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Clarification of the low-lying states of ^{9}Be

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Abstract
A newly developed technique for dealing with three-body decays of broad isolated levels is extended to deal with the broad, overlapping levels found at 2–9 MeV excitation energy in ^{9}Be. The levels are populated through beta-decay of ^{9}Li. The method gives firm evidence for the existence of several levels. Angular correlation studies allow spin values to be assigned.

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(Some figures in this article are in colour only in the electronic version.)

1. Introduction

The interest in very light nuclei has renewed recently due to the progress in *ab initio* calculations applied to the structure of light nuclei, now reaching the lowest energy states for several spin values in isobars with mass 9 and 10 [1, 2]. This development presents a challenge for experimentalists to complete the knowledge on the excited states. This task becomes increasingly hard when one moves to the unbound part of the spectrum. Even for a well-studied stable nucleus such as ^{9}Be there are large uncertainties at about 5 MeV excitation energy. *Ab initio* calculations have made an effort [1] to reach this region. They predict more $3/2^-$, $5/2^-$ and $7/2^-$ levels in the Q_β-window than are seen experimentally. Between 5–8 MeV excitation energy, there is an experimental indication of a tentative $3/2^-$ level at 5.6 MeV observed in a single experiment (p, p′) at 180 MeV in which spin assignment stems from theory [3]. The first $7/2^-$ state at 6.4 MeV has been firmly established [3] and a state at 7.94 MeV observed in beta decay has a controverted spin assignment. The difficulty of the region is that all levels are broad (width about 1 MeV) and disintegrate into 3-particles.

The partial decay channels of these broad levels are of interest. The properties of low-lying unbound states in ^{9}Be are relevant in the calculation of the ^{4}He(αn,γ) ^{9}Be reaction rate in the stellar scenario. This reaction is one of the key reactions which could bridge the mass gap at $A = 8$ to produce intermediate-to-heavy mass elements in alpha- and neutron-rich environments. A ternary process hardly plays a role in the formation of ^{9}Be. Instead the reaction reflects the nuclear structure of ^{9}Be with large neutron widths. The reaction is described by $\alpha + \alpha \rightleftharpoons {}^8$Be(n, γ)^{9}Be which takes place during the lifetime of ^{8}Be (10^{-16} s) in such a suitable astrophysical scenario as the neutrino driven wind [4]. So resonance states in ^{9}Be near threshold play an important role. Besides it has recently been pointed out [5] that the reaction $\alpha + \mathrm{n} \rightleftharpoons {}^5$He($\alpha$, γ)^{9}Be with the lifetime of ^{5}He (10^{-21} s) can have an additional contribution to the formation of ^{9}Be. A microscopic three-cluster study of the photoneutron cross-section for ^{9}Be shows that the ^{5}He + α channel is of growing importance at temperatures above 10^9 K($\approx$ 4 MeV). Lack of experimental information has prevented the incorporation of this channel in photodisintegration calculations. Therefore a good knowledge of the ^{9}Be system is very important with emphasis on the ^{5}He intermediate decay channel.

Due to its selection rules, β-decay provides a clean way to feed unbound states making beta delayed particle emission an excellent source of nuclear structure information. This approach has given a lot of information. If one knows the final state from the particle spectra one can derive the beta feeding to the different states. In a two-body break-up as in the beta-decay of ^{8}Li by measuring the single alpha-spectrum the process is fully determined. In a seminal paper, Barker [6] presented an R-matrix analysis of the α spectra following the decay of ^{8}Li and ^{8}B, which is applicable to spectra of single-particle emission to bound states. Later the formulation was expanded for cases where the final state is also a resonance and a second particle is emitted,

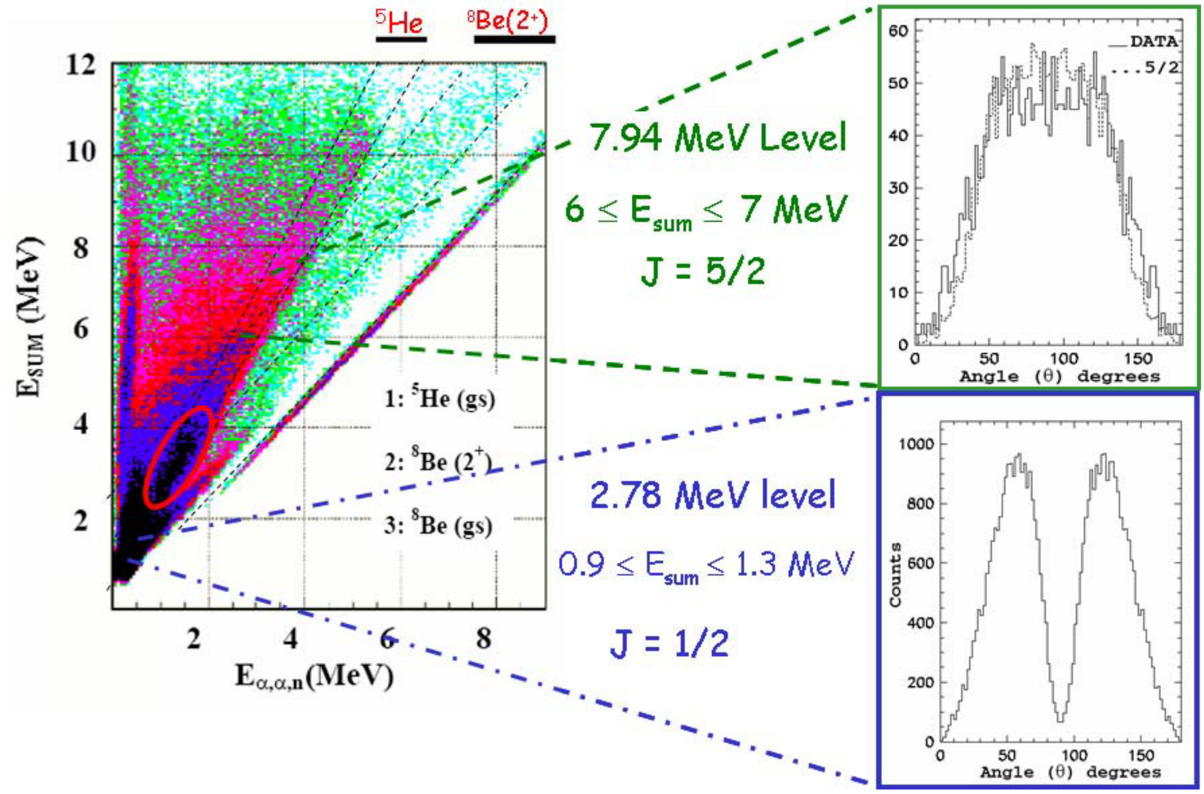

Figure 1. Scatter plot of the deduced $\alpha + \alpha$ + n sum energy plotted versus the individual particle energies (E_n is deduced from momentum conservation). The lines guide the eye through the contributions of the different partial channels. An increase in strength is observed at $E_{\mathrm{sum}} \sim 3$–4 MeV along the ^{5}He(g.s.) decay channel. On the right, the angular distributions for the regions corresponding to the 2.78 and 7.94 MeV levels in ^{9}Be are shown.

i.e., three-body sequential decay [7]. People have tried to explain the three-body break-ups for many years even though they only measured single spectra. But to do so one needs to introduce model assumptions and in several cases the same experimental data were explained assuming both sequential and direct decay, see [8]. With complete kinematics, these assumptions can be checked.

2. Experimental setup and analysis methods

The experiments discussed in this paper were carried out at the ISOLDE facility at CERN where we profit by low energy beams of high purity and good optical quality. The beam is stopped in a thin foil forming a point-like source.

The setup consisted of two telescopes in close geometry with double sided Si strip detectors (DSSSDs) in front and with thick surface barrier detectors in the back to be able to detect betas. More details of the setup can be found in [9, 10]. By the use of DSSSDs with ultrathin windows [11] and by lowering the energy of the incoming beam to 20 keV, the threshold for alphas was as low as 300 keV and the decay via the ^{8}Be(0$^+$) channel is clearly observable (see figure 1 and figure 1 of [12]).

Only a few levels in ^{9}Be are populated in the beta decay of ^{9}Li and the recoil imparted to the state is negligible so the breakup of the state is assumed to occur at rest. Therefore the conservation of energy and momentum serves to reconstruct the energy and direction of the third particle. To get the partial decay branches of each level, R-matrix calculations have been applied with Monte Carlo simulations to account for the different efficiencies for the two detected particles depending on the intermediate channel.

Inclusion of angular correlation is essential to obtain a good description of the data. The high granularity of the setup has allowed us to look at angular correlations. For non-interfering states, the direction of the first particle is isotropic and the second is distributed according to an angular correlation function $W(\theta) = \sum_{\nu=0}^{\nu_{\max}} A_\nu P_\nu(\cos(\theta))$, where P_ν are the Legendre polynomials of order ν and the coefficients A_ν are determined by the angular momenta involved in the process. The angular correlation has been studied following the formulation of Biederharn and Rose [13] that gives the distribution of the cosine of the angle between the first particle emitted in the CM system of ^{9}Be in this case and the direction determined by the other two.

In the following, the formulation used will be briefly sketched. In a two-step process j_1, j, j_2 are the spins of the initial, intermediate and final state respectively and l_1 and l_2 the orbital angular momenta of the particles emitted, with $|j_1 - j| \leqslant l_1 + s_1$, $|j_2 - j| \leqslant l_2 + s_2$. The order of the Legendre polynomial is limited by the triangular conditions in the Racah coefficients to $0 \leqslant \nu_{\max} \leqslant 2j$; $0 \leqslant \nu_{\max} \leqslant 2(l_1)_{\max}$; $0 \leqslant \nu_{\max} \leqslant 2(l_2)_{\max}$. If j is a half-integer, then j in the inequality above is replaced by $j - 1/2$. Therefore, whenever the intermediate state has spin zero or 1/2 there is isotropy between the two emissions. In case of two possible angular momenta for the first step: l_1 and l_1' since $l_1' = l_1 + 2$ this wave is usually less relevant due to the centrifugal barrier and often its contribution can be neglected. The asymmetry coefficients are given for spinless particles in the two-step process $j_1(l_1)j(l_2)j_2$ by

$$A_\nu = F_\nu(l_1 j_1 j) b_\nu(l_1 l_1) F_\nu(l_2 j_2 j) b_\nu(l_2 l_2),$$
$$b_\nu(ll) = 2l(l+1)/[2l(l+1) - \nu(\nu+1)],$$

where F_ν are functions of a geometrical nature and are determined by the angular momenta. Numerical values in terms of Racah coefficients are given in pages 747 and 748 of [13]. If one of the emitted particles is a nucleon an additional formula applies which includes interferences between the two possible combinations of spin and angular momentum of the nucleon (see p 752 of [13]). For most applications, one is interested in the extreme values of the correlation. These are given by treating the process as if it were a radioactive capture forming fictitious channel spins $j_1 \pm 1/2$ and substituting them by j_1 in the expression of the coefficients A_ν. Therefore the extreme patterns of correlations are $(j_1 \pm 1/2)(l_1)j(l_2)j_2$ and the previous formulae apply. The same applies if the nucleon is emitted in the second process.

We can determine the spin of the state by fitting the angular distribution and extracting the asymmetry parameter and then compare with the expected values for the different spins. This technique has been exploited to study the different regions along the ^{5}He channel.

3. Results

In this section, the studies done on the low energy states of ^{9}Be i.e., the levels $3/2^-, 5/2^-$ and $7/2^-$ populated in the allowed beta transitions from ^{9}Li are discussed. The energy, spin and decay modes of the narrow 2.43 MeV state in ^{9}Be are well known and the existing experiments agree that only 7% decay to the ^{8}Be(g.s.). The decay mode has been more widely discussed and data from reactions have been analysed both assuming sequential or direct decay. From our α–α data by momentum conservation, the energy and direction of the neutron have been deduced and the sum, $E_{\mathrm{sum}}(E^*(^9\mathrm{Be}) = E_{\mathrm{sum}} + 1.57\,\mathrm{MeV})$, is plotted versus the individual energies as shown in figure 1. The data have been selected with $E_{\mathrm{sum}} < 0.9$ MeV corresponding to the 2.43 MeV level in ^{9}Be and it is noticed that a better fit is obtained to the experimental distribution when the direct decay prescription of Bochkarev *et al* [14] is applied. This interesting result will be studied further in new data obtained recently.

The properties of the broad 2.78 MeV state are not so well known. The level was proposed by Chen *et al* [15] in their study of the beta-delayed time-of-flight neutron spectrum. The spin assignment was 1/2 as suggested by both the shell model and rotational model. The energy and width have been confirmed in subsequent experiments which, however, disagree in the decay branches. It has passed into the literature as mainly decaying to ^{8}Be(g.s.), (see [16] for the latest compilation), under this assumption the beta feeding was 3% [15]. Later in experiments done at CERN, the study of the beta delayed charged particle spectrum indicated a feeding of 7% via the ^{8}Be(2$^+$) and ^{5}He(g.s.) [17]. This result was confirmed in [7] that established a ratio of 2 to 1 to these two partial branches.

We decided to check the decay of the 2.78 MeV state to solve this question. The scatter plot shown in figure 1 indicates considerable intensity through the ^{5}He(g.s.) and ^{8}Be(2$^+$) channels. Lines to guide the eye are drawn indicating the contribution of the different channels. To investigate this further the angular distribution of the alphas which is sensitive to the spin of the states involved has been studied. The extreme correlation patterns for the partial channel $^9\mathrm{Be}^* \mapsto {}^5\mathrm{He(g.s.)} + \alpha \mapsto \alpha + \mathrm{n} + \alpha$ where the nucleon is emitted in the second step is given by $j_1(l_1)j(l_2)(j_2 + 1/2)$. Therefore, assuming $J = 1/2$ for the 2.78 MeV state of ^{9}Be, the extreme correlation patterns will be 1/2(2)3/2(1)1/2 corresponding to $\nu_{\max} = 2$ and $A_2 = 1$. In the scatter plot, the region $0.9 < E_{\mathrm{sum}} < 1.3$ MeV has been selected along the diagonal corresponding to the ^{5}He(g.s.) channel. At these low energies, the selection of the channel is not very clean and the contribution from the ^{8}Be(2$^+$) channel cannot be separated. So the extreme correlation patterns for the partial channel $^9\mathrm{Be}^* \mapsto {}^8\mathrm{Be}(2^+) + \mathrm{n} \mapsto \mathrm{n} + \alpha + \alpha$ has also been considered and they are $0(1)2(2)0(A_2 = 0)$ and $1(1)2(2)0(A_2 = 1)$. So for both channels we expect the same α–α distribution with minimum around 90° and maxima at 30° and 150°. As shown on the bottom right-hand side of figure 1, the angular distribution between one alpha and the direction of the centre of mass of the $\alpha + \mathrm{n}$ system gives the typical distribution of spin = 1/2. Even if in the region the contribution of the two channels co-exist they give, in this case, the same angular distribution for the α's. So in this way, it is demonstrated that there is a significant contribution of the breakup of the 2.78 MeV state that do not feed the 0$^+$ g.s. of ^{8}Be and give the first experimental evidence of the $1/2^-$ character of this state.

A 1.5(5)% beta-feeding was proposed by Langevin *et al* [17] to the 7.94 MeV state that he assumed to be $J = 1/2$. An analysis of the α–α angular correlation of the region of interest through the ^{5}He channel indicates a spin of 5/2 for this state, see upper right side of figure 1. This new spin value is in agreement with the unpublished results of $^{10}\mathrm{B(e, e'p)}^9\mathrm{Be}$ cited in [16]. One should bear in mind that the feeding observed in this region might have contributions from the tail of the 11.8 MeV state.

There is still some strength in the region around $E_{\mathrm{sum}} = 5$ MeV (see ellipse in figure 1). To elucidate this further, the alpha-projection spectrum was fitted using the contribution of the previously known levels in ^{9}Be fed in beta-decay: the 2.43, 2.78, 7.94 and 11.8 MeV states. Monte Carlo simulations have been performed to account for the different geometrical efficiencies of the particle detection in the different decay branches. The R-matrix formalism was applied for the simulation of the primary (interaction radius of 4.2 fm) and secondary decay branches (around 6 fm). Figure 2 shows the comparison between the alpha spectrum obtained from coincidences (black line) and the Monte carlo simulation of the contribution of the breakup of the 2.43 (green), 2.78 (dark blue), 7.94 (light blue) and 11.8 (red) MeV states. The contribution of the three 5/2 levels at 2.43, 7.94 and 11.8 MeV were added incoherently. When compared to the experimental alpha-spectrum, the simulations show missing intensity between 1–3 MeV in the projected α-spectrum. It is necessary to introduce a new level to account for this

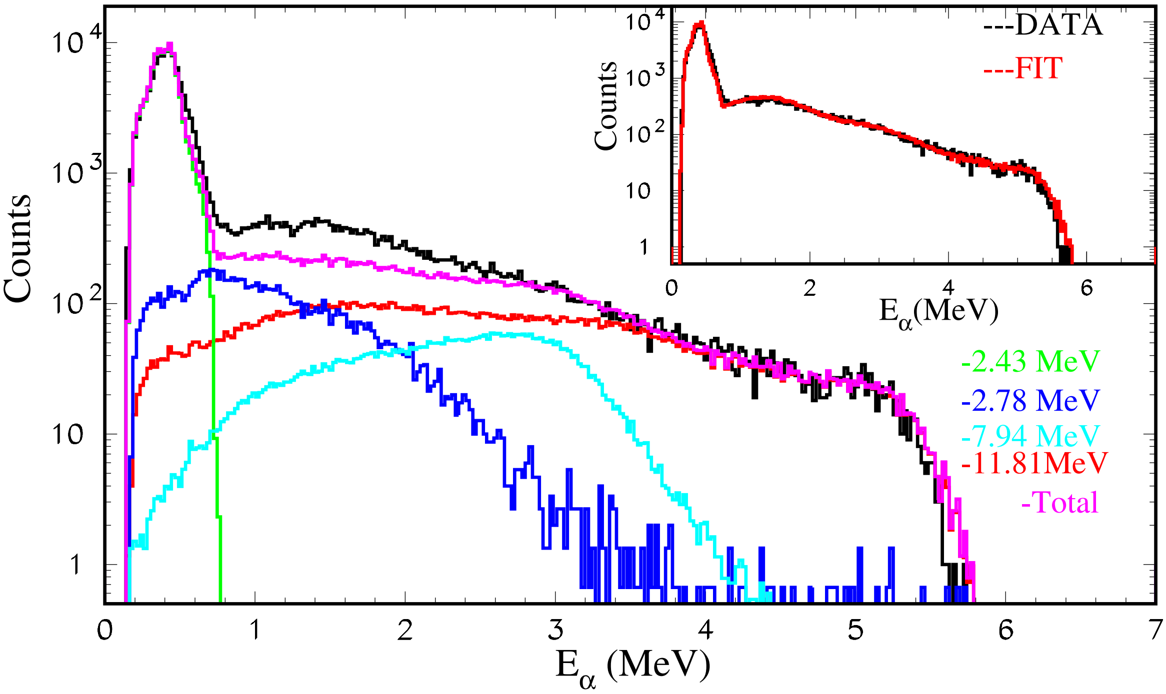

Figure 2. The projected α-spectrum (black line) was fitted using the R-matrix formalism for the contribution of the previously known levels in ^{9}Be fed in beta-decay at 2.43, 2.78, 7.94 and 11.8 MeV. The incoherent contribution of the different states is the fuchsia curve, indicating missing strength. When feeding to the 5 MeV state is considered an excellent fit is obtained as shown in the inset. From this fit the branching ratios and partial decay branches given in table 1 are derived.

Table 1. Excited states of ^{9}Be fed in the beta-decay of ^{9}Li. Comparison with *ab initio* calculations. Beta-decay branching ratios. Partial decay branches.

E^* (^{9}Be) (MeV)	I^π	Γ (keV)	E^*(^{9}Be) CDB2k of [1]	B.R.(%) singles	Partial ^{8}Be(0$^+$) + n	Decay branches ^{8}Be(2$^+$) + n	(%) ^{5}He(3/2$^-$) + α
g.s.	$3/2^-$		g.s.	49.2 ± 0.9^a	—	—	—
2.43	$5/2^-$	0.77 ± 0.15	2.78	31.9 ± 3.4^b	—^{c}	—^{c}	—^{c}
2.78	$1/2^-$	1080 ± 110	2.68	11.6 ± 2.2^d	23(3)	58(2)	19(1)
5.0	$3/2^-$	2000 ± 500	4.98	3.15 ± 0.4	<10	—	>90
7.94	$5/2^-$	≈ 1000	7.96	1.5 ± 0.4	<10	<20	>80
11.81	$5/2^-$	400 ± 30	13.02	2.7 ± 0.4	2(1)	11(6)	28(6)^e

[a]Taken from [16].
[b]Calculated assuming that 7% of the total decay branch of the 2.43 MeV state decays via ^{8}Be(g.s.).
[c]Fitting following the prescription of [14] as explained in the text.
[d]Calculated assuming that 3% of the ^{9}Li β-decay goes to the 2.78 MeV state and decay via ^{8}Be(g.s.).
[e]Contribution of the ^{8}Be(4$^+$), 12(8)%, and ^{5}He(1/2$^-$), 47(7)%, channels are considered, see [10].

discrepancy and its characteristics can be found from the study of the energy and angular distributions as described in the following.

We make use of the extra strength observed in the scatter plot, figure 1, and select the region at $3 < E_{\rm sum} < 4$ MeV along the ^{5}He channel, trying to avoid the contribution of the 2.78 MeV state. To be more selective we place a condition in the alpha of highest energy, $1.8 \times E_{\alpha_1} + 0.7 < E_{\rm sum} < 1.8 \times E_{\alpha_1} + 1.1$ (MeV). The projected spectrum was fitted using the R-matrix formalism assuming 3/2 and 5/2 spins for the state, and the α–α angular correlations were also fitted assuming both possible values for the spin of the state in ^{9}Be. Both favour spin 3/2 and the energy fit is best for a level at 5.0(5) MeV of width 2.0(5) MeV. Limiting values for energy and width are those for which the fit deteriorates. The decay branches deduced are mainly through ^{5}He(g.s.) with a maximum of 10% for decay via ^{8}Be(g.s.). Including this new level, the fit of the projected coincidence spectrum is excellent (see inset of figure 2). The agreement with the single data taken at the same time with a different setup is very good (see figure 4 of [12]).

In table 1, the results obtained in this work have been summarized. The energy of the levels populated in beta decay are compared with the latest *ab initio* calculations [1] using the very precise nucleon–nucleon (NN) interaction of CD-Bonn 2000 (CDB2k) [18]. In their calculations, several NN interactions are tested and CDB2k is the one that better reproduce the position of the 2.43 and 2.78 MeV states. The predicted energy values for the second $3/2^-$ state (new from this work) and second $5/2^-$ (7.94 MeV) states coincide well with the experimental ones. For comparison the branching ratios obtained by fitting the single spectrum are also given. The partial branches for the 11.8 MeV state determined previously in [10] are fixed in this work. Comparison with previous values is given elsewhere [12]. The partial decay branches deduced from the fit to the singles are included in table 1. Comparison with the expected spectroscopic factors calculated within the shell model [19] is reasonable.

4. Conclusion

Considering that ^{9}Be is a well-studied nucleus, it is surprising, at first glance, that new information on states fed in beta-decay is found at such a low energy as 5 MeV. The reason for the incomplete knowledge is the fact that due to the low Z of the nucleus the levels are very broad and their contributions overlap in a single-spectrum study. We have succeeded in ‘pulling out a new level’, thanks to the combined use of a selective and clean probe, the β-decay of the short-lived nucleus ^{9}Li, and a very modern detection set-up with essentially full kinematical coverage allowing for a complete characterization of the three-body final state. Furthermore, a first experimental determination of the spin of the 2.78 and 7.94 MeV states has been obtained.

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