

First observation of α -cluster states in the $^{14}\text{O} + ^4\text{He}$ interaction

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We measured $^{14}\text{O} + ^4\text{He}$ excitation functions for elastic scattering which demonstrate, for the first time, a well developed α -cluster structure in the proton rich nucleus, ^{18}Ne . We present the excitation energies and estimates of the spins for the dominant resonances using an \mathbf{R} -matrix approach. A resonance at 9.2 MeV excitation energy in ^{18}Ne is particularly interesting. The spin-parity of the state is found to be 3^- and the α particle reduced width for the state appears to be comparable to the single particle limit. We have found indications for unusually large size of the observed α -cluster configuration.

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Our knowledge of the α -cluster structure in atomic nuclei is mainly based on the investigation of self-conjugate $4N$ nuclei, like ^8Be , ^{12}C , ^{16}O , and so on (for the most recent review see [1]). Many theoretical calculations [2,3] have suggested that clustering remains in systems composed of a collection of α particles and valence nucleons. The available data on the α -cluster states in neutron rich nuclei are scarce [4–7], but they give indications for the developed cluster structures with very large moments of inertia. The study of non-self-conjugate nuclei has an advantage in that one can investigate isobaric analog states in mirror systems. Comparison of the results for both systems can bring new spectroscopic information and shed light on such properties as the radii of the cluster states. At present the data on the α -cluster states in proton rich nuclei are absent. There is no clear understanding of what will happen to cluster structure when valence protons are substituted for valence neutrons [3].

α clustering may play a role in helium burning in astrophysical systems. Indeed, even if astrophysical reactions involving helium do not proceed through strong α -cluster states (because of high excitation energy), these states can provide an α width to the states that are closer to the region of astrophysical interest through configuration mixing [8]. For many systems, the information needed to understand this can be obtained only in the reactions induced by radioactive beams.

This paper presents the first results on α -cluster states in ^{18}Ne from the resonant interaction of a radioactive ^{14}O beam with ^4He . The specific measurements were made with the knowledge that very detailed data have been obtained on $^{14}\text{C} + ^4\text{He}$ resonance scattering, and one can expect the results of the analysis soon [9].

The ^{14}O beam was obtained at the Texas A&M University Cyclotron Institute, using the recoil spectrometer MARS [10] and a primary ^{14}N beam impinging on a H_2 gas target cooled to liquid nitrogen temperature (see [11] for a more detailed description). The measurement of the $^{14}\text{O} + ^4\text{He}$

elastic-scattering excitation function was carried out using the thick target inverse kinematics (TTIK) method [12]. The TTIK method allows for the possibility to obtain a continuous excitation function from the initial energy down to the lowest detectable energy. The general setup used for this measurement was similar to that described in [11]. The main difference was that the large square particle detectors, which consisted of four $25\text{ mm} \times 25\text{ mm} \times 1\text{ mm}$ Si detectors, were placed along the back wall of the scattering chamber, which was filled with helium.

This increased the available distance to stop the ^{14}O ions before the detectors, allowing a lower gas pressure to be used in the scattering chamber. In turn, this provided for better particle identification by using the time-of-flight method, as described in [11]. Using time-of-flight with the TTIK technique (instead of $dE-E$) made it possible to detect low energy α particles with good particle identification in a large background of protons. A typical particle identification spectrum for a small square detector is shown in Fig. 1. The lowest locus corresponds to protons. Protons with an energy over 12 MeV punch through the detector and show up as the bend in the curve. The higher locus corresponds to α particles.

In the inset of Fig. 1, one can see a large spot above the α -particle locus. This is due to ^7Be , which is present as a contamination ($\sim 1\%$) in the ^{14}O beam. Because the two isotopes have the same Z/A ratio, ^7Be cannot be separated from the ^{14}O beam by MARS or by the time-of-flight method. Furthermore, as the ^7Be ions have a much longer range in helium than ^{14}O , they reach the particle detectors.

The ^7Be intensity was more than to 10^3 times larger than the intensity of the peaks in the α spectrum in the zero degree detector, and ^7Be contaminated the α spectra in a large region at small angles. An amplitude analysis of the light signals, produced by the beam particles in a thin plastic foil placed upstream of the scattering chamber [11], allowed us to discriminate against the ^7Be events at nonzero degree angles, as can be seen in Fig. 1 where the main part of the figure was produced using a veto on the beam contamination. At zero degrees ^7Be events were still present since the resolution

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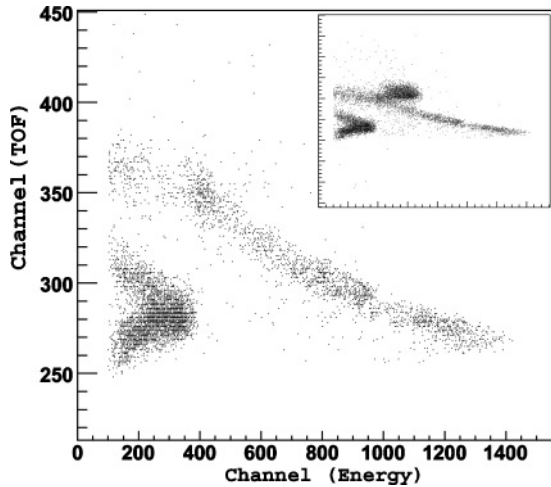


FIG. 1. Time of flight-energy particle identification spectrum for the products of the $^{14}\text{O} + ^4\text{He}$ interaction measured at three degrees in the laboratory frame. The inset shows the same spectrum without discrimination of the ^7Be contamination in the beam. See text for details.

in the thin scintillator was not good enough to discriminate the simultaneous $^7\text{Be} + ^{14}\text{O}$ events emerging from the same cyclotron beam bucket.

Three runs (ranging from two to seven days) corresponding to between 3×10^9 and 2×10^{10} integrated ^{14}O ions were made using ^{14}O beam energies between 33 and 57 MeV. The reasons for varying the primary beam energy were to better understand the contribution of the ^7Be contamination in the spectra, and to find a way to produce a low energy beam for application to astrophysical problems [11].

Figure 2 shows the the $^{14}\text{O} + ^4\text{He}$ excitation functions for the elastic scattering at 180° c.m. (0° in the laboratory system). The energy resolution of ~ 40 keV in the c.m. is smaller than the observed width of the majority of the peaks. [The energy spread in the beam, 1.6 MeV at 57 MeV incident energy, was the main contributor (~ 30 keV) to the final energy resolution.] The precision in the absolute values of the energies is better than 25 keV c.m. The energy region around 6 MeV was contaminated by ^7Be . Therefore the data obtained at a beam energy of 33 MeV, which were free from the ^7Be contamination in this region, were inserted in the figure for this excitation energy range. (A part of the 42 MeV data is shown in Fig. 2 to demonstrate the consistency of the results at low energy.) Also an excitation function for $\alpha + ^{14}\text{C}$ elastic scattering [13] is given in Fig. 2 for comparison. The $\alpha + ^{14}\text{C}$ excitation function was measured with a conventional method [13] and 169° was the largest angle that was measured in the backward hemisphere.

A few points of interest can be noticed from Fig. 2. (1) At the lowest energies, the resonance cross sections are close to the Rutherford ones without any normalization. (2) There are strong peaks in the $^{14}\text{O} + ^4\text{He}$ spectrum even at high excitation energy in ^{18}Ne , which is the evidence for α -cluster structure in ^{18}Ne . (3) While strong peaks are present both in the $^{14}\text{O} + ^4\text{He}$ and $^{14}\text{C} + ^4\text{He}$ spectra, the specific details are surprisingly different for the mirror reactions. For instance, the first strong

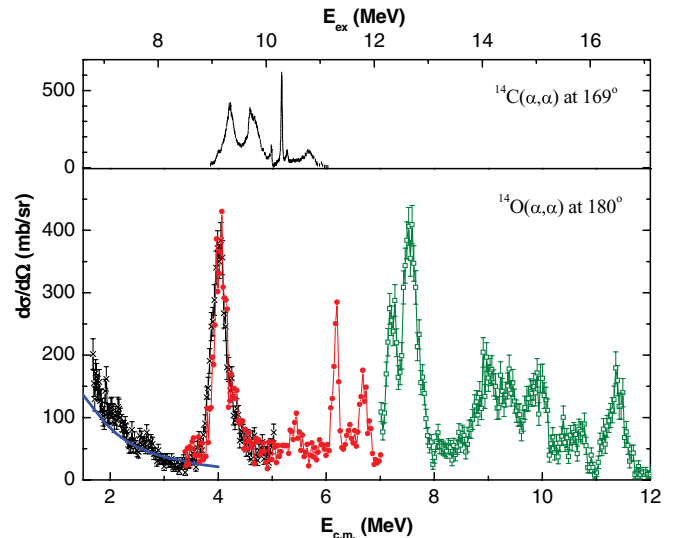


FIG. 2. (Color online) Excitation function for $^{14}\text{O} + ^4\text{He}$ elastic scattering at 180° c.m. (0° in the laboratory system). The excitation energies in ^{18}Ne are shown at the top. The data shown with dots are from the measurements at the 33 MeV initial ^{14}O energy. The data represented by crosses are from 42 MeV. The data shown with a boxes represent the measurements at the 57 MeV initial ^{14}O energy. The excitation function for $\alpha + ^{14}\text{C}$ [13] is shown at the top. The bold line gives the Rutherford cross section.

resonances at 9 MeV excitation energy seem to belong to mirror states in ^{18}O and ^{18}Ne . However, the next equally strong resonance in the ^{18}O spectrum, which corresponds to a 300 keV higher excitation energy, is absent in the ^{18}Ne spectrum. This is not due to the difference in angles for the two spectra. In particular, the angular distributions for the data in Fig. 2 show no evidence for a second strong peak in the $^{14}\text{O} + ^4\text{He}$ spectra.

Counting statistics for the low energy data were sufficient to make an **R**-matrix analysis of the angular distributions. We also present in Table I one level **R**-matrix estimates of the minimal possible values of spins for the most prominent high energy resonances in Fig. 2, assuming that the reduced width for the proton decay channel with the most favorable penetrability is $\sim 10\%$ of the reduced width for the α decay. The reduced proton width for the lowest three states in Table I was in the range 0.15–0.3 of of the reduced width for the α decay. To estimate the minimal value of spins for the higher energy resonances we assumed a smaller proton width. The ratio of 0.15 would result in an increase in the estimated spin values (Table I) by at least one unit. The simple analysis, which is presented here, provides a compact representation (Table I) of the experimental data. The uncertainties are still defined by the experimental precision. However, a more sophisticated **R**-matrix analysis with many interfering resonances, which we intend to include based on the $\alpha + ^{14}\text{C}$ data, can lead to slightly different results. Usually the corrections for the excitation energies and for the widths of the resonances do not exceed 1/3 of the widths, which are given by the simple analysis. Somewhat larger corrections might be expected for the broad low spin (1^-) resonances.

TABLE I. Resonance parameters. (The estimations of the minimal values of spins for high energy resonances are given assuming that the reduced width for the proton decay channel with the most favorable penetrability is $\sim 10\%$ of the reduced width for the α decay. The ratio of 0.15 would result in an increase in the estimated spin values by at least one unit.)

$E_{c.m.}$ (MeV)	$E_{ex}^{(^{18}\text{Ne})}$ (MeV)	Γ_{tot} (MeV)	Γ_{α} (keV)	J^{π}
3.6	8.7	0.5	260	$(1^-, 0^+)^a$
4.1	9.2	0.3	180	3^-
5.0	10.1	0.4	300	(1^-)
5.5	10.6	0.2		(≥ 2)
6.2	11.3	0.1		(≥ 4)
6.7	11.8	0.2		(≥ 3)
7.2	12.3	0.2		(≥ 4)
7.6	12.7	0.3		(≥ 5)
9.0	14.1			
9.4	14.5			
9.9	15.0			
11.4	16.5			

^aSee the text for the explanation.

Figure 3 presents the **R**-matrix fit for the low energy part of the $^{14}\text{O} + ^4\text{He}$ excitation functions using three resonances 1^- , 3^- , and 1^- , and the parameters given in Table I. The 3^- assignment for the strong peak is reliable. A 2^+ resonance

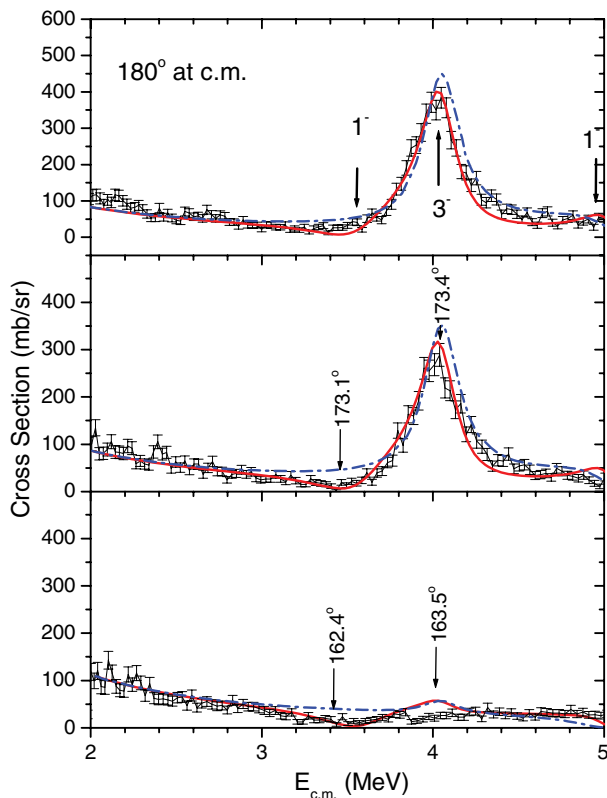


FIG. 3. (Color online) **R**-matrix fit for the low energy part of the excitation functions for $^{14}\text{O} + ^4\text{He}$ elastic scattering. The arrows indicate the c.m. angles. The dash-dot line shows the results of calculations without the first 1^- resonance.

would produce a smaller cross section at 180° and a steeper fall off with angle, while a 4^+ level would produce a too narrow peak with too fast a fall off. An analysis [14] of the $\alpha + ^{14}\text{C}$ data [13] also resulted in the 3^- assignment for the corresponding resonance in the ^{18}O spectrum. The strong and broad 1^- resonance at 3.6 MeV (c.m. energy) provides for a broad minimum and destructive interference with Rutherford scattering at the lowest energies. There is also evidence for a strong 1^- α -cluster resonance at a similar excitation energy in ^{18}O [7,14]. However, it is claimed in [14] that their analysis cannot rule out a 0^+ value, and, though in Ref. [7] only 1^- states could be observed, the excitation energy of the 1^- state in question was given with large uncertainties (9.16 ± 1 MeV). We also cannot rule out the 0^+ assignment on the basis of our data, but taking into account the data of Ref. [7], the 1^- assignment seems more probable. The strong 1^- resonance of Ref. [7] should be observed by our experimental approach.

As for the second 1^- state at 5.0 MeV, its inclusion mainly is based on more precise data [7] for a possible mirror 1^- state in ^{18}O (9.85 ± 0.5 MeV). The second 1^- resonance improves the fit in the energy region near the tail of the 3^- resonance.

The data obtained for the 3^- resonance can be used to obtain a more quantitative understanding of its structure through a comparison of the experimental α particle width with the single particle value calculated in a potential well without antisymmetrization. We used typical optical model parameters for the real part of the Woods-Saxon potential (see, for example [15]) of the α particle-nucleus interaction, $V_0 = -136$ MeV, $a = 0.6$ fm, $r_0 = 1.3$ fm. The depth of the potential was fit to generate the experimental excitation energy of the state. The calculated width is 270 keV. The measured α -particle decay width is 180 keV, which exhausts well over half of the limiting width. This is direct evidence for α -cluster structure in the state.

There are well known [16] 3^- α -cluster states in the nearby self-conjugate nuclei ^{16}O ($E_{ex} = 11.6$ MeV), and ^{20}Ne ($E_{ex} = 7.2$ MeV). The excitation energy of the level in ^{18}Ne is just in between these two values. The 3^- α -cluster states in ^{16}O and ^{20}Ne are members of the well known α -cluster rotational bands with negative parity and with 1^- states as the band heads. The band head is 2 MeV below the 3^- state in ^{16}O and 1.3 MeV in ^{20}Ne . Presumably, this difference is proportional to the square root of the effective radii of the systems. If one extends this argument to ^{18}Ne and takes the excitation energies for the 1^- and 3^- states from Table I, we conclude that there is a large increase in the radius of the α -cluster states in ^{18}Ne .

It also seems relevant to illustrate an astrophysical impact of the α -cluster data using a comparison with the ^{16}O case. The subthreshold 7.12 MeV 1^- state in ^{16}O plays an important role in astrophysical processes due to the $^{12}\text{C}(\alpha, \gamma)$ reaction. The well known 1^- α -cluster state in ^{16}O is at 9.6 MeV, well above the astrophysical energy region. Still it is important in providing for the dimensionless reduced α particle width of 0.017 ± 0.03 [8,17,18] for the 7.12 MeV state (and also corresponding interference). The $^{14}\text{O}(\alpha, p)$ reaction, involving the ^{18}Ne states near the α particle threshold (5.1 MeV), is an important issue in nuclear astrophysics [19,20] because it can influence the CNO cycles. The excitation energy of the 8.7 MeV (1^-) α -cluster state of the present work is too high to be directly involved in the process. However there is

another 1^- state at 6.15 MeV in ^{18}Ne [16]. Taking into account the excitation energies, quantum characteristics and general shell model considerations, one can assume a similar nuclear structure for the 7.12 MeV state in ^{16}O and 6.15 in ^{18}Ne , and the same order of magnitude for a cluster admixture to the main particle-hole configuration. Very difficult measurements of the time inverse $p(^{17}\text{F}, \alpha)^{14}\text{O}$ reaction [20] using a radioactive ^{17}F beam gave $0.04(+0.05; -0.025)$ for the reduced width in question at the same as in [17], 6.5 fm, channel radius. We believe that the accumulation of similar data will allow the possibility of predicting the α -cluster widths for experimentally difficult cases just as is done for single particle widths.

Another interesting point is the difference in the ^{18}Ne and ^{18}O spectra, which were obtained in resonance scattering. A clue to this may be in the difference of the decay thresholds for ^{18}O and ^{18}Ne . While the lowest decay threshold in ^{18}O is for an α particle decay, the lowest decay particle is a proton in ^{18}Ne . Therefore it is likely that some levels in ^{18}O that decay by α particles would not be observed in the present experiment because the corresponding states decay by protons. Clearly the comparison of the mirror spectra is useful to reveal details about nuclear structure. Of course, the comparison can be made only after a complete **R**-matrix analysis is done.

In summary, we measured $^{14}\text{O} + ^4\text{He}$ excitation functions for elastic scattering, which demonstrated, for the first time,

α -cluster structure in a proton rich nucleus ^{18}Ne . We estimated the reduced width for a 3^- state formed in resonant excitation, which appears to be comparable to the single particle limit. We also have indications for an unusually large size for the α -cluster configuration.

The states in ^{18}Ne that are important for stellar evolution are about 2 MeV lower than those observed here. Some progress in the study of the states with a lower excitation energy could be made with a longer experiment or through the use of the $^{17}\text{F}(p, \alpha)$ reaction [20]. However results for the lowest relevant energies still will be difficult to obtain by these techniques involving beams of the radioactive nuclei. We believe that further studies of the α -cluster states in $N \neq Z$ nuclei will provide the ground work for a better understanding of the α -particle widths in the energy region important for astrophysics.

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