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Excited states of ^{11}Be

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Abstract

The ^{11}B(^{7}Li,^{7}Be)^{11}Be reaction at 57 MeV incident energy was studied at forward angles in order to explore the ^{11}Be excitation energy spectrum. The ^{11}Be ground state and the states at $E^* = 0.32, 1.77, 2.67, 3.41, 3.89, 3.96, 6.05$ MeV excitation energies were populated. The state at 6.05 MeV (FWHM 320 ± 40 keV) has not been previously observed. The good energy resolution (~ 50 keV) allowed the identification of these transitions each for ^{7}Be in its ground and first excited state at $E^* = 0.429$ MeV. QRPA calculations reproduce the ^{11}Be level structure below 2 MeV of excitation energy. The strength observed at higher excitation energies is very likely produced mainly by core-excited components of ^{11}Be. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Heavy-ion charge exchange reactions (CEX) are a powerful tool for spectroscopic studies in exotic nuclei, and may be used to investigate the isovector response of near dripline nuclei. An exotic nucleus of great current interest is ^{11}Be because of its one-neutron halo structure [1,2]. Effects such as the inversion of $2s_{1/2}$ and $1p_{1/2}$ neutron orbitals [3,4] and the coupling in the ground state of the d-wave orbital of the valence neutron with the 2^+ excited state of the ^{10}Be core [5] have been observed via direct reactions. However, despite the many experimental [3–16] and theoretical studies [17–19], a satisfactory description of both the structure of ^{11}Be and the dynamics of reactions involving such a nucleus is not yet accomplished. In this Letter, we report on an investigation based on the ^{11}B(^{7}Li,^{7}Be)^{11}Be reaction to excite ^{11}Be states.

2. Experimental setup and main results

The experiment was performed at the IPN-Orsay Tandem laboratory using a 57 MeV ^{7}Li^{+++} beam and a 95% enriched ^{11}B self supporting target about 130 μg/cm^2 thick. The ^{7}Be ejectiles were detected by

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the IPN-Orsay split-pole spectrometer and the associated focal plane detector, which consisted of a position and angle sensitive multiwire drift counter, a proportional counter and stopping plastic scintillator. The range between 0° and 18° was explored. The solid angle covered was 0.5 msr for the 0° run and was set to values from 0.2 msr and 0.7 msr for the larger angle runs. The overall energy resolution was about 50 keV. Counts from ^{12}C impurities in the target were subtracted using the spectra measured in separate runs with a ^{12}C target, while those from ^{16}O impurities were identified through comparison with spectra measured in a previous experiment with a WO_3+C target [15]. The background from ^{11}B(^{7}Li, n^{7}Be)^{10}Be was modeled assuming a non-resonant 3-body phase space in the exit channel. Such an assumption is based on the interplay of kinematical selectivity of that reaction and ^{8}Be single particle structure [20].

In the spectra, nine peaks are assigned to transitions in which ^{7}Be remains in its $3/2^-$ ground state while ^{11}Be is either in the ground state or in the 0.32, 1.77, 2.67, 3.41, 3.89, 3.96, 6.05 MeV excited states, as shown in Fig. 1. Peaks marked by an asterisk refer to transitions in which ^{7}Be is in the 0.43 MeV $1/2^-$ first excited state. The excited states populated in the present experiment are also presented in Table 1. The centroids and the widths of ^{11}Be resonances have been obtained as mean values of the parameters of Gaussian fits of the peaks extracted independently at each angle. For the transitions to the excited state of the ^{7}Be ejectile, the broadening effect from the gamma-ray emission was taken into account. The uncertainties on the excitation energies are dominated by systematic errors.

An interesting feature of the spectra is the previously-unobserved structure at 6.05 MeV. The double-Gaussian fit to the ^{7}Be ground and first excited state, shown in Fig. 1 (c), gives a width of about 0.3 MeV. In Ref. [12] a theoretical calculation is presented for which a single particle (sd) neutron state ($3/2^+$) is expected at 6.70 MeV as the counterpart of the $5/2^+$ state at 1.77 MeV. However, the width of this state is in clear disagreement with an interpretation in terms of a single particle resonance. A simple model of a $d_{3/2}$ single-particle in a standard Woods–Saxon well with resonance energy 5.5 MeV gives a width of about 5 MeV; exceeding the observed width by a factor of about 20. Apparently, in the region between 3.4 and 4 MeV the width does not follow the trend expected for a configuration dominated by a single particle state. Liu and Fortune [12] find a similar behavior also for the level at 5.24 MeV. This suggests more complicated structures for these levels than a single particle excitation. Very likely, these states are bound states embedded in the continuum (BSEC) [22,23] connected with Dynamical Core Polarization (DCP). In this mass region BSEC structures have been observed before in stable nuclei, e.g., ^{13}C($3/2^+$, $E_x = 7.677$ MeV) [22,23]. A candidate for a $3/2^+$ BSEC in ^{11}Be at about the observed energy could be the coupling of the (excited) $1/2^-$ neutron orbit to the known ^{10}Be(1^-, 5.96 MeV) core state. Interestingly, a recent analysis of ^{19}C breakup reactions [24] also led to the conclusion that BSEC structures might be an important phenomenon in the low-energy continuum of neutron halo nuclei.

A comparison of the present spectra with previous CEX experiments shows some other noteworthy features. The 1.77 and 3.41 MeV states are observed here, the ground state is clearly separated from the 0.32 MeV state and both the 3.89 and 3.96 states are populated. While the population of the ground and the states at 3.41 and 3.96 MeV may be a result of the higher resolution of the present experiment, the excitation of the single particle state at 1.77 MeV is mainly due to the higher orbital angular momentum transfer in the heavy projectile–ejectile system (enhanced by the halo extension and the very negative Q-value [25]) and to the larger number of (^{7}Li,^{7}Be) spin transfers compared to the Gamow–Teller selectivity of both the (d,2p) and (t,^{3}He) CEX or the spin selectivity of π^+ electroproduction.

In order to get a first insight into the structure of the observed strength distribution a theoretical approach based on charge exchange QRPA theory was used. From former applications to stable nuclei [26] the model is known to account well for states which are predominantly given by a superposition of neutron particle–proton hole, i.e., two quasiparticle (2QP), states with respect to the ground state of the parent nucleus, in this case ^{11}B. The ^{11}B ground state was obtained in Hartree–Fock–Bogoliubov theory using the D3Y interaction of Ref. [27], including blocking of the $1p_{3/2}$ proton and neutron orbits. States in ^{11}Be are described in QRPA as correlated proton–neutron

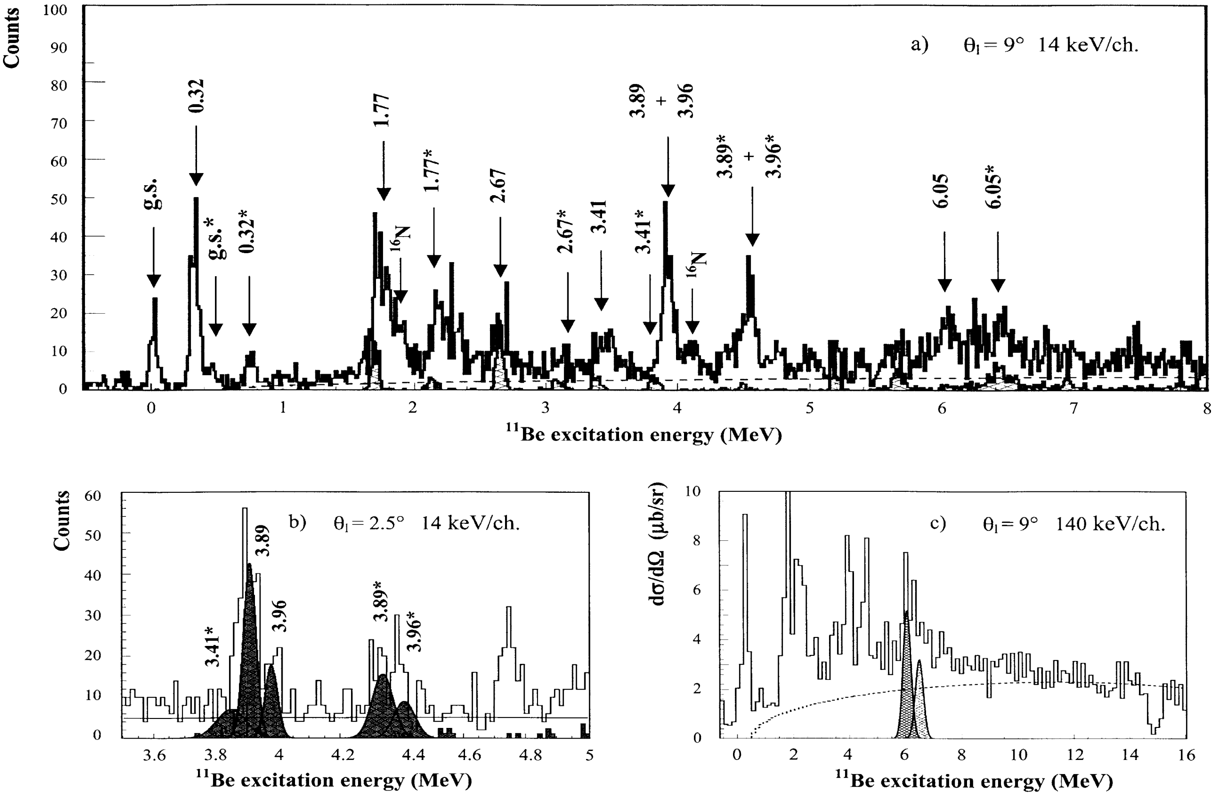

Fig. 1. Excitation energy spectra for the ^{11}B(^{7}Li,^{7}Be)^{11}Be reaction at 57 MeV. In the plots the peaks marked with an asterisk are associated to the excitation of ^{7}Be at 0.429 MeV. (a) Spectrum taken at 9°. The shaded histogram represents the normalized background of ^{12}C(^{7}Li,^{7}Be)^{12}B reaction, the dashed line represents the continuous shape obtained for the ^{11}B(^{7}Li,^{7}Be)^{10}Be+n 3-body phase space, shown in detail in part (c). (b) Detail of the fitted structure around 4 MeV in the spectrum at 2.5°. (c) Three-body phase space distribution [21] and detail of the fitted structures around 6 MeV.

Table 1
States populated in the ^{11}B(^{7}Li,^{7}Be)^{11}Be reaction

E_x (MeV)	Γ (keV)	J^π [3,12]	Structure [12,17]
		$1/2^+$	$^{10}\mathrm{Be}(0^+) \otimes (s1/2)$
0.32 ± 0.02		$1/2^-$	$^{10}\mathrm{Be}(0^+) \otimes (p1/2)$
1.77 ± 0.02	100 ± 10	$5/2^+$	$^{10}\mathrm{Be}(0^+) \otimes (d5/2, d3/2)$
2.67 ± 0.02	200 ± 10	$3/2^-$	$^{10}\mathrm{Be}(0^+) \otimes (p3/2)^{-1}$
3.41 ± 0.02	130 ± 10	$3/2^-$	$^{9}\mathrm{Be}(gs) \otimes (sd)^2{}_{0+}$
3.89 ± 0.02	< 50	$3/2^+$ [12] $5/2^-$ [3]	$^{10}\mathrm{Be}(2^+) \otimes (s1/2)$
3.96 ± 0.02	< 50	$3/2^-$	$^{9}\mathrm{Be}(gs) \otimes (sd)^2{}_{2+}$
6.05 ± 0.04	320 ± 40		

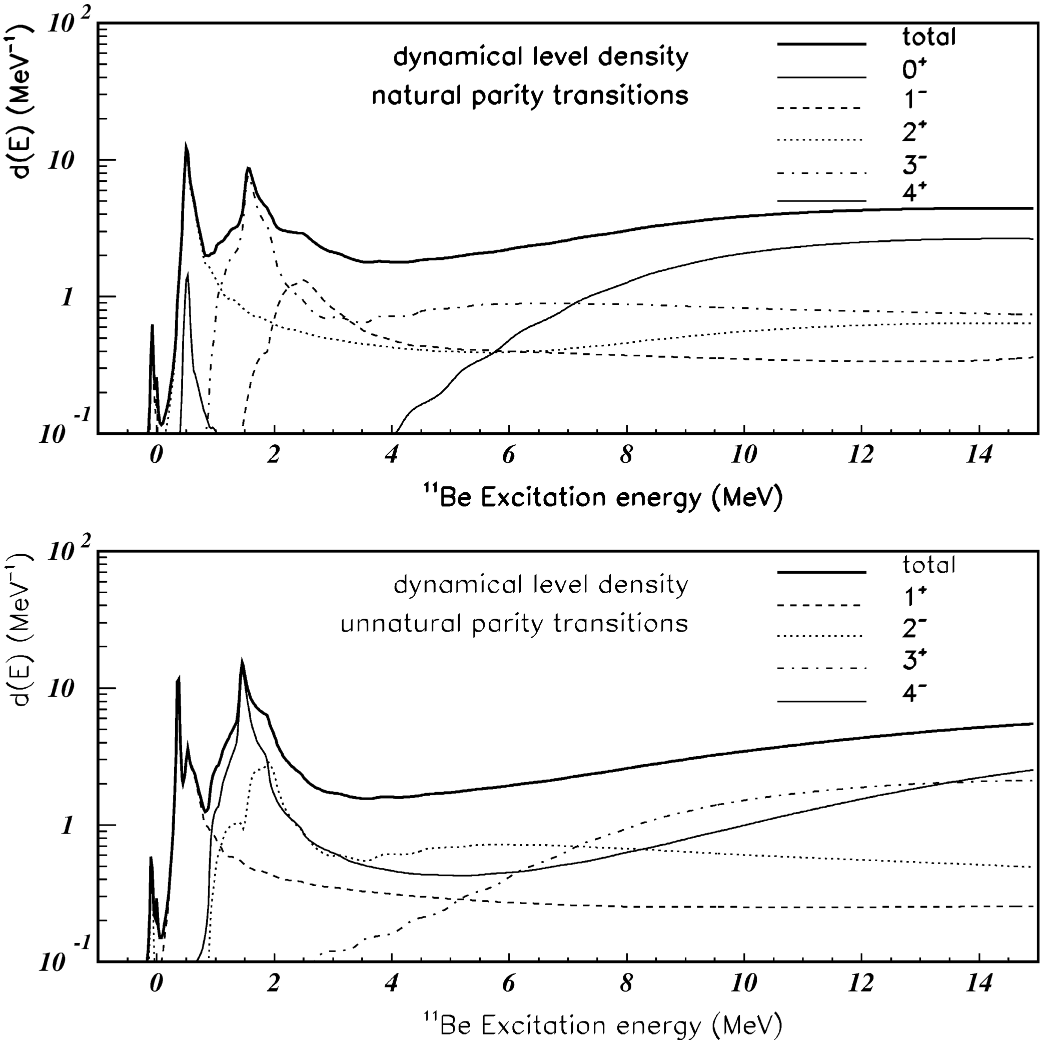

Fig. 2. Dynamical level densities for transitions from the $^{11}B_{gs}$ to the excited states of ^{11}Be. See text for details.

2QP excitations. The coupling to 4QP and higher order configurations was taken into account schematically by introducing a complex 1QP self-energy, similar to the structure model used in Ref. [28]. Transition strength distributions for multipolarities from 0^+, 0^- to 5^+, 5^- have been calculated, as shown in Fig. 2. Obviously, the model emphasizes the single particle content of the $^{11}B \rightarrow {}^{11}Be$ transitions, but will not account for details of core polarization.

The results indicate that the ground state of ^{11}Be is excited by 1^- and 2^- transitions obtained by the coupling of the $3/2^-$ ^{11}B ground state with the $1/2^+$ state in ^{11}Be. Similarly, a sharp concentration of 1^+ and 2^+ strengths around 0.3 MeV indicates a $1/2^-$ state at that energy in ^{11}Be. These results agree with the well-known observation of a $2s_{1/2}$ and $1p_{1/2}$ shell inversion in ^{11}Be. Since these states are known to contain a strong single particle component they should indeed be reproduced by the QRPA calculations. Hence, the fact that they are described by the model calculations might be taken to confirm the applicability of the QRPA approach to a dripline nucleus as ^{11}Be. One also notes a minor contribution (around 5%) of the 0^+ transition to the strength at 0.3 MeV. This is compatible with a $3/2^-$ component to the first excited state. At higher excitation energy noticeable components of 1^-, 2^-, 3^- and 4^- strengths concentrated around 1.8 MeV are obtained. This is in agreement with the $5/2^+$ single particle interpretation of the 1.77 MeV state in ^{11}Be. So, we can conclude that at least up to this energy the spectrum may be understood in terms of single particle degrees of freedom. However, the afore mentioned constraint of charge exchange QRPA to the dynamics of the leading particle becomes evident from a comparison to the spectra at higher energies. At excitation energy above 2 MeV the QRPA strength is distributed over a broad energy region of almost structureless shape. It is obvious that the observed fragmentation of the ^{11}Be spectrum is not reproduced, most likely owing to the neglection of the coupling of the valence neutron to ^{10}Be core excited states. More involved DCP investigations of core polarization effects in ^{11}Be are in progress, similar to the approaches in Refs. [29,30]. The principal importance of DCP in ^{11}Be was already shown by Vinh Mau [31] using the phenomenological particle-vibration model.

A quantitative description of the observed cross sections could, at least in principle, be obtained by an approach similar to Ref. [32], including the interfering contributions from direct charge exchange and sequential proton–neutron two-step transfer processes. A first attempt in this direction was made by comparing one-step direct charge exchange cross sections to the data. The shapes of the angular distributions leading to the ^{11}Be($1/2^+$, gs) and the ^{11}Be($1/2^-$, 320 keV) states were reasonably well reproduced for angles below 15° to 20°. Increasing deviations in shape to the measured angular distributions at larger scattering angles and, more severely, the considerable overestimation of the magnitude of cross sections by factors of three or more indicate the importance of two-step transfer processes at low incident energy. Also, calculations with the Franey–Love NN interaction [33] indicate considerable uncertainties in the strengths of the direct charge exchange interactions at these low incident energies, mainly in the tensor component. Standard two-step transfer theory is not directly applicable in the present case because unbound intermediate states will be involved. Beside the fact that adequate theoretical methods are not available or impossible to apply in a realistic calculation, also neither the structure nor optical potentials and other projectile-target interactions are known at present with sufficient accuracy for the intermediate channels populated in the $^{7}\mathrm{Li} + {}^{11}\mathrm{B} \to {}^{7}\mathrm{Be} + {}^{11}\mathrm{Be}$ reaction.

3. Conclusions

In summary, the principal new observation is the state at 6.05 MeV with a width of about 0.3 MeV in the ^{11}Be spectrum. Exploratory QRPA calculations indicate that the strength distribution, especially at excitation energies larger than 2 MeV should include correlations involving the excitation of the core. Valuable spin and parity information at low excitations energies, can be obtained from a comparison of the observed excitation energy spectra to the present QRPA-based approach with the observed. The theoretical results indicate the sharp structures seen at higher excitation energies cannot be understood in terms of simple single particle configuration attached to an inert ^{10}Be core. In particular, the small width is in clear disagreement with a single particle interpretation and indicates the presence of more complicated configurations, involving core degrees of freedom. Alternative interpretations in terms of rotational cluster structures in ^{11}Be, proposed by von Oertzen et al. [34], cannot be excluded but it is an open question whether they could be excited with a noticeable cross section in a charge exchange reaction. It is also not clear if they would lead to such sharp resonance structures as seen in the measured spectra. The measurements show the usefulness of heavy ion charge exchange reactions for spectroscopic studies in exotic nuclei, despite the fact that large uncertainties remain on the reaction dynamics of a low energy reaction involving an exotic nucleus like ^{11}Be.

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