Investigation of the $^{13}N(p,\gamma)^{14}O$ reaction using ^{13}N radioactive ion beams

Th. Delbar, W. Galster, P. Leleux, I. Licot, E. Liénard, P. Lipnik, M. Loiselet, C. Michotte, G. Ryckewaert, and J. Vervier
Institut de Physique Nucléaire and Centre de Recherches du Cyclotron, Université Catholique de Louvain, Louvain-la-Neuve, Belgium

P. Decrock, M. Huyse, and P. Van Duppen
Instituut voor Kern- en Stralingsfysika, Katholieke Universiteit Leuven, Leuven, Belgium

J. Vanhorenbeeck
Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Bruxelles, Belgium

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Intense ^{13}N radioactive ion beams have been produced by the two-accelerator method. They have been used to investigate the $^{13}N(p,\gamma)^{14}O$ reaction, in particular to measure directly its cross section in the energy region of interest in nuclear astrophysics. The results of a complete set of experiments thereby carried out on this reaction allowed the determining of the stellar conditions under which the cold and hot CNO cycles, for the nuclear "burning" of hydrogen and its transformation into helium, dominate.

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I. INTRODUCTION

The production of energy and the synthesis of elements in quiescent stars mostly occur through nuclear reactions between stable nuclei. It is conjectured that faster stellar processes, such as novae and supernovae explosions and stellar events at high temperatures and/or densities, involve nuclear reactions including radioactive nuclei in their entrance channels [1,2]. The full understanding of these processes requires the knowledge of the cross sections for the latter reactions in the energy range of astrophysical interest. Up to now, these cross sections have mostly been taken from theoretical calculations or deduced from indirect measurements, both methods involving considerable uncertainties: their direct determination is thus highly desirable. When the half-lives of the radioactive nuclei involved are short, the best method to measure these cross sections is to send radioactive ion beams (RIB) on stable targets rather than stable beams on radioactive targets [2]. The development of RIB with energies appropriate for nuclear astrophysics, i.e., between 0.2 and 1 MeV/nucleon, and with intensities suitable for such measurements, i.e., in the 10^9 particles per second range, thus represents a major breakthrough for the understanding of fast stellar processes.

Two methods can be used to produce RIB. The first involves a single accelerator, whose primary (stable) beam is sent on a target to produce secondary (radioactive) beams; one of these is separated from the primary beam and from the other secondary beams, producing a (ideally pure) RIB. This method has been used, either with high-energy primary beams (in the tens to hundreds of MeV/nucleon range), which are fragmented by their interaction with suitable targets [3] or with lower-energy primary beams (up to a few MeV/nucleon), which experience transfer reactions on various (generally deuterated) targets [4]. The former scheme yields high intensities (in the 10^9-10^{10} particles per second range) RIB, with, however, too high energies (tens to hundreds of MeV/nucleon) to be useful for direct measurements of reaction cross sections of astrophysical interest, except if they are strongly decelerated. The latter scheme produces RIB with adequate energies (up to a few MeV/nucleon), but with too low intensities (in the 10^4 to 10^7 particles per second range) to measure the cross sections for radiative capture reactions in the energy range that is of interest in nuclear astrophysics. The second method to produce RIB uses two accelerators. Beams from the first accelerator yield large quantities of the radioactive atoms of interest by a suitable nuclear reaction. These radioactive species are extracted from the (primary) target, ionized, brought to the desired energy by the second accelerator and sent on the (secondary) target to initiate the nuclear reaction of astrophysical interest. A RIB facility using this second method has been put into operation at Louvain-la-Neuve, Belgium [5]: it yields radioactive beams with suitable energies, intensities, and purities for use in nuclear astrophysics.

Within the nuclear reactions involving radioactive nuclei in their entrance channel, which are important in astrophysical events, the $^{13}N(p,\gamma)^{14}O$ radiative proton capture reaction is of special interest, since its cross section determines the stellar density and temperature conditions under which the so-called hot CNO cycle,

$$^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(\beta^+)^{14}N(p,\gamma)^{15}O(\beta^+)^{15}N(p,\alpha)^{12}C\ ,$$

competes with the cold CNO cycle,

$$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(\beta^+)^{15}N(p,\alpha)^{12}C\ .$$

The latter cycle is the main source of energy in main-sequence stars heavier than the Sun through the nuclear burning of hydrogen and its transformation into ^4He using ^{12}C as a catalyst [1,2]. The $^{13}N(p,\gamma)^{14}O$ reaction has been the first that has been studied with the Louvain-la-Neuve RIB facility. Partial results have been published in a letter [6], and some technical details on the experimental apparatus and methods of analysis, as well as on the production of the radioactive beam, have been given elsewhere [7–18]. In the present paper, we present a detailed description of the experiments carried out on this reaction.

In Sec. II, we describe the Louvain-la-Neuve RIB facility. Section III deals with the direct determination of the cross section for the $^{13}N(p,\gamma)^{14}O$ reaction in the energy region of astrophysical interest. We summarize, in Sec. IV, the other measurements related to this reaction, which have been carried out with our RIB facility, i.e., the investigation of the $^{13}N+p$ elastic scattering and of the $^{13}N(d,n)^{14}O$ g.s. stripping reaction; we also derive some astrophysical implications of this complete set of experiments dealing with the $^{13}N(p,\gamma)^{14}O$ reaction. Some conclusions and perspectives are presented in Sec. V.

II. PRODUCTION OF A ^{13}N RADIOACTIVE ION BEAM

The two-accelerator method outlined in Sec. I has been used to produce ^{13}N beams with adequate energies and intensities for carrying out experiments on the $^{13}N(p,\gamma)^{14}O$ reaction in the energy range of astrophysical interest. The general layout of the RIB facility is shown in Fig. 1. Large quantities ($\sim 10^{12}$ per sec) of ^{13}N atoms were produced by the $^{13}C(p,n)^{13}N$ reaction, whose thick-target yield at $E_p = 30$ MeV has been measured to be $Y = 1.6\times 10^{-3}$ ^{13}N nuclei per incident proton [12]. The first accelerator, the CYCLONE 30 cyclotron [13], can deliver proton beams in the 15-to 30-MeV energy range with intensities up to 500 μA. Various types of targets containing enriched ^{13}C were used [14], which consisted in graphite matrices or containers holding ^{13}C pellets or powders, the effective ^{13}C content in the beam path being about 50% of the total carbon content. The ^{13}N activity was extracted from these targets as ^{13}N-^{14}N molecules, using a small (~ 0.1 standard cm^3/h) nitrogen gas flow; the extraction efficiency ε_{extr} has been investigated [15], and shows a strong dependence on the target temperature and hence on the proton beam intensity (the target is only heated by the beam impact and not by external heating). In practice, 30-MeV proton beams, with intensities between 100 and 200 μA, were swept over the 3-cm-diam front face of the target, using sweeping magnets with frequencies of a few Hz. The value of ε_{extr} varied between 30 and 60%. As a result, a few 10^{11} ^{13}N nuclei per sec were extracted from the target. In order to reduce the radiation problems, the target was located in the 3-m-thick concrete wall separating the vaults of the two cyclotrons (Fig. 1).

The ^{13}N-^{14}N molecules were transferred to a single-stage electron cyclotron resonance (ECR) ion source, especially designed [16] to optimize the yields for low-charge states (1^+ to 3^+) atomic ions with respect to the injected molecules. Its ionization efficiency ε_{ion} has been measured under different conditions [16], and shows a strong dependence on the source pressure, which has to be minimized. The gas extracted from the target mainly originates from the outgasing due to the proton beam impact; it has been cleaned by chemical or cryogenic methods before admission in the ion source. In practice, source pressures in the [$(1-3)\times 10^{-5}$]-mbar region were achieved with an extraction hole diameter of 10 mm. This resulted in values of ε_{ion} in the 5–10% range for $^{13}N^{1+}$ ions.

These ions were extracted out of the ECR source (extraction voltage ≤ 7 kV), separated according to their mass-over-charge ratios by a 90° analyzing magnet, transported to the second accelerator, the CYCLONE cyclotron, using two lenses, and axially injected into the

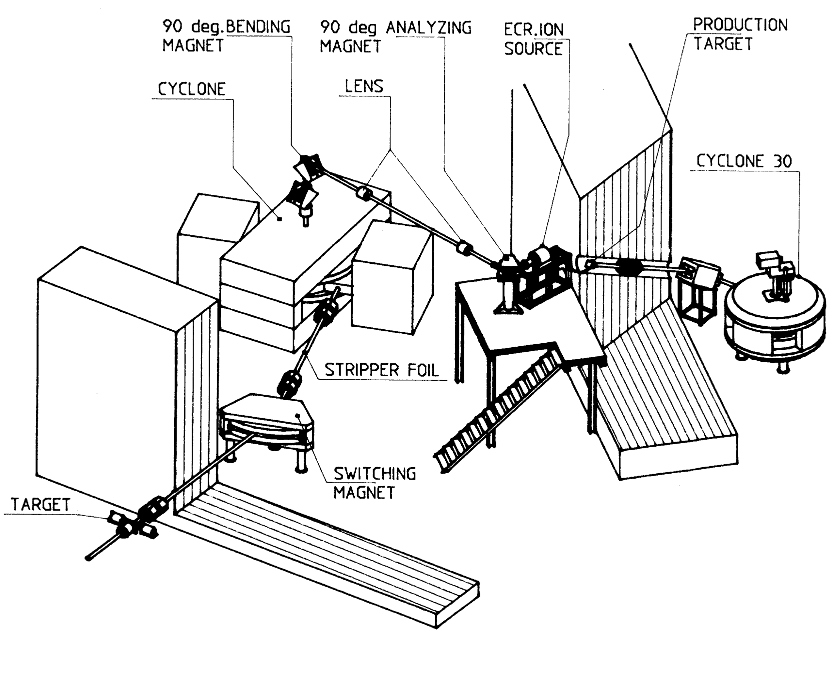

FIG. 1. General layout of the Louvain-la-Neuve radioactive ion beam facility.

machine through a 90° bending magnet (Fig. 1). CYCLONE is an isochronous cyclotron with a K value of 110 MeV, whose central region has been modified to allow its operation in the sixth harmonic mode [17], necessary to obtain the low energies (~ 0.65 MeV/nucleon) required for nuclear astrophysics experiments. The acceleration efficiency ε_{acc} of CYCLONE in this mode is in the 3–5 % range; this rather low value is partly due to the relatively poor vacuum conditions (pressure of approximately a few 10^{-6} mbar), which prevail in the central region of the cyclotron where the injected ions have low energies (≤ 7 keV).

The accelerated $^{13}N^{1+}$ ions extracted from CYCLONE were strongly contaminated by $^{13}C^{1+}$ and $^{12}CH^{1+}$ ions, whose relative mass differences with $^{13}N^{1+}$ ions are about 1.7×10^{-4}, with $^{13}C^{1+}$ and $^{12}CH^{1+}$ over $^{13}N^{1+}$ ratios of 10^3-10^4. In order to purify the radioactive beam from its stable isobaric contaminants, the accelerated $A=13$ beams were sent through a thin (25 $\mu g/cm^2$) carbon foil, where the $^{12}CH^{1+}$ molecular ions were dissociated and the $^{13}C^{1+}$ and $^{13}N^{1+}$ atomic ions were stripped, with $\sim$50% efficiency, into $^{13}C^{5+}$ and $^{13}N^{5+}$ ions, respectively. The latter were deflected by the switching magnet (Fig. 1) towards a Faraday cup, on which the ion current could be measured down to the electric pA range. Fine tuning of the most external correction coil of the CYCLONE magnetic field then allowed us to separate the $^{13}N^{5+}$ beam, as measured on the Faraday cup, from the $^{13}C^{5+}$ beam, with $^{13}C^{5+}$ over $^{13}N^{5+}$ ratios in the 10^{-4} range. The same procedure can be used for purifying $^{13}N^{2,3+}$ beams from $^{13}C^{2,3+}$, except that the carbon foil is no longer necessary due to the absence of $^{12}CH^{2,3+}$ ions. The isobaric separation of the $A=13$ ions turned out to be absolutely crucial for the feasibility of the experiments described in the present paper, as will be outlined in Sec. III.

As a result, beams of $^{13}N^{1+}$ and $^{13}N^{2+}$, with intensities of about 4 and 2×10^8 particles per sec, i.e., about 70 and 35 particles pA (ppA), respectively, and with contaminations from stable isobaric ions smaller than 10^{-4}, were available for the experiments described in Secs. III and IV.

III. DIRECT MEASUREMENT OF THE $^{13}N(p,\gamma)^{14}O$ REACTION CROSS SECTION

From the known level schemes of ^{13}N and ^{14}O, the $^{13}N(p,\gamma)^{14}O$ reaction cross section in the astrophysically important region should be mostly determined by a resonance at a center-of-mass energy of 0.545 MeV, with an orbital angular momentum for the captured proton $l_p=0$, corresponding to the first excited level of ^{14}O at an excitation energy of 5.173 MeV with spin and parity $J^\pi=1^-$ (Ref. [19]). The total width of this level has been measured to be $\Gamma=38.1$ (1.8) keV (Ref. [20]). Before the startup of the experiments described in the present paper, information on the partial γ width Γ_γ of this level was available from two sources. Indirect determinations of Γ_γ, through measurements of the gamma-to-total branching ratio in the decay of this level as populated through the $^{12}C(^3He,n)^{14}O^*$ reaction, had yielded $\Gamma_\gamma=2.7(1.3)$ eV (Ref. [21]) and 7.6(3.8) eV (Ref. [22]). Theoretical estimates of Γ_γ, using various models, were 2.44 eV (Ref. [23]), 1.9 eV (Ref. [24]), 1.2 eV (Ref. [25]), 1–10 eV (Ref. [26]), 4.1 eV (Ref. [27]). The expected value of Γ_γ thus spanned the (1–10)-eV range. In addition to resonance capture, direct capture contribution to the $^{13}N(p,\gamma)^{14}O$ reaction cross section can also be expected [28], although it will probably be rather small in the resonance region.

In view of this situation, three experiments were carried out dealing with the $^{13}N(p,\gamma)^{14}O$ reaction using ^{13}N radioactive ion beams: (i) the measurement of the partial γ width Γ_γ of the 0.545-MeV resonance, through the determination of the $^{13}N(p,\gamma)^{14}O$ reaction cross section in the resonance region, (ii) the measurement of the resonance energy E_R and total width Γ, through the study of the $^{13}N+p$ elastic scattering, also in the resonance region, and (iii) the determination of the spectroscopic factor S for the $^{13}N(d,n)^{14}O_{g.s.}$ reaction to the ^{14}O ground state (g.s.). The latter quantity can be used [28] to calculate the direct (nonresonant) capture contribution to the $^{13}N(p,\gamma)^{14}O$ cross section and its interference with the resonant contribution. Experiment (i) is described in the present section. Experiments (ii) and (iii) have been reported elsewhere [8,10], and their results will be summarized in Sec. IV.

The $^{13}N(p,\gamma)^{14}O$ reaction has been studied, in reverse kinematics, by sending a ^{13}N beam to a hydrogen-containing target. The latter was a polyethylene $(CH_2)_n$ foil, about 200 $\mu g/cm^2$ thick. The incident ^{13}N beam, with 8.2-MeV laboratory energy, was slowed down to 5.8 MeV through the target, thereby scanning completely the 0.545-MeV (center-of-mass) resonance. The behavior of these targets under the beam impact had been investigated in separate experiments with ^{13}C beams [7]. To diminish the loss of target material under long irradiation times (days), the polyethylene foils were mounted on a 28-cm inner diameter aluminium holder, which was rotated at a speed of about 1 revolution per sec. The target thickness was measured through the energy loss of ^{241}Am alpha particles. The target was located in a reaction chamber, represented in Fig. 2 and described in detail elsewhere [7]. This chamber also housed charged-particle silicon detectors at laboratory angles 17° and 27.3°, which registered the recoil protons and ^{12}C nuclei from the target and the scattered ^{13}N beam particles; lead shielding was placed in the backward direction, which protected the γ-ray detectors from the intense annihilation radiations originating from the part of the incident ^{13}N beam scattered by the target and deposited on the chamber walls. The remaining ^{13}N beam was stopped in a long (1.5-m) Faraday cup, i.e., about 2 m downstream from the target.

The capture γ rays were detected by a Ge diode, with a 70% relative efficiency with respect to a 7.6 cm$\times$7.6 cm NaI (Tl) crystal, located at backward angles, and in anticoincidence with a cosmic-ray "umbrella" (Fig. 2). The latter consisted of eight Cherenkov Plexiglas detectors, with dimensions of $8\times12\times60$ cm^3 each; this shield was located above the Ge diode and reduced its cosmic background by about a factor of 2 in the 2.75- to 7.5-MeV γ-ray energy range [18]. The γ-ray energy and the time difference between the γ-ray pulses and the cyclotron beam bursts were registered: the latter were defined by

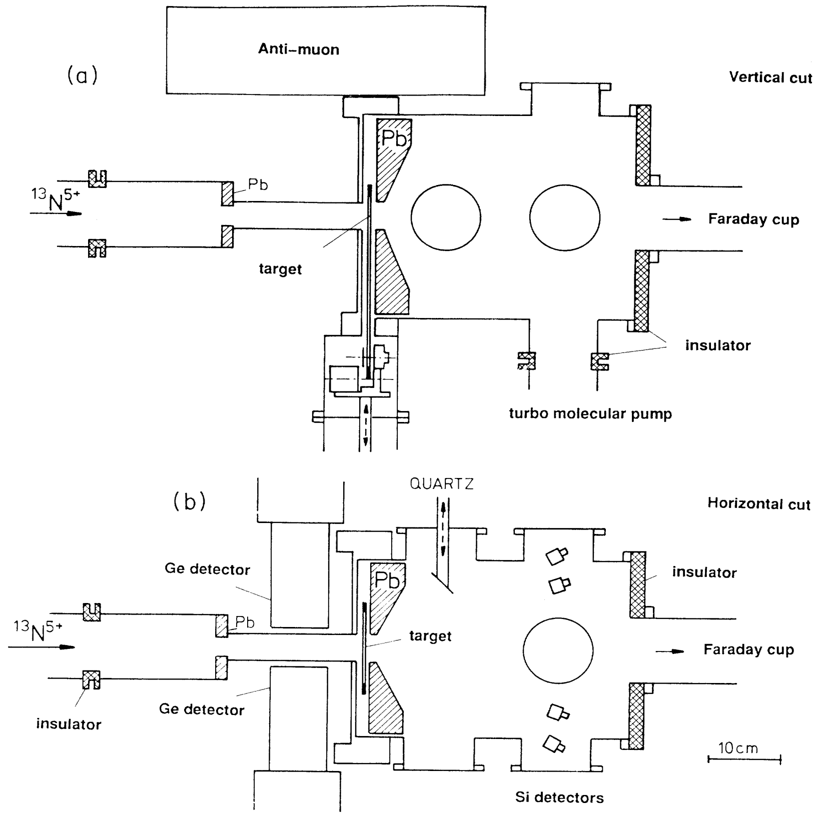

FIG. 2. Reaction chamber used in the present experiment. Vertical (a) and horizontal (b) cuts by planes containing the beam direction are shown. For further details, see Ref. [7].

the cyclotron radio frequency, whose phase with respect to the particle bunches was stabilized by a suitable electronic module [29] using, as a reference, the scattered ^{13}N beam particles registered by one of the charged-particle detectors. The dead-time and pile-up corrections were determined by feeding the preamplifier of the γ-ray detector with the pulses of a generator with a known fixed frequency, and by analyzing, in the γ-ray spectra, the peak arising from this pulser and its high-energy tail. The absolute full-energy peak efficiency of the γ-ray detector, shown in Fig. 3, was determined as follows: with standard intensity-calibrated γ-ray sources (up to 1.332 MeV), with a ^{56}Co source (up to 3.27 MeV), with a ^{24}Al source (up to 7.931 MeV) prepared by the $^{24}Mg(p,n)^{24}Al$ reaction and purified with the LISOL on-line isotope separation [30], and with the $^{13}C(p,\gamma)^{14}N$ reaction (up to 8.062 MeV) studied with the same setup as the $^{13}N(p,\gamma)^{14}O$ reaction [7].

The experimental apparatus and the methods used to analyze the data had been thoroughly tested beforehand by reinvestigating the well-known resonance at a center-of-mass energy of 0.512 MeV in the $^{13}C(p,\gamma)^{14}N$ reaction, as described in detail elsewhere [7].

The charged-particle spectrum, registered with the silicon detector located at 17° with respect to the incident beam direction, is represented in Fig. 4(a). The peak to the left and in the inset corresponds to the proton recoils; its shape proves that the $^{13}N+p$ elastic scattering in the energy range covered by the present experiment has an important resonance contribution, which is superimposed to and interferes with a Coulomb contribution, as shown in detail elseswhere [8]. The peak to the right originates from the ^{13}N projectiles elastically scattered by the ^{12}C atoms present in the target, and from the ^{12}C recoils (right shoulder). The spectrum of the time difference between the pulses from the Ge diode in the 3.8- to 5.2-MeV energy range, and the cyclotron radio frequency, is

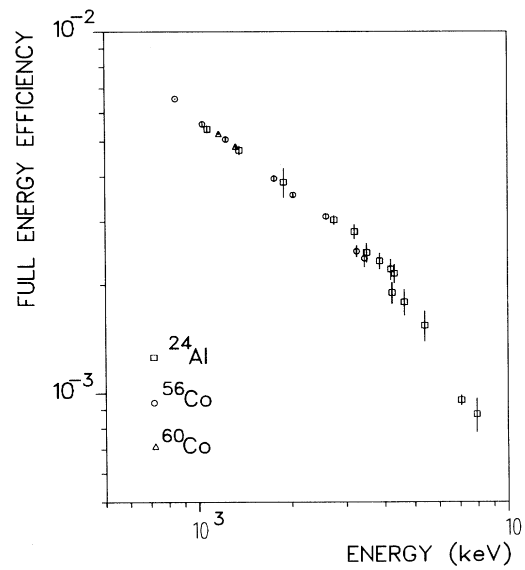

FIG. 3. Absolute full-energy peak efficiency of the Ge diode as a function of the γ-ray energy, determined with different calibration sources as explained in Sec. III.

represented in Fig. 4(b). The prompt peak, whose total width is about 10 nsec, is superimposed on a constant background, whose relative contribution to the total spectrum at the prompt peak is 64%. The spectrum of the prompt γ rays, after subtraction of the random events using Fig. 4(b), is shown in Fig. 4(c). It clearly displays the full-energy, first- and second-escape peaks, plus some Compton contribution, due to the 5.17-MeV capture γ ray from the $^{13}N(p,\gamma)^{14}O$ reaction. The positions and widths of the peaks are compatible with this assignment, taking into account the Doppler shift and broadening due to the high recoil velocity ($v/c=0.033$) of the $^{14}O^*$ (5.17 MeV) emitters and to the large solid angle of the γ-ray detector. The absence of any statistically significant structure between 7 and 8 MeV, which could arise from the $^{13}C(p,\gamma)^{14}N$ reaction [7], represents a further confirmation of the ^{13}N beam purity. The spectra of Fig. 4 correspond to an effective running time of 33 h, with a ^{13}N beam intensity of 50±10 particles pA as monitored by the Faraday cup some 2 m downstream from the beam. During that time, 85±18 counts have been registered in the full-energy peak of the 5.17-MeV line, i.e., about 3 counts per h.

The cross section for the $^{13}N(p,\gamma)^{14}O$ reaction, averaged over the 5.8- to 8.2-MeV (laboratory) or 0.414- to 0.586-MeV (center-of-mass) energy range covered by the present experiment, has been determined from the spectra of Fig. 4 in the following way. The number of counts in the full-energy peak of Fig. 4(c), with its 21% statistical uncertainty, was corrected for the dead-time and pile-up effects, and for the full-energy peak efficiency of the γ-ray detector; these corrections had 5 and 15 % sys-

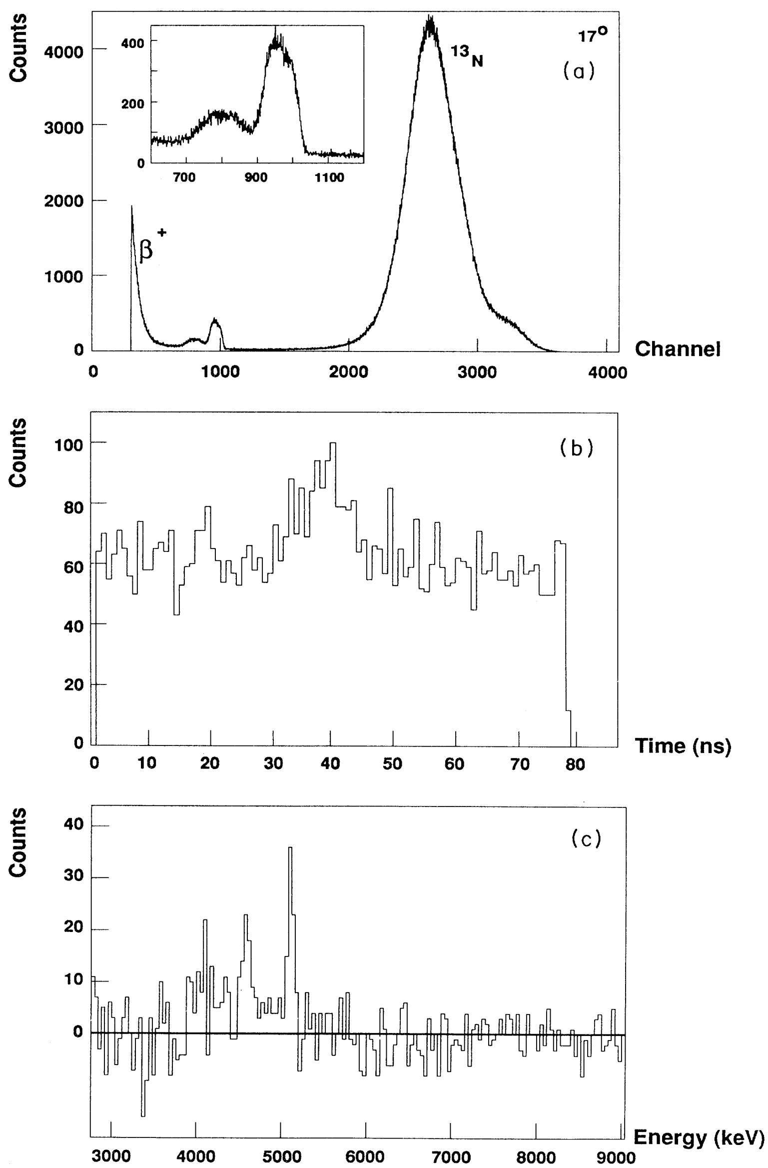

FIG. 4. (a) Charged-particle spectrum, at 17° laboratory angle, resulting from the interaction between an 8.2-MeV ^{13}N beam and a 200 $\mu g/cm^2$ $(CH_2)_n$ polyethylene target. (b) Spectrum of the time difference between the γ-ray pulses from the Ge diode in the 3.8- to 5.2-MeV energy range, and the cyclotron radio frequency. (c) Spectrum of the prompt γ rays from the $^{13}N(p,\gamma)^{14}O$ reaction, obtained by a subtraction procedure explained in Sec. III.

tematic uncertainties, respectively. The angular distribution of the 5.17-MeV capture γ ray was assumed to be isotropic in the center-of-mass system, in view of the $l_p=0$ character of the 0.545-MeV resonance; the correction for the laboratory system has been applied and amounts to 2.5% with a negligible uncertainty. The number of ^{13}N projectiles incident on the target was determined through the number of ^{13}N nuclei elastically scattered by the ^{12}C content of the target, extracted from Fig. 4(a) (peak to the right, corrected for the small ^{12}C recoil contamination); this number was corrected for the silicon detector solid angle and for the differential cross section of the $^{13}N+^{12}C$ elastic scattering. The latter was assumed to be of purely Coulomb origin, since the $^{13}N+^{12}C$ center-of-mass energy is less than 50% of the Coulomb barrier; the corresponding Rutherford differential cross section was integrated over the beam energy spread in the target and over the detector solid angle. These corrections introduced systematic uncertainties of 3.5% for the solid angle and 9% for the Rutherford cross section, mainly due to the uncertainty on the beam position on the target and hence on the scattering angle of the ^{13}N projectiles. The resulting value of σ is $106\pm22(\text{stat})\pm20(\text{syst})$ μb, the systematic uncertainties being combined quadratically.

It is very likely that the $^{13}N(p,\gamma)^{14}O$ reaction is dominated by the 0.545-MeV resonance in the energy range we have investigated. The $^{13}N+p$ elastic scattering includes an important resonance contribution, as pointed out before and in Ref. [8]. The widths of the γ-ray peaks are compatible with the Doppler broadening, as underlined above, and would have been much larger if direct capture had dominated over resonance capture. Finally, it is generally observed that resonance capture largely exceeds direct capture in the vicinity of resonances with total widths in keV for proton-capture reactions on light nuclei. Under the assumption of a dominating resonance capture, the above value of σ can be used to determine the partial γ width Γ_γ of the resonance, described by the Breit-Wigner formula. The stopping power of ^{13}N ions in polyethylene is needed for such calculations [2]. It has been taken from the tables of Northcliffe and Schilling [31]. Separate measurements of the stopping power of ^{14}N ions in the same energy range for the same material have confirmed the validity of these tables; they have also shown that this stopping power is approximately constant in the 5.8- to 8.2-MeV energy range spanned by the target, since it corresponds to the Bragg peak, in agreement with the stopping power tables [31,32]. In the deduction of Γ_γ from the above value of σ, the resonance energy E_R, and total width Γ we have obtained in a separate experiment (Ref. [8] and Sec. IV) have been adopted, i.e., $E_R=0.526$ MeV and $\Gamma=37$ keV; this slightly differs from the analysis contained in our first report of the present data [6]. The value of Γ_γ thereby deduced is $3.4\pm0.7(\text{stat})\pm0.7(\text{syst})$ eV; the systematic uncertainty includes an additional 10% uncertainty on the target thickness.

A second method to deduce Γ_γ from the results displayed in Fig. 4 is based on a detailed analysis of the recoil-proton component of the charged-particle spectrum of Fig. 4(a) (peak to the left and in the inset), along the lines detailed in Ref. [8]. The latter analysis yields the number of resonantly scattered recoil protons, which is proportional to the partial proton width Γ_p of the resonance, i.e., to the total width Γ to within 10^{-4} (since $\Gamma_\gamma\sim3$ eV and $\Gamma=\Gamma_\gamma+\Gamma_p\sim37$ keV). The number of γ rays, deduced from Fig. 4(c) as outlined above, is in turn proportional to the partial γ width Γ_γ, so that its ratio with the number of resonantly scattered protons yields Γ_γ/Γ_p. This second method has smaller systematic uncertainties, since the uncertainties on the detection angle of the recoil protons and on the target thickness have minor influences on the final result. The latter is $\Gamma_\gamma=3.1\pm0.7(\text{stat})\pm0.5(\text{syst})$ eV, in very good agreement with the value obtained above.

The final value of Γ_γ, and its uncertainties, was accordingly obtained in the following way. The number of γ rays was the same as in the first two methods. The number of resonantly scattered protons was taken as the average value between: (a) the directly determined number of resonantly scattered protons (second method above) and (b) the number of resonantly scattered protons deduced from the number of ^{13}N projectiles scattered by the ^{12}C content of the target (first method above) using the Breit-Wigner formula. The value of Γ_γ/Γ_p thereby determined yields: $\Gamma_\gamma=3.3\pm0.7(\text{stat})\pm0.6(\text{syst})$ eV.

The adopted value of Γ_γ determined as just described can be compared with the results of indirect measurements and of theoretical calculations of Γ_γ (Refs. [23–27]), and with more recent data obtained through the study of the Coulomb breakup of high-energy ^{14}O radioactive ion beams [33,34]. This comparison is displayed in Table I. Our result is at the borderline between those of the indirect measurements [21,22], which had 50% uncertainties and barely overlapped. Within the theoretical calculations of Γ_γ (Refs. [23–27]), the ones whose results are closest to our value are those of Refs. [23,27]. In particular, Descouvemont and Baye [27] predict that their calculated cross section for the $^{13}N(p,\gamma)^{14}O$ reaction, averaged over the same energy range as in our experiment, should be 98 μb, in excellent agreement with our data. The results of the Coulomb breakup experiments [33,34] also agree with our adopted

TABLE I. Comparison between the values of the partial γ width Γ_γ of the 0.545-MeV resonance in the $^{13}N(p,\gamma)^{14}O$ reaction, obtained during the course of the present experiment, and given by various authors, either from experiments [21,22,33,34] or from calculations [23–27].

Γ_γ (eV)	Reference
3.3 $(0.7)_{\text{stat}}(0.6)_{\text{syst}}$	Present
2.7 (1.3)	[21]
7.6 (3.8)	[22]
3.1 (0.6)	[33]
2.4 (0.9)	[34]
2.44	[23]
1.9	[24]
1.2	[25]
1–10	[26]
4.1	[27]

value of Γ_γ; this is reassuring for this type of experiment, in view of the question marks, which are attached to their analysis [35] and which should be reflected by an increase of their quoted uncertainties.

It should finally be noticed that the results of the present section are solely based on the data obtained with one 70% Ge-diode γ-ray detector. Another Ge diode, with a 90% efficiency, has also been used; the results obtained with it are fully compatible with those mentioned above, but, due to experimental problems, they could only be useful to qualitatively confirm them.

IV. ASTROPHYSICAL IMPLICATIONS OF THE $^{13}N(p,\gamma)^{14}O$ MEASUREMENTS

As indicated in Sec. III, two further experiments (ii) and (iii), in addition to experiment (i) described above, have been carried out on the $^{13}N(p,\gamma)^{14}O$ reaction, using the ^{13}N radioactive ion beams produced as outlined in Sec. II. They are reported in detail elsewhere [8,10] and their results are the following. The energy E_R and total width Γ of the 0.545-MeV resonance [experiment (ii)] have been directly measured in the $^{13}N+p$ interaction, and found to be 526(3) keV and 37.0(1.1) keV, respectively [8]: while the latter result agrees with a previous measurement [20] mentioned in Sec. III, the former is some 19 keV below the adopted value [19], i.e., 545(10) keV. We believe that our resonance energy is fairly reliable, since it results from the measurement of the (small) difference between the energies of the analog resonances in the $^{13}N+p$ and $^{13}C+p$ interactions [8], and since the $^{13}C+p$ resonance energy is fairly well established by several consistent measurements [9]. Furthermore, our value is compatible with the energy of the 5.17-MeV capture γ ray we have obtained (Sec. III), which is, however, affected by a large uncertainty due to the Doppler broadening mentioned above. It should be noticed that the 3-keV uncertainty we assign to E_R is mainly due to the uncertainty in the energy calibration of our recoil proton spectra [8]. The spectroscopic factor S for the $^{13}N(d,n)^{14}O$-g.s. reaction [experiment (iii)] has been determined to be 0.90(23) (Ref. [10]). From this result, the astrophysical $S(E)$ factor (defined in Refs. [1,2]) for the direct-capture component to the $^{13}N(p,\gamma)^{14}O$ reaction cross section, and its interference with the resonance-capture component, can be calculated [28]. The total $S(E)$ factor thereby determined, using the experimental values of Γ_γ (Sec. III), E_R and Γ (Ref. [8]), and including the resonance, direct and interference contributions to the $^{13}N(p,\gamma)^{14}O$ reaction, is shown in Fig. 5 (Ref. [10]).

The astrophysical $S(E)$ factor can in turn be used to determine, in a diagram where the product ρY_p between the stellar density ρ and the molar fraction Y_p of H in the stellar medium is plotted *versus* the stellar temperature T, those regions where the cold and hot CNO cycles (Sec. I) dominate. The results of such calculations, which involve standard technique [1,2], are shown in Fig. 6. The solid line corresponds to the equality between the rates of the $^{13}N(p,\gamma)^{14}O$ reaction and of the ^{13}N β^+ decay; the area between the dashed lines reflects the uncertainties in

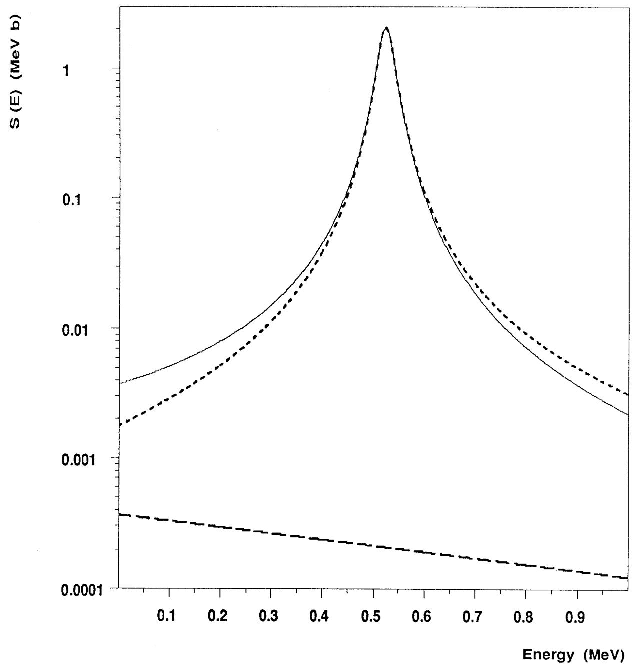

FIG. 5. Astrophysical $S(E)$ factor for the $^{13}N(p,\gamma)^{14}O$ reaction. The dashed, dotted, and full lines correspond to the direct, resonance, and total $S(E)$ factor, respectively. For further detail, see Ref. [10].

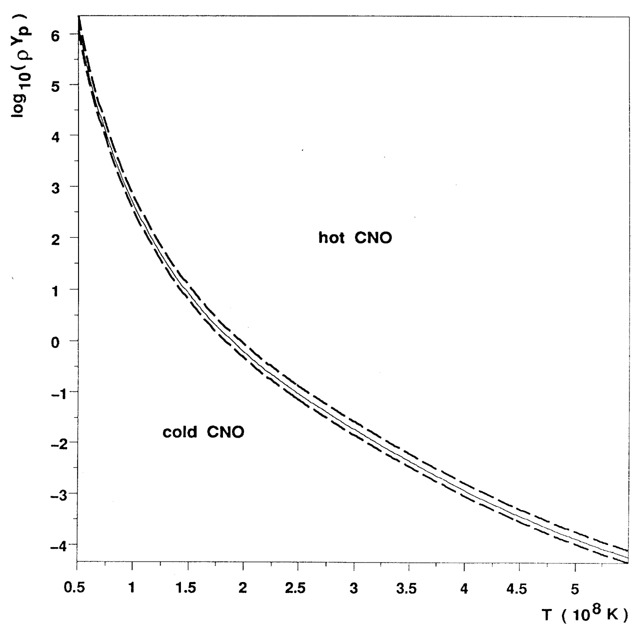

FIG. 6. Diagram of the product ρY_p between the stellar density ρ and the molar fraction Y_p of H in the stellar medium versus the stellar temperature T.

our experimental results given above, the main contribution to its width arising from the uncertainty in Γ_γ (Sec. III). The diagram of Fig. 6 results from the rather complete set of experiments (i) to (iii) carried out with ^{13}N radioactive ion beams on the $^{13}N(p,\gamma)^{14}O$ reaction, and is thus based on rather solid experimental foundations.

Some astrophysical consequences of the results of the present experiments have been investigated by Arnould *et al.* [36]. As compared to the previously accepted $^{13}N(p,\gamma)^{14}O$ rate in stellar media [37], obtained with $\Gamma_\gamma = 1.8$ eV, the present data suggest a rate that is about a factor of 2 faster. This has consequences on the mechanism of novae explosions, and in particular on the $^{13}C/^{12}C$ abundance ratio in nova ejecta, and on the nucleosynthesis of elements heavier than iron by the slow-neutron capture *s* process, in particular on the number of neutrons produced by the $^{13}C(\alpha,n)^{16}O$ reaction in asymptotic giant branch stars [36,38]. Other astrophysical implications of our data still have to be worked out.

V. CONCLUSIONS

The experiments described in the present paper represent the first complete set of investigations on a nuclear reaction of crucial interest in nuclear astrophysics, involving a short-lifetime nucleus in its entrance channel, carried out with low-energy high-intensity radioactive ion beams. Many more reactions of this type can be identified in nuclear astrophysics, whose experimental study is now feasible using these RIB. One of them is $^{19}Ne(p,\gamma)^{20}Na$, which represents a possible "escape" from the CNO cycles through the reaction and decay sequence:

$$^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na(p,\gamma)^{21}Mg \cdots$$

and which could lead to the nucleosynthesis of elements between ^{20}Ne and $A = 60$ by the so-called *rp* process [39]. This reaction is presently under study at the Louvain-la-Neuve RIB facility using ^{19}Ne beams produced in a similar way as outlined in Sec. II. It should, however, be pointed out that the $^{13}N(p,\gamma)^{14}O$ reaction is the least difficult reaction of this type amenable to experimental investigation: its cross section is dominated by a resonance with an exceptionally large partial γ width. Furthermore, its γ-ray spectrum is particularly simple, involving one γ ray of rather high energy, which accordingly emerges from a reasonably low background. The study of the other more difficult reactions will require the development of more refined detection techniques with a lower background; some of them are presently investigated in Louvain-la-Neuve. The investigation of these reactions will be made less difficult if higher-intensity RIB can be produced; one way to achieve this goal, in line with the techniques described in Sec. II, is to increase the acceleration efficiency ε_{acc} of the second accelerator, in the two-accelerator method. Such developments are now in progress at our laboratory.

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