100Volt, respectively. The reduced field value(E/P), which is the ratio of the electric field strength to the gas pressure, in the active volume was about 0.17Volt/(cm $\times$ Torr).

The energy spectra of the IMFs were measured inclusively at laboratory angles from 30° to 150° at steps of 20° . Coincidence measurements were also performed. The observed scatter plots for the case of the Au target are shown in Fig.5. Fragments heavier than Ca($Z=20$) are clearly seen to be separated. Lighter IMFs than O($Z=8$) were discriminated in order to reduce the dead time in the data-acquisition system. The merging of the loci formed by the IMFs at the lowest energy (less than about 1MeV/nucleon) corresponds to particles with insufficient energies to form their Bragg peak in the counter. Figure 6 shows a typical energy spectrum of Na detected at $\theta(\text{lab.})=90^\circ$. The low-energy cutoff in this spectrum indicates from the lowest energy of the possible particle identification. A Bragg-peak spectrum, which is made by selecting events of $E_{\text{IMF}} > 1.5 \text{MeV/nucleon}$ and by projecting onto the Bragg-peak axis, is presented in Fig.7. A clear separation of the IMFs can be seen. The width of the locus remains nearly constant as the atomic number increases. The drift of the Bragg-peak height during the experiment, i.e. 10days, was less than 1.5%.

6 Summary and acknowledgment

Two prototype Bragg-curve counters were constructed in order to study target multifragmentation at the KEK-PS. Both counters yielded resolutions of $\Delta E(\text{FWHM})/E < 1.0\%$ and $\Delta Z(\text{FWHM})/Z = 2.0\%$ for 70MeV ^{19}F ions elastically scattered from Al; these resolution values were as good as those reported for the existing BCCs. The continuous gas-flow system kept the pulse height of the Bragg peak satisfactorily stable for a constant temperature. We carried out a target multifragmentation experiment at the primary beam line of the KEK-PS, confirming the capabilities of these counters to work as actual IMF detector systems. These BCCs were found to be effective in the domain of $Z=2$ to more than 20 and $E/A \sim 1.2 \text{MeV}$ to several MeV/nucleon. Both

the atomic-number identification and the kinetic energy measurement for the heavy-ions are simultaneously possible. The exclusive data in this domain are valuable for studying multifragmentation. The characteristic sideward flow of the IMFs toward the 70° direction, as observed in the experiment, has been reported elsewhere[21].

Some of the problems to be considered in future work are the following: The lower limit of the energy measurement is slightly higher than 1.2MeV/u, and is rather high compared with the values in the previous experiments. In order to make a lower threshold available, it is most effective to make the time-constant for the Bragg peak shorter. In order to make this setting possible, it is essential to realize an environment that has negligibly low electrical noise. In addition, it is desired that the use of thinner films for the entrance windows is made available to reduce the energy loss.

We would like to thank Professors S. Morinobu and M. Takasaki for their valuable suggestions and encouragements throughout the present study. Prof. S.M. Lee and his group members provided warm support during the test experiment at the University of Tsukuba. Thanks are also due to the staff of the tandem accelerator in University of Tsukuba and Kyushu University for providing excellent ^{19}F -beams. This work was partly supported by a Grant-in-Aid for Scientific Research (C) (No. 06640423 and No. 06640389) of the Japan Ministry of Education, Science and Culture (Monbusho). It was performed also as a part of a Grant under the Monbusho International Scientific Research program (No. 06041115 and No. 07041103). One of authors (Yasuda) acknowledges the receipt of JSPS Fellowships for Japanese Junior Scientists.

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Table

time constant τ_s (μsec)	0.04	0.10	0.25
resolution(FWHM/peak channel)	2.32%	2.29%	2.16%

Table 1. Bragg-peak resolution for elastically scattered ^{19}F of 70 MeV.

Figure caption

Figure 1: Schematic drawings of the ‘four-in-one BCC’: plan view(top) and side view(bottom).

Figure 2: Schematic illustrations of the ‘large-acceptance BCC’: front view(left) and side view(right).

Figure 3: Schematic illustration of a Bragg-Curve Counter. The anode signal is picked up by a charge-sensitive pre-amplifier, and is then branched off into two main amplifiers with different shaping time constants (τ_s and τ_l).

Figure 4: Bragg peak vs. the energy plot for the F ions in the reaction $^{19}\text{F}+\text{Al}$ at 70MeV and $\theta(\text{lab.})=10^\circ$. Results for three different shaping times ($\tau_s=0.25, 0.10, 0.04\mu\text{sec}$) are shown together. The loci formed by ^{19}F in the cases of 0.04 and $0.10\mu\text{sec}$ time constants overlap each other, and can not to be distinguished in this figure.

Figure 5: Typical two-dimensional Bragg-peak (atomic number) vs. kinetic-energy plot for the IMFs detected in the p+Au reaction at $E_p=12\text{GeV}$ and $\theta(\text{lab.})=90^\circ$.

Figure 6: Energy spectra of Na isotopes detected in the p+Au reaction at $E_p=12\text{GeV}$ and $\theta(\text{lab.})=90^\circ$.

Figure 7: Z-spectrum for the IMFs detected in the p+Au reaction at $E_p=12\text{GeV}$, $\theta(\text{lab.})=90^\circ$ The events of $E_{\text{IMF}} > 1.5\text{MeV/nucleon}$ have been selected in the measurement.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7