Discovery of a New Broad Resonance in ^{19}Ne: Implications for the Destruction of the Cosmic γ-Ray Emitter ^{18}F

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Six proton-emitting states in ^{19}Ne were studied through the inelastic scattering reaction H(^{19}Ne, p)^{19}Ne*(p)^{18}F. Their energies and widths were derived from the protons detected at zero degree, while proton-proton angular correlations between the detector at zero degree and a segmented annular detector were used to determine their spin value. In addition to the known states, a new broad $J = \frac{1}{2}$ resonance has been evidenced at $E_x \approx 7.9$ MeV, ≈ 1.45 MeV above the proton emission threshold. By introducing this resonance, the ^{18}F(p, α)^{15}O destruction rate in novae is significantly enhanced. This reduces the chance to observe the cosmic γ-ray emission of ^{18}F from novae in space telescopes.

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Novae are nuclear explosions caused by the accretion of hydrogen onto the surface of a white dwarf star. In these events, temperatures can reach 3.5×10^8 K, allowing fast synthesis of stable and radioactive nuclei [1]. The observation of γ rays from nova ejecta should provide a rather direct way to investigate the nucleosynthesis and matter ejection mechanism [2]. The most powerful γ-ray emission coming from novae is predicted to be at energies of 511 keV and below, originating from positron annihilations. When the nova envelope becomes transparent enough for γ rays to escape, the main contribution to positron production is the long-lived ^{18}F radioactive nucleus (half-life 109.77 min). Therefore, the amount of radiation emitted scales with the ^{18}F content of the nova ejecta, which in turn depends strongly on its production and destruction rates. The ^{18}F(p, α)^{15}O reaction is believed to be the most important destructive reaction [3]. Despite a lot of experimental efforts [4–10], uncertainties remain in the determination of the rate of this reaction at novae temperatures. One potentially important source of uncertainty comes from interference among three $\frac{3}{2}^+$ resonances [11,12].

More recently, Dufour and Descouvemont [13] predicted the existence of two not yet observed $\frac{1}{2}^+$ states, one at 0.41 MeV below the proton emission threshold S_p and a second broad resonance at about 1.49 MeV above the threshold. If the existence and properties of these $\frac{1}{2}^+$ states were confirmed, the reaction rate at typical novae temperatures would be dominated by reactions through these states. It would follow that the importance of the interference contribution among the $\frac{3}{2}^+$ resonances would be much reduced. In the present Letter, we report the results of a new approach developed to study excited states in ^{19}Ne through the reaction ^{1}H(^{19}Ne, p)^{19}Ne*(p)^{18}F. Implications to the ^{18}F(p, α)^{15}O rate in novae are subsequently discussed.

The experiment was performed at the Centre de Recherches du Cyclotron at Louvain-la-Neuve (Belgium) using a ^{19}Ne^{6+} radioactive beam. The ^{19}Ne beam was produced with a mean intensity of $\approx 8 \times 10^7$ pps and accelerated to 9 $A \cdot$MeV. The beam was incident on a 3.5 μm thick polypropylene target during 100 hours. No deterioration of the target was observed during the experiment. The beam intensity was monitored in a beam catcher in which it was stopped. The value of the beam catcher current was compared to the one measured by a Faraday cup for normalization purposes. The Faraday cup was regularly inserted during the experiment, which established the normalization between the beam catcher and Faraday cup. With an upper limit of 1%, no contamination of the beam by ^{19}F was observed. A dedicated setting used a ^{19}F beam under similar conditions to calibrate the target and beam catcher thicknesses as well as the energies of the detectors using the inelastic scattering reaction ^{1}H(^{19}F, p)^{19}F*(α)^{15}N.

Excited states in ^{19}Ne were populated by inelastic scattering reactions ^{1}H(^{19}Ne, p)^{19}Ne* occurring in the target. Scattered protons were detected at zero degree by a $\Delta E - E$ telescope of silicon detectors located 50 cm downstream of the target, composed of a 500 μm ΔE detector (18 keV

FWHM resolution) and a 6 mm Si(Li) E detector (28 keV FWHM) cooled to $-25\,^{\circ}$C. The telescope covered a solid angle of 5 msr. We chose to detect scattered protons at 0° for three reasons: First, the best energy resolution for the excited states in ^{19}Ne* is obtained for this angle as the reaction is made in inverse kinematics. Second, due to the axial symmetry of this experimental configuration, the analysis of the proton-proton angular correlation is simplified. Third, a strong alignment of the populated states in ^{19}Ne [14] is obtained, resulting in a pronounced spin-dependent angular distribution when studying their decay. A 250 μm-thick aluminum foil, placed between the target and the telescope, was used as a beam catcher. The intense radioactive beam was stopped inside this catcher, while the scattered protons lost less than 20% of their energy when passing through it.

The study of unbound states in ^{19}Ne* ($S_p = 6.411$ MeV and $S_\alpha = 3.529$ MeV) was obtained by using a telescope of annular silicon detectors which measured the energy losses and residual energies of the emitted particles, respectively. Their characteristics are as follows: MSL type QQQ/2 (CD) detector [30 μm thick, 16 annular strips and 24 radial strips, resolution 28 keV FWHM], MSL type QQQ/1 (PAD) detector [single element 1.5 mm thick, 130 keV FWHM] [15–17]. This telescope was positioned between the target and the beam catcher, 10 cm downstream of the target. It covered laboratory angles between 4.3° and 21.6°.

The excitation energies in ^{19}Ne produced by inelastic scattering were derived from the proton energies detected at zero degree. Above the proton emission threshold, the requirement of another proton detected in CD-PAD [from ^{19}Ne$^*(p)^{18}$F] was used to suppress the background induced by reactions of the beam in the catcher. The corresponding differential cross section for the H(^{19}Ne, p)^{19}Ne* reaction is presented as a function of the ^{19}Ne* excitation energy in Fig. 1. The energy resolution in excitation energy of ^{19}Ne was measured to be 30 keV FWHM. This spectrum was analyzed with a multiple peak-fitting program. A minimum of 6 states is required to fit the proton spectrum within the excitation energy range $\approx$6.9–8.4 MeV. They are reported in Table I. These peaks correspond to excited states in ^{19}Ne produced by the inelastic scattering reaction, which have a large branching ratio (>10%) for proton emission. Gaussian shapes were used for all peaks, except for the broad resonance (labeled E in Fig. 1) at $\approx$7.9 MeV for which an energy-dependent Breit-Wigner shape [20] was used instead.

Angular distributions of the unbound protons were derived from the annular strips of the CD detector. As the scattered protons were detected at 0°, the excited states in ^{19}Ne* were expected to be nearly totally aligned [14]. Consequently, pronounced angular distributions (see Fig. 2) are obtained for the 6 peaks labeled in Fig. 1. These distributions were generated using energy regions

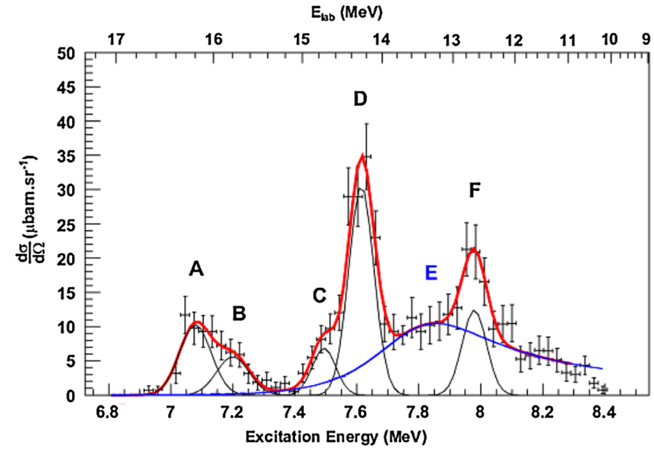

FIG. 1 (color online). The measured differential cross section for the H(^{19}Ne, p)^{19}Ne* reaction, with the associated proton detected at zero degree, is presented as a function of the ^{19}Ne* excitation energy (lower axis) and the measured energy in the laboratory (upper axis) corrected for energy losses in the beam catcher. This figure was obtained in coincidence with the detection of another proton in CD-PAD detectors coming from the emission channel ^{19}Ne$^*(p)^{18}$F. Gaussian-shaped peaks were used to fit five of the observed peaks. The broad peak E was fitted with a Breit-Wigner shape using an energy-dependent proton width.

where the overlap with neighboring peaks was minimized. The angular coverage in the center of mass was higher than 80% for most of the states, but, due to the kinematics of the reaction, it was lower for states having excitation energies above 7.8 MeV. The analysis of the angular correlation was used to assign the spin of the emitting states in ^{19}Ne by following the general method outlined by Pronko, Hirko, and Slater [21]. Note that it is analogous to the collinear γ-ray angular-correlation method of Ferguson [14]. As described in Refs. [14,21,22], the angular distribution should be of the form $d\sigma(\theta_{\rm CM})/d\Omega = \sum_{k={\rm even}} A_k P_k[\cos(\theta_{\rm CM})]$, where P_k are Legendre polynomials. Then, in the present case, it would be isotropic for the spin $J = \frac{1}{2}$ state, parabolic for $J = \frac{3}{2}$, biquadratic for $J = \frac{5}{2}$, and so on. As stated in Ref. [21], the angular distributions are parity independent, meaning that the parity of the observed states could not be inferred from this sole information. However, the most likely parity value can be derived from the following property. The proton-unbound states observed here have large proton widths. These states therefore emit protons with the lowest possible angular momentum value, for which the centrifugal barrier is the smallest. Based on this fact and on the ground state spin value 1^+ of ^{18}F, a parity value (+) is derived for the ^{19}Ne* spins $J = \frac{1}{2}$, $J = \frac{3}{2}$, $J = \frac{7}{2}\ldots$ and (−) for spins $J = \frac{5}{2}$, $J = \frac{9}{2}$, etc. The measured spins and favored parity values are presented in Table I.

Energies, widths, and spin values of the known states A and D in ^{19}Ne are remarkably reproduced by the present

TABLE I. Properties of the ^{19}Ne excited states measured in the present experiment are compared to results from previous measurements.

	This experiment				Previous measurements			
Label	E_r(keV)	E_x(MeV)	Γ (keV)	J^π	E_x(MeV)	Γ (keV)	J^π	Ref.
A	669(5)	7.079(5)	32(8)	$\frac{3}{2}^{(+)}$	7.075(1.6)	39(2.2)	$\frac{3}{2}^{+}$	[7]
B	793(31)	7.203(31)	35(12)	$\frac{3}{2}^{(+)}$	7.173(5)	···	···	[5]
					7.238(6)	···	···	[5]
C	1092(30)	7.502(30)	17(7)	$\frac{5}{2}^{(-)}$	7.500(9)	16(16)	···	[5]
					7.531(11)	31(16)	···	[5]
D	1206(5)	7.616(5)	21(10)	$\frac{3}{2}^{(+)}$	7.608(11)	45(16)	$\frac{3}{2}^{+}$	[18]
					7.644(12)	43(16)		[5]
E	1452(39)	7.863(39)	292(107)	$\frac{1}{2}^{(+)}$	···	···	···	
F	1564(10)	7.974(10)	11(8)	$(\frac{5}{2}^{-})$	7.944(15)	···	···	[19]
					8.069(12)	···	···	[19]

work, which demonstrates the reliability of the experimental method. For example, the first state labeled A is found at an excitation energy of $E_x = 7.079(5)$ MeV and a width $\Gamma = 32(8)$ keV, to be compared to $E_x = 7075(1.6)$ keV and $\Gamma = 39(2.2)$ keV [7,12]. The angular distribution of the corresponding protons can be fitted with a polynomial of order 2 (see Fig. 2), leading to $J = \frac{3}{2}$ and a favored (+) parity, which is in accordance with $J^\pi = \frac{3}{2}^+$ obtained in Refs. [7,12]. In addition to a good energy and width matching for the states B, C, and F, their spin assignments are deduced for the first time. They were so far only based on comparison with the mirror nucleus ^{19}F.

The 7.5–8.4 MeV region in Fig. 1 cannot be fitted without introducing at least one broad state. The analysis of the spectrum using a Breit-Wigner shaped peak gives an energy $E_x = 7.863(39)$ MeV and a total width $\Gamma = 292(107)$ keV. The angular distribution corresponding to this peak (labeled as E in Fig. 2) is flat, meaning that its spin value is $J = \frac{1}{2}^{(+)}$. This state is observed for the first time. Excellent agreement is found with the predictions of Ref. [13], which proposed the existence of a broad $1/2^+$ state at $E_x = 7.901$ MeV with $\Gamma = 296$ keV. In the range of energies considered in this Letter, the alpha emission channel H(^{19}Ne, p)^{19}Ne*(α)^{15}O could not be analyzed since it could not be distinguished from the competing reaction channel H(^{19}Ne, α)^{16}F*(p)^{15}O. Therefore, the alpha branching ratio, or alpha width Γ_α, could not be determined. Following the remarkable agreement between theory [13] and the present experiment for E_x and Γ, the theoretical value of $\Gamma_\alpha = 139$ keV will be retained in the following to estimate the impact of this broad resonance on the ^{18}F(p, α)^{15}O reaction cross section.

To ensure that this broad peak (E) does not originate from parasitic reaction-induced background, several checks have been made: (i) Proton energies and relative angles measured for this broad peak follow the expected kinematics relationship of the H(^{19}Ne, p)^{19}Ne*(p)^{18}F reaction, as well as the other peaks. Such correlations do not hold true for other possible reactions as H(^{19}Ne, p)^{19}Ne*(p)^{18}F* reaction or carbon-induced fusion-evaporation reactions from the $(CH_2)_n$ target. (ii) Random proton coincidences were generated by taking the proton parameters of two distinct events. The resulting background on the differential cross section is flat over the studied energy range and amounts to less than ≈10% of the peak height. (iii) A combination of more than one resonance, instead of a broad one, is unlikely as they should all exhibit the same angular distribution. Moreover, when

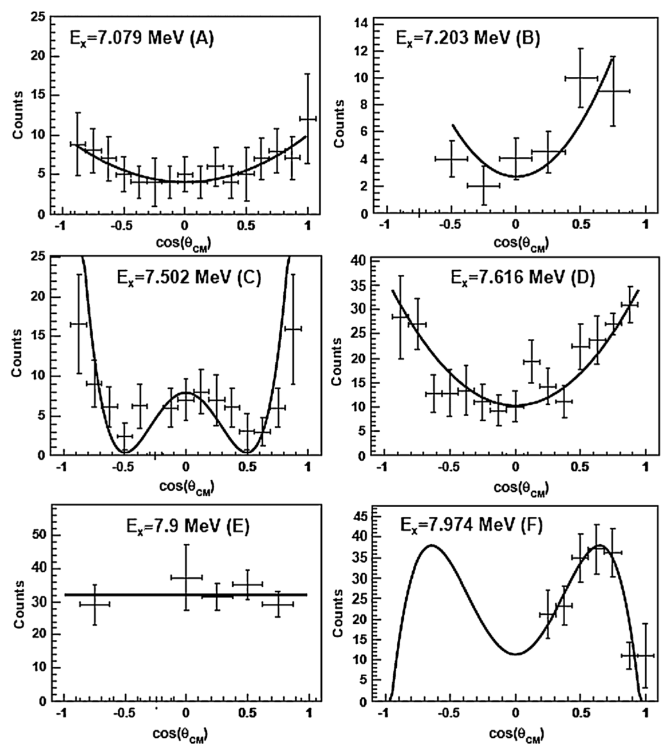

FIG. 2. Center-of-mass angular distributions measured for each excited state in ^{19}Ne*. Lines correspond to the best fits obtained in the present analysis. Part of the angular distribution of levels E and F was beyond the angular coverage of the detectors.

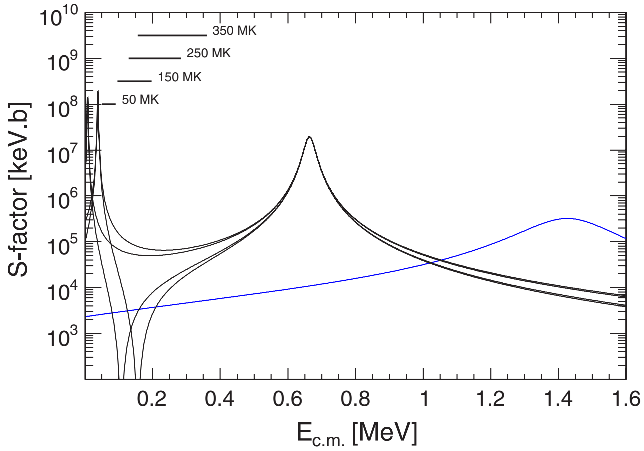

FIG. 3 (color online). The astrophysical S factor of the $^{18}F(p,\alpha)^{15}O$ reaction is plotted as a function of the center-of-mass energy. The corresponding novae temperatures are indicated by upper marks in the top left corner of the figure. The interference pattern of the three known $\frac{3}{2}^+$ states is shown [13]. The contribution of the new s wave state is superimposed in this figure. In the range of interest, this state could become the major contribution to the S factor.

using several peaks to fit the data, the agreement is not improved. (iv) Finally, no state was so far observed in this energy domain [12]. The presence of one broad resonance is therefore the only plausible interpretation to explain the excitation energy spectrum around 7.8 MeV.

The astrophysical factor $S(E)$, that is, the $^{18}F(p,\alpha)^{15}O$ reaction cross section with the Coulomb barrier penetrability function removed, is presented in Fig. 3 as a function of the center-of-mass energy. The first three $\frac{3}{2}^+$ states above the proton emission threshold lead to four distinct interference possibilities which are indicated by different continuous lines. In the range of interest corresponding to novae explosions, the S factor varies by more than 3 orders of magnitude, from $<10^2$ to 10^5 KeV $\cdot$ b. The contribution of the new broad s state is superposed in this figure. Even if located far away from the proton emission threshold, the low energy tail of this resonance contributes significantly to the $S(E)$ factor at novae temperatures. It becomes the dominant contribution in the case of destructive interferences between the $3/2^+$ states. It also brings so far the stringent lower limit of $S(E)$.

In summary, the scattering reaction $^1H(^{19}Ne,p)^{19}Ne^*(p)^{18}F$ was used in inverse kinematics to study the excited states in ^{19}Ne which can contribute to the $^{18}F(p,\alpha)^{15}O$ reaction cross section. Proton-proton coincidences between protons arising from the inelastic reaction and emitted from unbound $^{19}Ne^*$ states were used for determining energies, widths, and for the first time spin values of the resonant states. Besides the remarkable agreement with the insofar known resonances, a new broad $1/2^+$ resonance was found at about 1.4 MeV above the reaction threshold. The low energy tail of this resonance contributes to a significant enhancement of the ^{18}F destruction rate at nova temperature. This reduces significantly the chance to observe γ-ray emission of ^{18}F from a nearby nova explosion with existing telescopes. More generally, this newly used experimental method opens perspectives to study resonant states of astrophysical interest in other nuclei.

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