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Experimental Nuclear Astrophysics with the recoil mass separator ERNA

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Abstract. The ERNA collaboration (European Recoil mass separator for Nuclear Astrophysics) developed a recoil mass separator devoted to the measurement of the total cross section of radiative capture reactions of astrophysical interest. In particular, during the last two years the analysis of the data collected for the reaction $^{12}C(\alpha,\gamma)^{16}O$ has been completed and a new measurement of the cross section of $^{3}He(\alpha,\gamma)^{7}Be$ has started. The results obtained for these reactions are presented and the perspective of this experiment is discussed.

Key words. Stars: nucleosynthesis – Stars: helium burning– Stars: abundances – Cosmology: Big Bang nucleosynthesis

1. Introduction

Radiative capture reactions involving hydrogen or helium nuclei are of utmost importance in both nucleosynthesis and stellar evolution (Rolfs & Rodney 1988). Most of the existing data on these reactions has been gained by means of $\gamma-$ray spectroscopy, whereas the measurements are very difficult in view of the low cross sections and the relatively high background in the detectors. Since a couple of decades a new technique has been exploited, based on the direct detection of the nuclei produced during the reaction. A pioneering work was done at Caltech (Kremer et al. 1988), where $^{12}C(\alpha,\gamma)^{16}O$ was measured using a recoil mass separator and a NaI(Tl) detection setup. Here the insufficient beam suppression required a coincidence condition between $\gamma-$rays and recoils, thus reducing the advantages of the use of a recoil mass separator. Moreover, the acceptance of the separator was not large enough to collect all recoils, and a correction to the observed yields was necessary to obtain the total cross section. In 1994 a collaboration started called NABONA (NAples BOchum Nuclear Astrophysics) between the Institut für Experimentalphysik III of the Ruhr-Universität Bochum, the INFN-Sezione di Napoli and Dipartimento di Scienze Fisiche of the University of Naples Federico II, and for some experiments, the ATOMKI Institute, Debrecen . The aim of this collaboration was to measure the cross section of $^{7}Be(p,\gamma)^{8}B$. This experiment was performed using a ^{7}Be beam and a windowless hydrogen gas target in combination with a recoil separator (Gialanella et al. 2000) with sufficient beam suppression and acceptance to detect the recoils without the need of the coincidence condition with $\gamma-$rays. As a follow-up of the NABONA col-

Send offprint requests to: L. Gialanella laboration, a new collaboration between the same groups started, called ERNA, whose aim was to study $^{12}C(\alpha,\gamma)^{16}O$ using a new recoil separator installed at the 4MV Dynamitron Tandem Laboratorium of the Ruhr-Universität Bochum. In this contribution the working principles of ERNA are reviewed and the results obtained for $^{12}C(\alpha,\gamma)^{16}O$ are discussed. Also, the ongoing measurements of $^{3}He(\alpha,\gamma)^{7}Be$ are presented.

2. The RMS ERNA

Fig. 1 shows a schematic view of the ERNA setup, that has been described in details elsewhere (Schürmann et al. 2004,and references therein). Briefly, the ion beam emerging from the 4MV Dynamitron tandem is focused by a quadrupole doublet, filtered by a 52° analysing magnet, and guided into the 75° beam line of ERNA by a switching magnet (these elements are not shown in fig. 1). A quadrupole doublet (QD2) after the switching magnet is used to focus the beam on the gas target. For the purpose of beam purification, there is one Wien filter (WF1) before the analyzing magnet and one (WF2) between QD2 and the gas target. The windowless gas target can be operated in both flow-mode or in recirculation. Depending on the pressure in the inner target cell, the target thickness can be as high as about 4×10^{17} atoms/cm^2. The number of projectiles is determined through the detection of the elastic scattering yield in two collimated silicon detectors located in the target chamber at 75° from the beam axis. When it is operated in flow mode, an Argon post-target stripping system can be used in order to reach a well defined charge state distribution for the recoils, independently of where in the target they are formed. That is necessary in order to determine which fraction of recoils populates the charge state selected in the separator. After the gas target, the separator consists sequentially of the following elements: a quadrupole triplet (QT), a Wien filter (WF3), a quadrupole singlet (QS1), a 60° dipole magnet, a quadrupole doublet (QD4), a Wien filter (WF4), and finally a detector for the recoils. Finally, several steerers (ST), Faraday cups (FC), slit systems (SS), and apertures (AP) are installed along the beam line for setting-up and monitoring purposes. Typical beam suppression factors range from 10^{-10} to 10^{-12}, that can be effectively improved by at least 3 orders of magnitude using a detector for the recoils able to discriminate them from the leaky projectile beam ions. Different detectors are available for the detection of recoils: a ΔE-E telescope and a TOF-E (Time-Of-Flight vs Energy) one. The first detector is used at high energies, where the TOF difference between projectile and recoils is small, while the second one is used when the TOF difference between projectiles and recoils is large and a low energy threshold is required. A detection system is installed around the gas target in order to detect $\gamma-$rays in coincidence with the ^{16}O recoils: different detectors are available (HPGe, NaI and BaF_2), in order to optimize the specifications of the detection system to the experimental needs. It is very important to note that the full transmission of the recoils in the selected charge state is a key requirement for measuring the absolute capture cross section $\sigma(E_{eff})$ at the effective interaction energy E_{eff} using a recoil mass separator. Indeed, this is a condition for determining $\sigma(E_{eff})$ without a detailed knowledge of the distribution of the recoils in the phase space, which depends on the $\gamma-$ray energy and angular distribution, on target effects and beam emittance, in such a way that any correction for a missing transmission would strongly affect the accuracy of the determination of $\sigma(E_{eff})$. The transmission of the recoil through the separator T_{rms} essentially depends on its acceptance compared to the emittance of the recoils. The trajectories of the recoils in the separator can be calculated using a code based on the code COSY Infinity (Makino & Berz 1999). In view of the importance of a proper tuning of the separator, the optimum field settings were determined experimentally, just measuring the acceptance of ERNA as a function of the field settings, whereas significant deviations from the calculated values were found. The angular acceptance of ERNA has been measured using an ion beam with the same mass, energy and the same charge state as the recoils and an electrostatic deflection unit, which can deflect the

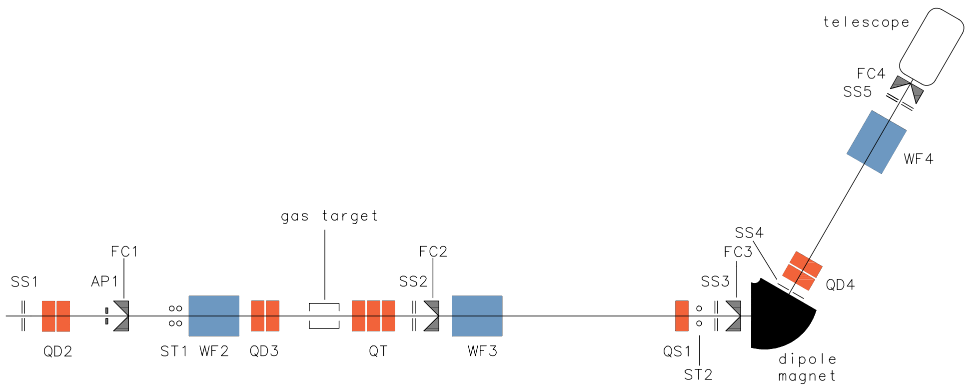

Fig. 1. Schematic diagram of the ERNA setup at the 4MV Dynamitron Tandem Laboratorium in Bochum. SS=slit system, QD=magnetic Quadrupole Doublet, AP=Aperture, FC=Faraday cup, ST=steerers, QT=magnetic Quadrupole Triplet).

beam at any position within the target region in order to simulate the recoil ion angular opening at the different geometrical locations where recoils are produced. The energy acceptance was measured by varying the beam energy from the accelerator. The energy region accessible for ERNA for a given reaction is defined as the one where one reaches full transmission within a region of ±70 mm around the target center, that includes more than 96% of the target nuclei. The charge exchange of the recoils in the rest gas along the separator results in a loss of recoils, which gives a final typical value of $T_{RMS} = 1^{+0.0}_{-0.01}$. Similarly, the detection efficiency must be well known, and it has been therefore accurately measuring radioactive source as well as ion beams. In the case of gaseous detectors, it is essentially determined by the transparency of the grids in the detector active volume, while for the TOF-E detector one has also to consider the efficiency of the microchannel plate used as a start. In both cases an energy and position independent detection efficiency was achieved, ranging from 95 to 98%.

2.1. $^{12}C(\alpha,\gamma)^{16}O$

The radiative capture reaction $^{12}C(\alpha,\gamma)^{16}O$ (Q = 7.16 MeV) takes place during stellar core helium burning, where ^{12}C is produced by the triple-alpha process. The capture cross section at the relevant Gamow energy (E_0 =0.3 MeV for $T = 2 \times 10^8$ K, determines - together with the cross section of the triple-alpha process and the convection mechanism at the edge of the stellar core - the abundances of Carbon and Oxygen at the end of Helium burning. This, in turn, strongly influences the nucleosynthesis of elements up to the iron region for massive stars (Imbriani et al. 2001) and the composition of

C/O White Dwarfs in the case of intermediate mass stars (Straniero et al. 2003).

A recent experiment confirmed that the reaction rate of the triple-alpha process is known with a precision of about 10% for temperatures of the order of 10^8 K (Fynbo et al. 2005). A similar precision is needed for the rate of $^{12}C(\alpha,\gamma)^{16}O$ to provide an adequate input for stellar models. The remarkable experimental efforts over the last decades focused on the observation of the capture $\gamma-$rays, including the already mentioned experiment (Kremer et al. 1988) that exploited the strong reduction of both room and beam induced background in the $\gamma-$ray spectra by means of the coincident detection of the ^{16}O recoils. Due to the low cross section and various backgrounds depending on the exact nature of the experiments, $\gamma-$ray data with useful but still inadequate precision were limited to centre-of-mass energies E_{cm}= 1.0 to 3.2 MeV. The cross section $\sigma(E_0)$ is expected to be dominated by p-wave (E1) and d-wave (E2) capture to the ($J^\pi = 0^+$) ^{16}O ground state. Two bound states, at 6.92 MeV ($J^\pi = 2^+$) and 7.12 MeV ($J^\pi = 1^-$) which correspond to subthreshold resonances at E_R = -245 and -45 keV, respectively, appear to provide the bulk of the capture strength through their finite widths that extend into the continuum. In order to model the energy dependence of the cross section, R-matrix analyzes are performed. In these analyzes the contribution of each amplitude to the total cross section is expressed in term of a possibly small number of resonances and, where present, a non resonant direct capture contribution. The parameters of the model are determined by a fit to the experimental data. The extrapolation at E_0= 300 keV is of course very sensitive to the properties of the nearby levels, but also it is sensitive to the properties of the high lying resonances, since they extend their tails to low energy. The effect of these resonances is usually summarized in single high energy so-called background resonances, one for each amplitude, which are in fact needed to obtain a good fit to the data.

Analyzes of the available capture data together with data from the $\alpha +^{12}$ C elastic scattering and the β-delayed α-decay of ^{16}N led still to large uncertainties in the extrapolation to E_0. This is due partly to the large errors, both statistical and systematic, affecting the low energy data, partly this is due to the weak constrains on the background levels. Clearly, new measurements at low energies are needed. However, of equal importance are also new measurements at significantly higher energies, well above the range of the experiments carried out to date, which may improve the experimental characterization of the background levels and may thus reduce the uncertainty in the astrophysical S-factor $S(E_0)$. There may exist even an s-wave capture (monopole E0) and significant capture amplitudes to excited ^{16}O states.

ERNA turned out to fulfil the requirements for measuring $^{12}C(\alpha,\gamma)^{16}O$ in the energy range E_{cm}=1.3 to 5.0 MeV, whereas in the lower part of this energy range measurements were hindered, where a low charge state for the recoils must be selected. In this case, the fraction of the impinging beam populating higher charge states than the recoils hits the plates of the first Wien filter, thus producing a high ^{16}O background and making the operation of the filter critical. The ERNA collaboration measured the total cross section of in the energy range E_{cm} =1.9 to 4.9 MeV (Schürmann et al. 2005,and references therein). A ^{12}C ion beam with beam intensity up to 5 particle μA was transported to the ^4He gas target, which was operated in flow mode. The Argon post stripper was then used in order to achieve charge state equilibrium before entering the separator. Fig. 2 shows a plot of the data measured with ERNA compared to the R-matrix fit on which is based a recently published reaction rate for $^{12}C(\alpha,\gamma)^{16}O$ (Kunz et al. 2002). Significant discrepancies are found at energies around E_{cm}=4.0 MeV and E_{cm}=3.0 MeV, where the fit strongly underestimates the total cross section, while it slightly overestimates the cross section on the high energy tail of the broad $J^\pi = 1^-$ resonance at E_{cm}=2.4 MeV. At this stage we cannot draw conclusions neither about the origin nor about the relevance for the extrapolation to E_0 of such discrepancies, that most likely originate from the contribution of the cascade transition through the 6.0 MeV $J^\pi = 0^+$ state

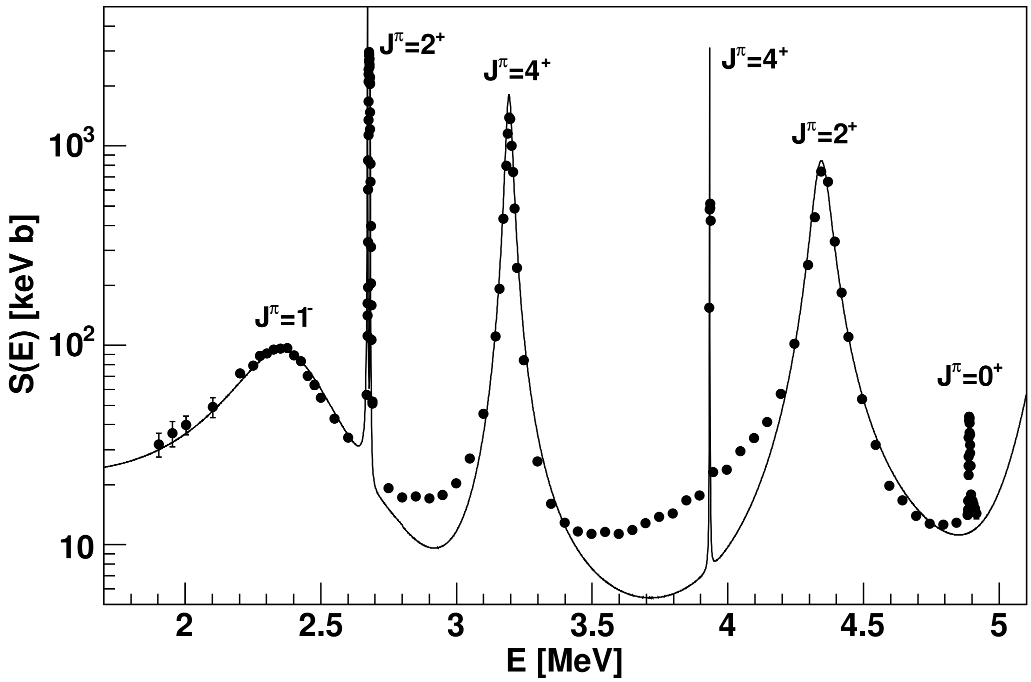

Fig. 2. S-factor data of the ERNA collaboration compared to the a fit to previous data (Kunz et al. 2001)

(Matei et al. 2006), that has been neglected in the fit.

A detailed study of the influence of these data on S_0 is in progress, that requires an R-matrix code including a fit to the different amplitudes as well as to the total cross section. Finally, a new resonance was found in $^{12}C(\alpha,\gamma)^{16}O$ at E_{cm} =4.9 MeV, corresponding to a known $J^\pi = 0^+$ state in ^{16}O (Tilley et al. 1993). Although this resonance is not of direct interest for nuclear astrophysics, its discovery in the radiative channel is an impressive example of the sensitivity of the ERNA setup for gamma spectroscopy, that will allow a clean identification of the different amplitudes in $^{12}C(\alpha,\gamma)^{16}O$. This, together with the high precision measurement of the total cross section, opens very encouraging perspectives for a highly improved determination of $S(E_0)$ for $^{12}C(\alpha,\gamma)^{16}O$.

2.2. $^3He(\alpha,\gamma)^7Be$

The radiative capture of $^3He(\alpha,\gamma)^7Be$ is the main process that produces ^7Be in the universe. There are two scenarios in which the production of ^7Be plays an important role in astrophysics. The first one is the hydrogen burning through the p-p chain (Bahcall et al. 2006), where $^3He(\alpha,\gamma)^7Be$ initiates the branch of the p-p chain responsible for the high energy component of the solar neutrino spectrum. The interest in this case is due to the fact that most solar neutrino detectors on earth are sensitive to this component and the better understanding of neutrino physics achieved by recent experiments put strong constraints in the comparison of the observed neutrino flux and the predictions of the solar models. Big bang nucleosynthesis is another scenario where ^7Be is produced. Here its role can be seen as a kind of reservoir for ^7Li, that was produced by the decay of ^7Be when the temperature of the universe became low enough to hinder its destruction by proton capture (Serpico et al.

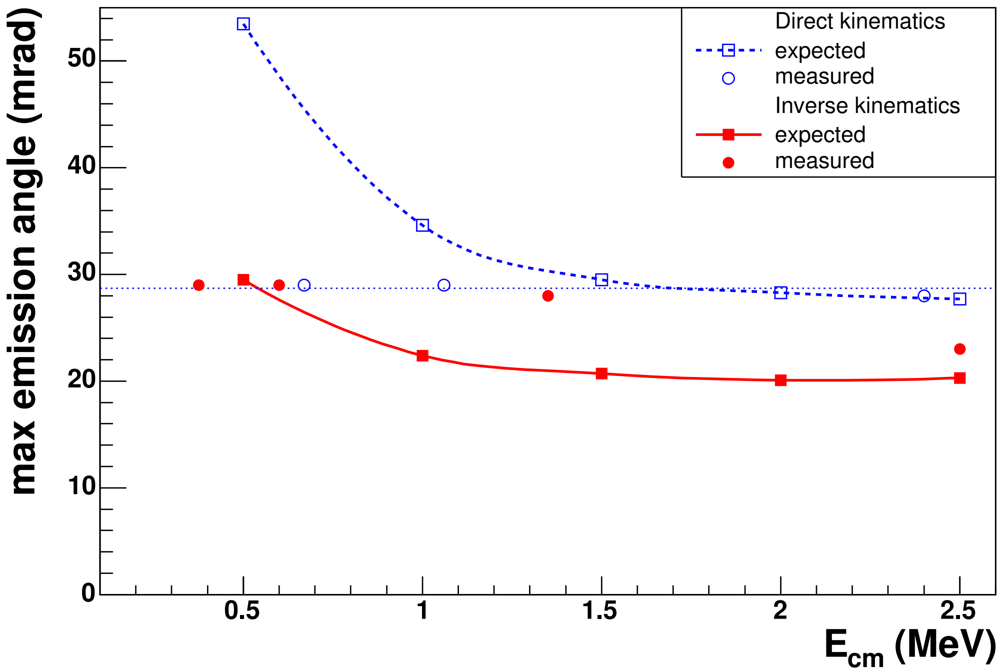

Fig. 3. Angular acceptance of ERNA compared with the recoil angular spread expected for the ^{7}Be recoils produced in ^{3}He$(\alpha,\gamma)^7$Be as a function of the center-of-mass energy. The solid and dotted curves refer to the predictions for direct and inverse kinematics, respectively, including both $\gamma-$ray emission and target effects. The full and empty circles represent the corresponding experimental values.

2004), in such a way that the predicted abundance of ^{7}Li after BBN linearly depends on the ^{7}Be production rate. The disagreement of the predicted abundance of ^{7}Be on the basis of nucleosynthesis models with the observation is a longstanding problem. For these reasons ^{3}He$(\alpha,\gamma)^7$Be has been intensively studied over the last decades. Experiments performed so far can be classified into two groups depending on the method followed to measure the cross section (Adelberger et al. 1998,and references therein). A group of experiments was based on the detection of the prompt $\gamma-$rays emitted in the reaction, while another one exploited the observation of the $\gamma-$rays emitted by a fraction of the produced ^{7}Be in their decay to ^{7}Li. The different experiments often provide inconsistent results, whereas it has been noticed that such inconsistency is not present in a separate analysis of each of the two groups, thus suggesting the presence of systematic effect in one of the two different methods, or, less likely, a possible non-radiative contribution. The results of recent experiments (Singh et al. 2004; Gyurky et al. 2007) seem to relax this problem. Nevertheless there are some open questions. In particular, the energy dependence of the cross section, which is believed to be determined in the low energy region by the direct capture to the ground and first excited states, relies in the energy range E_{cm} =1-2 MeV on the results of a single experiment (Parker & Kavanagh 1963), whose results could be biased by a wrong estimate of the branching ration between first excited state and ground state. Fig. 3 (Di Leva et al. 2006) shows the measured angular acceptance of ERNA for this reaction compared to the expected recoil opening angle in direct and inverse kinematics. The energy range E_{cm}=0.7-3 MeV is accessible for ERNA in inverse kinematics, where also the needed energy acceptance is achieved. The necessary

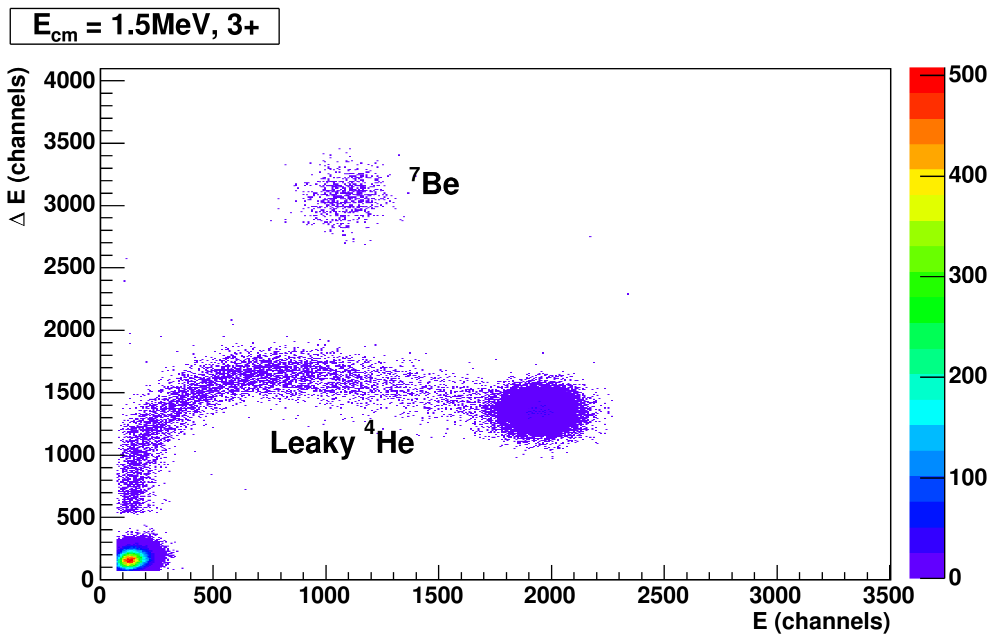

Fig. 4. ΔE − E matrix collected at E_{cm} =1.5 MeV for ^{3}He(α, γ)^{7}Be

^{3}He target was operated in recirculating mode, due to the high cost of ^{3}He gas, thus making the use of the Ar post-stripper unpracticable. In order to determine the charge state distribution of the recoils emerging from the target, measurements for all relevant ^{7}Be charge states have been done, both detecting the recoils alone and γ−rays in coincidence with the recoils. Fig. 4 shows a ΔE − E matrix collected at E_{cm} =1.5 MeV. At energy below E_{cm}=1 MeV, the TOF-E detector was used. Data analysis is in progress and final results are expected in the first months of 2007.

3. Conclusions

The results so far obtained using ERNA show that a recoil mass separator is a powerful tool for studying radiative capture reactions of interest in nuclear astrophysics. In particular, the study of ^{12}C(α, γ)^{16}O represents a breakthrough in this technique, since this is a difficult case involving stable and very abundant species, thus requiring the removal of the different kind of possible contaminations, and, at the same time, an exceptionally high acceptance and suppression of the separator, due to the high Q-value and the low cross section of this reaction. Since ^{3}He(α, γ)^{7}Be has been completed, the present plans of the ERNA collaborations for 2007 and 2008 focus again on ^{12}C(α, γ)^{16}O. A newly developed jet gas target will be used to investigate both ground state and cascade transitions in the accessible energy range for ERNA. As regards future plans, a significant extension of the measurements at lower energy will most likely require an additional charge selection element after the target in order to eliminate the beam components in charge states different from the selected one for the recoils before they can hit the Wien filter plates.

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