Clustering in $N \neq Z$ nuclei.

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Abstract. The structure of the $^{18}$O nucleus at excitation energies above the $\alpha$ decay threshold was studied using $^{14}$C+$\alpha$ resonance elastic scattering and ($^7$Li,$t$) $\alpha$-transfer reactions. A number of states with large $\alpha$ reduced widths have been observed, indicating that the $\alpha$-cluster degree of freedom plays an important role in this $N \neq Z$ nucleus. A $0^+$ state with an $\alpha$ reduced width exceeding the single particle limit was identified at an excitation energy of 9.9±0.3 MeV. We discuss evidence that states of this kind are common in light nuclei and give possible explanations of this feature. Also, the astrophysical implications of the cluster structure of $^{18}$O is discussed.

1. Introduction

$\alpha$ clustering manifests itself in light 4$N$ nuclei such as $^8$Be, $^{12}$C, $^{16}$O, and $^{20}$Ne through the existence of twin quasi-rotational bands of states with alternating parities and $\alpha$-particle reduced widths which are close to the single particle limit (see recent review by M. Freer [1] and references therein).

There are different approaches that attempt to describe the shell model and the $\alpha$-cluster structure of nuclei on an equal footing in order to shed light on the interplay between the $\alpha$-cluster and single particle degrees of freedom [1]. Data on the nucleon decay of $\alpha$-cluster states would be instrumental for such efforts. However, this data is practically absent due to the much higher nucleon decay thresholds in comparison with the thresholds for the $\alpha$ decay in the 4$N$ nuclei. It is more promising to observe nucleon decay from the $\alpha$-cluster states in $N \neq Z$ nuclei where the nucleon and $\alpha$-particle thresholds are close to each other. The study of non-self-conjugate nuclei has an advantage in that one can investigate $\alpha$-cluster states in mirror systems and use the Coulomb shift to extract information on the relationship between the cluster and single particle degrees of freedom. Unfortunately, the data on the $\alpha$-cluster structure of $N \neq Z$ nuclei is generally very limited.

Current interest in the $\alpha$-particle interaction with $N \neq Z$ nuclei is also strongly motivated by astrophysics [2]. Even if astrophysical reactions involving helium do not proceed through the strong $\alpha$-cluster states (because of high excitation energy), these states can provide $\alpha$ width to the states that are closer to the region of astrophysical interest through configuration mixing [3]. In order to better understand this process we investigated the $\alpha$-clusterization of the states in $^{18}$O ranging from just below the $\alpha$-decay threshold to ~4.5 MeV above the threshold. The properties of the higher lying states were studied through $^{14}$C+$\alpha$ resonance elastic scattering,
while the states nearest to the threshold were determined using sub-Coulomb (6,7Li,d/t) α-transfer reactions along with the Asymptotic Normalization Coefficient (ANC) technique.

2. A Study of the 18O Cluster Structure Through Resonance Elastic Scattering

We report here new measurements of α+14C resonance elastic scattering made using the Thick Target Inverse Kinematics (TTIK) method [4]. This experimental approach provided good statistics and excitation functions which were remarkably free of any background. The data provided a basis for a successful analysis of the excitation functions using a complete multi-level, multi-channel R-matrix approach [5]. As a result, we found that in 18O there is a system of strong α-cluster states. Both α and nucleon reduced widths of these α-cluster states were determined from the multi-channel R-matrix fit.

The experiment was carried out at the Florida State University John D. Fox Superconducting Accelerator Laboratory. The 25 MeV 14C beam was projected into the scattering chamber, which consisted of two compartments. The first compartment was under vacuum, the second was filled with 99.9% pure helium gas (4He). The two compartments were separated with a 1.27 µm Havar foil. The helium gas pressure in the second compartment was adjusted to stop the incoming beam before an array of Silicon detectors located at a distance of ~40 cm from the Havar foil. The accuracy of the absolute normalization of the cross section is 15%. Details of the method are given in [6].

The analysis of the excitation functions was performed using a multi-level, multi-channel R-matrix approach [5]. The 14C+α excitation functions measured in this experiment are continuous which excludes the possibility of missing a narrow resonance. The sensitivity of the data is demonstrated by the fact that even the 2+ state at 8.213 MeV, which has a width of ~1 keV, is still clearly visible in the 180° excitation function (see inset in Fig. 1). In addition, data from previous measurements of the 14C(α,α) [7] and 14C(α,n) [8] excitation functions were used. The R-matrix fit to the 14C(α,α) data is shown in Fig. 1. As can be expected most of the states also have substantial neutron widths, which are obtained through the (α,α) fit. We verified that the 14C(α,n) total cross section from Ref. [8] is reproduced rather well by R-matrix calculations performed using the parameters from the 14C(α,α) fit. One can notice that the R-matrix fit understimates the experimental cross section at the lowest energies for angles far from 180°. This is understood to be an effect of the finite dimensions of the beam spot.

The fourth panel in Fig. 1 is 90° data from [7]. The spectrum at 90° in c.m. is only influenced by states with even angular momentum and positive parity. This is an important simplification and makes the spectrum at 90° very valuable for the R-matrix analysis. Clearly, our data contains this information. However, for the purpose of a more clear representation of the data we used the spectrum of [7].

Twenty-four resonances were used to fit the data, some of them were previously known. Levels with large α-cluster reduced widths (θ^2 > 0.1) are given in Table 1.

Five levels with dimensionless α reduced width greater than 0.1 have been observed in 18O in the narrow excitation energy range between 9.1 and 9.9 MeV. Three of them have been suggested in previous publications [9–11]. The strong α-cluster state at 9.0 ± 0.2 MeV was first suggested in [9], where the 1− spin parity assignment was made on the basis of population of this state in 18N β decay. A more recent 18N β decay experiment [11] confirmed the 1− state at 9.16 MeV with a width of Γ = 420 ± 200 keV. Our R-matrix fit requires a 1− state at an excitation energy of 9.17±0.03 MeV in good agreement with [11]. The width of this state is lower in the present work (230±50 keV) but still within the error bars of [11]. Another 1− state observed at 9.85±0.5 MeV in [11] with a width of 560±200 keV is in very good agreement with the results of this work. The 3− at 9.39 MeV was previously suggested in [10] and has excellent agreement with the present results. The strong α-cluster 2− state at 9.77 MeV is identified for the first time in this work.
Nevertheless, existence of the broad disguise by interference with the sharp ones. This is especially true for the $0^+\sigma_{9.90}$ Rutherford cross section and the Rutherford with the broad $0^+$ dramatically due to the destructive interference of the $0^+$ effect of this state on the cross section is demonstrated in Fig. 2. The cross section is lowered single-particle limit. Using a classical approach one can interpret this as evidence that the $\alpha$ radii of 5.2 and 6.5 fm are 1.38 and 0.66 MeV observed experimentally. The $0^+\pi_1$ against it was that the characteristic interference pattern between two nearby $0^+$ follow the effect of the $0^+$ state in the spectrum of $14C$ elastic scattering measured at various angles, demonstrating the influence of the broad $J^\pi = 0^+$ state reported here. The red curves show the best $R$-matrix fit with the broad $J^\pi = 0^+$ state while the blue dash-dotted curve is the best fit without this state.

The most surprising finding of this work was the observation of a very broad $0^+$ state at $9.90\pm0.3$ MeV. Generally it is not easy to identify very broad resonances because they are disguised by interference with the sharp ones. This is especially true for the $0^+$ resonances. Nevertheless, existence of the broad $\alpha$-cluster $0^+$ state in the spectrum of $18O$ is certain. The effect of this state on the cross section is demonstrated in Fig. 2. The cross section is lowered dramatically due to the destructive interference of the $0^+$ state with Coulomb scattering. The Rutherford cross section and the Rutherford with the broad $0^+$ state at 9.90 MeV (3.7 MeV c.m.) are shown at two c.m. angles, 90° and 180°, in Fig. 2. Without this destructive interference it is not possible to reproduce the experimental data. As seen in the bottom panel of Fig. 1, the cross section calculated without the broad $0^+$ state is significantly larger than the experimental one. This is a clear indication of a $0^+$ resonance. All other resonances would not produce the right interference with the Rutherford scattering and could not be broad enough. One can follow the effect of the $0^+$ level at different angles in Fig. 1 and reach the same conclusion. We also considered the possibility of two narrower $0^+$ states instead of one. The decisive factor against it was that the characteristic interference pattern between two nearby $0^+$ states was not observed experimentally. The $\alpha$ particle reduced width amplitude of the $0^+$ state with channel radii of 5.2 and 6.5 fm are 1.38 and 0.66 MeV^{1/2}, respectively. Formally, both values exceed the single-particle limit. Using a classical approach one can interpret this as evidence that the $\alpha$ particle resides at a large distance from the $14C$ core.

A more detailed description of the observed $0^+$ state in $18O$ can be given using the potential model approach. The parameters of this model were extracted starting from the potential model.

Figure 1. (Color online) The excitation functions for $\alpha+14C$ elastic scattering measured at various angles, demonstrating the influence of the broad $J^\pi = 0^+$ state reported here. The red curves show the best $R$-matrix fit with the broad $J^\pi = 0^+$ state while the blue dash-dotted curve is the best fit without this state.

Figure 2. The top panel is the $\sin^2\delta_{J=0}$ from the $R$-matrix fit (solid curve) compared to the potential model prediction (dash-dotted curve). The middle and the bottom panel demonstrate influence of the broad $0^+$ state on the cross section at. The dash-dotted curve corresponds to Coulomb scattering and the solid curve shows the interference of the broad $0^+$ with Coulomb scattering.
Table 1. Levels with large $\alpha$-reduced width in $^{18}$O. $\Gamma_{tot}$, $\Gamma_\alpha$ and $\Gamma_n$ are the total and partial $\alpha$ and neutron widths, respectively. $\theta_\alpha^2 = \gamma_\alpha^2 / \gamma_{SP}^2$ is the dimensionless reduced width for the $\alpha$ channel, where $\gamma_{SP}^2 = \hbar^2 / \mu R^2$ is the single particle limit, calculated at channel radius 5.2 fm.

| $E_{exc}$ (MeV) | $J^\pi$ | $\Gamma_{tot}$ (keV) | $\Gamma_\alpha$ (keV) | $\theta_\alpha^2$ | $\Gamma_\alpha$ (keV) |
|----------------|--------|----------------------|----------------------|------------------|---------------------|
| 9.17(3)        | 1$^-$  | 229(50)              | 200(50)              | 0.24             | 29(7)               |
| 9.39(3)        | 3$^-$  | 151(50)              | 100(48)              | 0.45             | 51(15)              |
| 9.75(4)        | 1$^-$  | 628(100)             | 585(100)             | 0.43             | 43(10)              |
| 9.77(3)        | 2$^+$  | 251(50)              | 172(45)              | 0.20             | 79(20)              |
| 9.9(3)         | 0$^+$  | 2100(500)            | 2100(500)            | 2.6              | N/A                 |

for $^8$Be given in [12]. First, this potential model was used to investigate the $^{16}$O+$\alpha$ interaction by assuming the $\alpha$-cluster model [13] for the ground state of $^{16}$O, properly modified [14] to include antisymmetry and the strong repulsion between nucleons. The strong interaction between the incoming $\alpha$ and the target “alphas” is obtained by folding the Buck interaction [12] with the target $\alpha$-density in the ground state. The result is to produce a bound state for the ground state of $^{20}$Ne and a broad 0$^+$ state at 4 MeV in c.m. as observed in [15] with the same 0$^+$ phase shift behavior. The corresponding density distribution for this 0$^+$ resonance has an inner peak at 2 fm and an outer peak at 5 fm. The outer peak is at a separation distance beyond the sum of the charge radii of $^4$He and $^{16}$O and it contains most of the probability indicating that the broad 0$^+$ resonance in $^{20}$Ne appears to be a state with extreme $\alpha$-clustering.

The $^{18}$O system was then investigated using the $^{20}$Ne potential as a starting point but small changes in the strengths of the folded and repulsive potentials were used to reproduce the ground state of $^{18}$O. This potential produces a broad 0$^+$ state at 3.5 MeV in c.m. The experimental s-wave resonance phase shift from the R-matrix fit (solid black curve in Fig. 2a) is reproduced rather well by such a potential (dash-dotted blue curve in Fig. 2a). The density distribution for the broad 0$^+$ state in $^{18}$O is similar to the one in $^{20}$Ne. The outer peak is at 5.5 fm which is considerably larger than the sum of the charge radii for $^4$He and $^{14}$C. Both systems appear to show well separated $\alpha$-cluster configurations that correspond to extreme $\alpha$-clustering.

Due to the large distance between the $\alpha$ cluster and the core, one can speculate that levels of this kind should be a general feature of the interaction between an $\alpha$ particle and a core nucleus which is independent of the specific structure of the core. If this is the case then resonances of this kind should be present in all nearby nuclei at excitation energies on the order of 10 MeV above the first s-wave cluster state. Indeed, a broad (3 MeV) 0$^+$ level at an excitation energy of 10.3 MeV appears in $^{12}$C [16]. The most recent parameters, as given in [17], are an excitation energy of 10.73 MeV and a width of 1.72 MeV. However, there are still significant uncertainties in these values. Also, a broad 0$^+$ level ($\Gamma > 800$ keV) at an excitation energy of $\sim$8.5 MeV, was observed in $^{20}$Ne [15].

In order to understand the possible influence that these broad low spin resonances may have on astrophysically important reaction rates one must first determine the contribution of the near threshold states to the reaction rates. The contributions of the near threshold states in $^{18}$O to the reaction $^{14}$C($\alpha$, $\gamma$) are discussed in the following section.
3. Influence of Near Threshold states in $^{18}$O to the $^{14}$C($\alpha,\gamma$) Reaction Rate

The near threshold states in $^{18}$O are known to play a significant role in several astrophysical processes through the $^{14}$C($\alpha,\gamma$) reaction. It was suggested in [18] that the $^{14}$N($e^-,\nu$)$^{14}$C($\alpha,\gamma$)$^{18}$O reaction (NCO reaction) may trigger the helium flash in the core of low mass stars earlier than the $3\alpha$ reaction. Also, it was suggested by Nomoto and Sugimoto [19], and later by Hashimoto, et al. [20], that the NCO reaction may trigger the helium flash in accreting helium white dwarfs at a lower temperature and density than the $3\alpha$ reaction. However, this conclusion is rather sensitive to the actual value of the $^{14}$C($\alpha,\gamma$) reaction rate.

The $^{14}$C($\alpha,\gamma$) reaction is also important for production of $^{19}$F in asymptotic giant branch stars. Observations by Jorissen, et al., [21] show enhanced fluorine abundance in the atmosphere of K, M, MS, S, SC, and C asymptotic giant branch (AGB) stars. A detailed investigation of the $^{19}$F production in AGB stars has been performed recently by Lugaro, et al., [22] and it was determined that the major uncertainties in the production of $^{19}$F are associated with the uncertainties in the $^{14}$C($\alpha,\gamma$)$^{18}$O and $^{19}$F($p,p'$)$^{22}$Ne reaction rates.

The relevant temperature range for accreting helium white dwarfs is between 0.03 and 0.1 GK and for $^{19}$F nucleosynthesis in AGB stars it is $\sim$0.1 GK. At these energies(temperatures) the cross section for the $\alpha$ capture reaction on $^{14}$C is too low to be measured directly and has to be extrapolated. However, near threshold resonances in $^{18}$O may have a very strong influence on this extrapolation. Three states with excitation energies close to the $\alpha$ decay threshold at 6.227 MeV are known in $^{18}$O. These are the $1^-$ at 6.198 MeV, the $2^-$ at 6.351 MeV and the $3^-$ at 6.404 MeV. The $2^-$ state at 6.351 MeV is an unnatural parity state and cannot contribute to the $^{14}$C($\alpha,\gamma$) reaction at any significant level.

In order to extract the cluster properties of these states the sub-Coulomb $\alpha$-transfer reactions $^6$Li($^{14}$C,$d$) and $^7$Li($^{14}$C,$t$) were performed at the John D. Fox Superconducting Accelerator Laboratory at Florida State University. The use of inverse kinematics, $^{14}$C beam and $^6,^7$Li target, eliminates the background associated with ($^6,^7$Li,$d/t$) reactions on the unavoidable $^{12}$C admixture to the $^{14}$C target and provides a boost to the light recoils making them easier to detect.

Using the relation between the measured cross section and the DWBA calculated cross section we were able to extract the $3^-$ partial $\alpha$ width and the $1^-$ ANC. The partial $\alpha$ width of the $3^-$ state at 6.404 MeV in $^{18}$O is $\Gamma_\alpha = (7.8 \pm 2.7) \times 10^{-14}$ eV and the squared Coulomb modified ANC of the $1^-$ state at 6.198 MeV in $^{18}$O is 2.8$\pm$0.7 fm$^{-1}$. See [6] for the details of this method.

With the $\Gamma_\alpha$ for the $3^-$ state at 6.404 MeV and ANC for the $1^-$ at 6.198 MeV in $^{18}$O, the $^{14}$C($\alpha,\gamma$) reaction rate can be reliably extrapolated down to very low temperatures. At temperatures below 1 GK four major contributors to the $^{14}$C($\alpha,\gamma$) reaction rate can be identified. These are the direct capture (DC), resonance capture through the $4^+$ and $3^-$ states at 7.12 and 6.404 MeV and the sub-threshold resonance capture through the $1^-$ state at 6.198 MeV.

The reaction rates due to resonant and non-resonant capture are shown in Figure 3. At $T>$0.3 GK the $^{14}$C($\alpha,\gamma$) reaction rate is dominated by the $4^+$ state at 7.12 MeV. The $4^+$ resonance strength was measured directly [23; 24] and the uncertainty of the $^{14}$C($\alpha,\gamma$) reaction rate in this region is 17%. In the temperature range between 0.03 and 0.3 GK the $3^-$ state at 6.404 MeV dominates. This temperature range is of particular interest for helium accreting white dwarfs and AGB stars. The $3^-$ resonance strength was determined in this work with an uncertainty of 35%, which determines the new uncertainty for the $^{14}$C($\alpha,\gamma$) reaction rate in the temperature range of 0.03-0.3 GK. Below 0.03 GK, direct capture and capture due to the sub-threshold $1^-$ state at 6.198 MeV dominate. While direct capture was extrapolated from direct measurements in [23] and the S-factor due to the $1^-$ sub-threshold resonance was determined in this work with an uncertainty of 30% the reaction rate at this low energy region is still uncertain by two orders of magnitude due to the unknown interference between the direct and the $1^-$ sub-threshold resonance capture amplitudes.
The new $^{14}$C($\alpha$,\gamma) reaction rate may have the most profound effect on the evolution of accreting helium white dwarfs. It was suggested by [20] that under certain conditions the NCO reaction dominates over the 3$\alpha$ reaction and triggers a helium flash. However, this suggestion is sensitive to the actual $^{14}$C($\alpha$,\gamma) reaction rate. According to [20] $^{14}$C burning is ignited within helium white dwarfs when the central temperature reaches 0.066 GK while the 3$\alpha$ reaction does not begin until 0.080 GK. This prediction was based on a hypothetical $^{14}$C($\alpha$,\gamma) reaction rate which turned out to be a factor of 30 higher than the rate determined from our measurements. Comparison of the reaction rate in the temperature range of interest for helium accreting white dwarfs used by Hashimoto and the one determined from our experimental data is shown in Figure 4. The new, much lower reaction rate would change the NCO ignition temperature to higher values. Detailed calculations with the new $^{14}$C($\alpha$,\gamma) reaction rate are necessary to know whether the NCO reaction has an effect on the evolution of the helium accreting white dwarf.

It was found in [22] that uncertainties in the $^{14}$C($\alpha$,\gamma) and $^{19}$F($\alpha$,p) reaction rates are the main contributing factors to the uncertainty of the production of $^{19}$F in AGB stars. The authors of [22] cite 5 orders of magnitude uncertainty in the $^{14}$C($\alpha$,\gamma) reaction rate due to the unknown spectroscopic factor of the 3$^-$ state at 6.404 MeV. This uncertainty is eliminated now. Surprisingly, the “recommended” $^{14}$C($\alpha$,\gamma) reaction rate used in [22] is very similar to the reaction rate determined from our measurements. This fortuitous coincidence means that the yields of $^{19}$F calculated in [22] with the “recommended” $^{14}$C($\alpha$,\gamma) reaction rate are accurate and no new calculations are necessary.

4. Summary

In summary, we are only in the beginning phases of studying the $\alpha$-cluster structure of light N$\neq$Z nuclei. Here we report a measurement of the $^{14}$C+$\alpha$ elastic scattering excitation functions including a successful analysis using the complete R-matrix framework. We identified that the $\alpha$-cluster states in $^{18}$O have many surprising properties, foremost of which is the discovery of a broad, $\ell=0$ state which we suggest may be present in other nuclei in this mass range. This conclusion is strengthened through comparison with previous results [15–17; 25–27]. There is much work still ahead to prove this point. The discovery of the broad states in question within odd-even nuclei is an especially important and difficult task. Nevertheless, the possible influence that these broad low spin resonances may have on astrophysically important reaction rates along
with the insight they can give into $\alpha$ clustering justifies these efforts.

We also studied the influence of the cluster structure of near threshold states in $^{18}$O to the $^{14}$C($\alpha$, $\gamma$) reaction rate. The asymptotic normalization coefficients (ANCs) for the $1^-$ state at 6.198 MeV and $3^-$ at 6.404 MeV in $^{18}$O were measured in the $\alpha$-transfer reactions ($^7$Li,t) and ($^6$Li,d) on $^{14}$C in order to determine their contribution to the reaction rate. The new $^{14}$C($\alpha$, $\gamma$) reaction rate is a factor of 30 lower than the one used in [20]. Therefore, the importance of the NCO chain as a trigger for helium flashes in helium accreting white dwarfs suggested in [20] is reduced, if not eliminated all together. The “recommended” $^{14}$C($\alpha$, $\gamma$) reaction rate used in [22] for $^{19}$F nucleosynthesis calculation in AGB stars fortuitously coincides with that determined from our experimental data and the uncertainty of the $^{19}$F production in AGB stars associated with the $^{14}$C($\alpha$, $\gamma$) reaction rate is now eliminated. We hope that the new information on the $^{14}$C($\alpha$, $\gamma$) reaction rate will help to resolve the question of whether or not the NCO reaction chain can trigger helium flashes in cores of low-mass stars before the $3\alpha$ reaction does.

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