^{4}He decay of excited states in ^{14}C

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A study of the ^{7}Li(^{9}Be,^{4}He^{10}Be)^{2}H reaction at $E_{beam}=70$ MeV has been performed using resonant particle spectroscopy techniques and provides the first measurements of α-decaying states in ^{14}C. Excited states are observed at 14.7, 15.5, 16.4, 18.5, 19.8, 20.6, 21.4, 22.4, and 24.0 MeV. The experimental technique was able to resolve decays to the various particle bound states in ^{10}Be and provides evidence for the preferential decay of the high energy excited states into states in ^{10}Be at ~6 MeV. The decay processes are used to indicate the possible cluster structure of the ^{14}C excited states.

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I. INTRODUCTION

The study of clustering within nuclei has received renewed interest in the light of the potential impact that the underlying cluster structure has on valence particles, particularly in neutron-rich nuclei. The nucleus ^{8}Be has a pronounced α-α cluster structure, as evidenced by the deformed rotational band built on the ground state and the large α particle decay width [1,2]. Thus, the wave functions of neutrons introduced into this system are markedly affected by the two center nature of the underlying potential. This situation is reminiscent of the atomic binding of covalent molecules where electrons move in multicenter orbits characterized by the locations of the nuclei. For example, in the binding of O_2, the valence electrons reside in orbits with σ and π character, since such orbits result from the linear combination of *p*-type orbits which the atomic electrons occupy. Similarly, valence neutrons in the neutron-rich Be isotopes could occupy σ- and π-type orbits given that when separated the neutrons would reside in orbits in the helium nuclei with *p*-type characteristics.

Indeed, these ideas have been developed considerably in the case of the Be isotopes and there appears to be reasonably good evidence for states with both the σ and π characteristics in ^{9}Be and ^{10}Be [3–5]. There is also tentative evidence for the extension of these ideas to ^{11}Be [3–5] and ^{12}Be [6,7]. Somewhat remarkably these characteristics are also found in the calculations using the antisymmetrized molecular dynamics (AMD) framework, a model which, in principle, contains no explicit cluster, or molecular, content [8–10].

An extension to such ideas is the formation of three center molecules, principally formed from three α particles, i.e., ^{12}C. However, the building block for such linear molecules, the 3α chain state remains to be experimentally observed. There has been a long association between the 7.65 MeV (0^+) state and the chain configuration. However, it is now generally accepted, due to the lack of experimental evidence for a rotational 2^+ state, that this state is probably linked with a triangular arrangement of the three clusters [11]. The next possible candidate for the chain is the 10.3 MeV state. However, this resonance is broad and lies in a region where the spectroscopy of ^{12}C is extremely complex. Hence, there is no convincing evidence for the existence of the 3α chain. Indeed, molecular orbit model (MO) calculations, which reproduce well the properties of ^{10}Be [12], have found that the 3α state is unstable against the bending mode [13]. The same calculations [13,14] suggest that the introduction of valence neutrons may stabilize the chain structure.

The present paper presents an experimental study of the ^{7}Li(^{9}Be,^{14}C*$\rightarrow$^{10}Be+α)^{2}H reaction, in which the α decays of ^{14}C excited states both to the ^{10}Be ground state and to excited states are observed. These ^{10}Be states have previously been characterized in terms of their molecular structure [3–5].

II. EXPERIMENTAL DETAILS

The measurements were performed at the Australian National University's 14UD tandem accelerator facility. A 70 MeV ^{9}Be beam, of intensity 3 enA, was incident on a

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100 μg cm^{-2} Li_2O_3 foil. The integrated beam exposure was 0.45 mC.

Reaction products formed in reactions of the ^{9}Be beam with the target were detected in an array of four charged particle telescopes. These telescopes contained three elements which allowed the detection of a wide range of particle types, from protons to $Z=4-5$ nuclei. The first elements were thin, 70 μm, (5×5) cm^2 silicon detectors segmented into four smaller squares (quadrants). The second elements were position-sensitive strip detectors with the same active area as the quadrant detectors, but divided into 16 position-sensitive strips. These strips were arranged so that the position axis gave maximum resolution in the measurement of scattering angles. Finally, 2.5 cm thick CsI detectors were used to stop highly penetrating light particles. These detector telescopes provided charge and mass resolution up to Be, allowing the final states of interest to be unambiguously identified. The position and energy resolution of the telescopes was ~1 mm and 300 keV, respectively. Calibration of the detectors was performed using elastic scattering measurements of ^{9}Be from ^{197}Au and ^{12}C targets. The four telescopes were arranged in a crosslike arrangement, separated by azimuthal angles of 90°. Two opposing detectors were located with their centers at 17.3° and 17.8° (detectors 1 and 2) from the beam axis and with the strip detector 130 mm from the target, while the remaining pair were at the slightly larger angles of 28.6° and 29.7° (detectors 3 and 4), 136 mm from the target.

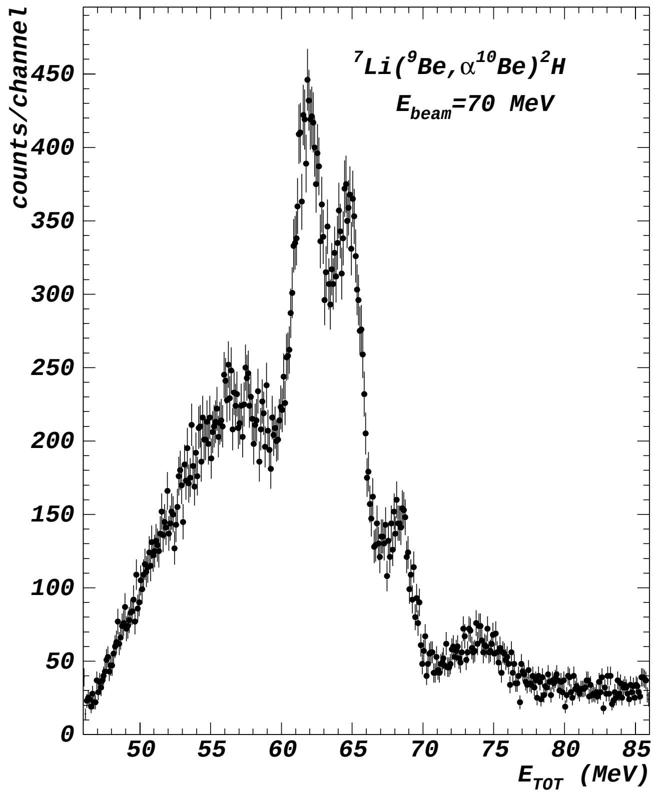

FIG. 1. Total energy spectrum for ^{4}He+^{10}Be coincidences, assuming a ^{2}H recoil. Only statistical uncertainties are plotted.

III. RESULTS

The resolution of ^{4}He and ^{10}Be loci in the spectra of the particle identification telescopes, and the measurement of the energies and angles of these detected particles permitted the kinematics of the ^{7}Li(^{9}Be,^{10}Beα)^{2}H reaction ($Q=-1.91$ MeV) to be fully reconstructed. Figure 1 shows the total energy spectrum ($E_{tot}=E_{Be}+E_\alpha+E_d$) for the two smaller angle detectors (1 and 2) for one of the two possible coincidence combinations. There are three clear peaks in this spectrum. The two highest energy peaks are separated by 3.4 MeV and the third by a further 2.6 MeV. These would thus correspond to all of the bound states in ^{10}Be. The highest energy peak ($E_{tot}=68.1$ MeV) corresponds to the production of ^{10}Be in the ground state, the next lower ($E_{tot}=64.7$ MeV) is the 3.4 MeV, 2^+ excitation, and the lowest energy peak ($E_{tot}\approx 62$ MeV) in this total energy spectrum corresponds to the population of the 5.958 MeV (2^+), 5.960 MeV (1^-), 6.179 MeV (0^+), and 6.263 MeV (2^-) states, which are unresolved in the present spectrum given the energy separation is only ~300 keV. The energy resolution in the total energy spectrum is ~2.0 MeV, i.e., worse than the intrinsic energy resolution of the telescopes. This inferior resolution is due to the very light mass of the recoil particle, since a relative small uncertainty in the measured momenta of the reaction products translates into a large uncertainty in the energy of the unobserved deuteron. Nevertheless, the resolution is sufficient to resolve the ^{10}Be spectrum into three components; the ground state, the 2^+ state, and the group of states at ~6 MeV. The spectrum also shows a broad bump at higher total energies, which has been identified as arising from ^{9}Be+α coincidences from the ^{7}Li(^{9}Be,^{9}Beα)^{3}H reaction leaking through the $A=10$ mass selection windows. This association has been confirmed by the analysis of this latter reaction using the appropriate particle masses. There is also a broad bump at lower energies which partially extends under the peaks. This contribution is from more complex final states (see later). Reactions from the oxygen and the inevitable carbon components in the targets have very negative Q values (<-19 MeV) and are thus not represented in the present spectrum.

Given the measurement of the momenta of the two fragments, potentially from the decay of ^{14}C, it is possible to reconstruct the excitation energy spectrum of this resonant particle. However, given that there are three particles in the final state, it is possible that they can be produced via the decay of either ^{6}Li into $d+\alpha$ or ^{12}B into ^{10}Be+d. Both of these possibilities were reconstructed and it is clear that there is no, or very little, contribution from either of these decay processes. Figure 2(a) shows the reconstructed ^{14}C excitation energy spectrum for α decays to the ^{10}Be ground state, for coincidences between the detectors 1 and 2. The spectrum shows a series of excited states between 14 and 22 MeV. The spectrum for detectors 3 and 4 covers the excitation energy range 18–32 MeV, and shows little evidence for states beyond 19.8 MeV, indicating that the decay strength is located at the lower excitation energies. The energies of the peaks are listed in Table I. It is possible that some of the peaks in these spectra correspond to multiple states, however with the

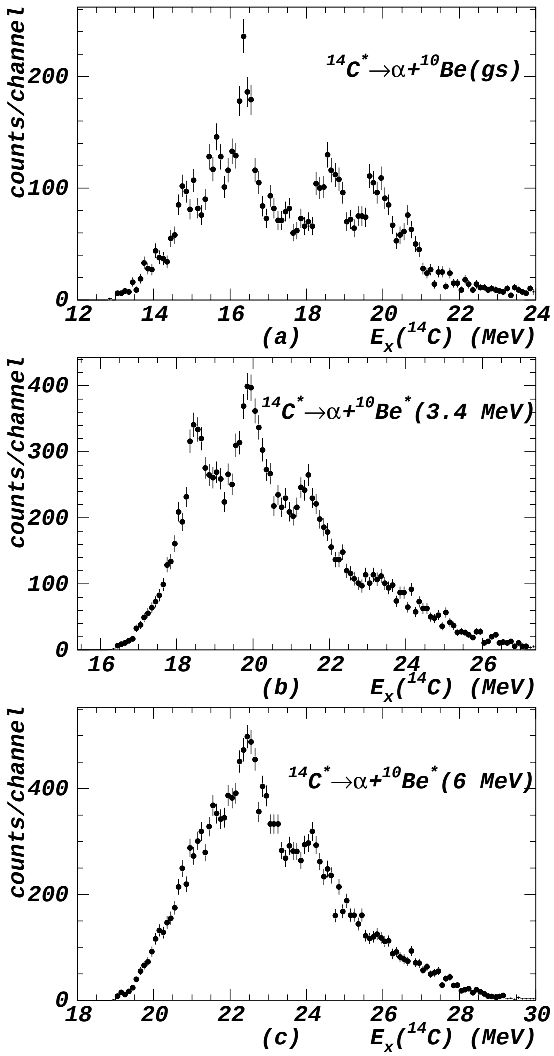

FIG. 2. ^{14}C excitation energy spectra for decays to (a) ^{10}Be ground state (b) ^{10}Be 3.4 MeV, 2^{+} state, and (c) ^{10}Be excited states at ~6 MeV. Error bars represent statistical errors only.

present excitation energy resolution (~300 keV) and statistics, it is not possible to be sure if the non-Gaussian peak shapes are due to multiple states or statistical fluctuations.

Figure 2(b) corresponds to α decays to the ^{10}Be(2^{+}) state as measured by the small angle detector pair. Again, the spectrum for the large angle detectors covers a higher excitation energy region from 20 to 34 MeV and shows no evidence of additional structures beyond those observed in Fig. 2(b). Once again, a series of excited states are observed several of which coincide with those that were observed to decay to the ^{10}Be ground state. Finally, the α decay spectrum for decays to the peak at ~6 MeV in Fig. 1 is shown in Fig. 2(c). There is an absolute uncertainty in the excitation energy scale of 300 keV, in this instance, given that it is not known which of the four ^{10}Be excited states are observed, indeed a combination may be involved. Thus, an excitation energy of 6 MeV has been assumed for ^{10}Be in this instance.

Many of the states observed in the present study have possible counterparts in the present energy level compilation for this nucleus [15], as indicated in Table I. For example, the states at 14.7, 15.5, and 16.4 MeV have all been observed in a study of the ^{9}Be(^{6}Li,p)^{14}C reaction [17]. This reaction is very similar to the present one and is almost certainly compound in nature, with the evaporation of a proton leading to the formation of ^{14}C. In the present case, there is also evidence for a compound population mechanism as when reconstruction of the ^{14}C excitation energy spectrum is performed for the background bump at low total energies in Fig. 1, excited states in ^{14}C may be observed. This may be explained if the reaction proceeds via the ^{16}N compound nucleus with the sequential emission of a proton and neutron to form excited states in ^{14}C which then subsequently undergo α decay. Unfortunately, since it is not possible to identify the excitation energy of ^{10}Be for this process, it is not possible to determine the excitation energy of the ^{14}C states populated via the n and p sequential emission process. An analysis of the angular distributions and angular correlations for the states observed in Fig. 2 using the techniques given in Ref. [16] was performed, but these were found to be essentially featureless, a consequence of the number of reaction amplitudes contributing to the reaction process due to the presence of nonzero spin particles in the entrance and exit channels. Thus, it is not possible to infer the spins of these states using this reaction. The present measurements do, however, provide the first observation of α-decaying states in this nucleus.

TABLE I. Excitation energies of ^{14}C states decaying into states in ^{10}Be. The uncertainties in these energies for decays to the ^{10}Be ground state and first excited state are 100 keV, and due to the ambiguity in the excitation energy of the 6 MeV peak, the uncertainty here is 300 keV. The previous measurements are from the tabulations of Ref. [15].

^{10}Be$_{gs}$	^{10}Be(2^{+})	^{10}Be(6 MeV)	Previous
14.7(0.1)			14.667 (4^{+})
15.5(0.1)			15.44 (3^{-})
16.4(0.1)			16.43
18.5(0.1)	18.5(0.1)		18.5
	[19.1(0.1)]		
19.8(0.1)	19.8(0.1)		
20.6(0.1)			
	21.4(0.1)		
		22.4(0.3)	
	[23.2(0.1)]		
		24.0(0.3)	

An interesting feature of the data is that the ^{14}C states which decay to the ground state and the ^{10}Be first 2^{+} state appear to be the same, with the 18.5 and 19.8 MeV states appearing in both spectra. On the other hand, decays to the 6 MeV states in ^{10}Be appear not to coincide despite there being an overlap in the excitation energy spectra of Figs. 2(b) and 2(c). There, would thus appear to be a preference for the decay of the lower excitation energy states in ^{14}C to either the ^{10}Be ground or first excited state, while the higher lying states (22.4 and 24.0 MeV) decay to the excited states at 6 MeV. In the absence of spin measurements, it is possible that the decay systematics reflect changing angular momentum barriers corresponding to decays to states of differing spins. However, the decay systematics do appear to be more complex than can be described by such a picture. As stated above, the decays to the ^{10}Be ground state and 2^+ (3.4 MeV) state appear to be similar and thus are largely unaffected by the change in the decay barrier. The decays to the 2^+, 1^-, 0^+, 2^- quartet at ~6 MeV, which would sample similar differences in the angular momenta barriers, highlights different states. This property, as, for example, is the case of excited states in ^{20}Ne [18,19] and ^{24}Mg [20], may rather be a reflection of changing structural overlap of the states in ^{14}C with those in ^{10}Be. This difference may perhaps be understood in terms of the structural content of the various ^{10}Be states. In a shell model description, the ^{10}Be ground state and first excited state correspond to the occupation of the $p_{3/2}$ orbit for the two valence neutrons. On the other hand, the 6 MeV states require the excitation of one or more of the neutrons to the s-d shell [3–5]. In the MO [12] and AMD [9] calculations that have been applied to ^{10}Be the ground and the first 2^+ state correspond to neutrons in π-like orbits, whereas the 6 MeV states require either two σ neutrons (0_2^+) or combinations of σ- and π-like neutrons (1^-, 2^-). Thus, it is possible that the lower energy ^{14}C excited states (14.7–21.4 MeV) are based upon neutrons in π-type molecular configurations, whereas the higher energy states (22.4 and 24.0 MeV) contain some σ-orbit parentage. However, it should be noted that there are some states which decay to the 2^+ state that are not strongly observed in decays to the ground state (e.g., 21.4 MeV) and vice versa (20.6 MeV). This would indicate that other effects may play a role in these decay processes, for example, angular momentum barriers and decay phase space. Whether these states correspond to single molecular-type configurations related by rotational excitations is unclear, and require measurements of the spins of the states. Nevertheless, there is a possibility that these states are related to molecular chains in ^{14}C.

IV. SUMMARY

Measurements of the ^{7}Li(^{9}Be,^{4}He^{10}Be)^{2}H reaction at $E_{beam}=70$ MeV provide evidence for a series of ^{14}C excited states between 14 and 25 MeV. These studies were able to resolve decays to the various particle bound states in ^{10}Be. The analysis indicates that decays to the ^{10}Be ground state and the first 2^+ state occur from the same states in ^{14}C, while a distinct set of states decay to the excited states at ~6 MeV. Given the proposed molecular content of the states in ^{10}Be, it is speculated that those in ^{14}C may also contain molecular characteristics. More definitive evidence will be provided by future measurements capable of determining the spins of these excited states.

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