Discovery of a new broad resonance in $^{19}$Ne: Implications for the destruction of the cosmic $\gamma$-ray emitter $^{18}$F


To cite this version:


HAL Id: in2p3-00370811
https://hal.in2p3.fr/in2p3-00370811
Submitted on 25 Mar 2009

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Discovery of a new broad resonance in $^{19}\text{Ne}$: Implications for the destruction of the cosmic $\gamma$-ray emitter $^{18}\text{F}$

J.C. Dalouzy$^{1}$, L. Achouri$^{5}$, M. Aliotta$^{2}$, C. Angulo$^{3,4}$, H. Benhabiles$^{6}$, C. Borcea$^{4}$, R. Borcea$^{4}$, P. Bourgault$^{1}$, A. Buta$^{4}$, A. Coe$^{6}$, A. Damnian$^{3}$, T. Davinson$^{2}$, F. de Grancy$^{1}$, F. de Oliveira Santos$^{1}$, N. de Séréville$^{7}$, J. Kiener$^{6}$, M.G. Pellegriti$^{1}$, F. Negoiță$^{4}$, A.M. Sánchez-Benítez$^{3}$, O. Sorlin$^{1}$, M. Stanoiu$^{1}$, I. Stefan$^{1,4}$, P.J. Woods$^{2}$

1 Grand Accélérateur National d’Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3. B. P. 50027, F-14076 Caen Cedex 5, France
2 School of Physics and Astronomy. University of Edinburgh. Edinburgh EH9 3JZ, United Kingdom
3 Centre de Recherche du Cyclotron. Université catholique de Louvain. B-1348 Louvain-la-Neuve, Belgium
4 Horia Hulubei National Institute of Physics and Nuclear Engineering. P.O. Box MG6 Bucharest-Margurele, Romania
5 Laboratoire de Physique Corpusculaire ENSICAEN. CNRS-IN2P3 UMR 6534 et Université de Caen. F-14050 Caen, France
6 CSNSM UMR 8609. CNRS-IN2P3/Univ.Paris-Sud Bât. 104, 91405 Orsay Campus, France
7 Institut de Physique Nucléaire UMR 8608. CNRS-IN2P3/Univ.Paris-Sud. F-91406 Orsay, France

(Dated: February 4, 2009)

Six proton-emitting states in $^{19}\text{Ne}$ were studied through the inelastic scattering reaction $H(^{19}\text{Ne},p)^{19}\text{Ne}^*(p)^{18}\text{F}$. 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. Besides the known states, a new broad $J = \frac{5}{2}^+$ resonance has been evidenced at $E_x \approx 7.9$ MeV, $\approx 1.45$ MeV above the proton emission threshold. By introducing this resonance, the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ destruction rate in novae is significantly enhanced. This reduces the chance to observe the cosmic $\gamma$-ray emission of $^{18}\text{F}$ from novae in space telescopes.

PACS numbers: Valid PACS appear here

Novae are nuclear explosions caused by the accretion of hydrogen onto the surface of a white dwarf star. In these events, temperatures can reach $3.5 \times 10^8$ K, allowing fast synthesis of stable and radioactive nuclei [1]. The observation of $\gamma$ rays from nova ejecta should provide a rather direct way to investigate the nucleosynthesis and matter ejection mechanism [2]. The most powerful $\gamma$-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 $\gamma$ rays to escape, the main contribution to positron production is the long-lived $^{18}\text{F}$ radioactive nucleus (half-life 109.77 min). Therefore, the amount of radiation emitted scales with the $^{18}\text{F}$ content of the nova ejecta, which in turn depends strongly on its production and destruction rates. The $^{18}\text{F}(p,\alpha)^{15}\text{O}$ 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 between three $3^+_2$ resonances [11, 12].

More recently, M. Dufour and P. Descouvemont [13] predicted the existence of two not yet observed $\frac{5}{2}^+$ 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 $\frac{5}{2}^+$ states were confirmed, the reaction rate at typical nova temperatures would be dominated by reactions through these states. It would follow that the importance of the interference contribution between the $\frac{5}{2}^+$ resonances would be much reduced. In the present paper, we report the results of a new approach developed to study excited states in $^{19}\text{Ne}$ through the reaction $^1H(^{19}\text{Ne},p)^{19}\text{Ne}^*(p)^{18}\text{F}$. Implications to the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ rate in novae are subsequently discussed.

The experiment was performed at the Centre de Recherches du Cyclotron at Louvain-la-Neuve (Belgium) using a $^{19}\text{Ne}^{6+}$ radioactive beam. The $^{19}\text{Ne}$ beam was produced with a mean intensity of $\approx 8 \times 10^7$ pps and accelerated to 9 A·MeV. The beam was incident on a 3.5 $\mu$m thick polypropylene target during 100 hours. During the experiment the beam intensity was monitored in a beam catcher in which it was stopped. The measured signal of the catcher was normalized to the one of a Faraday cup to provide an absolute determination of the integrated beam current. With an upper limit of 1%, no contamination of the beam by $^{19}F$ was observed. A dedicated setting used a $^{19}\text{F}$ 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 $^1H(^{19}\text{F},p)^{19}\text{F}^*(\alpha)^{15}\text{N}$.

Excited states in $^{19}\text{Ne}$ were populated by inelastic scattering reactions $^1H(^{19}\text{Ne},p)^{19}\text{Ne}^*$ 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 $\mu$m $\Delta E$ detector (18 keV FWHM resolution) and a 6 mm Si(Li) E detector (28 keV FWHM) cooled to $-25^\circ C$. The tele-

*Present address: Tractebel Engineering - Suez, Av. Ariane 7, B-1200 Brussels, Belgium
The measured differential cross section for the \( H^{19}\text{Ne},p^{19}\text{Ne}^* \) reaction, with the associated proton detected at zero degree, is presented as a function of the \( ^{19}\text{Ne}^* \) excitation energy (lower axis) and the measured energy in the laboratory (upper axis) corrected for energy losses in the beam catcher. This figure is conditioned with the detection of another proton in CD-PAD coming from the emission channel \( ^{19}\text{Ne}^*(p)^{18}\text{F} \). 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.

The study of unbound states in \( ^{19}\text{Ne}^* \), \( (S_p = 6.411 \text{ MeV and } S_\alpha = 3.529 \text{ MeV}) \), was obtained by using a telescope (CD and PAD) of annular silicon detectors which measured the energy losses and residual energies of the emitted particles, respectively. Their characteristics are as follows: CD detector \([30\mu m \text{ thick, 16 annular strips and 24 radial strips, resolution 29 keV FWHM}]\), PAD detector \([1.5 \text{ mm thick, 130 keV FWHM}]\). This telescope was positioned between the target and the telescope, 10 cm downstream of the target. It covered laboratory angles between 4.3° and 21.6°.

The excitation energies in \( ^{19}\text{Ne} \) 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 \( ^{19}\text{Ne}^*(p)^{18}\text{F} \)) was used to suppress the background induced by reactions of the beam in the catcher. The corresponding differential cross section for the \( H^{19}\text{Ne},p^{19}\text{Ne}^* \) reaction is presented as a function of the \( ^{19}\text{Ne}^* \) excitation energy in Fig. 1. The energy resolution in excitation energy of \( ^{19}\text{Ne} \) 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 \( \approx 6.9 - 8.4 \text{ MeV} \). They are reported in Table I. These peaks correspond to excited states in \( ^{19}\text{Ne} \) 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 \( \approx 7.9 \text{ MeV} \) for which an energy dependent Breit-Wigner shape \([19]\) 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 \( ^{19}\text{Ne}^* \) 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 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 and Lindgren [20]. Note that it is analogous to the collinear $\gamma$-ray angular correlation method of Ferguson [14]. As described in [14, 20, 21] the angular distribution should be of the form $d\sigma/d\Omega = \sum_{k=even} A_k P_k(\cos(\theta_{CM}))$, 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. [20] 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 $I^g$ of $^{18}$F, a parity value (+) is derived for the $^{19}$Ne$^*$ spins $J = \frac{3}{2}$, $J = \frac{5}{2}$ ... and (-) for spins $J = \frac{1}{2}$, $J = \frac{3}{2}$ etc. The measured spins and favored parity values are presented in Table I.

Energies, widths and spins values of the known states A and D in $^{19}$Ne are remarkably reproduced by the present 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 $E_x = 7.075(1.6)$ 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 $J^x = \frac{3}{2}^+$ 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 to 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 $J = \frac{3}{2}^+$. 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 paper, the alpha emission channel $H(^{19}Ne, p)^{19}Ne^*(\alpha)^{15}O$ could not be analyzed since it could not be distinguished from the competing reaction channel $H(^{19}Ne, O)^{16}F^*(p)^{15}O$. Therefore the alpha branching ratio, or alpha width $\Gamma_\alpha$, could not be determined. Following the remarkable agreement between theory [13] and the present experiment for $E_x$ and $\Gamma$, the theoretical value of $\Gamma_\alpha = 139$ keV will be retained in the following to estimate the impact of this broad resonance on the $^{18}F(p, \alpha)^{15}O$ 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 proton intensities, as well as the other peaks. Such correlations do not hold true for other possible reactions as $H(^{19}Ne, p)^{19}Ne^*(p)^{15}F^*$ reaction or carbon-induced fusion-evaporation reactions from the $(CH_2)_n$ target. (ii) Uncorrelated proton correlations 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 $\approx 10\%$ 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 using several peaks to fit the data, the agreement is not improved. (iv) Finally no state was so


To summarize, the scattering reaction $^{18}F(p, \alpha)^{15}O$ was used in inverse kinematics to study the excited states in $^{19}$Ne which can contribute to the $^{18}F(p, \alpha)^{19}O$ 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 $\gamma$-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.

We thank the Centre de Recherches du Cyclotron at Louvain-la-Neuve for delivering the $^{19}$Ne beam. We acknowledge the support of the European Commission within the Sixth Framework Programme through I3-EURONS (contract no. RI3-CT-2004-506065), the support from the French-Romanian collaboration agreement IN2P3-IFIN-HH Bucharest n°03-33 and the support from the UK STFC. One of us (A.B) acknowledges also the partial financial support from CNCSIS, Romania.