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7.07 MeV resonant state in ^{19}Ne reexamined through a new measurement of the ^{18}F$(p,\alpha)^{15}$O reaction and ^{18}F(p,p) scattering

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A new measurement of the ^{18}F(p,α) reaction and the ^{18}F(p,p) elastic scattering was performed at the Radioactive Ion Beam facility in Louvain-la-Neuve. Values were deduced for the resonance energy, total width, partial width, and resonance strength of the 7.07 MeV level in ^{19}Ne, confirming and increasing the precision of a first result obtained several years ago in the same lab.

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The ^{18}F(p,α) reaction is important in hydrodynamic hydrogen burning occurring in explosive astrophysical environments like novae or x-ray bursts. In particular in O-Ne-Mg novae, ^{16}O is rapidly burned to ^{15}N by the chain ^{16}O$(p,\gamma)^{17}$F$(\beta^+)^{17}$O(p,γ) ^{18}F$(p,\alpha)^{15}$O$(\beta^+)^{15}$N. High nitrogen abundances recently observed in the ejecta of such novae support this view [1]. Moreover, the competition between ^{18}F burning, and ^{18}F decay to ^{18}O is an important factor that has to be known in order to estimate the probability that a nearby nova can be observed from space through the 511 keV γ rays from ^{18}F [2]; the launch of ESA's INTEGRAL mission [3] in 2002 makes this point particularly crucial.

It is clear from previous measurements that the rate of the ^{18}F$(p,\alpha)^{15}$O reaction is dominated, in part of the relevant temperature domain, by a resonant state at 7.07 MeV in ^{19}Ne [4]. However, two direct measurements yielded very different results with regard to some parameters of this state: the Louvain group [4,5] measured a total width of 37 ± 5 keV and a resonance strength of 5.6 ± 0.6 keV, while the Argonne group [6] obtained a width of 13.6 ± 4.6 keV and a resonance strength of 2.1 ± 0.7 keV. A summary of previous measurements also addressing the problem of the mirror state in ^{19}F was recently published [7]. In order to resolve this discrepancy, a new measurement of the H(^{18}F$,\alpha)^{15}$O reaction and the H(^{18}F$,p)^{18}$F scattering was undertaken in Louvain-la-Neuve.

Similar to our previous work, a 14 MeV ^{18}F beam [8] of mean intensity $2\times10^5\ \mathrm{s}^{-1}$ bombarded a 275 μg/cm^2 thick polyethylene target. Charged particles scattered or recoiling from the target were recorded in an annular silicon strip detector called LEDA. LEDA is segmented in eight sectors covering about 90% of the azimutal angle ($\Delta\phi\simeq40°$); each sector contains 16 strips of 5 mm width. LEDA is positioned at 23.6 cm from the target, covering the polar angle region between 12° and 26° in the lab frame with an angular resolution of about 1°. Each strip is equipped with relevant electronics providing with both the energy (E) and timing (t) information; the latter is measured with respect to the cyclotron RF. The identification of particles is obtained from an (E,t) two-dimensional plot for each strip. The energy loss of the ^{18}F ions in the target allows the covering of most parts of the broad resonance corresponding to the formation of the 7.07 MeV level in ^{19}Ne.

Compared to our first measurement [5], the following improvements were brought to the experimental setup. (i) The integrated beam intensity was larger by a factor of 5 resulting in much better statistics in the measurement; in particular, recoil proton spectra from the ^{18}F(p,p) scattering were reconstructed now with an energy bin of 11 keV/channel instead of 40 keV/channel in [5]. (ii) An Al foil covering the detector to prevent scattered ^{18}F ions to reach it was removed: as a consequence, the energy loss and straggling of α particles were strongly reduced, resulting in much cleaner spectra at every angle. (iii) The energy calibration of the spectra was obtained as follows: for α-particle spectra, a three-line α source (^{239}Pu, ^{241}Am, ^{244}Cm) was used and the linearity of the response was checked with a precision pulser; for proton spectra, a correction factor of 0.986 was applied to the α-source calibration, corresponding to the measured ratio of the energies required for the production of one electron-hole pair ($\epsilon_\alpha/\epsilon_p=0.986\pm0.02$) [9]; the proton calibration was checked by an additional study of the ^{18}O(d,p) reaction and the ^{18}O(d,d) scattering on a CD_2 target and of the ^{18}O(p,p) scattering on a CH_2 target. The calibration was performed separately for each strip of LEDA.

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Similar to our previous measurements, a possible contamination of the ^{18}F beam by the ^{18}O isobar was checked by observing α particles from the ^{18}O(p,α) reaction in the energy region above the α particles from ^{18}F(p,α) (the Q values for both reactions differ by 1.1 MeV); the same upper limit as before (a few %) was deduced for the ratio of ^{18}O to ^{18}F ions in the beam.

Protons and α particles from the ^{18}F(p,p) and ^{18}F(p,α) reactions were thus clearly separated in two-dimensional spectra. Eight strips were summed in order to obtain a proton spectrum and an α spectrum for each polar angle. The typical number of counts in a proton (α particle) spectrum were 4000 (100).

Let us first examine the analysis of the proton spectra; experimental spectra were compared to calculated ones obtained the following way. The thick target was divided in 50 thin slices. For each slice, the energy distribution of the beam was calculated using stopping power tables [10] and the Bohr formula for the energy straggling; the cross section for elastic recoil protons containing a Coulomb, a resonant, and an interference term [11], was introduced to obtain the energy distribution of protons emitted to the lab angle domain covered by each strip of LEDA. The energy loss of protons in the target and in the detector dead zone were subtracted. Multiple scattering of the beam and the protons in the target introduced a kinematical broadening. This, as well as the energy resolution of the detector, was taken into account by convoluting the proton spectra with a Gaussian function of which the FWHM depended on the scattering angle and on the proton energy, following a procedure defined in [11]. A global fitting of the spectra was realized; it was found important to fit not only the part of the spectrum close to resonance, but the whole spectrum including the upper and lower energy edges. The fit contained four ''significant'' parameters, i.e., the resonance energy (E_R), the total width of the resonance Γ_{tot}, the ratio of the partial proton to total width (Γ_p/Γ_{tot}), and the normalization factor, i.e., the product of the integrated beam intensity (I), the target thickness, and the fraction of the azimuthal angle covered by the detector.

Two sets of parameters were obtained, under the hypothesis of a $J^\pi=3/2^+$ or $1/2^+$ resonance. The χ^2 criteria did not allow us to select one of both. Figure 1 shows several spectra and fits. Table I contains the best fit parameters. A previous measurement of the ^{19}F$(^3$He$,t)$ reaction [12] yielded $\Gamma_p/\Gamma_{tot}=0.37\pm0.04$, which allows us to unambiguously define J^π of the resonant state as $3/2^+$, confirming our previous attribution [5], but in a much more precise manner.

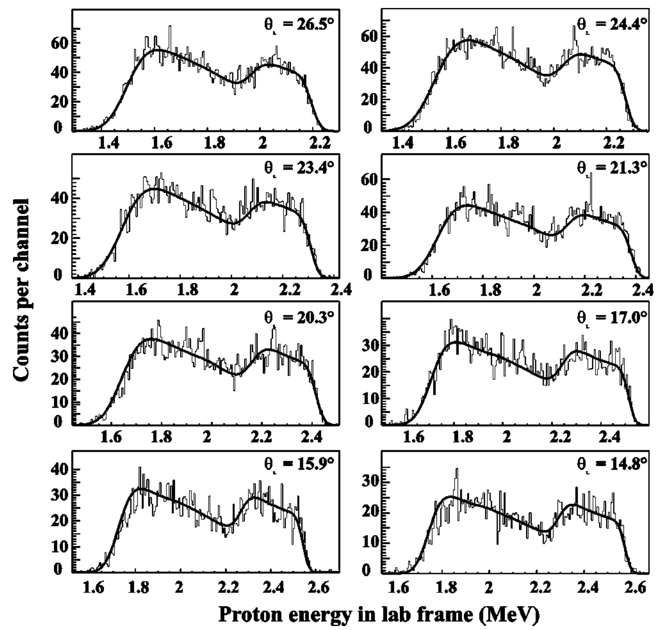

FIG. 1. Proton spectra measured at several polar angles in the lab system (histograms), and best global fits obtained as described in the text (solid lines); the fits with $J^\pi=1/2^+$ and $J^\pi=3/2^+$ are indistinguishable on these plots. The best fit parameters are reported in Table I.

Errors reported in Table I are the statistical ones and the systematic ones. The latter were obtained as follows: in addition to the significant parameters, the fit also contained two ''experimental'' parameters, i.e., the ^{18}F beam energy and the stopping power for ^{18}F ions in CH_2. The best values were 13.9 MeV for the former (instead of a nominal 14 MeV) and, for the latter, a stopping power larger by 10% with respect to [10]; in fact a measurement of the stopping powers for light ions in CH_2 performed in our lab [13] yielded a result for 1 MeV/amu ^{19}F ions that showed the same discrepancy with [10]. A variation of these ''experimental'' parameters within reasonable limits ($\pm$100 keV for the beam energy, $\pm$10% for the stopping power, allowed us

TABLE I. Results obtained from the present work: from the ^{18}F(p,p) scattering under the hypothesis of a $J^\pi=1/2^+$ or $3/2^+$ for the resonant state (first two lines), from the ^{18}F(p,α) reaction (third line); global result (fourth line) obtained by combining the second and third lines. In the last column $I(10^9)$ represents the integrated ^{18}F beam intensity, which is part of the normalization factor defined in the text. The resonance strength $\omega\gamma$ from the proton spectra was calculated using Eq. (2).

	E_R (keV)	Γ_{tot} (keV)	Γ_p/Γ_{tot}	$\omega\gamma$ (keV)	$I(10^9)$
Proton spectra ($J^\pi=1/2^+$)	660±1±1.7	34.3±2.2±1.7	0.873±0.026±0.02	1.3±0.3±0.15	4.41±0.03±0.08
Proton spectra ($J^\pi=3/2^+$)	656±1±1.7	31.5±1.9±1.7	0.467±0.013±0.02	5.2±0.3±0.15	4.47±0.03±0.08
α spectra	659±1±1.7	37±2±1	-	4.6±0.1±0.1	-
Global result	657.5±0.7±1.7	34.2±1.4±1.7		4.7±0.1±0.15	

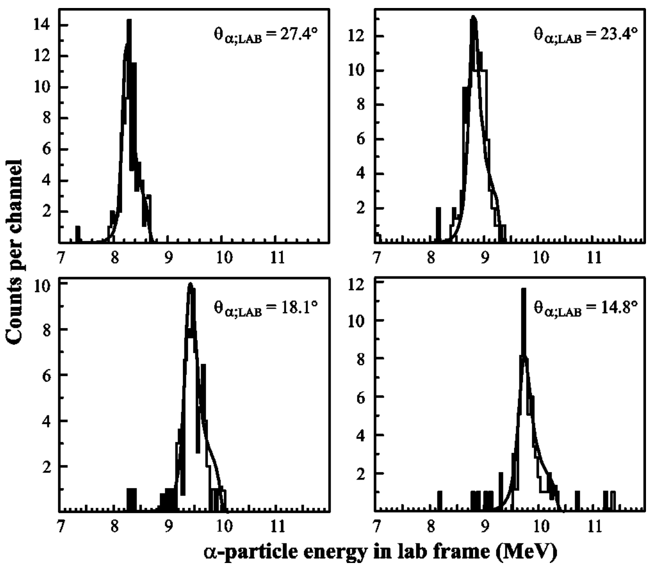

FIG. 2. α-particle spectra measured at several angles (histograms) and calculations (solid lines); the parameters of the latter are the resonance energy and the total width (see text).

to obtain the systematic errors quoted in Table I.

The α spectra were analyzed independently of the proton spectra. For each polar angle, the α spectrum was dominated by a well-defined peak (Fig. 2), implying the presence of a resonant state. The resonance energy and total width were introduced as parameters in a calculation of the α spectra based on the same program as the one used in the proton spectra, with the same experimental parameters. Here, however, the quantities to be reproduced in the α spectra were the centroid of the peak and the root mean square deviation with respect to the centroid. Each spectrum provided thus a value for E_R and Γ_{tot}. It should be noted that E_R and Γ_{tot} are independent of $\Gamma_\alpha/\Gamma_{tot}$ and I. The mean value of the resonance energy and total width deduced from the α spectra are 659.0$\pm$1.0$\pm$1.7 keV and 37.0$\pm$2.0$\pm$1 keV, respectively (Table I); errors are defined as in the analysis of the proton spectra and they were obtained the same way. In addition, using the normalization factor obtained from the proton spectra, and extrapolating the detected number of α particles to the entire solid angle ($l=0$), it was possible to calculate the resonant yield and therefrom the resonant strength $\omega\gamma$. After correcting for the ''finite'' character of the target thickness, the resonant strength was 4.6$\pm$0.1$\pm$0.1 keV (Table I), in fair agreement with our former measurement [5], i.e., 5.6 $\pm$0.6 keV; for the latter, only statistical errors had been considered: systematic errors of the same importance as the present ones (i.e., 2%) should be added, as the main contribution to systematic errors come from the uncertainty in the energy loss.

It is interesting to note that the relation $\omega\gamma = \omega\Gamma_p \cdot \Gamma_\alpha/\Gamma_{tot}$, where $\Gamma_{tot}=\Gamma_p+\Gamma_\alpha$, implies that $\gamma/\Gamma_{tot} \leqslant 1/4$ or

$$\omega \geqslant 4\frac{\omega\gamma}{\Gamma_{tot}}. \qquad (1)$$

Two conclusions can be deduced from this inequality.

(i) As the resonant state is formed via a $l=0$ orbital momentum, $\omega \leqslant \frac{4}{6}$ and thus $\Gamma_{tot} \geqslant 6\omega\gamma$, or $\Gamma_{tot} \geqslant 29$ keV which is satisfied by our measurements.

(ii) The resonance strength and the total width from the α spectra allow us to write $\omega \geqslant 0.37$ (2σ), which again excludes $J^\pi=1/2^+$ in agreement with and independently from the proton data.

Finally, the parameters deduced from the proton spectra, i.e., Γ_{tot}, and Γ_p/Γ_{tot} can be introduced in

$$\omega\gamma = \omega\frac{\Gamma_p}{\Gamma_{tot}}\left(1-\frac{\Gamma_p}{\Gamma_{tot}}\right)\Gamma_{tot} \qquad (2)$$

in order to calculate $\omega\gamma$: the deduced values (Table I) are $\omega\gamma=5.2\pm0.3\pm0.15$ keV ($J^\pi=3/2^+$) and $\omega\gamma=1.3\pm0.3 \pm0.15$ keV ($J^\pi=1/2^+$). Once more, only the value obtained with $J^\pi=3/2^+$ is in agreement with the α-particles measurement.

The two determinations of E_R, Γ_{tot}, and $\omega\gamma$, from the proton spectra with $J^\pi=3/2^+$ and from the α spectra, can be combined to yield global values, which are reported in the last line of Table I. Statistical errors in the proton and the α spectra were combined in quadrature in the global result. Being not independent, systematic errors were not combined.

In summary, a complete set of data was obtained for the ^{18}F(p,α) reaction and the ^{18}F(p,p) scattering around the 7.07 MeV resonance in ^{19}Ne. Recoil protons and α particles were detected and analyzed thoroughly; in particular, the data analysis procedure was revisited completely with respect to the one used in previous work performed in our lab, and several experimental effects contributing to nonstatistical uncertainties were incorporated. Consistent determinations of the resonance energy, the total width, and the resonance strength were deduced. Values from the present work are in agreement with our previous experiment [5] and with charge-exchange reaction [12].

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