Recoil mass separators for nuclear astrophysics: the role of ERNA

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Abstract. The measurements of radiative capture reactions can be performed in inverse kinematic detecting directly the recoil produced in the nuclear reaction using a recoil mass separator (RMS). The development of RMS allows the possibility to overtake both the problems of gamma background signal and purity and production of target. The European Recoil Separator for Nuclear Astrophysics (ERNA) is a RMS designed with the main goal of determining the $^{12}C(\alpha,\gamma)^{16}O$, presently hosted at Center for Isotopics Research and Cultural hEritage laboratory of Department of Mathematics and Physics, University of Campania Luigi Vanvitelli, Caserta Italy (CIRCE-DMF). A general discussion on measurement techniques with recoil mass separator will be presented in this contribution with a focus on the ERNA one.

1 Introduction

The radiative capture reactions (α,γ) and (p,γ) are involved in stellar evolution and nucleosynthesis in several astrophysical scenarios [1, 2]. Their paramount importance in nuclear astrophysics triggered several experiments devoted to measurements where the direct experimental information on radiative capture reactions has been collected measuring the reaction yields through the observation of the emitted γ-rays [3, 4]. Due to the lower cross section at astrophysical energies of interest, usually, the gamma counting rate is too low with respect to the environmental and instrumental detector background. The signal to background ratio limitation stimulated the developments of two different approaches to perform direct measurements: one consists in performing experiments underground, the other using RMS. Thanks to the underground installation, the environmental background is reduced by several orders of magnitude[5]. The resulting enhancement of the signal to noise ratio allows lower energies measurements where fewer reaction events are expected. Depending on the particular reaction, background contributions may still be induced by the beam and impurity in the target. The RMS allows the radiative capture reaction measurements with the direct detection of the recoil, overtaking the background problem. The RMS measurements are performed in inverse kinematic with the advantage to have completely different systematic uncertainty with respect to the direct measurements.

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The first RMS devoted to the measurement of nuclear cross section of astrophysical interest was built at Caltech [6], although the limited beam suppression imposed to detect recoils in a coincidence with capture γ-rays in NaI detectors at the target position. Later, the NABONA Collaboration (NAples BOchum Nuclear Astrophysics) built and commissioned a RMS devoted to the measurement of the ^{7}Be(p, γ)^{8}B cross-section relying only on recoils detection, using a windowless hydrogen gas target and a ^{7}Be beam [7]. Building upon this successful experience, the same groups started a new project to realize the ERNA RMS at the 4MV Dynamitron Tandem Laboratorium of the Ruhr-Universität Bochum (Germany) [8, 9, and reference therein], with the aim of studying the ^{12}C(α, γ)^{16}O reaction. In the following years, up to nowadays, several RMS devoted to the nuclear astrophysics study are commissioned around the world, more information about the other RMS are reported in [10, and reference therein].

2 Principles of RMS experiments

In a radiative capture reaction, the fusion of projectile and target particles produces a nucleus that recoils in the laboratory frame system with a momentum quite similar to the one of the projectile [11]. The energy spectrum of the recoils is included in the range $[E_{r,1} - \Delta E_\gamma, E_{r,0} + \Delta E_\gamma]$, where $E_{r,0}$ and $E_{r,1}$ are the energy of the recoil produced at beginning and at the end of the target, respectively, while ΔE_γ is the maximum energy shift of the recoils due to the emission of a γ-ray with energy $E_\gamma = Q + E_{cm}$, given by

$$\Delta E_\gamma = \frac{E_\gamma^2}{2 \cdot M_r \cdot c^2} + \frac{E_\gamma}{c^2} \cdot \sqrt{\frac{2 \cdot E_b}{M_r}}, \tag{1}$$

The momentum transfer in γ-ray emission produces a recoil angle up to a maximum angle $\theta_{\gamma,max}$ given by

$$\theta_{\gamma,max} = arctan \frac{E_\gamma}{c \cdot p_{cm,lab}}, \tag{2}$$

where $p_{cm,lab}$ is the momentum of the center-of-mass in the laboratory reference system.

This means that the secondary beam composed by the recoils will be diverging right after the target and needs to be focused toward the beam axis to be efficiently transported further. Measuring in inverse kinematics decreases the divergence of the beam in the laboratory frame facilitating the recoils transmission. Typical recoils to projectile ratios ranges from 10^{-10} to 10^{-17} or lower, depending on the cross-section under study. In order to count the recoils in a detector, most of the primary beam (projectiles particles) need to be filtered out after the target. Therefore, an RMS consists of a series of filters and focusing elements that allows for an efficient suppression of the primary beam and ensures the transport of all recoils (in a given charge state) at the end detector such that they can be identified and counted.

The number of recoils N_r observed in the final detector, having an efficiency ϵ, is given by [1]

$$N_r = N_b \cdot T_{RMS} \cdot \Phi_{q_r} \cdot \epsilon \cdot \int_{E_b - \Delta E_b}^{E_b} \frac{\sigma(E)}{|\mathrm{d}E/\mathrm{d}N_t|} \mathrm{d}E \ , \tag{3}$$

where N_b and $T_{RMS}(q)$ are, respectively, the number of projectiles impinging on the target and the transmission of the recoils from the target to the final detector, when the recoil charge state q_r with probability Φ_{q_r} is selected.

The interaction cross-section $\sigma(E)$ is integrated over the beam energy loss in the target ΔE_b at the beam energy E_b that is determined by the stopping power of the beam ions in

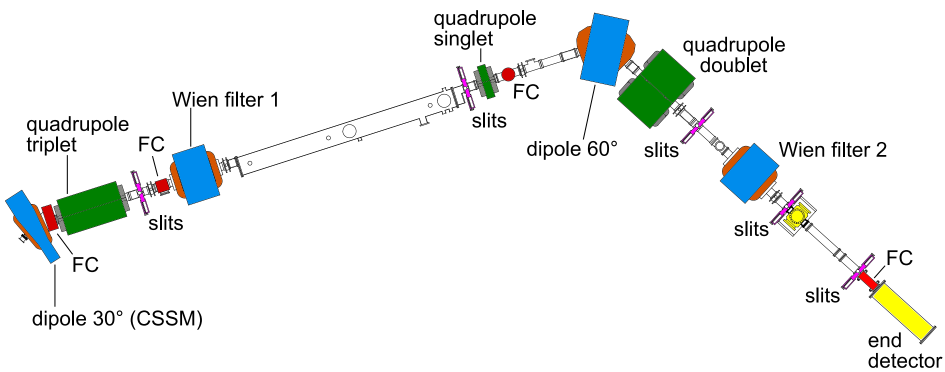

Figure 1. Layout of the ERNA RMS at the CIRCE-DMF Tandem Accelerator Laboratory. CSSM indicates the charge state selection magnet; FC indicates the Faraday cups along the separator [10].

the target $\mathrm{d}E/\mathrm{d}N_t$, where N_t is the number of nuclei per unit target area. Of course, an accurate and precise determination of $\sigma(E)$ relies on an adequate estimate of all quantities in Equation (3).

The full acceptance of recoils is a crucial issue in experiments with mass separators. Corrections for missing acceptance of recoils depend critically upon their actual distribution in the phase space [12], that is difficult to predict depending on the details of target effects and γ-ray angular distribution. The most effective method to know in detail the acceptance of the separator, i.e., the capability of the RMS to transport to the end detector the recoils regardless of their angle and energy, is to directly measure it. This can be done using a pilot beam mimicking the recoils beam properties, achieved using an electrostatic deflection unit, and varying the beam energy to sample the emittance of the recoils and determine their transmission through the RMS, as reported in [9, 13].

3 The ERNA separator at CIRCE

In 2009, ERNA was moved to the Tandem Accelerator Laboratory of the CIRCE-DMF, University of Campania, Caserta, Italy, where a 3.0 MV NEC 9SDH-2 Pelletron accelerator is located [14]. This has provided the opportunity for an upgrade in the separator's layout. In particular, a further charge filtering element, the Charge State Selection Magnet (CSSM in the following), has been placed after the gas target and before the first focusing element of the separator. The layout of the separator is shown in Figure 1.

3.1 Experimental setup

Two 40-sample MC-SNICS (Multicathode source of Negative Ions by Cesium Sputtering) Cs-sputter negative ion sources are available. One, with the spherical ionizer option and inlet gas, is used for the production of stable species ion beams and AMS (accelerator mass spectrometry) measurements. A second one is dedicated to the production of offline radioactive ion (RI) beams, in particular ^{7}Be [15]. This offers the opportunity to investigate processes with both stable and RI beams.

Depending on the reaction under study, the separator has been equipped with different windowless gas targets: extended ^{4}He and ^{3}He target for the study of the ^{12}C$(\alpha,\gamma)^{16}$O and ^{3}He$(\alpha,\gamma)^{7}$Be, respectively [8, 13], another different extended ^{4}He one for the study of ^{15}N(α,γ)^{19}F [16], an extended H_2 target for the measurement of the ^{7}Be(p, γ)^{8}B cross-section [17], and a supersonic jet ^{4}He one [18] in view of the measurement of the ^{12}C(α,γ)^{16}O at even lower energies. The gas targets are provided with an additional Ar gas layer (poststripper) so that recoils reach charge state equilibrium regardless of the reaction position within the target.

As said, an RMS is an alternating series of filters and focusing elements. The first filtering element of ERNA is the CSSM placed at the shortest distance allowed by geometrical constraints from the target. Its role is to select a single charge state for both projectile and recoil ions before the actual mass separation takes place. The next filtering element is the first velocity filter (Wien filter 1) that removes most of the primary beam thanks to the fact that projectiles and recoils have similar momenta and thus different velocities. The other filters are the 60° dipole magnet and the second velocity filter (Wien filter 2) that suppress the part of the primary beam that for different reasons may pass Wien filter 1, e.g., scattering in the target area. The recoils beam focusing is provided by the magnetic quadrupole triplet, the quadrupole singlet, and the quadrupole doublet. Several FCs, slit systems, wire scan, apertures, and a magnetic steerer (not shown in Figure 1) are installed along the RMS beam line for setting-up and diagnosis purposes. Depending on the capture reaction characteristics, the end detector can be either a ΔE-E ionization chamber telescope (ICT) or a Time Of Flight Energy (TOF-E) detection system. For the measurements of ^{12}C(α,γ)^{16}O angular distribution a gamma array based on NaI detectors has been developed and installed at target position.

ERNA collaboration is also involved in the study of nuclear reactions in direct kinematics which does not involve the RMS system. For this purpose an array of GASTLY (GAs-Silicon Two-Layer sYstem) detectors [19] for the measurements of reactions with charged particles in the exit channel. The use of the GASTLY array allowed for unambiguous identification of both protons and alpha particles.

ERNA is fully computer-controlled, which allows, through sophisticated algorithms, to tune the beam both in automatic and manual mode always supervisionated by interlocks that define the right restrictions and, in the end, ensures long-term stability.

3.2 Scientific results

The ERNA collaboration performed successfully several measurements and proved to be a valuable tool in the measurement of the total cross-section of radiative capture reactions of astrophysical interest. The first results were from the measurement of the total cross-section of the ^{12}C(α,γ)^{16}O reaction [20]. This measurement significantly extended the energy range of the measurements available at that time with a considerable improvement on the overall precision. It was possible to get a new insight on the relevance of the cascade transitions that were later investigated by DRAGON [21] and ERNA [22].

The use of ERNA RMS for the measurement of the ^{3}He(α,γ)^{7}Be reaction cross-section also led to relevant results. Besides giving an important contribution to solve the then long-standing issue of the difference between extrapolation based on experiments selected according to the measurement method, the results indicated that at energies above $E_{\mathrm{c.m.}} \simeq 1$ MeV the energy dependence was significantly different from the one foreseen by the most adopted models [13].

The ERNA RMS was used to measure the reaction yield of the ^{15}N(α,γ)^{19}F resonances at $E_{\mathrm{c.m.}}$ = 1323 and 1487 keV. For this purpose, enhanced intensity of N beam from a SNICS source was thoroughly investigated [23]. The yield of the two resonances was observed as a function of the energy, thus, from the convolution of the cross-section expressed as a Breit–Wigner function and the target density profile, the widths Γ_γ and Γ_α could be extracted for both resonances. A detailed description of the analysis is given in [16].

More recently, the ERNA Collaboration completed the measurement of the ^{7}Be(p,γ)^{8}B total cross-section in the energy range $E_{\rm eff}$=367.2 keV to 812.2 keV using the radioactive ^{7}Be beam available at CIRCE-DMF with intensities up to 10^9 pps [15]. The measurement performed using the inverse kinematics approach, provided for the first time a results with adequate precision to determine the cross-section of ^{7}Be(p,γ)^{8}B at astrophysical energy. The experimental apparatus has been described in detail in [17, 24]. A detailed description of the data analysis is presented in [25] and its supplemental material.

As said, ERNA collaboration is involved not only in the RMS measurements. In the last years, studies of other nuclear reactions in direct kinematics, apparatuses developments and measurements of astrophysical interest have been performed [19, 26–30]. Recently, the ^{12}C+^{12}C reaction was studied using a partial configuration available in the first development phase of the GASTLY detector array, i.e., four GASTLY detectors with the SSD as an entire pad. The thick target yield has been measured in the energy range $E_{\rm c.m.}$=2.51 – 4.36 MeV and the astrophysical S-factors of ^{12}C(^{12}C,p)^{23}Na and ^{12}C(^{12}C,α)^{20}Ne have been extracted [28].

4 Conclusion

RMS allow to detect directly the recoils produced in a fusion process, overtaking the problem of the unfavorable signal to background ratio, typical in nuclear astrophysics experiments. The RMS measurements are usually performed in inverse kinematic, hence, the target, beam and detection system are completely different with respect to standard technique in direct kinematic, this assures the possibility to explore very different systematic errors. ERNA is the unique European RMS devoted to nuclear astrophysics measurements and is actually hosted at CIRCE-DMF laboratory, Caserta. The ERNA separator proved to be a valuable tool in the measurement of the total cross-section of radiative capture reactions of astrophysical interest. The experimental program of the ERNA collaboration aims at the extension at low energy ranges of the ^{12}C$(\alpha,\gamma)^{16}$O and ^{15}N$(\alpha,\gamma)^{19}$F cross-sections, and of the ^{7}Be$(\mathrm{p},\gamma)^{8}$B at $E_{cm} >$ 1 MeV. Similarly, also the charged particle spectroscopy measurements will continue with the investigation of the ^{12}C+^{12}C and ^{12}C+^{16}O fusion process extending the energy range measured in the last few years. Owing to the good performances of the ERNA RMS and GASTLY, several other reactions can be envisioned in the longer term.

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