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Structure of states in ^{12}Be via the ^{11}Be(d, p) reaction

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ABSTRACT

The s-wave neutron fraction of the 0^+ levels in ^{12}Be has been investigated for the first time through the ^{11}Be(d, p) transfer reaction using a 5 A MeV ^{11}Be beam at TRIUMF, Canada. The reaction populated all the known bound states of ^{12}Be. The ground state s-wave spectroscopic factor was determined to be $0.28^{+0.03}_{-0.07}$ while that for the long-lived 0^+_2 excited state was $0.73^{+0.27}_{-0.40}$. This observation, together with the smaller effective separation energy indicates enhanced probability for an extended density tail beyond the ^{10}Be core for the 0^+_2 excited state compared to the ground state.

Understanding the structure evolution from stable to halo nuclei requires systematic studies of changes in orbital occupancies. So far only Borromean nuclei, with unbound core + n clusters, have

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shown a two-neutron halo structure, such as in ^{11}Li [1]. The existence of such a structure in a non-Borromean nucleus is not yet established and investigating this in ^{12}Be is of particular interest. The disappearance of the conventional $N = 8$ magic number in ^{12}Be is suggested from the lowering of the 2_1^+ state [2]. This is associated with the $2s_{1/2}$ and $1d_{5/2}$ orbitals intruding into the p-shell. ^{11}Be is known to be a one-neutron halo with the neutron dominantly occupying the $2s_{1/2}$ orbital with spectroscopic factor $S \sim 0.74$ in agreement with the one-neutron removal cross-section [3]. This is also in agreement with the observations from transfer reactions [4–6].

The one-neutron separation energy (S_n) of ^{12}Be is 3169(16) keV, while that of ^{11}Be is 504(6) keV [7], and ^{11}Li has a two-neutron separation energy of 369.15(65) keV [8]. An important question is how the increase in neutron separation energy due to pairing influences the neutron distribution in the $2s_{1/2}$ orbital.

Here we report the first measurement that determines the s-wave neutron occupancy of the 0^+ bound states in ^{12}Be through the ^{11}Be$(d, p)^{12}$Be neutron-transfer reaction. Since the ground state of ^{11}Be is $1/2^+$, the selectivity of this reaction offers a clean way to disentangle the s-wave occupancies for the 0^+ levels. The results are therefore the first clean determination of the ^{12}Be$_{gs}$ spectroscopic factor without any influence of the isomeric 0^+ excited state. The observations also show the s-wave composition of the 0^+ excited state.

The first excited state (2^+) in ^{12}Be was observed at 2.11(2) MeV through inelastic scattering [2,9] and heavy ion transfer [10]. A state at 2.68(3) MeV, was interpreted as an $l = 1$ excitation [9, 12] which is considered to be the same state as observed in the ^{10}Be$(t, p)^{12}$Be reaction at 2.73(3) MeV [11]. Recently, a long-lived 0^+ state at 2.24(2) MeV [13] was populated in the production of a ^{12}Be secondary beam. The mean lifetime of the state was determined to be 331(12) ns [14]. The presence of this state makes it important to investigate the s-wave configuration in the two bound 0^+ levels of ^{12}Be.

The spectroscopic factor (S) for the ^{11}Be$_{gs} + n(2s_{1/2})$ configuration in ^{12}Be$_{gs}$ was found to be 0.42 ± 0.06 from a one-neutron removal reaction [15]. This is smaller than the $2s_{1/2}$ component in ^{11}Be as expected due to larger neutron separation energy. The ^{12}Be$_{gs}$ has p-wave and d-wave spectroscopic factors of 0.37 ± 0.06 [15] and 0.48 ± 0.06 [16], respectively. The small s-wave probability in ^{12}Be makes it necessary to explore whether any of the bound excited levels have a ^{11}Be$_{gs} + n(2s_{1/2})$ configuration. It should be mentioned here that in the neutron removal reactions the ^{12}Be beam cannot be distinguished as being in its ground state or its 0_2^+ long-lived state. It is therefore of utmost importance to find the s-wave strength through a different method that is free from this problem. In this work, the ^{11}Be$(d, p)^{12}$Be reaction provides the first clean signature of the s-wave strength for the ground state and the 0_2^+ state.

Theoretically, the s-wave spectroscopic factor for the 0_2^+ level was predicted in [17] to be 1.34, but it is stated that these numbers should not be taken too seriously, since the matrix elements used are appropriate to a ^{12}C core. Ref. [18], with different wavefunctions, discusses an increased s-wave spectroscopic factor of 1.06 for the ground state while that for the excited 0_2^+ state is predicted to be 0.54.[1] Models of ^{11,12}Be based on a deformed potential [19] consider the ground state and the 0_2^+ excited state to be linear combinations of $1/2[220]^2$ and $1/2[101]^2$ two-neutron configurations with equal amplitudes. A study based on a ^{10}Be $+ n + n$ three-body structure model discussed the second 0^+ excited state to have two neutrons in the $1p_{1/2}$ orbital [20]. No experimental information exists on the detailed configuration of the excited states in ^{12}Be.

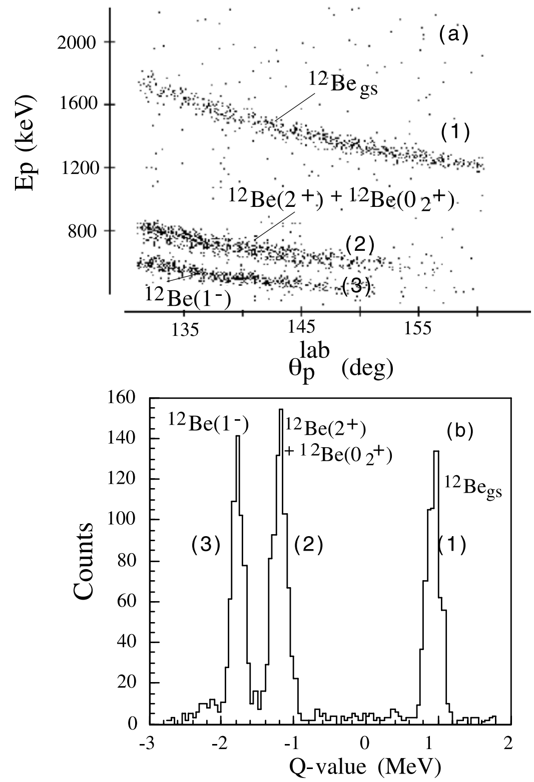

Fig. 1. (a) The kinematic loci of the protons identified in the upstream silicon detector in coincidence with ^{12}Be in the downstream silicon detector. (b) The Q-value spectrum integrated over the full angular range. The different states of ^{12}Be are labeled in the figure.

The experiment was performed at the ISAC-II facility, TRIUMF, Canada. The radioactive ^{11}Be beam was extracted from the TRILIS laser ion source [21], and accelerated to 5 A MeV by the ISAC-I room-temperature RFQ and DTL [22] accelerators, followed by the new ISAC-II superconducting linear accelerator. The uncertainty in the average beam energy was $< 10\,A$ keV. An accelerated beam intensity of typically 10^5 ions/s was delivered to a 40 μg/cm^2 self supporting $(CD_2)_n$ reaction target whose thickness was measured from energy-loss using a standard alpha source. The beam spot size at the target was < 3 mm in diameter.

A 140 μm thick annular S3 type double-sided silicon strip detector detected the protons in the backward direction covering laboratory angles of 130°–160°. The 24 ring segments of the detector defined the scattering angle. The reverse side of the detector is segmented azimuthally into 32 sectors. The scattered ^{12}Be along with ^{11}Be from elastic scattering were detected in another annular silicon detector placed 75 cm downstream of the reaction target with laboratory angular coverage of 0.8°–2.7°. This coverage ensured detection of the protons and ^{12}Be nuclei in coincidence. The coincident detection suppressed nearly all the background events making it possible to identify the kinematic loci for the ^{11}Be$(d, p)^{12}$Be reaction through proton energy and angle correlations (Fig. 1a). The coincidence efficiency was determined from a Monte Carlo simulation and the region with efficiency $\geqslant 70\%$ is shown in Fig. 3.

The Q-value spectrum constructed from the energy and angle of the detected protons is shown in Fig. 1b integrated over the

[1] This value is considering the s^2 wavefunction probability to be 0.27 instead of 0.17 which is likely a misprint in [18] because it does not lead to a total probability of unity.