α:2n:α Molecular Band in ^{10}Be

M. Freer,[1] E. Casarejos,[2] L. Achouri,[3] C. Angulo,[2] N. I. Ashwood,[1] N. Curtis,[1] P. Demaret,[2] C. Harlin,[4] B. Laurent,[3] M. Milin,[5] N. A. Orr,[3] D. Price,[1] R. Raabe,[6] N. Soić,[5] and V. A. Ziman[1]

[1]*School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom*
[2]*CRC/LLN Centre de Recherches du Cyclotron, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[3]*Laboratoire de Physique Corpusculaire, ISMRA and Université de Caen, IN2P3-CNRS, 14050 Caen Cedex, France*
[4]*School of Electronics and Physical Sciences, University of Surrey, Guildford, Surrey, GU2 7XH, United Kingdom*
[5]*Department of Experimental Physics, Rudjer Bošković Institute, Bijenička 54, HR-10000 Zagreb, Croatia*
[6]*Instituut voor Kern- en Stralingsfysica, University of Leuven, B-3001 Leuven, Belgium*

(Received 12 August 2005; published 30 January 2006)

The 10.15 MeV resonance in ^{10}Be has been probed via resonant ^{6}He + ^{4}He elastic scattering. It is demonstrated that it is the $J^\pi = 4^+$ member of a rotational band built on the 6.18 MeV 0^+ state. A Γ_α of 0.10–0.13 MeV and $\Gamma_\alpha/\Gamma = 0.35$–0.46 were deduced. The corresponding reduced α width, γ_α^2, indicates one of the largest α-cluster spectroscopic factors known. The deformation of the band, including the 7.54 MeV, 2^+ member, is large ($\hbar^2/2I = 200$ keV). Such a deformation and the significant degree of clusterization signals a well-developed α:2n:α molecular structure.

DOI: 10.1103/PhysRevLett.96.042501 PACS numbers: 21.10.Re, 25.70.−z, 27.20.+n

The competition between the mean field, which describes aspects of nuclear structure such as single-particle properties and the magic numbers, and clustering, in which subunits of nucleons behave in a collective manner, is intriguing [1]. The phenomenon of clustering is not only limited to $A = 4n$ nuclei, but as was considered by Hafstad and Teller as early as 1938 [2], clustering could also be important in nuclei such as ^{9}Be, where an α:n:α structure was proposed. Here the analogy with molecular structure was invoked, as in their model the neutron was *exchanged* between the two α cores.

The possible existence of molecular-type structures has generated considerable experimental and theoretical effort to characterize such systems. The most obvious of these are the beryllium isotopes. From the theoretical perspective the molecular traits of rotational bands have been described in terms of the exchange nucleons, being in either σ- or π-type orbitals [3]. Experimental progress validating this picture has, however, been less dramatic. In ^{9}Be two rotational bands have been identified with neutrons in σ and π orbits [3]. The characterization of the α:2n:α system, where the *two* valence neutrons are in molecular orbitals, has been less successful. The present status is summarized by Milin *et al.* [4]. The molecular band is associated with the 6.18 MeV (0_2^+) level, which is linked to the 2^+ state at 7.54 MeV. The corresponding 4^+ state is believed to be the 10.15 MeV state [5]. Measurements of the spin and parity of the state have, however, produced conflicting results [4,6] due to the model dependent nature of the analysis. Antisymmetrized molecular dynamics calculations of ^{10}Be, which are free from structural constraints, predict that the 0_2^+ state in ^{10}Be at 6.18 MeV should have a cluster structure [7], in which the two valence neutrons are located between two α cores, and exhibit spatial distributions characteristic of σ molecular orbitals. The presence of the neutrons increases the separation between the two α particles emphasizing the cluster structure.

Often in the past, evidence for cluster structures has been circumstantial, but here we provide definitive experimental evidence for the characterization of the associated exotic molecular rotational band, demonstrating that the molecular picture does indeed extend to the $2\alpha + 2$ valence neutron system.

The present measurements were performed at the Louvain-la-Neuve cyclotron facility with a 7.5 MeV ^{6}He^{1+} beam of intensity $\sim 2 \times 10^6$ pps (additional measurements were made at 6.1 and 11.1 MeV). The beam entered the reaction chamber through a 2.5 μm thick mylar window. The LEDA and LAMP detection systems [8] were mounted within the reaction chamber (Fig. 1) which was filled with helium gas (150 mb). These arrays are composed of 16-element annular strip detectors with an inner radius of 50 mm and an outer radius of 130 mm. The

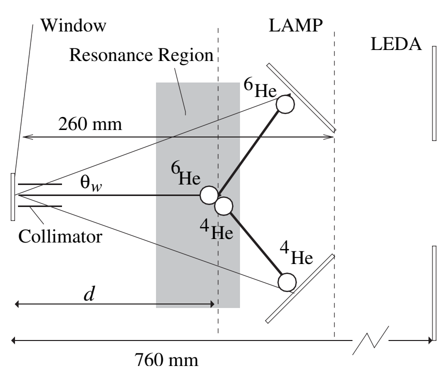

FIG. 1. Experimental setup. The region in the gas volume in which the 10.15 MeV ^{10}Be resonance is formed is indicated (shaded zone). The resonance subsequently decays into ^{6}He + ^{4}He which are detected in coincidence in the LAMP array.

LEDA array was composed of 8 of such detectors and the LAMP array from 6. Each LEDA sector spanned an azimuthal angle of 45°, in the case of the LAMP array 60°. A 60 mm long collimator was used to prevent ^{6}He beam particles being scattered from the window into the LAMP array. Scattering from the window was, however, observable in the LEDA array, and this was used to provide a measure of the incident number of nuclei (normalized to the beam intensity measured by a precision Faraday cup). The integrated number of beam particles was $(9.4 \pm 1.0) \times 10^{10}$.

The silicon detectors were calibrated with α sources, and the individual strip resolution was typically 40 keV (FWHM). In addition, two monitor detectors were used: one just behind the window on a retractable arm and the other at the rear of the chamber. Once calibrated, these were used to measure the energy loss of the beam in the window and gas. The energy loss of the beam in the gas was characterized by increasing the pressure in 30 mb steps from 0 to 150 mb. This also provided a measure of the energy straggling, which was found to be 110(10) keV for 70 cm of helium gas at 150 mb.

The technique of thick target resonant elastic scattering using a gas target [9] was employed here. After passing through the mylar window, the ^{6}He projectile traverses the helium gas slowing down. When the ^{6}He energy coincides with the equivalent center-of-mass energy of a ^{10}Be excited state, a resonance may form which then subsequently decays back into ^{6}He + ^{4}He. As shown in Fig. 1, the two decay products were then detected in coincidence. The technique was validated by a measurement with a 16 MeV ^{12}C beam to populate the 10.35 MeV (4^+) resonance in ^{16}O.

The coincident detection of both of the decay products obviates the need for particle identification to select the reaction channel, as the correlation between the particle energies reveals the associated 2-body kinematics. The measurement provides an accurate determination of the energy of the reaction products after they have traversed the gas and a measurement of the angle (θ_w, Fig. 1) with respect to the beam axis referenced with respect to the entrance window. The resolution with which this angle could be determined (~2.5°) was limited by the strip width (5 mm) and the size of the beam spot (~10 mm diameter). For helium nuclei the differential energy loss of beam and reaction products through the gas is relatively small, which allows an accurate calculation of the laboratory energies of the two reaction products at the point of formation of the resonance. From the measured energies, which were corrected for the energy loss in the gas assuming the detection of a ^{6}He nucleus traversing 13 cm of gas, the center-of-mass emission angle of the two particles was calculated. As it is not known if the particle detected was ^{6}He or ^{4}He there is an ambiguity in the calculated center-of-mass angle owing to the uncertainty in mass. However, over the range of coverage this leads to an uncertainty of $\theta_{c.m.} < 5°$. The calculated center-of-mass angles for both particles were found to be 180 degrees apart (within the above uncertainty) confirming the observation of the ^{6}He + ^{4}He final state.

In addition to the center-of-mass emission angle, the measured energy permits the calculation of laboratory angle of each particle, assuming $A = 4$ or 6. This angle, combined with the measured detection angle, θ_w, allows the distance, d, at which the interaction took place within the gas volume to be determined. Owing to the greater variation of the laboratory kinematics with the assumed mass, compared to that for the calculation of the center-of-mass angle, the variation in the calculated value of d is more significant.

To provide a detailed picture of the nature of the reaction and detection processes together with the impact of the uncertainty in the assumed masses, detailed Monte Carlo simulations have been performed. The resonance formation was simulated according to a single Breit-Wigner line shape, the properties of which (E_r, Γ) were taken from Ref. [6]. The angular distributions of the decay products were given by Legendre polynomials of an order which reflects the spin of the resonance, given that the two initial and final state particles were spin zero. The masses of the two particles were then selected at random and the simulated data were then processed via the same procedures that were employed for the analysis of the reaction data. The simulations also included the effect of the finite beam spot size, position, and energy resolution of the detectors, the absence of inactive strips, and energy and angular straggling in the window. The results demonstrated that an incorrect assumption of the particle mass produces an uncertainty in the location of the interaction within the gas volume of 4 cm, compared to a total possible interaction length of 20 cm. This is sufficient to locate the point of formation and decay of the resonance.

Figure 2 shows the calculated center-of-mass angle plotted against the distance from the window for the 7.5 MeV data and the simulations for a resonance at 10.15 MeV with a width of $\Gamma = 296(15)$ keV. From the two-dimensional distribution, it can be seen that the features of the data are well reproduced. Figure 3 shows the variation in the yield with center-of-mass angle, and is compared with simulations for spin 2, 4, and 6 decays. Figure 3 demonstrates that the resonance does not possess negative parity as was claimed in Ref. [6], as this would produce a minimum at $\theta_{c.m.} = 90°$. It should be noted that analysis used to extract the spin in Refs. [4,6] was model dependent, whereas the present is not. The minima in the data exclude spins 2 and 6 and are reproduced by the $J^\pi = 4^+$ simulation as result which agrees with Ref. [4].

Following the spin determination, it is possible to link this state with the 6.18 MeV (0^+) and 7.54 MeV (2^+) states, forming a rotational band extending to $J^\pi = 4^+$ (inset in

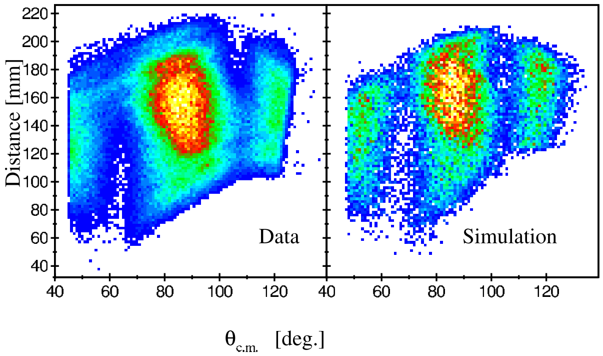

FIG. 2 (color online). The reconstructed center-of-mass emission angle ($\theta_{\rm c.m.}$) vs the interaction distance. The left-hand panel shows the experimentally determined distribution, and the right the result of simulations for a resonance at 10.15 MeV with $\Gamma = 296$ keV [6] and $J^\pi = 4^+$.

Fig. 3). The 6.18 MeV state has a long lifetime (1.1 ps) which may be explained in terms of the structure being different to that of the ^{10}Be ground and first excited state. The 7.54 MeV state has been shown to have an anomalously large reduced α width [10] [confirmed in Ref. [4]]. Thus, if the present resonance is a member of this band then a large reduced width for α decay would also be expected.

The present data can provide a measure of the α width (Γ_α) of the resonance. For this analysis the data in the range $\theta_{\rm c.m.} = 70$ and $110°$, where the effects of the experimental acceptances are reduced, were used. From the simulations it was determined that the efficiency for detecting, in coincidence, the ^{6}He + ^{4}He pairs is 1.37(0.07)%. This compares with 7.2% of the fraction of the P_4^2 Legendre polynomial which lies within the same interval. The energy and angle integrated cross section over the resonance is found to be 0.327(0.040) $b \cdot$ MeV. The α-decay width may be then calculated from integrating the theoretical resonance profile (formed from two spin zero nuclei);

$$\int_0^\infty \frac{\pi}{k^2} \frac{J(J+1)\Gamma_\alpha^2}{(E-E_r)^2 + \Gamma^2/4} dE \simeq 2J(J+1)\frac{\pi^2}{k^2}\frac{\Gamma_\alpha^2}{\Gamma}. \quad (1)$$

The present cross section thus corresponds to a value of Γ_α of 0.13(0.01) MeV, or $\Gamma_\alpha/\Gamma = 0.46(0.03)$.

The minima in the angular distributions in Fig. 3 correspond to very low yields. There will, however, be a contribution from Rutherford scattering. In order to estimate this contribution an analysis of the "singles" data has been performed (Fig. 4) for three beam energies. The difference between the distributions is marked, with the oscillatory pattern only appearing for the "on resonance" data. Owing to the ^{4}He–^{6}He detection ambiguity, the distributions contain contributions from both the forward and backward center-of-mass angle yields (particularly at 6.1 MeV). Thus, the calculated elastic scattering yields have been filtered through the Monte Carlo simulations. The elastic scattering was calculated using the ^{6}Li + ^{4}He optical model parameters from Ref. [11] (Table II, set 4). The agreement with the 6.1 MeV data is good, including the increase in yield at backward angles which is a consequence of the aforementioned contribution from both the ^{6}He and ^{4}He. The agreement with the 11.1 MeV data is good at small angles, but the discrepancy at larger angles indicates that here the refractive elements in the scattering are not so well accounted for. The oscillatory behavior of the distributions in the data acquired at 7.5 MeV data is not

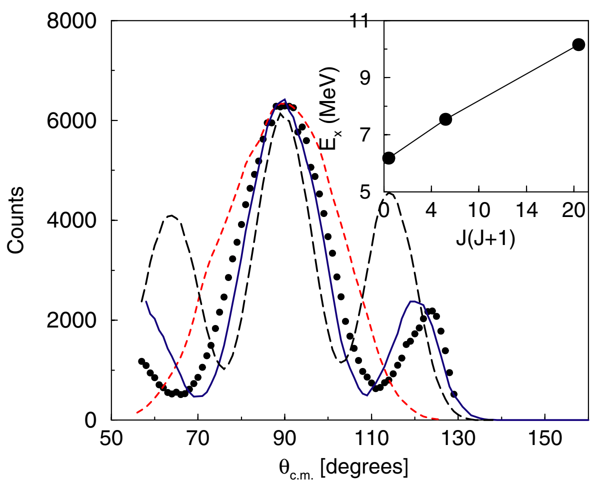

FIG. 3 (color online). Experimentally determined center-of-mass distribution (data points) compared with simulations for the decay of a spin 4 (blue-solid line), 2 (red-dashed line), and 6 (black-long-dashed line) resonance. The inset shows the energy-spin systematics of the rotational band of which the present 4^+ state is a member.

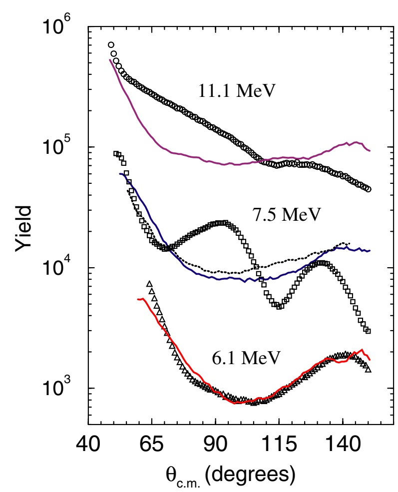

FIG. 4 (color online). Normalized angular distributions for the singles data measured at beam energies of 11.1 (circles × 10), 7.5 (squares × 1), and 6.1 MeV (triangles × 0.1). The solid lines overlaid over the three data sets correspond to the elastic scattering as simulated by the Monte Carlo calculations. The dotted line shows the Rutherford scattering contribution for the 7.5 MeV data.

observed in the simulations. The experimental and simulated distributions (at 7.5 MeV) between 70 and 110° have been used to estimate the resonance and elastic scattering contributions. This analysis indicated that the maximum contribution to the data from nonresonant elastic scattering is 50%. Thus Γ_α lies in the range 0.10–0.13, and $\Gamma_\alpha/\Gamma =$ 0.35–0.46.

Given that the resonance has $J = 4$, there is a substantial centrifugal barrier through which the decay must proceed. The reduced width, for which the barrier penetration is factored out, may be calculated as: $\gamma_\alpha^2 = \Gamma_\alpha/2P(4)$, where $P(4)$ is the probability for tunneling through the Coulomb and centrifugal barriers. The reduced width is strongly dependent on the channel radius, $R = R_0(A_1^{1/3} + A_2^{1/3})$, and ranges from $\gamma_\alpha^2 = 0.17$–0.93 MeV for channel radii with $R_0 = 1.8 - 1.4$ fm. These may be compared with the Wigner limit, $\gamma_{\alpha W}^2 = 3\hbar^2/2\mu R^2$ and $\theta_\alpha^2 = \gamma_\alpha^2/\gamma_{\alpha W}^2$, for which θ_α^2 ranges from 0.66 to 2.23. A comparison with the Wigner limit provides a measure of the probability for finding an α particle in the decaying state, but are often difficult to interpret owing to the strong dependence on channel radius. Thus, as a benchmark the decay of the α-cluster nucleus ^{8}Be has been examined. Studies of the 2^+ and 4^+ excited state in ^{8}Be indicate values of θ_α^2 of 1.14 to 1.32 [the latter was calculated with $R_0 = 1.1$ [12]] [12,13], and for the ^{8}Be ground state ~15% of the Wigner limit was observed [14], the latter for the channel radius of $R_0 = 1.8$ fm. For $R_0 = 1.4$ fm, $\theta_\alpha^2 = 0.45$ and 1.26 for the ground and first excited state, respectively. Thus, the degree of clusterization in the 10.15 MeV ^{10}Be state is at least as large as in ^{8}Be.

The present measurement of $\Gamma_\alpha/\Gamma = 0.35$–$0.46$ is for the decay of the resonance to the ^{6}He ground state. The remainder of the decay strength may be via the ^{6}He unbound 2^+ first excited state at 1.8 MeV, for which the centrifugal barrier is reduced. This in part would compensate for the higher Coulomb barrier (the barrier penetrability is similar to that for the decay via the ground state). Alternatively, the ^{10}Be resonance could neutron decay. From the present measurement it is not possible to unambiguously identify reaction processes in which the excited ^{6}He nucleus decayed into $2n + \alpha$ since the neutrons are not observed. However, we observe events at sum energies $(E_1 + E_2) \sim 1$ MeV less than the resonant elastics data (the $\alpha + 2n$ breakup threshold is 0.974 MeV). These events have azimuthal angles which are close to 180° apart, and are thus likely arise from the $^6\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He} + 2n$ reaction. If it is assumed that these events correspond to the decay of the ^{10}Be resonance, rather than from inelastic excitations, then they correspond to ~40% of the strength in the ^{6}He ground-state channel (taking into account the change in detection efficiency). It has already been noted by Soić *et al.* [5] that the 10.15 MeV state does not strongly neutron decay to $^9\mathrm{Be}_{\mathrm{g.s.}}$, even though the penetrability factor for this process is larger than that for the α decay (a factor of 6). Given that it is predicted that the 10.15 MeV state is part of a rotational band with a σ^2 neutron configuration [7], the decay to the ^{9}Be 1.68 MeV $(1/2^+)$ state should be favored. Owing to the $l = 4$ decay barrier and the reduced decay energy, the decay probability is 3 orders of magnitude smaller for this channel. The ^{9}Be state then neutron decays to the ^{8}Be ground state. We have analyzed coincidences in which two particles were emitted with a difference in azimuthal angles being less than 60°. From the reconstructed ^{8}Be relative energy spectrum 170 events were found consistent with the decay of $^8\mathrm{Be}_{\mathrm{gs}}$, thus placing an upper limit on the decay to $^9\mathrm{Be}(1/2^+, 1.68\ \mathrm{MeV})$ of 10^{-3} with respect to $^4\mathrm{He} + {}^6\mathrm{He}_{\mathrm{g.s.}}$ decay. Thus, we conclude the 10.15 MeV decays predominantly to $^4\mathrm{He} + {}^6\mathrm{He}_{\mathrm{g.s.}}$.

The present measurements demonstrate that the 10.15 MeV resonance in ^{10}Be has a *very* large α-particle component (as well developed as in ^{8}Be) and thus a well-developed molecular structure. Moreover, this resonance appears to be the 4^+ member of a rotational band built on the 6.18 MeV (0_2^+) state. The rotational gradient ($\hbar^2/2I$, I being the moment of inertia) of the band is 0.20 MeV. This may be compared with that for the ^{8}Be and ^{9}Be ground-state bands of 0.57 and 0.53 MeV, respectively. In other words, the separation of the two α clusters is greatly enhanced in ^{10}Be a feature which is seen in the antisymmetrized molecular dynamics calculations for the ^{10}Be 6.18 MeV (0^+) state [7] and which, as noted earlier, arises from the presence of the *molecular* neutrons between the two α cores. The present measurements thus provide strong support for the molecular model descriptions of ^{10}Be, and that the molecular α:$2n$:α cluster structure is dominant in the rotational band based on the 6.18 MeV, 0_2^+ state.

We would like to acknowledge the unstinting efforts of the LLN cyclotron operations staff. R. R. is a PDF of the Fund for Scientific Research—Flanders, Belgium (F. W. O.-Vlaanderen).

[1] N. Itagaki *et al.*, Phys. Rev. C **70**, 054307 (2004).
[2] L. R. Hafstad and E. Teller, Phys. Rev. **54**, 681 (1938).
[3] W. von Oertzen, Z. Phys. A **354**, 37 (1996); Z. Phys. A **357**, 355 (1997).
[4] M. Milin *et al.*, Nucl. Phys. **A753**, 263 (2005).
[5] N. Soić *et al.*, Europhys. Lett. **34**, 7 (1996).
[6] N. Curtis *et al.*, Phys. Rev. C **64**, 044604 (2001).
[7] Y. Kanada-En'yo *et al.*, Phys. Rev. C **60**, 064304 (1999).
[8] T. Davinson *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **454**, 350 (2000).
[9] K. P. Artemov *et al.*, Sov. J. Appl. Phys. **52**, 408 (1990).
[10] J. A. Liendo *et al.*, Phys. Rev. C **65**, 034317 (2002).
[11] P. V. Green *et al.*, Phys. Rev. C **53**, 2862 (1996).
[12] C. M. Jones *et al.*, Phys. Rev. **117**, 525 (1960).
[13] S. A. Afzal *et al.*, Rev. Mod. Phys. **41**, 247 (1969).
[14] J. L. Russell *et al.*, Phys. Rev. **104**, 135 (1956).