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Recoil separator ERNA: ion beam purification☆

D. Rogalla[a], S. Theis[a], L. Campajola[b], A. D'Onofrio[c], L. Gialanella[a], U. Greife[a], G. Imbriani[b], A. Ordine[b], V. Roca[b], C. Rolfs[a,*], M. Romano[b], C. Sabbarese[c], F. Schümann[a], F. Strieder[a], F. Terrasi[c], H.P. Trautvetter[a]

[a]Institut für Physik mit Ionenstrahlen, Fakultät für Physik und Astronomie, Ruhr-Universität Bochum, Bochum, Germany

[b]Dipartimento di Scienze Fisiche, Università Federico II, Napoli and INFN, Napoli, Italy

[c]Dipartimento di Scienze Ambientali, Seconda Università di Napoli, Caserta and INFN, Napoli, Italy

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Abstract

For improved measurements of the key astrophysical reaction $^{12}C(\alpha,\gamma)^{16}O$ in inverse kinematics, a recoil separator ERNA is developed to detect directly the ^{16}O recoils with nearly 100% efficiency. Since the ^{12}C projectiles and the ^{16}O recoils have essentially the same momentum and since the ^{12}C ion beam emerging from an accelerator usually passes through a momentum filter, a sufficient absence of an ^{16}O beam contaminant in the ^{12}C ion beam is of utmost importance for ERNA. In the present work, a Wien filter together with a $\Delta E - E$ telescope are used to investigate the beam contaminants accompanying a momentum-filtered ^{12}C ion beam and to measure the level of ion beam purification achievable with the Wien filter. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The capture reaction $^{12}C(\alpha,\gamma)^{16}O$ ($Q = 7.16$ MeV) takes place in the helium burning of Red Giants [1] and represents a key reaction of nuclear astrophysics. The cross section at the relevant Gamow energy, $E_o = 0.3$ MeV, determines not only the nucleosynthesis of elements up to the iron region but also the subsequent evolution of massive stars, the dynamics of a supernova, and the kind of remnant after a supernova explosion. For these reasons, the cross section $\sigma(E_o)$ must be known with a precision of at least 10%. In spite of tremendous experimental efforts over nearly 30 yrs [2–9], one is still far from this goal. Nearly all efforts have focused on the observation of the capture γ-rays with an array of standard gamma-ray detectors, such as Ge detectors (with a typical efficiency below 0.1% for $E_\gamma = 8$ MeV). Due to the low capture cross section (e.g. 50 nb at $E_{cm} = E = 2.42$ MeV, decreasing rapidly into the pb range at lower energies) and the hampering effects of cosmic rays in the

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* Corresponding author. Tel.: + 49-234-700-3602; fax: + 49-234-7084-172.

E-mail address: rolfs@ep3.ruhr-uni-bochum.de (C. Rolfs).

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detectors, γ-ray data with sufficient precision were limited to energies above $E = 1.2$ MeV.

To improve the situation, a new experimental approach is in preparation called European Recoil separator for Nuclear Astrophysics (ERNA). In this approach, the reaction is initiated in inverse kinematics, $^4He(^{12}C, \gamma)^{16}O$, i.e. a ^{12}C ion beam is guided into a windowless ^4He jet-gas target and the kinematically forward-focused ^{16}O recoils are detected in the beam line. The direct observation of the ^{16}O recoils requires an efficient recoil separator [5,10,11] to filter out the intense ^{12}C beam particles from the ^{16}O recoils. The number of ^{16}O recoils per incident ^{12}C projectile is 1×10^{-18} for $\sigma = 1$ pb and $n(^4He) = 1\times10^{18}$ atoms/cm^2. The recoil separator must also filter out beam contaminants, small-angle elastic scattering products, and background events from multiple scattering processes leading to a degraded tail of the projectiles. If the filtering of the recoil separator is sufficiently effective (with a beam suppression factor of the order $R_{rec} = 10^{-15}$ at $E = 0.7$ MeV), the ^{16}O recoils can be counted directly in a $\Delta E - E$ telescope placed in the beam line at the end of the recoil separator, where the telescope allows for particle identification. Previous measurements [11] have shown that a "beam suppression factor" of the telescope alone of $R_{tel} = 10^{-3}$ can be achieved leading to a total suppression factor of $R_{tot} = R_{rec}R_{tel} = 10^{-18}$ at $E = 0.7$ MeV for the planned separator. In a recoil separator, it is necessary to make a charge state selection of the recoils, causing a reduction in the number of recoils transmitted through the separator. However, since there is usually a charge state representing about 50% of the total recoils produced, this reduction is not too serious. The recoil separator ERNA will consist sequentially of a Wien (velocity) filter, a momentum filter, another Wien filter, a $\Delta E - E$ telescope (ionisation-chamber), and a series of focusing and diagnostic elements. The high detection efficiency of the ^{16}O recoils and the negligible contribution of cosmic-ray events in the $\Delta E - E$ coincidences probably allows a measurement of the $^4He(^{12}C, \gamma)^{16}O$ cross section to as low as $E = 0.7$ MeV ($\sigma \cong 1$ pb), if other requirements (see below) can be fulfilled.

Since the ^{12}C projectiles and the ^{16}O recoils have essentially the same momentum and since the ^{12}C ion beam emerging from the accelerator passes usually a momentum filter (analysing magnet), a sufficient absence of an ^{16}O beam contaminant in the ^{12}C ion beam incident on the gas target is of utmost importance for the new approach: the ^{16}O beam contaminant and the ^{16}O recoils cannot be distinguished in the recoil separator, since both have the same momentum (and velocity). The contaminant ^{16}O beam is usually many orders of magnitude weaker than the ^{12}C beam (and thus difficult to observe by current measurements or other experimental techniques), but it could be more intense than the intensity ratio 10^{-18} between the ^{16}O recoils and the ^{12}C projectiles at $E = 0.7$ MeV. In the previous study of $^4He(^{12}C, \gamma)^{16}O$ using a recoil separator [5], the ^{16}O contamination was eliminated by the requirement of recoil-gamma coincidences using an array of gamma-detectors around the ^4He gas target, at the price of a reduced total detection efficiency. Alternatively, the ^{16}O contamination can be minimized if a Wien filter is installed before the analysing magnet, thus purifying the projectiles emerging from the analysing magnet. If the beam purification needs to be higher, a second Wien filter can be placed between the analysing magnet and the gas target. In the present work, a Wien filter (installed after the analysing magnet) together with a $\Delta E - E$ telescope were used [12] to investigate the beam contaminants accompanying a momentum-filtered ^{12}C ion beam and to measure the level of beam purification achievable with a single Wien filter.

2. Equipment and setup

The ^{12}C, ^{14}N, and ^{16}O ion beams were provided by the 4 MV Dynamitron tandem accelerator at the Ruhr-Universität Bochum. Details of the accelerator have been described elsewhere [13,14]. Briefly, the negative ion beam is produced with a sputter ion source at 130 kV potential, selected then by a 90° injection magnet, focused by a gridded lens, and accelerated to the terminal voltage of the tandem (Fig. 1). After electron stripping in a nitrogen gas, the positive ions emerging from the tandem are focused by a magnetic quadrupole doublet, filtered then with respect to momentum and charge state

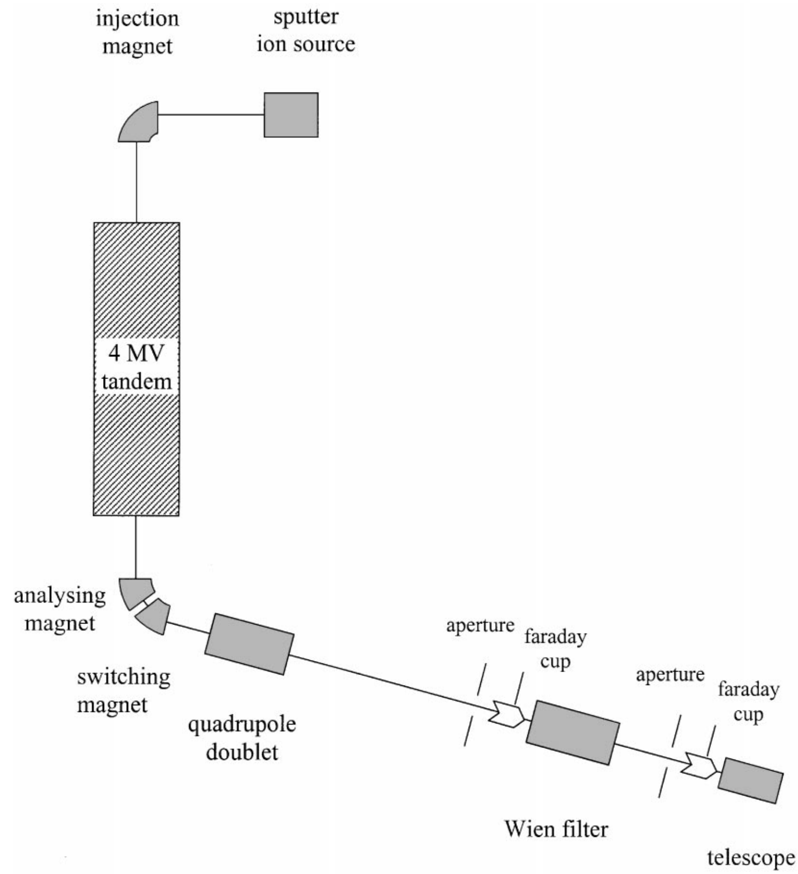

Fig. 1. Schematic diagram of the 4 MV Dynamitron tandem accelerator with relevant components of the experimental setup (Wien filter and $\Delta E - E$ telescope) used in the present work.

by a 52° analysing magnet, and guided into the 75° beam line by a switching magnet. Finally, a magnetic quadrupole doublet is used to focus the beam on the center of the apparatus.

The design of the Wien filter followed closely that reported previously [15]. Briefly, it contains two parallel electrostatic plates (78 mm width, 850 mm length, 36 mm distance) installed above and below the beam axis in a rectangular beam pipe (108 mm × 118 mm). The electric field is produced by positive and negative voltages applied to the plates (power supplies with analog remote control: FUG, model HCN14-20000; 20 kV/0.6 mA, voltage stability $< 1 \times 10^{-4}$ over 8 h). The Wien filter involves also two pole shoes (117 mm width, 790 mm length, 110 mm distance) installed on the right and left sides of the beam pipe. The magnetic field is created by a current through coils wound around the pole shoes (power supply with analog remote control: DELTA, model SM70-22; 70 V/22 A, current stability $< 1 \times 10^{-4}$ over 8 h). The field strength is measured using a commercial Hall probe (GROUP3, model DTM-130; 0.03% precision) as well as home-made Hall probes. The measurements show that the field varies laterally by less than 1% over a distance of 15 mm on both sides of the beam axis; along the beam axis, the field is homogeneous within 1% and drops sharply near the edges of the pole shoes, leading to an effective field length of 877 mm (expectation = 866 mm). In comparison, the electric field has an effective length of 874 mm.

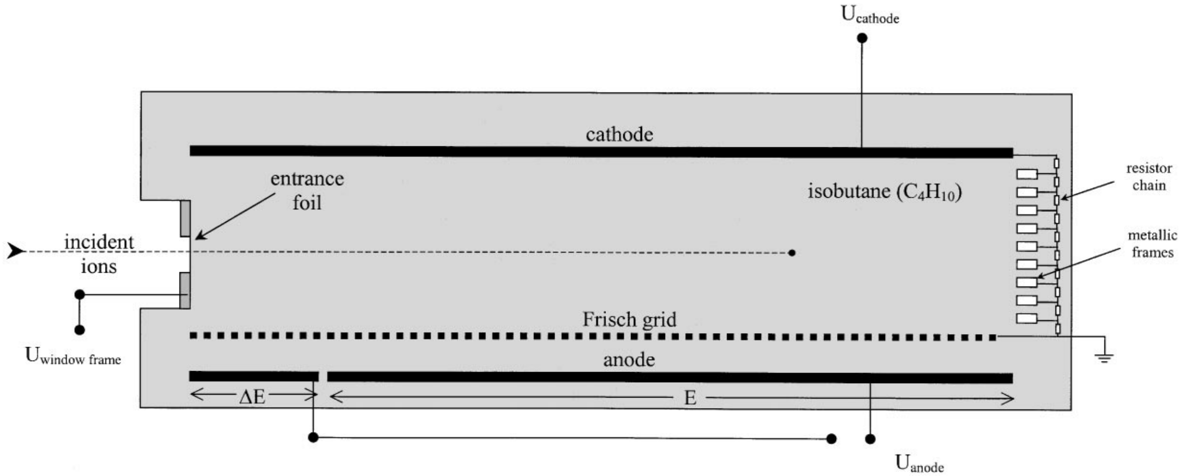

Fig. 2. Cross section of the cylindrical ionisation chamber. The ion beam enters the chamber – through a thin foil – along the axis and is stopped in the isobutane gas filling the chamber. In order to achieve a nearly homogeneous field over the entire active volume, 9 rectangular metallic frames between the cathode and the grid are used as a voltage divider (50 MΩ resistors). A voltage of 180 V is applied to the window frame holding the entrance foil.

The design of the $\Delta E - E$ telescope (Fig. 2) also closely followed previous work [16]. It consists of a cylindrical chamber filled with isobutane at a pressure of 7 mbar. The gas is continuously refreshed (i.e., about one chamber volume per hour) using an automatic control system, which also keeps the pressure constant within 0.6%. The ionisation chamber contains a Frisch grid between the anode and the cathode, consisting of 55 μm thick tungsten wires at a distance of 1.5 mm. The active volume of the ionisation region has a width of 140 mm, a height of 104 mm (= distance between cathode and grid) and a length of 710 mm. The beam enters the axis of the chamber through a 0.8 μm thick polypropylene foil (10 mm diameter) at a 2 mm distance from the active volume. With the grid at ground level, the electric field in the active volume is produced by a 300 V voltage applied to the cathode. In order to achieve a nearly homogeneous field over the entire active volume, 9 rectangular metallic frames between the cathode and the grid are used as a voltage divider (50 MΩ resistors). The electric field between the anode and the grid is created by a 320 V voltage applied to the anode. The anode (at a distance of 19 mm from the grid) is divided into a region corresponding to ΔE-signals (length = 70 mm) and a region corresponding to E-signals (length = 640 mm), with a 3 mm gap between the two regions. The telescope can handle a counting rate up to 3 kHz without significant deterioration. The signals from both detectors are analysed and stored in list-mode using a multi-parameter data acquisition system.

3. Experimental procedures and results

For the calibration of the $\Delta E - E$ telescope, the ion beam was scattered on a suitable target and the ejectiles were observed in the telescope placed at 30° at a 1.02 m distance from the target. The solid angle was defined by an aperture of 3 mm diameter at a distance of 0.29 m from the entrance foil of the telescope. With a 10 μg/cm^2 thick C target and an ^{16}O ion beam of E_{lab} = 4–15 MeV (in discrete energy steps), the resulting $\Delta E - E$ matrix reflects both ^{16}O and ^{12}C ions at well-defined energies (Fig. 3). This procedure was performed in each experimental run. Similar data were obtained also for a ^{14}N ion beam (Fig. 3).

For the investigation of beam contaminants in a momentum-filtered ^{12}C ion beam, the setup

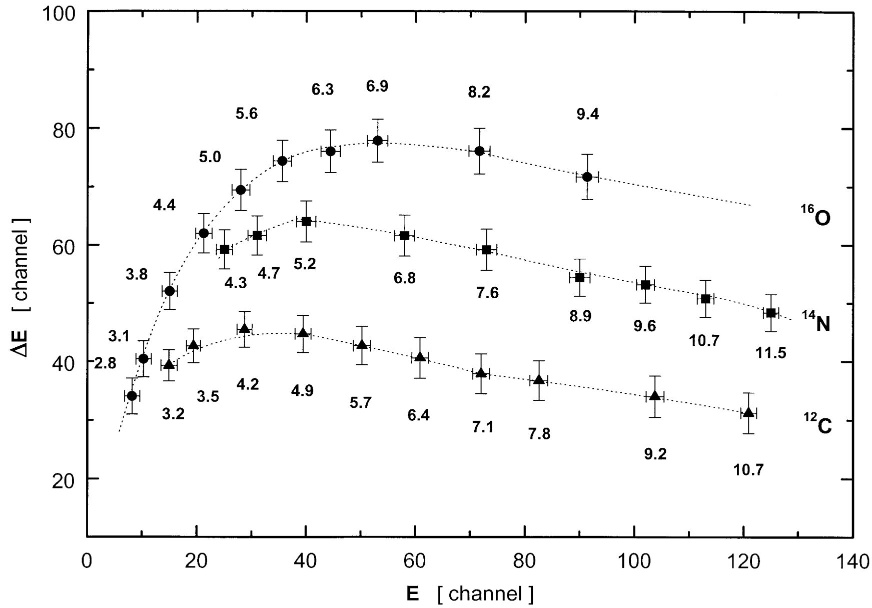

Fig. 3. Identification points of the $\Delta E - E$ matrix for ^{12}C, ^{14}N, and ^{16}O ions incident on the telescope at discrete energies (given in units of MeV at the data points). The dotted curves through the data points are to guide the eye only.

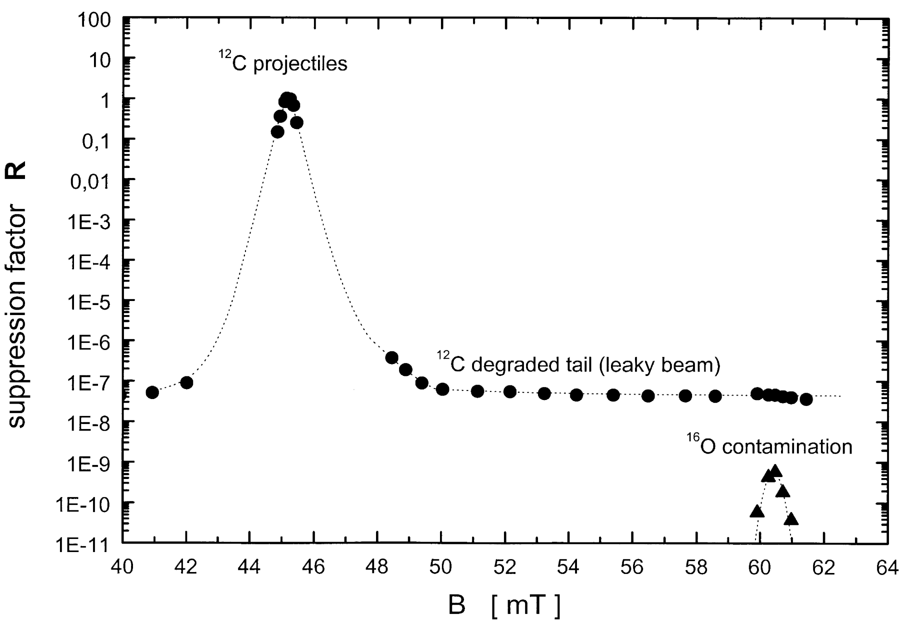

Fig. 4. Suppression factor R of a 10 MeV momentum-filtered $^{12}C^{3+}$ ion beam achieved with the Wien filter (Fig. 1). The ^{12}C peak at $B = 45.2$ mT has a FWHM of 0.39 mT. Another peak – observed at $B = 60.5$ mT (FWHM = 0.47 mT) with the telescope – is identified with a contaminant ^{16}O beam having the same momentum and charge state as the incident ^{12}C ion beam. The dotted curves through the data points are to guide the eye only.

shown in Fig. 1 was used. The ^{12}C beam was first focused through a 5 mm diameter aperture on a Faraday cup (FC #1) in front of the Wien filter, where the Wien filter had a 12.8 m distance to the last focusing element: a magnetic quadrupole doublet. In a second step, the beam was focused through an aperture of 2 mm diameter on a Faraday cup (FC #2) in front of the $\Delta E - E$ telescope, with the telescope at a 3.7 m distance from the Wien filter. This aperture was used as a filtering aperture with the Wien filter switched on. In a third step, the Wien filter was turned on: for a given electric field, the magnetic field was varied until the same beam current was observed at FC #2 as in the case with zero fields of the Wien filter. The relation between both fields was found to be linear within 0.4% demonstrating an acceptable quality of the Wien filter. The projectile suppression factor R is defined as the ratio of the number of beam particles N_t transmitted through the Wien filter to the number of incident particles N_i, i.e. with the Wien filter turned off. The incident flux N_i was determined by the beam current at FC #2 preceding the telescope; its corresponding current at FC #1 in front of the Wien filter was checked frequently. With the voltage producing the electric field set at a fixed value of typically 20 kV (i.e. $\pm$ 10 kV), the transmitted flux N_t after the Wien filter was determined as a function of magnetic field strength, either via current measurement at FC #2 (for high N_t values) or with the $\Delta E - E$ telescope (for low N_t values). The resulting suppression factor for a $^{12}C^{3+}$ ion beam with $E_{lab} = 10$ MeV as function of the magnetic field strength B of the Wien filter is shown in Fig. 4, where the flat part with a suppression factor of about $R = 4 \times 10^{-8}$ represents the degraded tail of the projectiles. The ^{12}C peak at $B = 45.2$ mT has a FWHM of 0.39 mT. A field strength $B = 60.3$ mT corresponds to the velocity of a contaminant ^{16}O beam (corresponding – in the planned $^{4}He(^{12}C, \gamma)^{16}O$ experiment – to the velocity of the ^{16}O recoils). The identification matrix (Figs. 5 and 6) shows indeed the presence of a contaminant ^{16}O beam, whose peak intensity drops at other field strengths (Fig. 4) with a FWHM of 0.47 mT, similarly to that of the ^{12}C projectiles. The energy of the contaminant ^{16}O beam is about 3/4 the energy of the ^{12}C incident beam, as expected from the momentum filter for equal charge states. Furthermore, the leaky ^{12}C beam (Figs. 5 and 6) has about the same velocity as that of the contaminant ^{16}O beam, as expected from the action of the Wien (velocity) filter, and represents a velocity-filtered section of the degraded tail of the ^{12}C beam (Fig. 4). Finally, the intensity ratio of the ^{16}O peak to the ^{12}C peak (Fig. 4) is about 6×10^{-10}. If the injection magnet after the sputter ion source is set at mass 16 (rather than at mass 12 for the ^{12}C ion beam), the telescope shows the dominant presence of ^{16}O ions, at the same point in the matrix (Fig. 5). Thus, the main source of the ^{16}O beam contamination lies

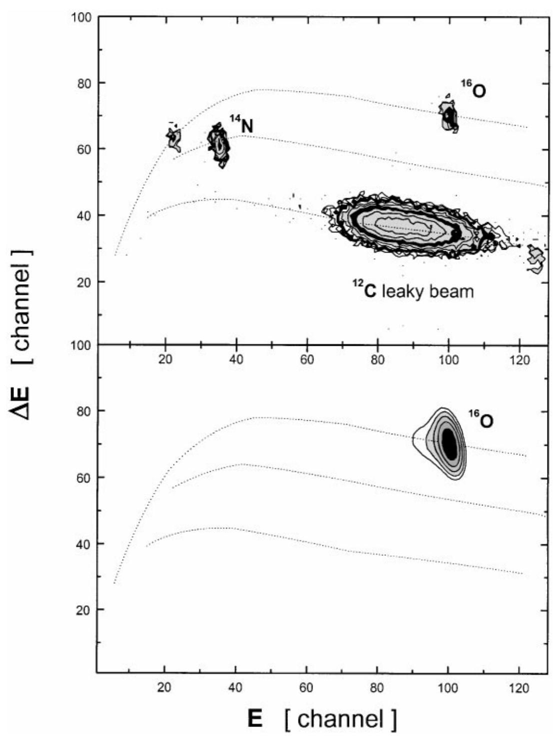

Fig. 5. The $\Delta E - E$ identification matrix for a $^{12}C^{3+}$ ion beam of 14 MeV is shown with the injection magnet (Fig. 1) set at mass 12 (upper part) and at mass 16 (lower part): the contaminant ^{16}O beam appears at the same point in the matrix. Also visible in the upper part is a contaminant ^{14}N beam arising from the nitrogen stripper gas. The peak far to the left represents another contaminant ^{16}O beam with a 2^{+} charge state. The dotted curves correspond to the expected locations of these ions in the matrix.

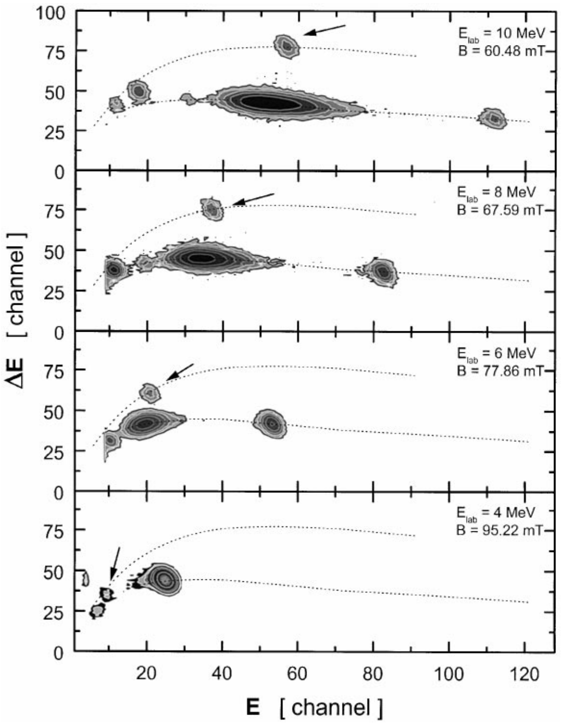

Fig. 6. The $\Delta E - E$ identification matrix is shown for $^{12}C^{3+}$ projectile energies of $E_{lab} = 4$–10 MeV, with an associated change in the magnetic field strength B of the Wien filter corresponding to the expected value for the contaminant ^{16}O ion beam. The observed contaminant ^{16}O beam in the matrix is identified by an arrow. The energetically highest peak (with relatively low intensity) corresponds to the incident ^{12}C ion beam with neutral charge state. The dotted curves correspond to the expected locations of the ^{12}C and ^{16}O ions in the matrix.

in the ion source setup arising from the presence of oxygen in the sputter material and the finite mass resolution of the injection magnet. Since the energy of the observed contaminant ^{16}O beam is about 3/4 the energy of the ^{12}C incident beam, it must correspond to a section of a degraded ^{16}O tail. The identification matrix (Figs. 5 and 6) reveals also the presence of a ^{14}N contaminant beam, mainly due to the use of nitrogen as stripper gas: if oxygen is used as stripper gas, the nitrogen peak is nearly absent. In order to minimize the intensity of the contaminant ^{16}O beams, we used nitrogen as stripper gas.

4. Conclusions

The data (Fig. 5) indicate that the ^{12}C ion beam intensity can be suppressed by a single Wien filter to about $R = 4 \times 10^{-8}$. Since the studies of $^{4}He(^{12}C, \gamma)^{16}O$ using the recoil separator ERNA include the combination of a Wien filter, a momentum filter, and another Wien filter, the above result suggests that the needed suppression factor of $R_{rec} = 1 \times 10^{-15}$ (Section 1) can be achieved with ERNA.

The ^{16}O beam purification P(^{16}O) of a momentum-filtered $^{12}C^{3+}$ ion beam (from the 4 MV Dynamitron tandem) using a single Wien filter is about $P(^{16}O) = 6 \times 10^{-10} \times 4 \times 10^{-8} = 2 \times 10^{-17}$, where we have assumed an ^{16}O degraded tail identical to that of the ^{12}C ion beam (Fig. 5). Since the number of ^{16}O recoils per incident ^{12}C projectile is 1×10^{-18} for $\sigma = 1$ pb and $n(^{4}He) = 1 \times 10^{18}$ atoms/cm^2, the above ^{16}O beam purification is not quite sufficient using a single Wien filter. For this reason, one Wien filter will be installed – in the ERNA project – before the analysing magnet and a second Wien filter will be placed between the analysing magnet and the jet-gas-target, where this setup should provide a sufficient ^{16}O beam purification for the ERNA aims. It should be pointed out that an ultra-clean ion implantation in some specific materials, e.g. ^{12}C implantation in diamond, may require an ion beam purification of the level achieved here with the single Wien filter.

The $\Delta E - E$ telescope (Fig. 2) is designed for an entrance window of up to 40 mm diameter, which allows the full cone of ^{16}O recoils from $^{4}He(^{12}C, \gamma)^{16}O$ to be observed after the ^{12}C beam filtering in the separator. With the present window foil of 0.8 μm thickness, the ^{16}O recoils and the ^{12}C leaky beam can be resolved sufficiently with the $\Delta E - E$ telescope down to about $E_{lab}(^{12}C) = 4.0$ MeV (Figs. 3 and 6); a thinner entrance foil of the telescope could lower this energy limit. Alternatively, the time-of-flight technique including large-area channel-plate-detectors may be used to achieve the needed resolution at energies below $E_{lab}(^{12}C) = 4.0$ MeV; this possibility will be explored in the near future.

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References

[1] C. Rolfs, W.S. Rodney, Cauldrons in the Cosmos, University of Chicago Press, Chicago, 1988.
[2] P. Dyer, C.A. Barnes, Nucl. Phys. A 233 (1974) 495.
[3] K.U. Kettner, H.W. Becker, L. Buchmann, J. Görres, H. Kräwinkel, C. Rolfs, P. Schmalbrock, H.P. Trautvetter, A. Vlieks, Z. Phys. A 308 (1982) 73.
[4] A. Redder, H.W. Becker, C. Rolfs, H.P. Trautvetter, T.R. Donoghue, T.C. Rinkel, J.W. Hammer, K. Langanke, Nucl. Phys. A 462 (1987) 385.
[5] R.M. Kremer, C.A. Barnes, K.H. Chang, H.C. Evans, B.W. Filippone, K.H. Hahn, L.W. Mitchell, Phys. Rev. Lett. 60 (1988) 1475.
[6] J.M.L. Ouellet, H.C. Evans, H.W. Lee, J.R. Leslie, J.D. MacArthur, W. McLatchie, H.B. Mak, P. Skensved, J.L. Witton, X. Zahao, T.K. Alexander, Phys. Rev. C 54 (1996) 1982.
[7] G. Roters, Thesis, Ruhr-Universität Bochum, 1996, to be published.
[8] D. Rogalla, Diplomarbeit, Ruhr-Universität Bochum, 1997, to be published.
[9] L. Gialanella, Thesis, Ruhr-Universität Bochum, 1999, to be published.
[10] M.S. Smith, C. Rolfs, C.A. Barnes, Nucl. Instr. Meth. A 306 (1991) 233.
[11] L. Gialanella et al., Nucl. Instr. Meth. A 376 (1996) 174.
[12] S. Theis, Diplomarbeit, Ruhr-Universität Bochum, 1999.
[13] H.P. Trautvetter, K. Elix, C. Rolfs, K. Brand, Nucl. Instr. Meth. 161 (1979) 173.
[14] S. Wüstenbecker, H.W. Becker, C. Rolfs, H.P. Trautvetter, K. Brand, G.E. Mitchell, J.S. Schweitzer, Nucl. Instr. Meth. A 256 (1987) 9.
[15] F. Terrasi, L. Campajola, A. Brondi, M. Cipriano, A. D'Onofrio, E. Fioretto, M. Romano, C. Azzi, F. Bella, C. Tuniz, Nucl. Instr. Meth. B 52 (1990) 259.
[16] L. Campajola, A. Brondi, A. D'Onofrio, G. Gialanella, M. Romano, F. Terrasi, C. Tuniz, C. Azzi, S. Improta, Nucl. Instr. Meth. B 29 (1987) 129.