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Evidence for $^{15}$O+$\alpha$ resonance structures in $^{19}$Ne via direct measurement


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(Dated: October 11, 2017)

States in the astrophysically important $^{19}$Ne nucleus have been populated directly using the $^{15}$O+$\alpha$ reaction with a radioactive $^{15}$O beam. Due to the challenges involved, this represents the first such $^{15}$O measurement with high resolution and the first dedicated to exploring the cluster structure. This measurement comprises three experiments: the first to develop the $^{15}$O radioactive beam, the second the resonant scattering study and the third to measure the precise energy loss of O ions in $^1\text{He}$ to reduce systematic uncertainties. The results show evidence for $^{15}$O+$\alpha$ cluster structure which could explain earlier results pointing to the increased $\alpha$ branching ratio in the astrophysical reaction rate for high-spin near-threshold resonances. Absolute differential cross sections have been measured. Additionally, spins, parities and partial decay widths, essential for nuclear reaction-rate calculations, have been extracted using an $R$-matrix analysis.

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INTRODUCTION

One of the nuclear reactions with fundamental significance for understanding the on-set of the thermonuclear runaway on the surface of accreting neutron stars or X-ray bursts is $^{15}$O($\alpha,\gamma$)$^{19}$Ne. This reaction, though not fully elucidated, is thought to trigger the colossal release of energy in accreting neutron stars that is observed as X-ray bursts [1-3], marking the break out from the hot-CNO cycles and the commencement of rapid proton capture. As a result, the structure of the low-lying energy levels close to the $^{15}$O+$\alpha$ threshold in $^{19}$Ne [4, 5] ($S_\alpha=3.528$ MeV [6]) is extremely important. Any enhancement of $\alpha$ or reduction in the ($\alpha,\gamma$) rate has significant consequences for energy production in the universe.

A second crucial role is played by the $^{19}$Ne excitation region around the proton threshold ($S_p=6.411$ MeV [6]) due to its importance for the destruction of the key rino-nuclide $^{18}$F [7-9] — this isotope survives long enough to provide evidence of nucleosynthesis via observable $\gamma$-ray emission. Destruction is via proton-unbound states in $^{19}$Ne through the reaction $^{18}$F(p,$\alpha$)$^{15}$O.

From a nuclear structure perspective it is well known that heavier neon isotopes exhibit strong $\alpha$ clustering even in the ground states with $^{20}$Ne [10-12] and $^{21}$Ne [13, 14] being two of the best examples known to date. Thus, the question arises about the possibility of $\alpha$ clustering in $^{19}$Ne and whether similar states above the $\alpha$ and proton thresholds exhibit $^{15}$O+$\alpha$ structure, and if so, to what extent. This letter reports on the direct measurement of the $^{15}$O+$\alpha$ reaction using resonant scattering [15] with a radioactive $^{15}$O beam developed specifically for this study. In this way the rotations of the near $\alpha$-threshold states were populated, and thereby their underlying structure established.

The method, as implemented here, enables $\alpha$ strength to be measured directly via elastic scattering across a large excitation-energy range using one beam energy. The nature of the technique makes it ideally suited to use with low-intensity, large-energy-profile beams. Previously, there has been a single attempt using an $^{15}$O beam and a small gas-cell where only one resonance was populated with low resolution [16].

In Thick Target in Inverse Kinematics (TTIK) resonant scattering [15], a low-intensity beam is incident on an extended gas target. As the projectiles slow down in the gas, elastic scattering reactions across a
A wide range of center-of-mass (com) energies can take place (corresponding to a range of depths within the gas). The pressure of the gas is tuned such that the beam completely stops in the gas, allowing a detector to be placed at 0°, i.e., on the beam axis. The elastic scattering leads to energetic light particles which, due to their lower-rate of energy loss, can traverse the gas and be recorded by the detector. The result is that low-intensity beams can be used to measure large-range excitation functions in one measurement with one initial beam energy. In the current work the technique is refined by using Time-Of-Flight (TOF) [17] to remove contributions from processes other than elastic scattering [18]. This is the first resonant scattering experiment at the EXOTIC facility [19, 20].

**EXPERIMENTAL TECHNIQUE**

The 28.5 MeV $^{15}$O radioactive ion beam was produced with the EXOTIC facility [19, 20] at the Laboratori Nazionali di Legnaro (LNL, Italy) by means of the in-flight technique via the $p^{(15}$N,$^{15}$O)$n$ reaction. A primary 80 MeV $^{15}$N$^{5+}$ beam was delivered by the LNL-XTU tandem Van de Graaff accelerator and impinged on a H$_2$ gas target at a pressure of 1 bar and cooled with liquid nitrogen, corresponding to an equivalent target thickness of about 1.35 mg/cm$^2$ of H$_2$.

The $^{15}$O beam was selected and purified from the scattered primary $^{15}$N beam and other contaminant nuclei by tuning the 30°-bending magnet, Wien-filter and six quadrupole lenses of the EXOTIC facility. Two parallel plate avalanche counters (PPACs) [21] were placed downstream prior to the beam entering the scattering chamber. The PPACs were utilized as counters and for timing and on-line monitoring of the $^{15}$O beam (PPAC A predominantly during tuning and as a reference/check for PPAC B). Finally, the $^{15}$O beam crossed a 2.2 μm thick Havar window that separated the scattering chamber filled with $^4$He gas at a pressure of 467 mbar from the high vacuum beam line (see Fig. 1). The $^4$He gas pressure and temperature were continuously monitored and did not change appreciably during the experiment. The $^{15}$O beam intensity was typically in the range 1-2×10$^4$ particles/s with ≈99% purity. (Aside: development of the $^{15}$O beam was carried out by the present authors approximately 1 year prior to the experiment and is reported in Ref. [22].)

The apparatus for detecting the elastically scattered light charged particles, illustrated in Fig. 1, consisted of one 300 μm double-sided silicon strip detector (DSSSD) from the EXPADEX detector array [21], capable of stopping α particles up to 24 MeV. The 6.4×6.4 cm$^2$ 0° DSSSD was segmented here into 16 strips — orthogonal on each face — yielding 256 effective pixels. The angular acceptance of this 0° detector is 3.5° in the laboratory frame (6.5° com) for scattering events occurring at the entrance of the chamber and 6.6° in the laboratory frame (14.5° com) for those events occurring at a distance of approximately 310 mm from the window.

**ANALYSIS**

The identification of α-particles was performed by measuring the TOF between an $^{15}$O particle crossing PPAC B and the detection of the recoiling α-particle in the silicon detector, as done, for example, in Ref. [17].

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**FIG. 1.** (color online) Schematic (not to scale) of the experimental apparatus. The detection system consisted of a DSSSD and two PPACs required for the Time-Of-Flight measurement and beam tracking.

**FIG. 2.** (color online) A plot of detected energy versus TOF. Alpha particles originating from elastic scattering (and selected for further analysis) correspond to the locus inside the black long-dashed contour. The corresponding simulated distribution is indicated by the red continuous line. The red short-dashed line corresponds to α particles originating from inelastic scattering, demonstrating that events from this process can be excluded from the analysis, but in this instance, have not been observed. The intensities are given by the heatmap color scale. Note, that as inelastic excitation reduces the available kinetic energy, these reactions take place in the gas closer to the window for the same detected α energy. Since the α particles travel faster than the $^{15}$O ions, this reduced $^{15}$O flight path leads to a shorter TOF, giving the position of the inelastic locus as shown here.
In the present experiment the TOF measurements also allowed the discrimination between elastic and inelastic scattering [18]. The identification plot, Fig. 2, shows TOF versus detected α-particle energy. The calculation for α-particles that are elastically (upper solid red line) or inelastically scattered (lower short-dashed red line) are superimposed on the experimental data. (Inelastic scattering would lead to an excited 15O* recoil, the first excited state of which lies at 5.183 MeV [23].) As can be seen, there is no evidence of inelastic events in the data. Clean (proton- and inelastic-free) elastic scattering events were selected by a graphical cut (black long-dashed line) in Fig. 2. Additionally, the information from PPACB, the measured efficiency of which is ≈90%, was used to count the beam particles entering the scattering chamber in order to obtain the absolute elastic scattering differential cross sections.

Once the elastically scattered α-particles are selected it is possible to transform the detected α-particle energy into center-of-mass energy, $E_{\text{com}}$, providing the stopping powers of 4He and 15O in 4He are known. Knowledge of the stopping power for the incident beam in 4He gas is critical in this method, since any inaccuracies generate distortion in the deduced excitation function as shown in Fig. 2 of Ref. [24]. For this reason instead of using the stopping power calculated with codes such as SRIM [25] etc., which can introduce systematic errors as large as 15%, the stopping power for 16O in 4He has been measured [26]. This enabled the associated values for 15O in 4He to be deduced as the electronic stopping power depends only on the atomic features of the ion. This scaling from a known isotope only requires of the velocity change arising from the mass difference which can be easily calculated. To emphasize the importance of this correction, an interaction taking place 200 nm after the window leads to an energy loss for 15O of 16.9 MeV (28.5→11.6 MeV) and for an elastically scattered α produced at the same position, the energy loss is 2.1 MeV (7.7→5.6 MeV).

The resulting elastic scattering excitation function is shown in Fig. 3. The energy resolution of (FWHM) ≈20-30 keV in the com frame (corresponding to FWHM≈50 keV in the laboratory frame) has been found, from Monte-Carlo simulations [27], to be approximately constant over the measured energy range. The resolution is an effect of energy and angular beam spread and also includes intrinsic detector and electronics contributions.

**R-Matrix analysis**

In order to extract widths, partial decay branches, energies and spins for the states, the R-matrix method was used which solves the coupled Schrödinger equations for several reaction channels in order to fully describe the properties of the populated levels. A comprehensive description can be found in Ref. [28].
The energy levels of $^{19}$Ne from the present $R$-matrix fit, compared with candidate states taken from the compilation for $^{19}$Ne [30] and more recent references where indicated. Statistical errors arising from the $R$-matrix fit are given in parentheses, but for the energies in the first column there is an additional systematic uncertainty of ±50 keV. Energies in **bold** are newly observed in the present work. Note that only measured widths from the literature are listed for $^{19}$Ne. See text for details. Where multiple assignments are given, $\theta_i^2$ corresponds to the first. Grey shading highlights the new information obtained in the current work. Additionally, the properties of corresponding levels in $^{19}$F [30] are quoted in the final three columns.

<table>
<thead>
<tr>
<th>$^{19}$Ne current work</th>
<th>$^{19}$Ne literature</th>
<th>$^{19}$Ne current work</th>
<th>$^{19}$Ne literature</th>
<th>$^{19}$F literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{c}$ (MeV)</td>
<td>$E_{r}$ (MeV)</td>
<td>$l$</td>
<td>$\Gamma_{\alpha}$</td>
<td>$\Gamma_{\gamma}$</td>
</tr>
<tr>
<td>5.359(6)</td>
<td>5.351(6)</td>
<td>$1/2^+$</td>
<td>10(3)</td>
<td>10(3)</td>
</tr>
<tr>
<td>5.487(4)</td>
<td>5.463(20)</td>
<td>$3/2^+$</td>
<td>9(2)</td>
<td>9(2)</td>
</tr>
<tr>
<td>5.704(8)</td>
<td>5.613(7)</td>
<td>$3/2^+$</td>
<td>10(1)</td>
<td>21(8)</td>
</tr>
<tr>
<td>5.983(9)</td>
<td>6.013(7)</td>
<td>$3/2^+$</td>
<td>10(1)</td>
<td>21(8)</td>
</tr>
<tr>
<td>6.197(8)</td>
<td>6.621(1)</td>
<td>$1/2^+$</td>
<td>10(1)</td>
<td>21(8)</td>
</tr>
<tr>
<td>6.279(2)</td>
<td>6.395(5)</td>
<td>$1/2^+$</td>
<td>6(2)</td>
<td>6(2)</td>
</tr>
<tr>
<td>6.395(5)</td>
<td>6.437(9)</td>
<td>$1/2^+$</td>
<td>181(58)</td>
<td>181(58)</td>
</tr>
</tbody>
</table>

$^a$ $^{19}$F(p,o) $^{15}$O [34]; $^b$ $^{19}$F(p,p) $^{19}$F [35,36]; $^c$ $^{19}$F(p,p) $^{19}$F & $^{18}$F(p,o) $^{15}$O [37]; $^d$ Inelastic scattering $p(^{19}$Ne,p)$^{19}$Ne [38]; $^e$ $^{20}$Ne(p,d)$^{19}$Ne [7]; $^f$ Ref. [16]; $^g$ $^{19}$F(^3He,t)$^{19}$Ne Ref. [39]; $^h$ Ref. [40]; $^i$ See text for details.

**RESULTS AND INTERPRETATION**

The absolute $R$-matrix cross sections (red solid line of Fig. 3) are within 4% of the values obtained independently from the experimental data via measurement of the beam current using PPACB (data of Fig. 3). As can be seen from Table I, many of the levels compare well with previously observed states and the most likely candidates from the literature based on spin, parity and energy are given for comparison. Those marked in bold in Table I are newly observed in the current work, i.e. no comparable state is known in the literature; two of these lie below the proton threshold. Furthermore, very little information exists in the literature for the widths – both total and partial – of states in the excitation region populated here. This paucity has been noted by Tan et al. [41]. Where information does exist, it is often based on the reduced width of the equivalent mirror states in $^{19}$F. However, the physical properties of states are quoted here only where measured data exist to provide a like-for-like comparison. Also note that only the 7.153 MeV level has a non-negligible proton width of 19(14) keV, consistent with the literature value of 14(2) keV [37]. Further to this we shall discuss the results, the final three columns of Table I contain the excitation energies, spins and parities and total widths for corresponding states in the mirror partner $^{19}$F [30].

The spins and parities obtained here agree well with previous results where available, in several cases support-
ing previous tentative assignments, e.g. for the 5.983, 6.279 and 6.395 MeV levels. The large energy difference between the tentatively observed 8.790 MeV state and the 8.920 MeV literature value implies that these could be different levels. For the states populated only one is observed to have a non-negligible proton decay – the 7.153 MeV state. This is due to the selectivity of the reaction. The resonance technique used here, by its nature selectively populates states which undergo disintegration via α decay, once again highlighting the usefulness of making this direct measurement over indirect techniques which can suppress states with α character. It should be noted that the 8.814 MeV state has large uncertainties on both the width and energy and as such remains tentative, since additional components from overlapping levels cannot be resolved. In part, this is due to the full energy not being fully inside the explored excitation energy range. As a result, no associated mirror state is included.

Partial widths for all the states have been extracted from the R-matrix fit, which for most of the levels is the first such measurement. Note that due to the possibility of states with small natural widths occurring, the $\theta^a$ values in Table I could, in such cases, represent upper limits. Where width data have been reported there is qualitative agreement with the exception of the 7.153 MeV α width and 7.568 MeV total width. For the former, the uncertainty is large, perhaps indicating an additional juxtaposed α-decaying resonance. For the 7.568 MeV state, either a resonance different to that reported in the literature has been populated or there is an additional, unidentified level at a similar excitation energy. The relatively large uncertainty on the observed energy ($\pm 27$ keV) could be indicative of this latter scenario.

In terms of mirror structure, there is a good correspondence between the newly observed levels in $^{19}$Ne and their counterparts in $^{19}$F, with differences been in general $<200$ keV and in most cases $<100$ keV.

For near-threshold resonances knowledge of the partial decay widths (as well as energies) are needed as these affect reaction-rate calculations, so the large number of states for which α-width data have been obtained represents a key result for the destruction of $^{19}$F via $^{18}$F$(p,\alpha)^{15}$O.

In terms of the underlying structure, recently Otani et al. [42] have performed calculations of $^{15}$O+$\alpha$ rotational bands in a simple potential model calculation using the well known $^{16}$O+$\alpha$ cluster band configurations and $^{15}$N+$\alpha$ elastic scattering data. The analog states of the $^{16}$O+$\alpha$ 0+, 2+, 4+ and 6+ rotational sequence in $^{20}$Ne leads to doublets (one favored and one unfavored signature) for all but the 0+ state, resulting in $^{19}$Ne levels with spins of $1/2^-$ → $17/2^-$. Table II and Fig. 4 summarize both the calculated and experimental levels. It can be seen that the newly observed $13/2^-$ level at 8.428 MeV is very close to the predicted rotational level. Though not a unique assignment in this case ($11/2^+$ yields a fit comparable to that of Fig. 3) there is a corresponding $13/2^-$ level in $^{19}$F at 8.288 MeV. Previously no $13/2^-$ level was known in $^{19}$Ne in this energy regime. Additionally, the spin of the $11/2^-$ state at 8.790 MeV in the present study is consistent with that given in Ref. [30], though there is a 200 keV energy difference possibly indicating this may be a previously unobserved level. Despite being relatively weak, this resonance is only reproduced well via an $11/2^-$ assignment, but the parity remains uncertain. However, looking across the entire band, the agreement between calculated and measured excitation energy is good, albeit tentative. Otani and coworkers further predict the $17/2^-$ and $15/2^-$ levels at 14.05 and 14.44 MeV respectively as analogs of the $8^+ 15$O+$\alpha$ state in $^{20}$Ne.

In order to further explore the structure of the observed states, the reduced-width-to-Wigner limit, $\theta^2$ (Eq. 2), was examined for the α-decay branches. A significant number of the observed levels have a relatively large ratio to the Wigner limit, above the nominal 10% that is used to indicate significant α preformation. This is as expected due to the predisposition of the reaction for populating states with $^{15}$O+$\alpha$ character.

Focusing on the predicted $^{15}$O+$\alpha$ cluster band members (Table II), it can be seen that $\theta^2$ values obtained here are the first values established from measurements. It was noted by Tan et al. [41] that the upper limit they obtained for the branching ratio of the 4.14 MeV level of 1.2(0.5)$\times 10^{-3}$ was unexpectedly large and might indicate a possible α-cluster configuration. This gives it a more significant role in the hot CNO break out – dominating in some temperature regimes. (Note that part or all of the $\alpha$ strength could be from the 4.197 MeV state in $^{19}$Ne Expt. $\theta^2$)}

\begin{align*}
\text{TABLE II} & \quad \text{Expt.} & \quad \text{Calc.} & \quad \text{Sp}^{(19\text{Ne})} & \quad \text{Sp}^{(19\text{F})} \\
{\frac{5}{2}^-} & \quad 1618 & \quad 32 & \quad 1600 & \quad 32 \\
{\frac{7}{2}^-} & \quad 1518 & \quad 32 & \quad 1560 & \quad 32 \\
{\frac{9}{2}^-} & \quad 275 & \quad 12 & \quad 520 & \quad 12 \\
{\frac{11}{2}^-} & \quad 250 & \quad 12 & \quad 114 & \quad 12 \\
\end{align*}

\begin{align*}
\text{FIG. 4. Energy levels of }^{19}\text{Ne corresponding to the }^{15}\text{O}+\alpha \\
\text{rotational bands. The levels predicted in Ref. [42] (in the middle) are compared with the levels experimentally measured} & \quad \text{in the present work and Ref. [30] (on the left) and to the} \\
\text{corresponding }^{15}\text{N}+\alpha \text{ negative parity band in }^{19}\text{F (on the} & \quad \text{right) [30, 43].}
\end{align*}
TABLE II. Comparison of the calculated and measured $\alpha +^{15}$O rotational levels. Lines shaded grey represent the new information obtained in the current work.

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$I^\pi$</th>
<th>$\theta^2_\alpha$</th>
<th>$E_x$ (MeV)</th>
<th>$I^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.27509(13)$^a$</td>
<td>$\frac{3}{2}^-$ (bound)</td>
<td>0.52</td>
<td>$\frac{1}{2}^+$</td>
<td></td>
</tr>
<tr>
<td>1.51756(3)$^b$</td>
<td>$\frac{5}{2}^-$ (bound)</td>
<td>1.56</td>
<td>$\frac{1}{2}^-$</td>
<td></td>
</tr>
<tr>
<td>1.6156(5)$^b$</td>
<td>$\frac{5}{2}^-$ (bound)</td>
<td>1.66</td>
<td>$\frac{1}{2}^-$</td>
<td></td>
</tr>
<tr>
<td>4.140(4)$^b$</td>
<td>($\frac{5}{2}^-\frac{1}{2}^-$) &amp; $\leq 1^c$</td>
<td>3.98</td>
<td>$\frac{1}{2}^-$</td>
<td></td>
</tr>
<tr>
<td>4.197(2)$^b$</td>
<td>($\frac{3}{2}^-\frac{1}{2}^-$) &amp; $\leq 0.1^c$</td>
<td>4.18</td>
<td>$\frac{1}{2}^-</td>
<td></td>
</tr>
<tr>
<td>8.428(2)$^a$</td>
<td>($\frac{3}{2}^+\frac{1}{2}^+$)$^b$</td>
<td>0.31(4)$^b$</td>
<td>7.98</td>
<td>$\frac{3}{2}^-</td>
</tr>
<tr>
<td>(8.790)$^a$</td>
<td>($\frac{11}{2}^+\frac{1}{2}^+$)$^b$</td>
<td>0.10(3)$^d$</td>
<td>8.26</td>
<td>$\frac{1}{2}^-</td>
</tr>
<tr>
<td>14.2(3)$^b$</td>
<td>—</td>
<td>—</td>
<td>13.67</td>
<td>$\frac{7}{2}^-</td>
</tr>
<tr>
<td>14.5(3)$^b$</td>
<td>—</td>
<td>—</td>
<td>14.26</td>
<td>$\frac{5}{2}^-</td>
</tr>
</tbody>
</table>

$^a$There is an uncertainty of $\approx 50$ keV on the calculated energies for $\frac{1}{2}^-$ and above, from extracting the values from Fig. 3 of Ref. [42]. $^b$Ref. [30]. $^c$Based on the level properties given by Tan et al. [41]. $^d$Present work.

Comparing to the band structure in $^{19}$F as shown in Fig. 4, the similarities are, as expected, striking and supportive of the clustering than observed in $^{15}$O rotational structure. The favored state having the larger $\alpha$-width-to-Wigner ratio in each instance, but all four levels possessing significant ratios, i.e., $>0.1$.

To explain the increased role played by some levels in the astrophysical $^{15}$O($\alpha,\gamma$)$^{16}$Ne reaction that is important for break out from the hot CNO cycles and, therefore, for X-ray bursts due to the subsequent onset of rapid proton capture reactions. Additionally, levels have been newly identified close to the proton threshold, which may have consequences for the destruction of $^{18}$F, though more work is needed to establish the magnitude of proton widths in this energy region.

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CONCLUSION

In summary, the challenging direct measurement of states in $^{19}$Ne via the resonant elastic scattering of a radioactive $^{15}$O beam on an extended $^4$He gas target has been achieved across a wide energy range for the first time. Levels in the 5.3 – 8.8 MeV excitation-energy region have been explored, with a significant number (at least seven) newly observed in the present work. Additionally, partial widths have been extracted for the observed levels, the majority (thirteen) for the first time. Reliable cross sections have been measured across the full range of levels populated representing important input to reaction-rate models.

Evidence for the predicted $\alpha +^{15}$O rotational structure has been obtained. Such an enhanced $\alpha$ structure could explain the increased role played by some levels in the astrophysical $^{15}$O($\alpha,\gamma$)$^{16}$Ne reaction that is important for break out from the hot CNO cycles and, therefore, for X-ray bursts due to the subsequent onset of rapid proton capture reactions. Additionally, levels have been newly identified close to the proton threshold, which may have consequences for the destruction of $^{18}$F, though more work is needed to establish the magnitude of proton widths in this energy region.

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