EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

The (d,p) reaction on ^{11}Be: Bringing clarity to our understanding of the structure of ^{12}Be

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J. Chen[1], D. K. Sharp[2], B. P. Kay[3], C. R. Hoffman[3], T. L. Tang[3], Y. Ayyad[1] D. Bazin[1], M. J. G. Borge[4,5] P. A. Butler[6], S. J. Freeman[2], L. P. Gaffney[6], M. Labiche[7] I. Lazarus[7], J. L. Lou[8], A. O. Macchiavelli[9], B. Olaizola[4], R. D. Page[6], R. Raabe[10], O. Poleshchuk[10], A. Ceulemans[10], K. Riisager[11] J. P. Schiffer[3], S. M. Wang[1]

[1] *FRIB/NSCL Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2] *Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK*
[3] *Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[4] *ISOLDE, CERN, CH-1211 Geneva 23, Switzerland*
[5] *Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[6] *University of Liverpool, Liverpool L69 7ZE, UK*
[7] *Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, UK*
[8] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[9] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[10] *KU Leuven, Intituut voor Kern-en Stralingsfysica, 3001 Leuven, Belgium*
[11] *Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark*

Spokesperson: J. Chen [chenjie@frib.msu.edu], D. K. Sharp [david.sharp@manchester.ac.uk]
Contact person: B. Olaizola [bruno.olaizola@cern.ch]

Abstract: A quantitative description of the interplay between the p-, $s-$ and d-shell configurations in ^{12}Be still eludes us, despite numerous attempts via direct and indirect reactions. To resolve this situation we propose a study of the ^{11}Be(d,p)^{12}Be reaction at a beam energy of 10 MeV/u, at which the results can be clearly interpreted in terms of well-understood reaction mechanisms and with good Q-value resolution. To achieve this, we request 16 shifts of beam time with a 10-MeV/u ^{11}Be beam. Outgoing protons will be analyzed in ISS to achieve the necessary 100-keV FWHM resolution.

Requested shifts: [16] shifts, (split into [1] runs over [1] years)

Introduction

In weakly bound nuclear systems approaching the drip-lines, the interplay between localized shell-model states and the continuum dramatically changes the structure of nuclei [1]. One of the most recognizable examples is the ground state (g.s.) of ^{11}Be, which is known as a one-neutron halo nucleus [2, 3, 4]. Its wave function is extended in space and strongly influenced by the $s_{1/2}$ continuum causing the g.s. inversion with respect to the $1/2^-$ state, indicating the break down of the $N = 8$ magic number.

This effect is associated with the behavior of the low-lying $s_{1/2}$, $p_{1/2}$ and $d_{5/2}$ single-particle states in light nuclei, where the $s_{1/2}$ single-particle energy increases less rapidly than states with higher angular momenta [5, 6, 7, 8]. In recent years, a great deal of data on the light *psd*-shell nuclei has emerged, particularly for the more loosely bound systems. The trend in the low-lying $1/2^+$ and $5/2^+$ states, over a large range of binding, behaves in a systematic way depending largely on Z as shown in Fig. 1(a). This pattern in the existing data is striking and has become subject of intensive discussion.

The available data on ^{12}Be are ambiguous and limited. It has also been quite difficult to access via well understood probes such as single-nucleon transfer reactions as its nearest neighbors are all unstable. The low-lying states are expected to be either two $s_{1/2}d_{5/2}$ neutrons coupled to a ^{10}Be ground state, $p_{1/2}$-shell configurations, or a mixture of these. We propose a measurement of the (d,p) reaction on ^{11}Be to help resolve current ambiguities in the low-lying structure of ^{12}Be and enhance our understanding of the interplay between the $s_{1/2}$, $p_{1/2}$ and $d_{5/2}$ single-particle energies around the weakening magic number $N = 8$.

Several low-lying bound states are known from a variety of studies which include, but are not limited to, the (t,p) reaction [9, 10], neutron-knockout reactions [11, 12], break-up reactions [13, 14], charge-exchange [15], and inelastic scattering and/or decay strength measurements [16, 17, 18, 19]. There have been three recent measurements of the (d,p) reaction, which are discussed later [20, 21, 22]. In these measurements, we see various exotic structures such as shell weakening and cross-shell excitations, but some ambiguities still persist and some information is still missing experimentally.

The general consensus is that the low-lying bound states have excitation energies of 0.0, 2.109, 2.251, and 2.715 MeV, with $J^\pi = 0^+_1$, 2^+_1, 0^+_2, and 1^-, respectively. S_n and S_{2n} lie at 3.17 and 3.67 MeV. Above this, there are two unbound states at 4.56 and 5.70 MeV with unknown spin and parity. Their widths are moderately narrow at $\lesssim$100 keV [10].

The (d,p) reaction will probe the $s^2_{1/2}$, $s_{1/2}p_{1/2}$ and $s_{1/2}d_{5/2}$ configurations, which form states of 0^+, 0^-, 1^-, 2^+, and 3^+. The g.s.(0^+_1) has shown to be dominant d-wave configuration [12], and the 0^+_2 has been shown to have moderate s-wave strength in various reactions though by to what degree remains ambiguous. The 0^+_3 state was predicted by most theories to be around 4.0–5.0 MeV carrying a moderate s-wave strength. There has been no experimental confirmation of the expected 3^+ ($s_{1/2}d_{5/2}$) state [which should be populated in (d,p)] nor the 4^+ ($d^2_{5/2}$) state [which will not be populated in (d,p)]. They are expected to appear at roughly 5.5 and 5.8 MeV through simple calculation. The 5.70-MeV state has for some time been considered likely to be the 4^+ based on calculations and experiment [24]. As with the 2^+_1, the 2^+_2 is likely to be mixed and not pure $d^2_{5/2}$ [25], which allows us to probe the $s_{1/2}d_{5/2}$ component in the (d,p) reaction. The location of the 2^+_2 is not known, but estimates place it a hundred keV or so below the expected 3^+ state. It is the mixing of these states that will allow us to determine the $s_{1/2}$ and $d_{5/2}$ single-particle energies in this measurement, though the latter relies on the (credible) assumption that the 5.70-MeV state is the 4^+. Not only should we be able to resolve the experimental and theoretical debates in literature as to the spin-parities the low-lying states, we should be able to extract the centroids of the $s_{1/2}$ and $d_{5/2}$ strength in ^{12}Be for the first time.

These low-lying states in open-quantum systems such as ^{12}Be provide many challenges for the traditional theories, including the shell model [27, 28], ppRPA [29], AMD model [31] and three-body model calculations [32, 33]. They have partially reproduced ^{12}Be low-lying states by adjusting the potential parameters, but were still limited by the description of the deformed ^{10}Be core and the continuum-coupling effects. Recently, Gamow shell model (GSM) and Gamow coupled-channel method (GCC) incorporating the continuum coupling effect have become powerful tools for describing weakly bound and unbound states in nuclei [34, 35, 36]. These calculations raise more interest to study the low-lying weakly bound or unbound states in ^{12}Be, since they contain different cross-shell orbitals located in the continuum, and could be good candidates to investigate the weak-binding effect [1]. The excitation energies of these states were strongly reduced compared to the shell model calculation [36] due to the weak-binding or the continuum-coupling effect (see Fig. 2). Considering various ingredients in these theories, the measurement of weakly-bound single-particle structures in ^{12}Be will be an essential benchmark.

Although there have been three recent measurements of the (*d*,*p*) reaction, they are just limited to the bound state and did not achieve the required Q-value resolution to isolate the 0_2^+ and 2_1^+ state, which is just 150 keV apart. Furthermore, their energies were not optimized for the (d,p) reaction or with the best angular coverage, so the data cannot be easily interpreted in terms of well-tested reaction mechanisms. The first measurement of the ^{11}Be(*d*,*p*) reaction in inverse kinematics was made by Kanungo *et al.* [20], who measured the (*d*,*p*) reaction at 5 MeV/u at TRIUMF using an array of annular Si detectors. The measurement covered only a few degrees in c.m. angle, making for very limited angular distributions, and suffered from poor resolution (>200 keV FWHM) and thus the 2_1^+ and 0_2^+ were not resolved. There is a more recent ^{11}Be(d,p) measurement [21] using an isomer-tagging method to resolve the 0_2^+. However, this measurement suffered from low statistics, giving rise to larger uncertainties. These two measurements agree on a larger *s*-wave spectroscopic factor for the 0_2^+ state than the g.s, but the uncertainties in both are large. As such, there is some degree of skepticism, e.g. Ref. [26], towards the results and the interpretation that the excited 0^+ state has a halo-like structure.

Another measurement, by Johansen *et al.* [22], was done at ISOLDE at 2.8 MeV/u using T-REX and MINIBALL. The low beam energy meant that reliable extraction of spectroscopic factors was prohibited. They also claim to rule out a low-lying 0^- state predicted by the theory. However, one would naively expect (from the 0_1^- state lying ∼800 keV above the 1_1^- in ^{14}C) a 0^- state somewhere close to the S_n threshold with a factor of three less cross section than the (quite strong) 1^- state in the (*d*,*p*) reaction, but will still be visible in the proposed measurement.

Using ISS to measure the ^{11}Be(*d*,*p*)^{12}Be reaction will allow us to resolve all the low-lying bound states and those observed above the one- and two-neutron separation energies including the 0_3^+, 2_2^+ and 3^+ which are expected to lie between ∼ 4.0 to ∼6.0 MeV. We propose a measurement at 10 MeV/u. Our aim is to extract cross sections and relative spectroscopic factors at the ∼10% level for these states.

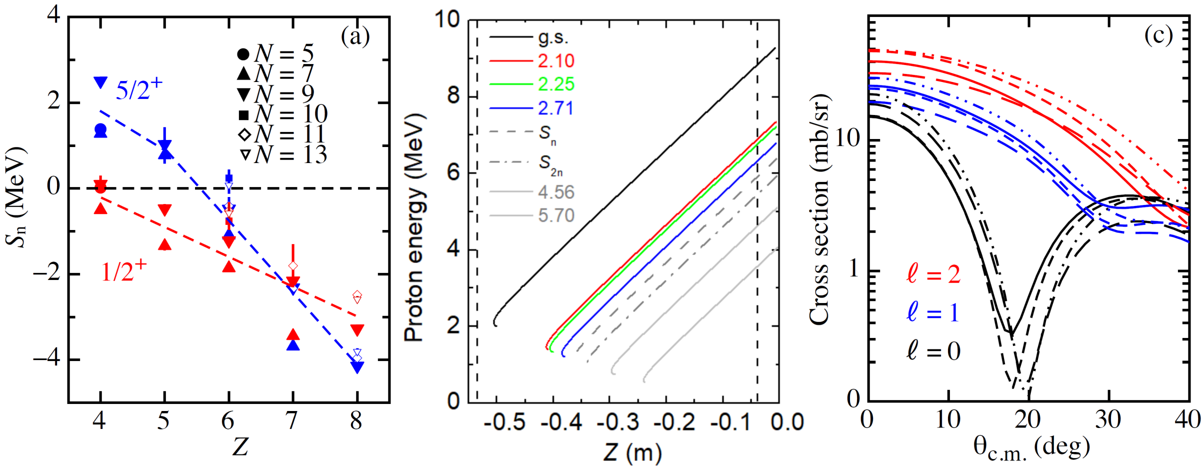

Figure 1: In panel (a), the neutron separation energies of $1/2^+$ and $5/2^+$ single-particle excitations in light nuclei as a function of proton number Z are shown. Kinematics lines for protons at 2.3 T for the ^{11}Be(d,p)^{12}Be reaction at 10 MeV/u with the vertical dashed lines showing approximately the coverage of the Si array (b), and example angular distributions for $\ell = 0$, 1, and 2 transfer (c) with the different grades of line showing different optical-model parameterizations (see references in Ref. [38]) in the DWBA calculations.

Experimental details

Such a ^{11}Be(d,p) measurement has been considered at Argonne using an in-flight produced beam, but the emittance of the beam prohibits a high-resolution measurement. A ^{11}Be beam will not be available at this intensity for several years at FRIB. ISOLDE and ISS represent the ideal combination for this measurement and an opportunity to clarify our understanding of this fascinating nucleus, ^{12}Be, removing many of the existing ambiguities. It allows for identification of all the low-lying state in ^{12}Be below 6 MeV owing to its very good resolution of around 100 keV. The measurement will complement a new background free measurement of the ^{10}Be$(t,p)^{12}$Be planned at FRIB in 2021 using SOLARIS, which will populate pair-correlated states in ^{12}Be [37].

We will use a single target-array setting covering a c.m. angle range of at least $10^\circ < \theta_{\mathrm{c.m.}} < 35^\circ$, which is possible with a magnetic field of 2.3 T. The silicon array will cover 6 cm$< Z <$54 cm upstream of the target. Example proton kinematic lines can be seen in Fig. 1(b) along with angular distributions for $\ell = 0$, 1, and 2 transfer (c). Recoil detection will be achieved by the standard Si E-ΔE technique using annular Si detectors of 80 μm and 500 μm. This thickness is enough to stop all the forward going Be isotopes from the ^{11}Be(d,p) reaction. It will be placed 70 cm downstream of the target, which will have a full acceptance for the Be isotopes in the c.m. angles of interest. Such a setup is routine using ISS.

In some previous experiments with light in-flight-produced beams, the excitation resolution has not been optimal. This is largely due to the beam properties (emittance,

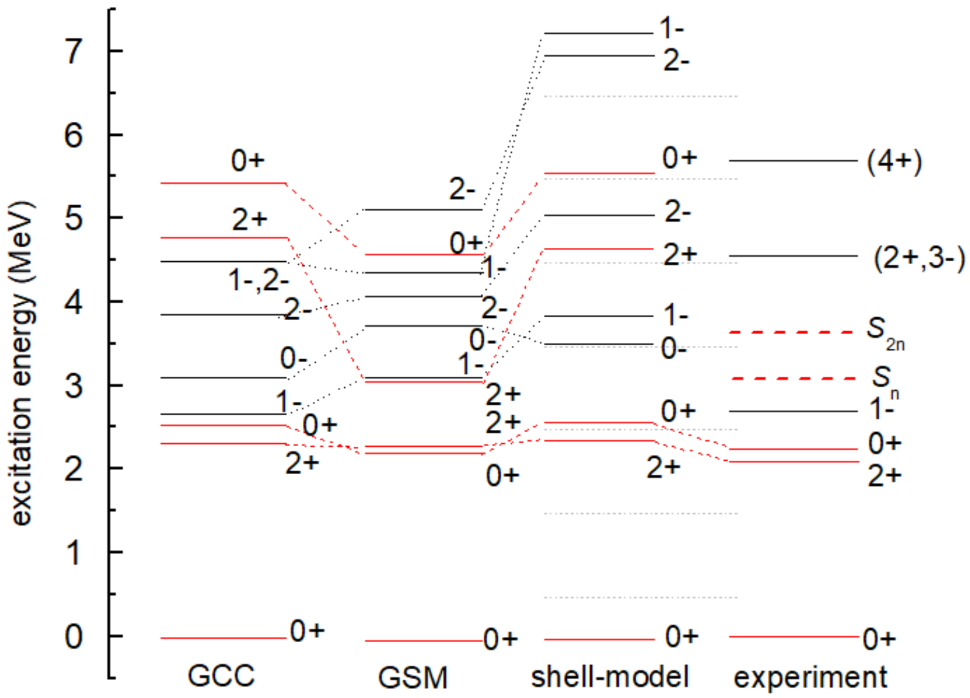

Figure 2: From left to right panels, the predicted states using the GCC, GSM and shell model calculations are shown together with the experimentally observed states (the right most panel). The excitation energies of the resonances in the GSM and GCC approaches are lower than the shell model, possibly due to the continuum coupling effect [1].

radial extent, and energy resolution) and use of relatively thick targets to compensate for weak beams. Here, resolution is important and we will use a thin deuterated polyethylene (CD_2) target of around 80 μg/cm^2. A Q-value resolution of ∼100 keV will be will be dependent on the amount of energy loss in the target.

Rate estimates are based on the assumption of an angular coverage of $10° < \theta_{\text{c.m.}} < 35°$ on the Si array. The estimated beam intensity is expected to be 1×10^5 ion per second [22, 40]. Cross sections have been determined by DWBA calculations using Ptolemy [39] with the standard bound-state parameters and optical-model parameters (see references in Ref. [38]). Beams energies in the range of 6-12 MeV/u were explored. The yield for all ℓ transfers of interest here is optimum at 6 MeV/u and decreases with higher beam energy. However, we opt to measure at 10 MeV/u which is a compromise between yield and the proton kinematics. The higher energy is necessary to have the appropriate c.m. angular coverage for protons following the population of states in the ∼3-6 MeV excitation-energy range in ^{12}Be.

The rates are estimated for the bound states at 0.00, 2.10, 2.24, and 2.70 MeV. The angle-integrated cross sections are 2.5, 10.1, 1.0, and 5.6 mb, respectively. While it is known the spectroscopic factors are $S < 1$, the literature shows significant variation. We assume an average of $S = 0.5$ for all states for the sake of these estimates. An integrated yield of ∼500 counts would be required to extract reliable angular distributions. This corresponds to 100 counts in an angular bin at the peak of the angular distribution and a 10% statistical uncertainty. As such, we estimate approximately 200, 780, 80 and 430 counts per day if we assume $S = 0.5$ for the four low-lying states. **15 shifts** (5 days) are required, together with another **one shift** to optimise the tune into the ISS and the experimental setup.

Summary of requested shifts:

The available data on ^{12}Be are ambiguous and limited. It has been difficult to probe via transfer reactions at ideal energies, around 10 MeV/u. As such, we propose a measurement of the ^{11}Be(d,p) reaction at ISOLDE with the new ISOLDE Solenoidal Spectrometer to help resolve the long-standing uncertainties in the low-lying structure of ^{12}Be and to better determine the $s_{1/2}$, $p_{1/2}$ and $d_{5/2}$ single-particle energies, which are interesting in the exploration of weak binding effects in light neutron-rich nuclei. We request **16 shifts** of beam time to measure the ^{11}Be(d,p)^{12}Be reaction at 10 MeV/u. The ^{11}Be beam will be produced at an estimated intensity of $1{\times}10^5$ ions per second using HIE-ISOLDE. Outgoing protons will be measured using the silicon array in the magnetic field of ISS to achieve a resolution of 100-keV, which allows for isolation of all the low-lying states in ^{12}Be.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *The ISOLDE Solenoidal Spectrometer*

Part of the	Availability	Design and manufacturing
ISOLDE Solenoidal Spectrometer	☒ Existing	☒ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed ISS installation.

Additional hazards:

Hazards			
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature			
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity			
Static electricity			
Magnetic field	2.3 T		
Batteries			
Capacitors			
Ionizing radiation			
Target material	Deuterated polyethylene (50-400 μg/cm^2)		
Beam particle type	^{11}Be		
Beam intensity	1×10^5		
Beam energy	10 MeV/u		
Cooling liquids			
Gases			
Calibration sources:	☒		
• Open source	☒ (α calibrations source 4236RP)		
• Sealed source			

• Isotope	^{148}Gd, ^{239}Pu, ^{241}Am, ^{244}Cm		
• Activity	1 kBq, 1 kBq, 1 kBq, 1 kBq = 4 kBq		
Use of activated material:			
• Description			
• Dose rate on contact and in 10 cm distance			
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant			
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)			
Mechanical properties (Sharp, rough, slippery)			
Vibration			
Vehicles and Means of Transport			
Noise			
Frequency			
Intensity			

Physical			
Confined spaces			
High workplaces			
Access to high workplaces			
Obstructions in passageways			
Manual handling			
Poor ergonomics			

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): N/A