Publication Year	2017
Acceptance in OA@INAF	2020-08-27T11:53:03Z
Title	þÿ M e a s u r e m e n t o f 1 3 2 3 a n d 1 4 8 7 k e V r e s o n a n c e s i n 1 5 N separator ERNA
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DOI	10.1103/PhysRevC.95.045803
Handle	http://hdl.handle.net/20.500.12386/26873
Journal	PHYSICAL REVIEW C
Number	95

Measurement of 1323 and 1487 keV resonances in ^{15}N(,)^{19}F with the recoil separator ERNA

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(Received 31 October 2016; published 13 April 2017)

Background: The origin of uorine is a widely debated issue. Nevertheless, the ^{15}N(,)^{19}F reaction is a common feature among the various production channels so far proposed. Its reaction rate at relevant temperatures is determined by a number of narrow resonances together with the direct capture and the tails of the two broad resonances at $E_{c.m.}$ = 1323 and 1487 keV.

Purpose: The broad resonances widths, and , have to be measured with adequate precision in order to better determine their contribution to the ^{15}N(,)^{19}F stellar reaction rate.

Methods: Measurement through the direct detection of the ^{19}F recoil ions with the European Recoil separator for Nuclear Astrophysics (ERNA) were performed. The reaction was initiated by a ^{15}N beam impinging onto a ^{4}He windowless gas target. The observed yield of the resonances at $E_{c.m.}$ = 1323 and 1487 keV is used to determine their widths in the and channels.

Results: We show that a direct measurement of the cross section of the ^{15}N(,)^{19}F reaction can be successfully obtained with the recoil separator ERNA, and the widths and of the two broad resonances have been determined. While a fair agreement is found with earlier determination of the widths of the 1487 keV resonance, a signi cant difference is found for the 1323 keV resonance

Conclusions: The revision of the widths of the two more relevant broad resonances in the ^{15}N(,)^{19}F reaction presented in this work is the rst step toward a more rm determination of the reaction rate. At present, the residual uncertainty at the temperatures of the ^{19}F stellar nucleosynthesis is dominated by the uncertainties affecting the direct capture component and the 364 keV narrow resonance, both so far investigated only through indirect experiments.

DOI: 10.1103/PhysRevC.95.045803

I. INTRODUCTION

The origin of ^{19}F is a widely debated issue in astrophysics. Several stellar environments have been proposed as F production sites: core-collapse supernovae [1], Wolf-Rayet stars [2], and asymptotic giant branch (AGB) stars [3]. Among them, only in AGB stars is uorine synthesis con rmed by direct spectroscopic observation of [F/Fe] enhancements (see Refs. [4,5, and references therein]), and recent studies seem to exclude the rst two scenarios [6,7]. It was early recognised that the ^{15}N(,)^{19}F reaction is a leading process for the ^{19}F production when He burning is active. Although the H burning ashes are heavily depleted in ^{15}N, which is ef ciently destroyed by proton capture, these ashes are enriched in ^{14}N. Various reaction chains may lead to the production of ^{15}N nuclei at relatively low temperatures, 100 MK. A likely reaction chain is ^{14}N(n,p)^{14}C(,)^{18}O(p,)^{15}N, which however requires an ef cient neutron source. Some ^{15}N may be also produced by ^{14}N(,)^{18}F($^{+}$)^{18}O(p,)^{15}N, where the protons need to be simultaneously released by the ^{14}N(n,p)^{14}C reaction. Therefore the presence of a neutron source is a key requirement. This condition is actually ful lled in low-mass AGB stars undergoing thermal pulses, where the ^{13}C(,n)^{16}O reaction is known to be the main neutron source powering the s-process nucleosynthesis in their He-rich mantles [8]. The competition with some reactions that destroy ^{15}N and/or ^{19}F, such as ^{15}N(p,)^{12}C, ^{19}F(n,)^{20}F, ^{19}F(p,)^{16}O, and ^{19}F(,p)^{22}Ne, should also be carefully considered; see, e.g., Refs. [9,10] for recent experimental works, and Ref. [11] for a review.

The rate of the ^{15}N(,)^{19}F reaction at relevant AGB temperatures, 20 to 120 MK depending on the star's mass, is determined by a number of narrow resonances, the most

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important being the $E_{c.m.}$ = 364 keV one, together with the direct capture (DC) component and the tails of two broad resonances at $E_{c.m.}$ = 1323 and 1487 keV. The strength of the $E_{c.m.}$ = 364 keV resonance has been determined through an indirect measurement reported in Ref. [12]. Due to the model dependence of the result, an uncertainty of a factor of 2 is assumed for this quantity. In the same work the spectroscopic factors of most of the ^{19}F bound states were determined, and on the basis of a single-particle transition model the DC component has been estimated. On this latter quantity, according to the survey in Ref. [13], an uncertainty of 40% is generally assumed. The mentioned uncertainties influence the determination of the reaction rate at relevant AGB temperatures.

II. EXPERIMENTAL SETUP AND PROCEDURES

The measurement of the ^{15}N(,)^{19}F reaction yield was performed in inverse kinematics, i.e., a ^{15}N beam [14] impinging onto a ^{4}He windowless gas target, using the European Recoil separator for Nuclear Astrophysics (ERNA). ERNA was originally installed and commissioned at the Dynamitron Tandem Laboratorium of the Ruhr-Universität Bochum, Germany [15–17]. In 2009 it was moved to the Center for Isotopic Research on Cultural and Environmental heritage (CIRCE) laboratory in Caserta, Italy [18]. The separator underwent a major upgrade with the addition of the Charge State Selection dipole Magnet (CSSM) directly downstream of the target. A schematic view of the present ERNA layout is shown in Fig. 1. The ion beam emerging from the 3 MV tandem accelerator is transported through the CIRCE AMS beamline: a 90 analyzing magnet and an electrostatic analyzer provide the necessary ion beam purification from recoil-like contaminants. The magnetic field of the analyzing magnet is used to determine the beam energy, while its uncertainty is determined by the opening of the magnet's image slits. The settings used in the presented measurements result in a beam energy uncertainty of about 7 keV [19]. The beam is guided into the 40 beam line of ERNA by a switching magnet. A quadrupole triplet after the switching magnet is used to focus the beam onto the windowless gas target [20]. After the gas target, the separator consists sequentially of the following elements: a 30 dipole magnet (CSSM), a quadrupole triplet (QT), a Wien filter (WF1), a quadrupole singlet (QS), a 60 dipole magnet, a quadrupole doublet (QD), a Wien filter (WF2), and a detector for recoil identification and counting. Finally, several Faraday cups (FC), and slit systems are installed along the beam line for diagnostic purposes. A Si detector is placed at about 25 in the laboratory frame with respect to beam axis, and is collimated with a 1 mm diameter aperture in the second downstream pumping stage of the gas target. This is used to monitor the scattering rate of ^{15}N ions on the post-stripper Ar gas (see below) needed to determine the number of projectiles impinging on the target, N_p. The scattering on Ar ensures a smooth behavior of the elastic scattering yield. Determinations of the ratio of the impinging beam charge with respect to the scattering yield are performed several times between the cross section measurements.

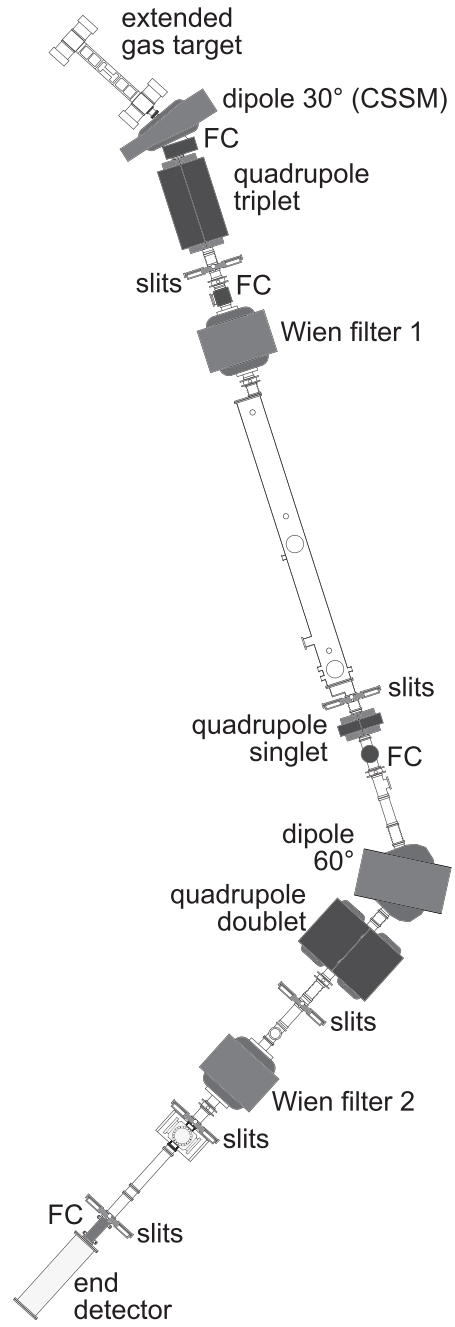

FIG. 1. Schematic view of the ERNA recoil separator.

The reaction yield is given by

$$Y_i = N_p \; {}_q T_{RMS} \int_{E_{15_N} \check{S} T_t}^{E_{15_N}} \frac{(E)}{(E)} \, dE, \qquad (1)$$

where $_q$ is the probability of recoils in the $q+$ charge state to enter the separator, T_{RMS} is the separator transmission of recoils in charge state $q+$ to the end detector, is the detection efficiency, $E_{^{15}N}$ is the beam energy, T_t is the target thickness, and (E) is the stopping power of N ions in He. All of these quantities have to be determined in order to extract the cross section from the observed yield.