Indirect study of the astrophysically important $^{15}O(\alpha,\gamma)^{19}Ne$ reaction through $^{2}H(^{18}Ne,^{19}Ne)^{1}H$

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The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is generally considered as a potential breakout reaction from the hot CNO cycle. Under nova conditions, the reaction rate is dominated by a single sub-Coulomb resonance at $E_{c.m.}=504$ keV which corresponds to a ^{19}Ne excitation energy of $E_R=4.033$ MeV. Results from a $d(^{18}Ne,^{19}Ne)p$ experiment show that states of astrophysical interest are populated in this reaction. An upper limit for the α-branching ratio of the 4.033 MeV state was identified and branching ratios for other states in ^{19}Ne were found to be in good agreement with stable beam based results.

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At temperatures found in cataclysmic variable stellar environments the hot CNO cycle provides the main route for conversion of hydrogen to helium: the rate of energy generation is limited by the β lifetime of ^{15}O and ^{15}O is the waiting point of hot-CNO cycles starting from ^{12}C and ^{16}O seed nuclei [1]. Further rises in temperature and pressure can ignite a thermonuclear runaway in which charged particle induced capture reactions become more likely than β decays and conversion of the remaining nuclei into heavier proton-rich isotopes sets in rapidly [2]. The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is generally considered to be a potential breakout reaction from the hot CNO cycle [3]. The ^{19}Ne nuclei produced can be converted further via subsequent proton radiative capture reactions into ^{20}Na and heavier proton-rich elements. The radiative α capture on ^{15}O is the least well known of these reactions [4]. The $^{15}O(\alpha,\gamma)$ reaction rate depends dominantly on the properties of a single sub-Coulomb resonance at $E_{c.m.}=504$ keV, which corresponds to a $\frac{3}{2}^{+}$ level in ^{19}Ne at 4.033 MeV excitation energy.

No direct measurements of this reaction have been reported up to now. An indirect method, i.e., an α-transfer reaction in mirror nuclei, has been used to estimate the partial α-decay width Γ_α for the level of interest in ^{19}Ne [5]. However, this approach is affected by uncertainties related to the direct character of the transfer reaction and the need to infer an identical shell model configuration of the ^{19}Ne 4.033 MeV level to that of its mirror level in ^{19}F. Interestingly, approximations such as the equality of the gamma widths and of the reduced alpha widths in ^{19}F and ^{19}Ne have been questioned [6].

An alternative indirect approach to deduce the $^{15}O(\alpha,\gamma)$ rate can be based on the fact that the partial α-decay width Γ_α is small compared with the total resonance width Γ [7] for the 504 keV resonance. Then from knowledge of the resonance energy E_R, the spins involved ($\mathbf{I}_{^{19}Ne}=\mathbf{I}_\alpha+\mathbf{I}_{^{15}O}+\ell$) [12], the branching ratio Γ_α/Γ and Γ, the reaction rate coefficient $\langle\sigma v\rangle$ as a function of temperature T can be deduced as follows:

$$\langle\sigma v\rangle\propto\left(\frac{2\pi}{\mu kT}\right)^{3/2}\hbar^2\frac{2I_{^{19}Ne}+1}{(2I_\alpha+1)(2I_{^{15}O}+1)}\left(\frac{\Gamma_\alpha}{\Gamma}\right)\Gamma_\gamma \times\exp\left(-\frac{E_R}{kT}\right). \quad (1)$$

A study of the $^{19}F(^{3}He,t)^{19}Ne^{*}(\alpha)^{15}O$ reaction, using this approach, gave some useful information concerning the α-branching ratios for states in ^{19}Ne above 4.3 MeV excitation energy [8]. However, no information on the α-decay of states below 4.3 MeV was obtained [13].

In this paper we report a measurement that has been performed in order to populate the states of astrophysical interest in ^{19}Ne via a ^{18}Ne induced neutron stripping reaction on deuterated polyethylene targets. The experiment was undertaken at the radioactive nuclear beam facility of the Cyclotron Research Centre at Louvain-la-Neuve, Belgium [9]. A ^{18}Ne beam, with an energy of $E_{lab}=54.3(3)$ MeV and an average beam intensity of 10^6 pps, impinged on a 0.4-mg/cm^2-thick $(CD_2)_n$ target. A $(CH_2)_n$ target was used for background determination purposes. The reaction products were detected using three single sided silicon strip Louvain Edinburgh Detector Arrays as shown in Fig. 1 [10]. A total of 320 detector elements were used and both energy and time-of-flight for reaction fragments with respect to the cyclotron

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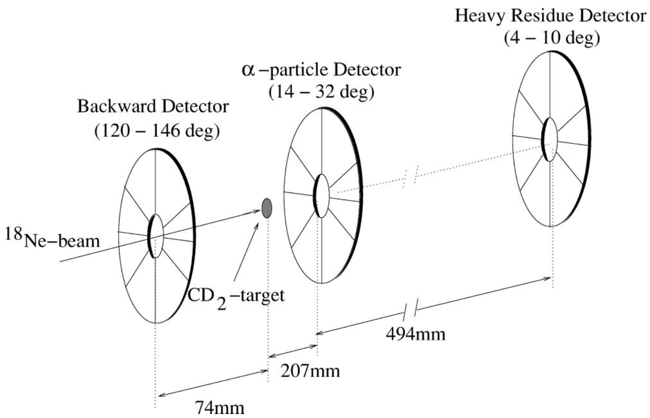

FIG. 1. Sketch of the experimental setup (see text).

frequency were recorded for each strip to enable identification of the light reaction products.

The detector arrays were positioned around the target to measure the protons produced in the $d(^{18}\mathrm{Ne},^{19}\mathrm{Ne}^{*})p$ reaction and subsequent α-particle decays of the excited states in ^{19}Ne. The protons that tag the formation of excited states in ^{19}Ne were detected in a detector array (hereafter the backward detector) covering a laboratory angular range from 120° to 146° in $\approx 1.6°$ steps (cf. Fig. 1). An α-particle and heavy residue detector array were positioned to cover 14° to 32° and 4° to 10°, respectively, in steps of $\approx 1.1°$ and $\approx 0.75°$, respectively. Special care was taken in focusing the cyclotron beam in order to measure at such small forward angles.

The backward detector was energy calibrated using a triple line α source. The angular dependence of the energy loss in the detector dead layer was taken into account. The two forward detectors were calibrated using elastic scattering

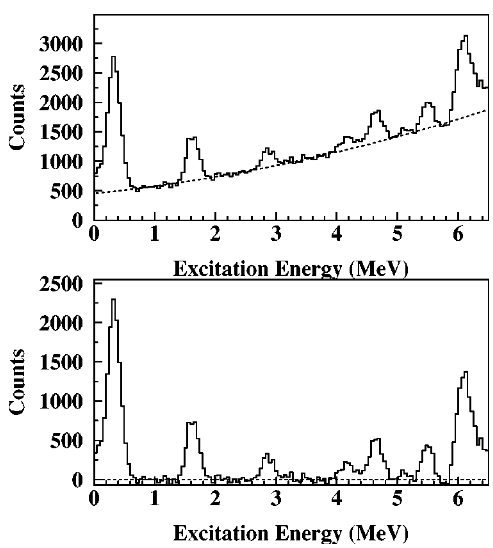

FIG. 2. ^{19}Ne excitation energy spectrum obtained from protons produced in the scattering of ^{18}Ne by a deuterated polythene target performed at 54.3 MeV incident energy and detected at $\Theta_{lab}=120°-146°$ (kinematically corrected). The upper panel shows the original spectrum and the lower panel shows the spectrum obtained after background subtraction.

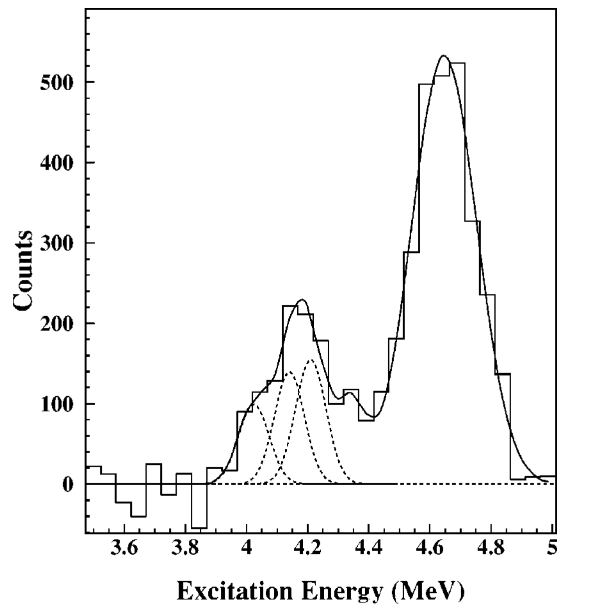

FIG. 3. ^{19}Ne excitation energy spectrum in the region of astrophysical interest obtained from protons produced in the scattering of ^{18}Ne by a deuterated polythene target performed at 54.3 MeV incident energy and detected at $\Theta_{lab}=120°-146°$. The dashed lines show individual Gaussian contributions by the three states in this region and the solid line shows the total fit.

of ^{18}Ne on carbon in addition to the triple line α source, taking into account the angle dependent energy losses in both the target and the detector dead layer.

The upper panel of Fig. 2 shows the ^{19}Ne excitation energy spectrum obtained from protons measured in the backward detector. The major background component in this spectrum arises from fusion of ^{18}Ne with carbon target nuclei and so data on $(\mathrm{CH}_2)_n$ were taken to evaluate the extent of this component. The equivalent spectrum obtained for the $(\mathrm{CH}_2)_n$ target was featureless and linearly increasing with energy. This spectrum was then normalized to the spectrum in Fig. 2 to account for differences in running time, beam intensity, and target thickness. The normalized $(\mathrm{CH}_2)_n$ data reproduce the regions between peaks for the $(\mathrm{CD}_2)_n$ target below 3 MeV. However, for higher excitation energies there is an excess of counts in the $(\mathrm{CD}_2)_n$, which is assumed to arise from fusion on deuterons and thus not present in the $(\mathrm{CH}_2)_n$ data. A polynomial fit was then made to regions of the excitation spectrum where there are no known states. This fit, shown in the upper panel of Fig. 2, was then subtracted from the data to give the lower panel. The errors in the calculated population of each state take into account the differences between the linear $(\mathrm{CH}_2)_n$ and the polynomial fit.

Figure 3 shows a magnified excitation energy spectrum in the region of astrophysical interest. A prominent peak centered around 4.65 MeV corresponds to four states in ^{19}Ne: 4.549 MeV($3/2^-,1/2^-$), 4.600 MeV($5/2^+$), 4.635 MeV($13/2^+$), and 4.712 ($5/2^-$) MeV. No attempt was made to fit separate components in this peak. At lower excitation energies, a peak contains proton events to three levels in ^{19}Ne: 4.033 MeV($3/2^+$), 4.140 MeV($9/2^-$), and 4.197 MeV($7/2^-$), with a clear contribution from the 4.033 MeV

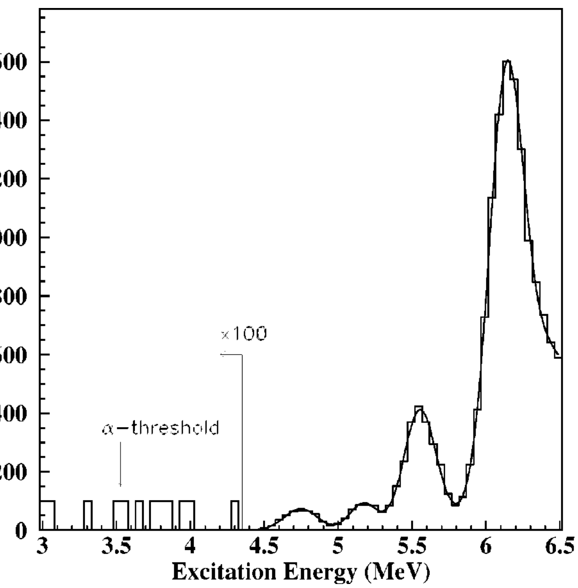

FIG. 4. ^{19}Ne excitation energy spectrum obtained from protons produced in the scattering of ^{18}Ne by a deuterated polythene target performed at 54.3 MeV incident energy, detected at $\Theta_{lab} = 120°-146°$. Events have been filtered by the conditions that the event multiplicity is 3 and the summed energy is consistent with the event being $d(^{18}\mathrm{Ne},p)^{19}\mathrm{Ne}^*(\alpha)^{15}\mathrm{O}$ (see text). The vertical scale below 4.3 MeV has been expanded by a factor of 100.

astrophysical level. A three-Gaussian fit to this peak was performed; free parameters were the peak heights and the peak energies, while a common sigma equal to the data bin, i.e., 50 keV, was imposed. This value is close to the 38 keV calculated energy resolution resulting from the quadratic summation of all sources (detector, electronics, target). Finally, a slight increase in the number of counts around 4.35 MeV could correspond to the formation of the 4.379 MeV($7/2^+$) level.

The spectrum in Fig. 4 was obtained by the condition that the reaction event multiplicity is three, which is consistent with the $d(^{18}\mathrm{Ne},p)^{19}\mathrm{Ne}^* \rightarrow \alpha + ^{15}\mathrm{O}$ reaction path. However, an additional total energy filter had to be applied to discriminate against events originating from random coincidences with the intense beam related β^+-background. Moreover, further background rejection was achieved by demanding that the relative angles at which coincident α particles and heavy residues were detected were kinematically allowed.

Alpha branching ratios (B.R.'s) can be determined by comparing intensities in the triples and singles spectra, both being corrected by the appropriate detection efficiencies, which were obtained by Monte Carlo simulations [11]. No decay events were detected for the 4.033 MeV state, which allows us to give an upper limit of 0.01 to the B.R. of this level. This upper limit does not contradict the theoretical estimate of 10^{-4} [7]. The same upper limit of 0.01 was obtained for the B.R. of the 4.140 and the 4.197 MeV levels. The spectrum in Fig. 4 shows an accumulation of counts below 5 MeV which corresponds to the most prominent peak in Fig. 3. A B.R. of 0.32 ± 0.03 is obtained for this peak. The error takes into account both statistical and systematic errors. In this energy range, three α decaying states have been observed [8] at 4.549 MeV (B.R.$=0.07\pm0.03$), 4.600 MeV (B.R.$=0.25\pm0.04$), and 4.712 MeV (B.R.$=0.82\pm0.15$). However, when comparing the angular distribution for this peak in Fig. 3 with distorted-wave Born approximation (DWBA) calculations performed for different angular momentum transfers, it appears that an $l=2$ transfer reproduces perfectly the data, indicating the dominance of the 4.600 MeV level [11]. For the 5.09 MeV level ($J^\pi = 5/2+$), which is well separated in this work, a B.R. of 1.8 ± 0.9 is obtained, in agreement with Ref. [8], within the error range. The next peak at 5.5 MeV in Figs. 2 and 4 contains three levels; one of them at 5.351 MeV was used in Ref. [8] to calibrate their detection efficiency. As this level has an expected B.R. of 1.0, our determination of 1.3 ± 0.3 for the B.R. of this triplet is consistent with this. The most prominent peak in Fig. 2 and 4 contains two levels, at 6.013 MeV($3/2-,1/2-$) and 6.092 MeV($1/2+$); our DWBA calculations favor $l=0$, suggesting the dominance of 6.092 MeV. The B.R. obtained in this study, in a stable beam based experiment [8] and derived from theory [7], are compared in Table I.

TABLE I. Branching ratios and upper limits on Γ_α/Γ_t from the present and previous experimental studies (the value in brackets is a theoretical estimate by Langanke *et al.* [7]).

^{19}Ne E_x (MeV)	B_α (present work)	B_α (previous work [8])
4.033	<0.01	$(10^{-4})^{a}$
4.140	<0.01	
4.197	<0.01	
4.549		0.07 ± 0.03
4.600	0.32 ± 0.03	0.25 ± 0.04
4.712		0.82 ± 0.15
5.092	1.8 ± 0.9	0.90 ± 0.09
5.351/5.424/5.463	1.3 ± 0.3	
6.013/6.092	0.96 ± 0.20	

[a]Theoretical value taken from Langanke [7].

In conclusion, despite the low beam intensity associated with the ^{18}Ne radioactive beam, the large detection solid angle, as well as the high granularity of the detectors used, allow this experiment to obtain useful data. Further for an increase in beam intensity by three orders of magnitude, which is expected to become available with the next generation of RNB facilities, it is clear this reaction could be used for the determination of Γ_α for the 4.033 MeV level in ^{19}Ne.

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[12] l denotes the transferred angular momentum.
[13] However, in a recent work by B. Davids *et al.* (nucl-ex/0206002), the $p(^{21}\mathrm{Ne},t)^{19}\mathrm{Ne}$ reaction at 43 MeV/nucleon was used to measure Γ_α/Γ of several states in ^{19}Ne, including the 4.033 MeV level for which a value of $2.4\pm1.9\times10^{-4}$ was obtained.