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Angular correlation measurements for the $\alpha+{}^6$He decay of ^{10}Be

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The $\alpha+{}^6$He decay of ^{10}Be has been studied via the ^{7}Li(^{7}Li$,\alpha\,{}^6$He)α reaction at 58 MeV. The excitation energy of the ^{10}Be nucleus was determined following the coincident detection of the α and ^{6}He decay products. A study of the fragment angular correlations has provided a spin assignment consistent with the previously reported value of 3^- for the 10.15 MeV state in ^{10}Be. A tentative assignment of (4^+), 6^+ is proposed for the 11.76 MeV state.

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I. INTRODUCTION

In recent years there have been a number of both experimental [1–10] and theoretical reports (see, for example Refs. [11–15]) on the structure of the neutron rich nucleus ^{10}Be. One intriguing open question relating to the structure of this nucleus concerns the location of the first 4^+ state. In an extensive study and DWBA analysis of the ^{7}Li(α,p) reaction [1] a tentative assignment of 4^+ was given to the excited state at 11.76 MeV. A rotational band was proposed in that work, built on the 0^+ ground state with additional members at 3.37(2^+) and 11.76 MeV(4^+). In a later experiment [2] the α-particle decay of excited states in ^{10}Be was studied. In both of these measurements the previously observed state at 9.4 MeV [16] was reported at 9.6 MeV and a new state was observed at 10.2 MeV. This new state was proposed as the 4^+ member of a rotational band built on the excited 0^+ state at 6.18 MeV [2]. A more recent study of the ^{7}Li(^{7}Li$,\alpha\,{}^6$He)α reaction [4,6] provided more accurate energies of 9.56 and 10.15 MeV for the 9.6 and 10.2 MeV states. In addition a study of the α and ^{6}He angular correlations indicated J^π values of 2^+ and 3^- for the 9.56 and 10.15 MeV states, respectively. The 3^- assignment for the 10.15 MeV state appears to invalidate the earlier [2] speculation that this state could be a 4^+ rotational band member. It does, however, agree well with recent predictions [11,12] of a 3^- state near this excitation. In an attempt to obtain firm spin assignments for the $\alpha+{}^6$He breakup states in ^{10}Be a repeat measurement of the ^{7}Li(^{7}Li$,\alpha\,{}^6$He)α reaction has been performed.

II. EXPERIMENTAL DETAILS

The experiment made use of a 58 MeV ^{7}Li beam provided by the 14 UD tandem Van de Graaff accelerator of the Australian National University. This was used to bombard a nominally 100 μg/cm^2 Li$_2$O target supported by a 8 μg/cm^2 ^{12}C backing. The integrated beam exposure was 0.3 mC.

The α and ^{6}He breakup fragments arising from the decay of excited states in ^{10}Be were detected in an array of four (50 mm × 50 mm) detector telescopes. Each telescope consisted of a 70 μm thick silicon ΔE detector, a 500 μm thick silicon strip detector, and a 10 mm thick CsI scintillator. The strip detectors were segmented into 16 independent resistive strips, each providing position information along the strip length with a resolution of ~0.3 mm. Position resolution in a direction orthogonal to the strip length was limited to ±1.5 mm, the width of each strip. The energy resolution for 34 MeV ^{7}Li ions elastically scattered from Au was 190 keV. In addition to position and energy information each telescope provided particle identification for all isotopes from H to Be via standard $\Delta E-E$ techniques. Two of the telescopes were placed in a horizontal plane with respect to the beam axis, with one telescope positioned either side of the beam. The detectors were centered at 18° and the target to silicon strip detector distance was 135 mm. The second telescope pair were placed in a vertical plane, one above and one below the beam, at angles of 28°. The target to silicon strip detector distance was 140 mm. For the horizontal (in-plane) telescope pair the strips of the silicon strip detectors were horizontal. For the vertical (out-of-plane) pair the strips were vertical.

III. EXPERIMENTAL RESULTS

After selection of events in which an α particle and a ^{6}He nuclei were detected the energy of the undetected recoiling particle was determined from momentum conservation. In

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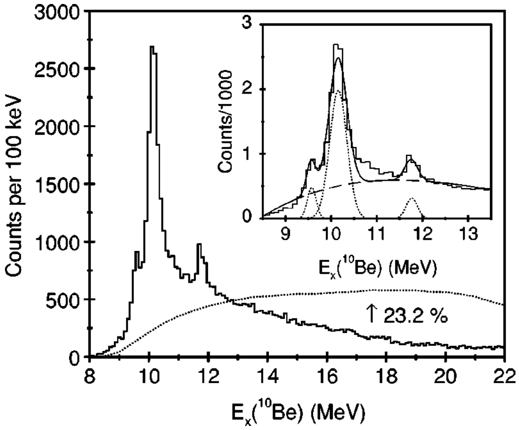

FIG. 1. ^{10}Be excitation energy spectrum for all $\alpha+{}^{6}$He coincident events. The dotted line indicates the experimental detection efficiency. In the inset the states are shown fitted with Gaussian line shapes (dotted lines) above a smoothly varying background (dashed line). The overall fit is given by the smooth solid line.

order to select the ^{7}Li(^{7}Li, α ^{6}He)α reaction a Q-value spectrum, similar to Fig. 3 in Ref. [6], was then produced. This allowed the selection of events where all three final state particles were emitted in their ground states. A study of the α and ^{6}He decay fragment relative energy allowed the ^{10}Be excitation energy spectrum to be obtained (see Fig. 2 of Ref. [6]).

In Fig. 1 the ^{10}Be excitation energy spectrum corresponding to coincidences between all possible detector telescope pairs is shown. The previously [9] observed states at 9.56, 10.15, and 11.76 MeV may be seen in this spectrum. The dotted line indicates the experimental detection efficiency obtained from a Monte Carlo simulation of the reaction. The efficiency rises from 8.6% at 10 MeV to a maximum value of 23.2% at 17.5 MeV. This shows that the absence of higher excitation states is not attributable to the experimental acceptance. In the inset to Fig. 1 the three states listed above are shown fitted with Gaussian line shapes (indicated by the dotted lines) and a smoothly varying background (dashed line). The overall fit is given by the smooth solid line. This fit to the data was unconstrained, with the peak centroids, widths, and areas being free parameters. The yield appearing above the overall fit line between the 10.15 and 11.76 MeV states most likely arises from the previously observed [6,9] states at 10.55 and 11.2 MeV. These cannot be fitted reliably, however. The results of the fit are listed in Table I as are all of the states in ^{10}Be observed to decay to the $\alpha+{}^{6}\mathrm{He}_{\mathrm{g.s.}}$ channel listed in Refs. [6,9]. The widths for the 9.56, 10.15, and 11.76 MeV states as seen in Fig. 1 are greater than the previously reported values and indicate an experimental excitation energy resolution of the order of 300 keV. This value is at odds with a Monte Carlo predicted resolution of approximately 130 keV, the discrepancy being likely to arise from dependencies which remain in the data and slight variations in the calibrations between the four detector telescopes. The widths are therefore listed as upper limits only as a reliable subtraction of the experimental resolution cannot be performed. There appears to be no evidence in Fig. 1 for the previously observed states at (11.93), 13.05, 13.85, or 14.68 MeV [9]. The background in Fig. 1 most likely arises from events where the detected ^{6}He is the recoil from the

TABLE I. Energies, widths, and spins of the states observed in the $\alpha+{}^{6}\mathrm{He}_{\mathrm{g.s.}}$ decay of ^{10}Be.

Present work			Refs. [6,9,16]		
E_x (MeV)	Width (keV)	$J^{\pi}(\hbar)$	E_x (MeV)	Width (keV)	$J^{\pi}(\hbar)$
			7.542±0.001	6.3±0.08	2^+
9.58±0.06	<230		9.56±0.02	141±10	2^+
10.16±0.03	<450	(3^-)	10.15±0.02	296±15	3^-
			10.57		
			(11.23±0.05)	(200±80)	
11.77±0.11	<300	$(4^+,6^+)$	11.76	121±10	(4^+)
			(11.93±0.1)		
			13.05±0.1		
			13.85		
			14.68±0.1		
16.67±0.02	<570				
17.76±0.02	<525		17.79		
19.53±0.02	<600				
(20.6)			20.8±0.1		
(23.05±0.03)					
(23.77±0.02)			23.65±0.05		
(24.53±0.02)			24.25±0.05		
(26.23±0.02)					
			27.2±0.2		

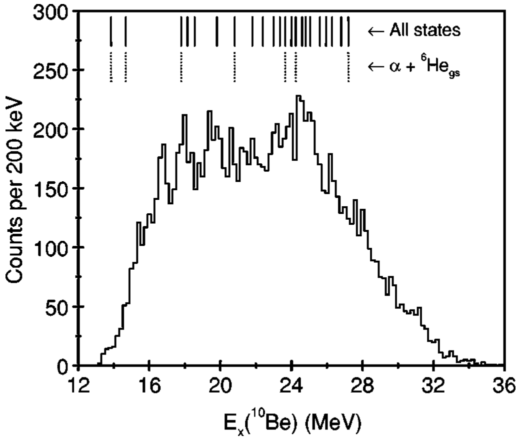

FIG. 2. ^{10}Be excitation energy spectrum for the out-of-plane detector pair only. The energies of all states listed by Fletcher *et al.* [9] are indicated by the vertical solid lines. The vertical dotted lines highlight the states in ^{10}Be that decay to $\alpha + {}^{6}\mathrm{He}_{\mathrm{g.s.}}$.

^{7}Li(^{7}Li, ^{8}Be*)^{6}He reaction with the ^{8}Be* excited to one of the many known states between 16.6 and 28.6 MeV [16]. The ^{8}Be excitation energy spectrum reconstructed from the detected and reconstructed α particles exhibits a featureless continuum in this excitation energy region centred at approximately 24 MeV.

The excitation energy spectrum for the out-of-plane detector pair is shown in Fig. 2. The energies of all states in ^{10}Be recently listed by Fletcher *et al.* [9] in this excitation energy region are indicated by the vertical solid lines. The subset observed in the $\alpha + {}^{6}\mathrm{He}_{\mathrm{g.s.}}$ decay of ^{10}Be are highlighted by the vertical dotted lines. There does not appear to be any evidence in the present data for the states reported [9] at 13.85, 14.68, and 27.2 MeV. However, the well established [16] state at 17.79 MeV may be observed and the existence of states at (20.8), 23.65, and 24.25 MeV appears to be supported (see Table I). Additional peaks at an energies of 16.67, 19.53, (23.05), and (26.23) MeV may also be seen. The 16.67 MeV state might correspond to either the 16.1 or 17.2 MeV states reported by Freer *et al.* [7] who note a systematic uncertainty of 0.5 MeV. The states at 19.53, (23.05) and (26.23) MeV may correspond to those observed previously in the $p + {}^{9}$Li decay of ^{10}Be at (19.8) and 23.0 MeV and in the $d + {}^{8}$Li and $d + {}^{8}$Li* decay of ^{10}Be at 26.3 MeV [9].

The spins of the most prominent states in ^{10}Be seen in Fig. 1 (those at 10.15 and 11.76 MeV) have been studied using the correlation technique discussed in Ref. [6]. This method involves fitting the experimental correlation function W(ψ) with a sum of associated Legendre polynomials weighted by a Gaussian m-substate population distribution centered at $m=0$. The experimental correlation functions were obtained for events within the range $-5° \leqslant \theta^{*} \leqslant +5°$, where θ^{*} is the center-of-mass scattering angle of the excited ^{10}Be nucleus. These $\theta^{*} \sim 0°$ events were divided into 10° wide bins in ψ, where ψ is the angle between the relative velocity vector between the α and ^{6}He decay fragments and the beam axis. Excitation energy spectra were produced for each ψ range and the number of events above background $N(\psi)$ in both the 10.15 and 11.76 MeV states was obtained for each bin using a Gaussian peak fitting routine with unconstrained centroid energies and widths. The experimental correlation function was obtained by scaling $N(\psi)$ by the experimental detection efficiency for each ψ bin, which was found using a Monte Carlo simulation of the ^{7}Li(^{7}Li, α ^{6}He)α reaction and the detection system employed in the experiment.

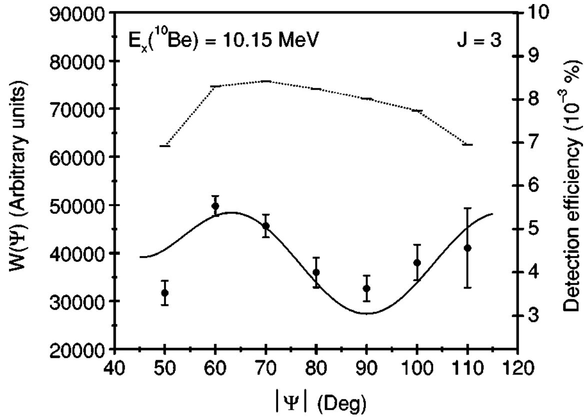

FIG. 3. Experimental (data points) and fitted (solid line) correlation functions for the state at 10.15 MeV in ^{10}Be. A value of $J=3$ was assumed in the fit. The Monte Carlo efficiency curve used to correct $N(\psi)$ is shown by the dotted line.

In Fig. 3 the experimental correlation function $W(\psi)$ is shown for the 10.15 MeV state in ^{10}Be. The fit to the data using the technique described in Ref. [6] for an assumed spin of $J=3$ is shown by the solid line. The Monte carlo efficiency curve used to correct $N(\psi)$ is shown by the dotted line. For this state the fit assuming $J=3$ has a value $\chi^{2}/D=4.0$ where D is the number of degrees of freedom. The fits for alternative values of J have appreciably higher values of χ^{2}/D, witrh $\chi^{2}/D=9.5$ for $J=1$ and 2 and $\chi^{2}/D=13.2$ and 13.7 for $J=4$ and 5, respectively. The average variation in fitted peak centroid energy from the value listed for this state in Table I for the different ψ bin excitation energy spectra was 20 keV. The average variation in width from the fitted value for all data (the width of the state as seen in Fig. 1) was 50 keV. The present $J=3$ assignment for the 10.15 MeV state in ^{10}Be is consistent with that reported previously by Curtis *et al.* [6] The width parameter for Gaussian m-substate population distribution for the best fit is $y=0.308$ [6]. This indicates relative m-substate populations of 0.759 ($m=0$), 0.234 ($m=1$), 0.007 ($m=2$), and $\sim 2 \times 10^{-5}$ ($m=3$).

For the 11.76 MeV state, previously assigned $J^{\pi}=4^{+}$ [1], the average variation in fitted peak centroid energy for the different ψ bin excitation energy spectra from the value listed in Table I was 50 keV. The average variation in fitted width from that seen for this state in Fig. 1 was 80 keV. A fit with a fixed peak width equal to this value, 300 keV, produced an $N(\psi)$ distribution almost identical in shape to that used to produce Figs. 4 and 5(a) [with an average increase in $N(\psi)$ of 9%].

In Fig. 4(a) the fit assuming $J=4$ is shown (solid line), for which $\chi^{2}/D=21.3$ and $y=0.608$. The dashed line indicates the result of a fit constrained to a value $y=0$. This corresponds to a 100% population of $m=0$ and therefore a pure

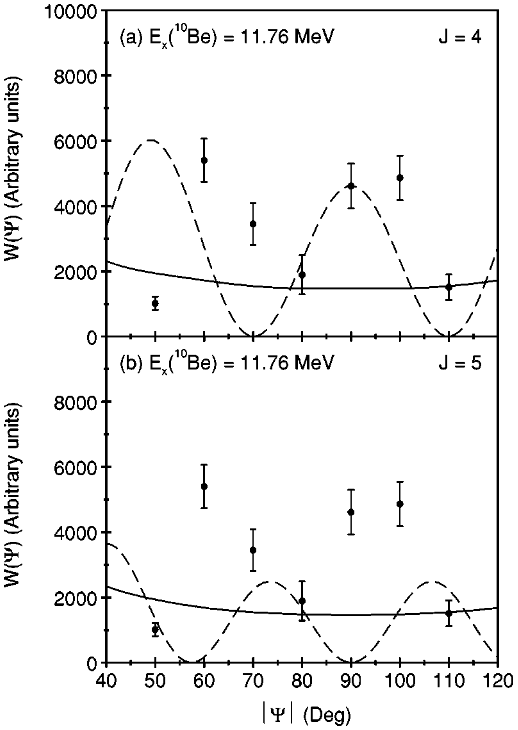

FIG. 4. Experimental (data points) and fitted (solid and dashed lines, see text) correlation functions for the state at 11.76 MeV in ^{10}Be. A value of (a) $J=4$ and (b) $J=5$ was assumed in the fit.

Legendre polynomial $|P_4|^2$. This line has been normalized to the experimental W(90)° value and has $\chi^2/D=135.7$. Figure 4(b) shows the fit assuming $J=5$ (solid line), for which $\chi^2/D=21.5$ and $y=0.697$. The fit for $J=5$ constrained to $y=0(|P_5|^2)$ is shown by the dashed line and has a value of $\chi^2/D=28.0$. In Fig. 5(a) the fit assuming $J=6$ is shown (solid line) along with the Monte Carlo efficiency curve used to correct $N(\psi)$ (dotted line). For $J=6\chi^2/D=7.0$. This value is significantly lower than the values for higher spins, for which $\chi^2/D=17.5(J=7)$ and $21.3(J=8)$.

In order to check that the oscillations observed in W(ψ) for the 11.76 MeV state do not arise from variations in the background upon which the peak sits (Fig. 1) a correlation function has been produced for the excitation energy region 12.3–13.0 MeV. This is shown in Fig. 5(b) and is seen to be of a smoothly varying form. This indicates that the background below the 11.76 MeV peak does not give rise to the W(ψ) amplitude variations seen in Figs. 4 and 5(a) and that the oscillations therefore genuinely reflect the spin of the state.

In can be seen in Fig. 4 that $J=4$ and 5 do not satisfactorily describe the data, although the $|P_4|^2$ fit might be improved with an increased amplitude and given the sparse nature of the data cannot be dismissed. The fit with $J=5$ and $y=0(|P_5|^2)$ is out of phase with the experimental data and is more easily ruled out. In Fig. 5(a) the fit with $J=6$ can be seen to provide a much better description of the data and on the basis of the significantly lower χ^2/D value would seem to be the more likely spin value. Therefore a tentative assignment of $J=(4)$, 6 is proposed for the 11.76 MeV state in ^{10}Be. The value of y for the $J=6$ fit is 0.084, indicating relative m-substate populations of 0.922, 0.077, and $\sim 5\times 10^{-5}$ for $m=0$, 1, and 2, respectively. Although it is not possible to make a definite spin assignment for this state it is clear that the W(ψ) distribution has a different character to that for the 10.15 MeV state. With greater certainty it can be seen from the maximum close to $\psi=90°$ that the state must have even spin and positive parity.

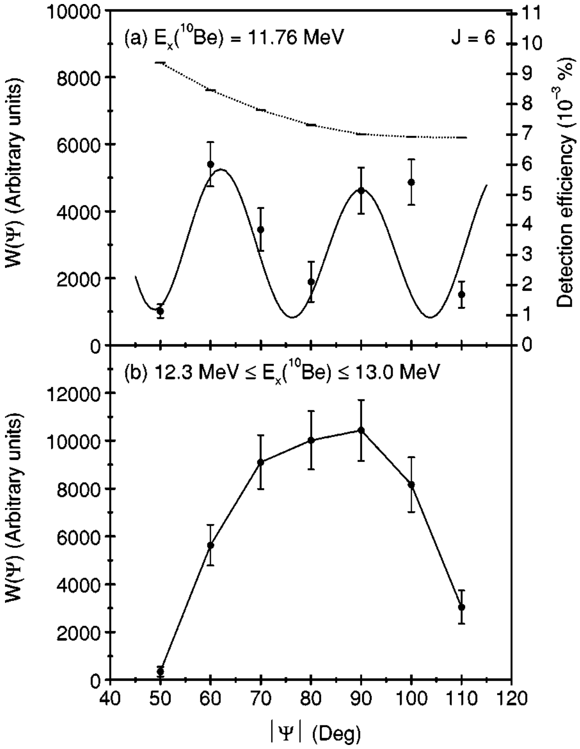

FIG. 5. (a) Experimental (data points) and fitted (solid line) correlation functions for the state at 11.76 MeV in ^{10}Be. A value of $J=6$ was assumed in the fit. The Monte Carlo efficiency curve used to correct $N(\psi)$ is shown by the dotted line. (b) Experimental correlation function for the excitation energy region 12.3–13.0 MeV in ^{10}Be. The solid line is to guide the eye.

The integrated double differential cross section for the ^{7}Li(^{7}Li,$\alpha\,^6$He)α reaction, with respect to the solid angles covered by the two telescopes in which the α and ^{6}He decay fragments were detected, is $d^2\sigma/d\Omega_1 d\Omega_2=(0.19\pm0.02)$ mbsr^{-2}. This value assumes a target of 100 μg/cm^2 Li$_2$O. However, it is possible that the target was not lithium oxide but lithium carbonate (Li$_2$CO$_3$). If this was the case then $d^2\sigma/d\Omega_1 d\Omega_2=(0.46\pm0.05)$ mbsr^{-2}.

IV. SUMMARY

The $\alpha+{}^6$He breakup of ^{10}Be has been studied using the ^{7}Li(^{7}Li,$\alpha\,^6$He)α reaction at a beam energy of 58 MeV. A study of the α and ^{6}He decay fragment angular correlations has provided a spin assignment consistent with the previously reported value of $J=3$ for the 10.15 MeV state in ^{10}Be.

A tentative assignment of $J=(4)$, 6 is proposed for the 11.76 MeV state. The question relating to the location of the first 4^+ state in ^{10}Be is still unanswered and it remains an ongoing experimental challenge to obtain firm spin assignments for the majority of states in this nucleus above the α-decay threshold.

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