Determination of the $^{13}N(p,\gamma)^{14}O$ Reaction Cross Section Using a ^{13}N Radioactive Ion Beam

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The cross section for the astrophysically important $^{13}N(p,\gamma)^{14}O$ reaction has been measured directly with an intense (3×10^8 particles/s) and pure (> 99%) 8.2-MeV ^{13}N radioactive ion beam. The average value, for the 5.8–8.2-MeV ^{13}N energy range, is 106(30) μb. The partial γ width of the resonance which occurs in this reaction at a center-of-mass energy of 0.545 MeV has been deduced to be 3.8(1.2) eV. It is compared with theoretical predictions and indirect determinations.

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The direct measurement of the cross section for nuclear reactions which involve radioactive nuclei in their entrance channel and which could play an important role in some astrophysical sites and events is a topic of great current interest in nuclear astrophysics [1]. An example is the $^{13}N(p,\gamma)^{14}O$ reaction, which is a key element in the hot CNO cycle whose reaction and decay sequence is as follows [1,2]:

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

The knowledge of the cross section for this reaction is crucial to determine the stellar conditions under which this hot CNO cycle competes with the cold CNO cycle,

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

which contributes to the production of energy in main-sequence stars like the Sun [1,2]. In the relevant range ($T\geq10^8$ K) of stellar temperatures, the cross section for the $^{13}N(p,\gamma)^{14}O$ reaction should be mostly determined by an $l_p=0$ resonance at $E_{\text{c.m.}}=0.545$ MeV, which corresponds to the 1^- first excited level of ^{14}O at 5.173 MeV [3], and whose total width Γ has been measured to be 38.1(1.8) keV [4]. Its partial γ width Γ_γ has been calculated by various authors using different models [5–9]: Their values lie in the 1–10-eV range. In the present paper, we present the results of an experiment during which, for the first time, the cross section for the proton-capture reaction on ^{13}N has been measured directly, using a ^{13}N radioactive ion beam (RIB) in the energy range of the above-mentioned resonance. Our experimental data will be compared with the results of the theoretical calculations [5–9], and with those of indirect determinations of Γ_γ [10–12] which also cover the 1–10-eV range.

The cross section for nuclear reactions involving radioactive nuclei with half-lives much shorter than 1 h can be measured by producing and accelerating a beam of these nuclei and by bombarding a stable target with it [2]. A RIB facility has recently been developed at Louvain-la-Neuve [13], with energies and intensities suitable for this type of experiment, using two accelerators. A 30-MeV proton cyclotron produces large quantities (2×10^{12}/s) of ^{13}N nuclei ($T_{1/2}=10$ min) by the $^{13}C(p,n)^{13}N$ reaction. These are extracted from the ^{13}C target, transformed into $^{13}N^+$ ions by an electron-cyclotron-resonance ion source, and injected into a second cyclotron which brings them to the desired energy. With respect to the results described in Ref. [13], the intensity of the RIB has been considerably increased, to an average value of 3×10^8 particles/s, i.e., 50 particle pA, over a 3-day running time, and the beam contaminants (^{13}C and ^{12}CH ions) have been drastically reduced, down to a maximum value smaller than 1%, using the mass selectivity of the second cyclotron. These improvements turned out to be crucial for the feasibility of the present experiment.

The $^{13}N(p,\gamma)^{14}O$ reaction has been studied using an apparatus which was tested previously with the $^{13}C(p,\gamma)^{14}N$ reaction [14]. In a reverse kinematics configuration, the ^{13}N beam, with an incident energy of 8.2 MeV and a diameter smaller than 5 mm, is sent onto a polyethylene $(CH_2)_n$ target whose thickness is 180(18) μg/cm^2, as determined with a ^{241}Am α source. The properties and behavior of such targets under irradiation with heavy-ion beams have been extensively tested with ^{13}C beams [14]. A surface-barrier diode, positioned at 17° with respect to the incident beam direction, detects the scattered ^{13}N projectiles and the ^{12}C and H recoils; the corresponding spectrum is shown in Fig. 1(a). The ^{13}N peak yields, after subtraction of the small (< 5%) ^{12}C recoil contribution, the number of ^{13}N nuclei incident on

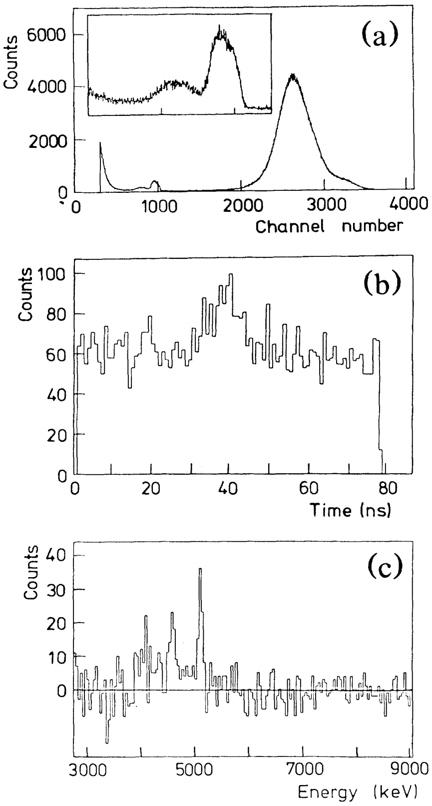

FIG. 1. (a) Charged-particle spectrum from the interaction between an 8.2-MeV ^{13}N beam and a $(CH_2)_n$ polyethylene target. The peak to the right corresponds to the scattered ^{13}N projectiles and ^{12}C recoils (right shoulder), the peak to the left and in the inset, to the proton recoils. (b) Spectrum of the time difference between the γ-ray pulses from the Ge diode and the cyclotron radio frequency, for a 3.8–5.2-MeV γ-ray energy window. (c) Spectrum of the prompt γ rays resulting from the $^{13}N(p,\gamma)^{14}O$ reaction, after subtraction of the random events. These spectra correspond to an effective running time of 33 h, with a ^{13}N beam intensity of 50 ± 10 particle pA as monitored with a shielded Faraday cup some 2 m downstream from the target.

the target, assuming pure Rutherford scattering of the ^{13}N projectiles by the ^{12}C target nuclei. This hypothesis is justified by the low ^{13}N-^{12}C center-of-mass energy (3.9 MeV) and by the small center-of-mass scattering angle (34°). The proton-capture reaction on ^{13}N is studied through the 5.173-MeV capture γ rays from the 1^- first excited level to the ground state of ^{14}O. They are detected by a large-volume Ge diode (relative efficiency of 70%), positioned in the backward hemisphere at an average angle of 129°. To generate γ-ray spectra with an improved signal-to-background ratio, the time difference between the Ge pulses and the radio frequency of the accelerating cyclotron is registered together with the energy information. Furthermore, the Ge diode is vetoed by a large cosmic-ray "umbrella," made of Plexiglas Cherenkov detectors and located above the γ-ray spectrometer. The dead-time and pileup corrections, which are important due to the radioactivity of the beam, are determined with a pulse generator. The relative full-energy peak efficiency of the Ge diode in the 0.8–8-MeV energy range is measured with a ^{56}Co source, with a ^{24}Al source produced by the $^{24}Mg(p,n)^{24}Al$ reaction in a separate experiment, and with the $^{13}C(p,\gamma)^{14}N$ reaction [14]; the absolute efficiency is obtained with calibrated γ-ray sources.

The spectrum of the time difference between the Ge pulses and the cyclotron radio frequency is shown in Fig. 1(b). It clearly displays the prompt peak emerging from the random events. The prompt γ-ray spectrum, after subtraction of the random events using time windows determined from Fig. 1(b), is represented in Fig. 1(c) for the 3–9-MeV energy range. The only statistically significant structures appear at the expected positions for the full-energy peak and for the first- and second-escape peaks (plus some Compton contribution) of the 5.173-MeV line, taking into account the Doppler shift due to the high recoil velocity ($v/c = 0.033$) of the ^{14}O nuclei in the reverse kinematics. The relative intensities of the three peaks agree with the results deduced from calibration spectra [14]. The absence of any structure between 7 and 8 MeV, i.e., at the expected positions of the three peaks from the most intense γ-ray transition in the $^{13}C(p,\gamma)^{14}N$ reaction [14], represents a further confirmation of the ^{13}N beam purity.

From the ratio between the intensities of the 5.173-MeV full-energy peak in the γ-ray spectrum of Fig. 1(c) and of the ^{13}N peak in the charged-particle spectrum of Fig. 1(a), one can determine the ratio between the total cross section for the $^{13}N(p,\gamma)^{14}O$ reaction and the differential cross section for the Rutherford scattering of the ^{13}N projectiles by the ^{12}C target nuclei at $\theta_{lab} = 17°$. These cross sections correspond to the range of the ^{13}N projectile energies in the target, i.e., 5.8 to 8.2 MeV. Isotropy is assumed for the capture γ-ray emission, in view of the $l_p = 0$ character of the 0.545-MeV resonance. The Rutherford cross section, weighted over this energy range, has been calculated taking into account the spread in the scattering angles. The resulting proton capture cross section in ^{13}N is 106(30) μb. The 28% experimental uncertainty results from the quadratic combination of the following contributions: 21% from statistics (85 ± 18 counts in the γ-ray peak); 15% for the full-energy γ-ray detection efficiency; 5% for the dead-time and pileup corrections; 3.5% for the charged-particle detector solid angle; and 9% for the Rutherford cross section, mainly due to the uncertainty on the beam position on target, and hence on the scattering angle of the ^{13}N projectiles.

The proton capture on ^{13}N in the energy range covered by the present experiment should be dominated by the 0.545-MeV c.m. resonance referred to above. Two strong hints that this is actually the case are present in our experimental data. First, the spectrum of the proton recoils in the surface-barrier diode [Fig. 1(a)] shows that the 0.545-MeV resonance dominates the nuclear scattering of protons by ^{13}N in the 5.8–8.2-MeV range of ^{13}N energies; the method used to analyze this spectrum, to reach the latter conclusion, and to further determine the incident ^{13}N beam energy and the energy and the width of the resonance will be described elsewhere [15]. Second, the widths of the γ-ray peaks in the spectrum of Fig. 1(c) are compatible with their Doppler broadening due to the detection geometry. Furthermore, it is generally observed that resonant capture largely exceeds direct capture in the vicinity of resonances with keV total widths for proton-capture reactions on light nuclei. Under the assumption of a dominating resonant capture, which is also supported by the theoretical calculations referred to above [5–9], one can analyze our experimental data in terms of a Breit-Wigner resonance with the above-mentioned energy and total width Γ, and deduce from them its partial γ width Γ_γ. The effective stopping power of ^{13}N nuclei in polyethylene, which is needed for these calculations [2], has been deduced from a separate measurement of the stopping power of ^{14}N ions at the same incident energy per nucleon; the latter experiment also showed that this stopping power is approximately constant in the 5.8–8.2-MeV energy range (Bragg peak), in agreement with the tables of Northcliffe and Schilling [16]. The result obtained in such a way is $\Gamma_\gamma = 3.8(1.2)$ eV. The 30% experimental uncertainty results from the quadratic combination of the various contributions mentioned above, plus a 10% uncertainty on the target thickness.

Our result for Γ_γ is compared in Table I with the theoretical predictions [5–9] and with indirect determinations [10–12]. It allows us to discriminate between the various models proposed so far, and shows us that the closest theoretical value is the one of Ref. [9]. It also resolves the discrepancies between the different indirect measurements in view of its improved experimental uncertainty. The calculated cross section of Ref. [9], the sum of resonant and nonresonant contributions, averaged over the energy range covered by the present experiment with a constant ^{13}N effective stopping power, amounts to 98 μb, in agreement with our data.

Investigations of the most important astrophysical consequences of our result have been carried out, whose conclusions will be published elsewhere [17]. They deal with the following topics: the determination of the stellar conditions, temperatures, and densities under which the cold and hot CNO cycles can develop; the study of the mechanism responsible for the explosion of novae where the $^{13}N(p,\gamma)^{14}O$ reaction is expected to play a crucial role, and in particular the calculation of the $^{13}C/^{12}C$ abundance ratio in the nova ejecta; and the limits to the nucleosynthesis of elements heavier than iron by neutron capture in stellar environments where the necessary neutrons are expected to be produced by the $^{13}C(\alpha,n)^{16}O$ reaction [18], for example, in situations where hydrogen can be ingested by a helium-burning layer in red giants.

The results described in the present paper open a new era in nuclear astrophysics which was called for in 1984 by Fowler [1]: the direct measurement of the cross sections for radiative capture reactions involving short-half-life radioactive elements using radioactive ion beams. The Louvain-la-Neuve RIB facility [13] allows the production of such beams with the required energies, intensities, and purities. Nuclear reactions of this type other than $^{13}N(p,\gamma)^{14}O$, which are of considerable astrophysical interest and which involve, for example, the radioactive nuclei ^{11}C, ^{14}O, and ^{19}Ne, are thereby accessible to such investigations, and will accordingly be studied in the near future.

TABLE I. Partial γ width Γ_γ of the 0.545-MeV resonance in the $^{13}N(p,\gamma)^{14}O$ reaction, deduced from the results of the present paper, predicted by theoretical calculations [5–9], and determined by indirect methods [10–12]. The data of Ref. [12] include the ratio $\sigma_{n_0}/\sigma_{n_1}$ between the production cross sections for the ground state and first excited level of ^{14}O in the $^{14}N(p,n)^{14}O$ reaction at $E(^{14}N)=175$ MeV, which is still to be determined.

Γ_γ (eV)	Reference
3.8(1.2)	Present
2.44	5
1.9	6
1.2	7
1–10	8
4.1	9
2.7(1.3)	10
$\leq 7.6(3.8)$	11
$1.4(7)\sigma_{n_0}/\sigma_{n_1}$	12

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