The double isobaric analog of ^{11}Li in ^{11}B

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The double isobaric analog state of ^{11}Li in ^{11}B has been identified in the ^{12}Be(p,2n)^{11}B reaction. The state was discovered through its two-proton decay branch. From detected $2p$ + ^{9}Li events, its excitation energy was determined to be 33.57(8) MeV using the invariant mass method. This excitation energy was found consistent with a halo structure expected for all members of the isobaric sextet containing ^{11}Li$_{g.s.}$. The momentum correlations of the detected protons, were found to have both "diproton" and "cigar" components.

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Exotic nuclear configurations have been found in nuclei located close to the drip lines where there is large excesses of either protons or neutrons and thus large values of isospin T. For example close to the neutron drip line we find neutron-halo nuclei (^{6}He, ^{8}He, ^{11}Li, ^{11}Be, ^{14}Be, ^{8}B, ^{17}B, etc) where the wavefunctions of the loosely-bound outer neutrons extend a considerable distance beyond from the radius of the core[1]. On the other hand, proton-rich systems just beyond the proton drip lines can have exotic decay modes such as two-proton decay (^{6}Be, ^{8}C, ^{12}O, ^{16}Ne, etc [2]). These exotic states on either side of the N=Z are not unrelated, for instance the two-neutron-halo nucleus ^{6}He is the mirror of the two-proton-decay nucleus ^{6}Be. The four-neutron-halo nucleus ^{8}He is the mirror of ^{8}C which decays by two sequential steps of two-proton decay [3].

Such exotic configuration are not confined to just the regions of the drip lines. Each drip-line nucleus is part of an isobaric multiplet whose members have similar nuclear configurations. The members with $N \sim Z$ are located at high excitation energies often making them difficult to identify amongst the large density of lower T levels. So more generally, the frontier where similar exotic structures are to be found is the region of high T not just large isospin projection.

As an example, ^{8}He and ^{8}C with T=2 are connected by an isobaric quintet. The next proton-rich member of this quintet, the isobaric analog state (IAS) in ^{8}B also undergoes two-proton decay [3]. This state represents a new class of two-proton emitters where single-proton emission is energetically allowed but isospin forbidden while two-proton decay conserves both quantities. A second member of this class can be found in the A=12 quintet, where the isobaric analog of the two-proton emitter ^{12}O in ^{12}N also undergoes two-proton decay [4].

While most complete quintets (T=2) have been found for A=4n and A < 40, there are no complete sextets (T=5/2). For A < 19, most sextets have, at most, only one known member (T_Z=T). In this work we will focus of the isobaric sextet containing ^{11}Li$_{g.s.}$ (T = T_Z=5/2, J^{π}=3/2^{-}), a well studied two-neutron-halo nucleus. A second member of this sextet, the isobaric analog of ^{11}Li in ^{11}Be (T_Z=3/2) was found by Teranishi *et al.* [5] in 1997 using the invariant-mass method to determine its mass from its detected decay products.

In the halo and core model of Suzuli and Yabana [6], the wavefunctions of the three most neutron-rich members are expressed in terms of their core and halo components

$$\left|{}^{11}\mathrm{Li}_{g.s.}\right\rangle = \left|{}^{9}\mathrm{Li}_{g.s.}\right\rangle |nn\rangle\,, \tag{1}$$

$$\begin{aligned}\left|{}^{11}\mathrm{Be}_{IAS}\right\rangle &= \sqrt{3/5}\left|{}^{9}\mathrm{Be}\right\rangle_{T=3/2}|nn\rangle \\ &\quad+\sqrt{2/5}\left|{}^{9}\mathrm{Li}_{g.s.}\right\rangle|np\rangle_{T=1}\,,\end{aligned} \tag{2}$$

$$\begin{aligned}\left|{}^{11}\mathrm{B}_{DIAS}\right\rangle &= \sqrt{3/10}\left|{}^{9}\mathrm{B}\right\rangle_{T=3/2}|nn\rangle \\ &\quad+\sqrt{6/10}\left|{}^{9}\mathrm{Be}\right\rangle_{T=3/2}|np\rangle_{T=1} \\ &\quad+\sqrt{1/10}\left|{}^{9}\mathrm{Li}_{g.s.}\right\rangle|pp\rangle\,.\end{aligned} \tag{3}$$

For the ^{11}Be$_{IAS}$, the two-neutron halo contribution (60%) is bound, but the n+p contribution (40%) is unbound by 1.020(20) MeV explaining why ^{11}Be$_{IAS}$ was discovered through the n+p+^{9}Li exit channel.

For the double isobaric analog state (DIAS) of ^{11}Li in ^{11}B, in addition to $2n$ and n+p halo contributions, we now have a small component with a $2p$ halo (10%). The latter two components are both expected to be unbound and in this work we report on the observation of this third member of the sextet, $^{11}B_{DIAS}$, through the detection of its $2p$+^{9}Li exit channel.

The experimental data comes from a previously published experiment utilizing a secondary ^{12}Be beam at E/A=50 MeV produced at the Coupled-Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University. See Refs. [7, 8] for details of the experiment. The beam impinged on a 1-mm-thick target of polyethylene or a 0.4-mm-thick target of carbon. The decay products were detected in the 16 element HiRA array [9] located 60 cm from the target which determined the identity, angle, and energy of each detected particle.

The total decay kinetic energy E_T is determined from the invariant mass method and the distribution of E_T is shown in Fig. 1 for the data obtained from the polyethylene target. Although the number of events is small, and thus the statistical uncertainties are large, a peak at E_T=2.70(8) MeV is still evident. Including the masses of the decay products, the mass excess of this state is 42.24(8) MeV leading to an excitation energy of 33.57(8) MeV. We were able to separate this state from the large density of other states near this excitation energy due to high selectivity of the decay channel. The other expected decay branch, n+p+$^{9}Be_{IAS}$, is unstable by 1.14(8) MeV and as the $^{9}Be_{IAS}$ core in this case is itself unstable [10], the final exit channel will be $2n$+p+2α for this undetected branch.

The solid curve shows a fit to the data assuming a Breit-Wigner intrinsic line shape with the effects of the detector resolution incorporated via the Monte-Carlo simulations of Ref. [8]. The dashed curves shows an estimate of the background and the fitted decay width of this peak is Γ=306(182) keV. This can be compared to the value of 490(70) keV determined by Teranishi *et al.* for the neighboring ^{11}Be member of the sextet.

Most of these events in Fig. 1 were produced from interactions with the hydrogen component of the target as the equivalent spectrum obtained with the carbon target was almost empty. Thus most of the yield of this T=5/2 state is produced via the ^{12}Be(p,2n)^{11}B reaction.

To the extent that isospin T is a good quantum number, the mass of all members of a multiplet should be independent of T_Z in the absence of Coulomb forces. If two-body forces are responsible for charge-dependent effects, Wigner found the mass excesses can be described by a quadratic dependence called isobaric multiplet mass equation (IMME) [11]:

$$\Delta M(T,T_Z) = a + b\,T_Z + c\,T_Z^2. \qquad (4)$$

The largest deviations to a quadratic dependence have been found for A=7, 8, and 9 [11–13], however even in these cases, deviations are at most 100 keV and thus the IMME can be used to extrapolate the masses of unknown members of a multiplet with good accuracy.

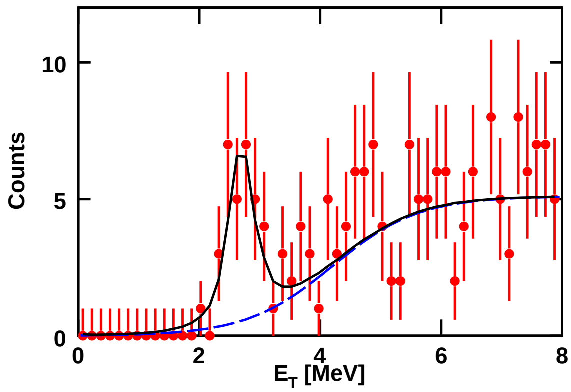

FIG. 1. (Color online) Distribution of total decay kinetic energy E_T determined from the detected $2p$+^{9}Li events. The solid curve shows a fit to the data with a single Breit-Wigner peak including the experimental resolution and the dashed curve indicates the estimated background.

TABLE I. Mass excesses for the A= 11 isospin T=5/2 sextet and the IMME coefficients obtained from them

Nucl.	T_Z	Mass Excess [MeV]	Reference	a, b, c [keV]
Li	5/2	40.728 (1)	[14]	a=42795(150)
Be	3/2	41.335 (20)	[5]	b=-1193(170)
B	1/2	42.24 (8)	This work	c=147 (44)

With a third member of the A=11 sextet now found, we are able to determine the parameters of the IMME. The mass excesses of the three known members and the quadratic coefficients deduced from these are listed in Table I. Using the IMME, we extrapolate the mass excess of $^{11}O_{g.s.}$ as ΔM=46.70(84) MeV which gives a $2p$ decay energy of E_T=3.21(84) MeV. The latter is only 0.5 MeV greater than the value obtained for the T_Z=1/2 member in this work.

The T_Z dependence of the masses is plotted in Fig. 2. The change in mass has two main contributions. If we start at ^{11}Li and move to the more proton-rich systems the neutron-proton mass difference ($M_n - M_{^1H}$ =0.7823 MeV) will lead to smaller isobaric masses. However this is more than counterbalanced by the increasing Coulomb energy.

If the nucleon wavefunctions are frozen along a multiplet and the nucleus can be approximated as homogeneous sphere of radius R, then the last two coefficients of the IMME are [11, 15]

$$c = \frac{0.6e^2}{R}, \qquad (5)$$

$$b = b^* + (M_n - M_{^1H}), \qquad b^* = -(A-1)c. \qquad (6)$$

The mass excesses of isospin doublets (T=1/2) for A=11 were reproduced using a and R as fit parame-

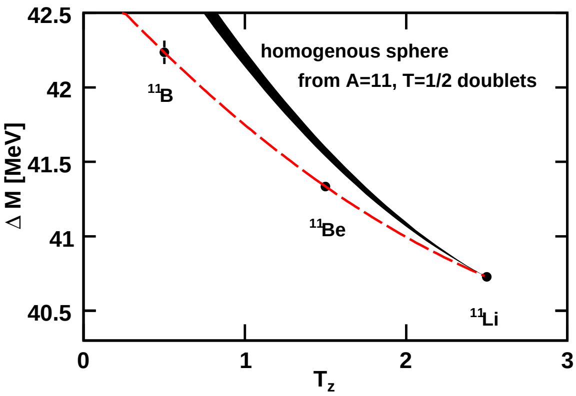

FIG. 2. (Color online) Mass excesses of the three known members of the A=11 sextet plotted as a function of isospin projection. The solid band shows the prediction for a homogeneous sphere with the same radius as the T=1/2 A=11 doublet. The dashed curve shows the quadratic IMME curve which passes through the three data points.

ters. We obtained R=3.125(1) and 3.261(1) fm for the lowest J^π=3/2$^-$ and 1/2$^-$ doublets, respectively. The solid band in Fig. 2 shows the predicted mass dependence for the J^π=3/2$^-$ sextet from homogeneous spheres of the same radii (The band encompasses the range of radii associated with these doublets). It is clear that the Coulomb energy dependence is significantly reduced in the sextet (T=5/2) compared to the doublets (T=1/2) and this undoubtedly reflects the more extended halo structure of the sextet.

If we assume a core-halo model where the wavefunctions are frozen along the sextet, then the last two coefficients of the IMME are

$$b^* = \frac{1}{5}\left(3b^*_{core} - V_{pp} - 12\overline{V_{c-p}}\right), \tag{7}$$

$$c = \frac{1}{20}\left(6c_{core} + V_{pp} + 6\overline{V_{c-p}}\right) \tag{8}$$

where V_{pp} is the self Coulomb energy of the $2p$ halo and the Coulomb energy between the core and a halo proton is

$$V_{c-p} = Z_{core}\overline{V_{c-p}}. \tag{9}$$

For the core parameters c_{core} and b^*_{core}, we have fit the A=9 quartet (T=3/2) assuming a homogeneous sphere obtaining R_{core}=3.29 fm. Although the A=9 quartet is known to deviate from the quadratic form of the IMME [12], our fit reproduces the experimental mass excesses to 7 keV or less.

From the fitted values of b and c, we deduce $\overline{V_{c-p}}$ = 0.369(17) MeV and V_{pp} = -0.85(93) MeV. It is not surprising that V_{pp} is not well constrained as the $2p$ halo only occurs as a 10% contribution to ^{11}B [Eq. (3)].

These Coulomb energies are compared to calculations where the halo protons have wavefunctions identical to the ^{11}Li neutron halo wavefunctions calculated by Hagino and Sagawa with a three-body model [16]. These calculations predict important dineutron contributions to the halo and reproduce the measured dipole response of ^{11}Li. For the core-proton potential, the core is taken to have a Gaussian charge distribution

$$\rho_{ch}(r) = \frac{Z_{core}}{(r_b\sqrt{\pi})^3} e^{-\frac{r^2}{r_b^2}} \tag{10}$$

where r_b is constrained from the experimental charge radius of ^{9}Li ($\sqrt{< r^2_{ch} >}$=2.217(35) fm) [17].

The calculated Coulomb energies are $\overline{V_{c-p}}$ = 0.3615 MeV and V_{pp} = 0.42 MeV quite consistent with the experimental values indicating that ^{11}Be$_{IAS}$ and ^{11}B$_{DIAS}$ have similar halo structures to ^{11}Li$_{g.s.}$.

As in Ref. [5], the difference in the masses can also be expressed in term of the Coulomb displacement energies which give the difference in Coulomb energies between members of the multiplet. Based on the core-halo model these are

$$\Delta(^{11}\mathrm{Be}_{IAS} - ^{11}\mathrm{Li}) = \frac{3}{5}[M(^9\mathrm{Be}_{IAS}) - M(^9\mathrm{Li}_{g.s.})] + \frac{2}{5}V_{^9\mathrm{Li}_{g.s.}-p}, \tag{11}$$

$$\Delta(^{11}\mathrm{B}_{DIAS} - ^{11}\mathrm{Be}_{IAS}) = \frac{3}{10}[M(^9\mathrm{B}_{IAS}) - M(^9\mathrm{Li}_{g.s.})] + \frac{3}{5}V_{^9\mathrm{Be}_{IAS}-p} - \frac{1}{5}V_{^9\mathrm{Li}_{g.s.}-p} + \frac{1}{10}V_{pp}. \tag{12}$$

With the calculated Coulomb energies, we obtain values of 1.375 and 1.797 MeV consistent with the experimental values of 1.389(20) and 1.69(8) MeV, respectively.

The calculations ignore the small effects of charge-symmetry and charge-independence breaking interactions [18]. In addition the assumption of frozen wavefunctions will not be strictly correct as the protons are more loosely bound and thus their wavefunctions should be more extended. Also there is the three-body Thomas-Erhman effect discussed for A=12 quintets by Grigorenko *et al.* which caused a increased s^2 contribution for the proton-rich members [19]. Significant s^2 is also present for the A=11 sextet [20]. The good agreement with the present calculations suggest that these effects are small.

The experimental energy correlations between the decay products are displayed in Fig. 3 in the Jacobi Y and T systems [21]. Although the statistical errors are large, a couple of points can be made. First in Fig. 3(a) we show the energy distribution in the Jacobi Y system, i.e., the relative kinetic energy in the ^{9}Li-p degree of freedom. For sequential decay through a narrow intermediate state in ^{10}Be, we would expect two narrows peaks associated with the energies of the two emitted protons or one narrow peak at $E_{^9\mathrm{Li}-p}/E_T$=0.5 if the energies of the two protons are the same. Instead we observe one broad peak centered at $E_{^9\mathrm{Li}-p}/E_T$=0.5 (equal proton energies on average) similar to the results obtained for the two-proton

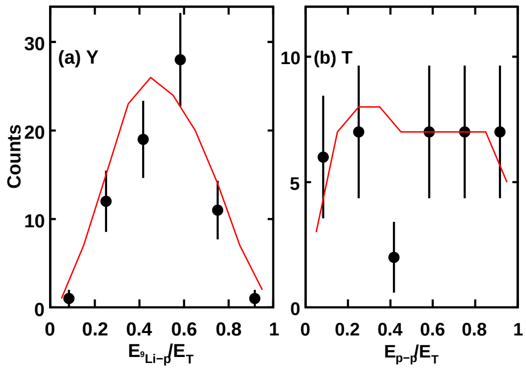

FIG. 3. (Color online) three-body correlations displayed as energy distributions in the Jacobi (a) Y and (b) T systems. For comparison, the correlations measured for the two-proton decay of ^{6}Be [13], normalised to the same number of events, are shown by the curves.

decay of ^{6}Be [13] indicated by the solid curve. Such a distribution is expected for prompt two-proton decay as the product of the two proton barrier penetration probabilities $[P(E_{^9\mathrm{Li}-p})P(E_T - E_{^9\mathrm{Li}-p})]$ is minimized for equal-energy protons.

The energy distribution in the Jacobi T system, i.e., the relative kinetic energy in the p-p degree of freedom, is shown in Fig. 3(b) and it too is roughly similar in shape to the results for ^{6}Be (curve). Both show similar magnitudes of "diproton" (low E_{p-p}/E_T) and "cigar" decays (high E_{p-p}/E_T). In the analysis the experimental ^{6}Be correlations in Ref. [21] it was argued, based on a comparison with a three-body cluster model that fit the data, that these detected correlations are a reflection of the correlations of the protons inside of the ^{6}Be nucleus but which become smeared out in the barrier penetration process. The deduced internal "diproton" and "cigar" spacial configurations are well separated and of similar magnitude in ^{6}Be and, by isospin symmetry, the neutrons in the halo of the mirror nucleus ^{6}He also were predicted to show the same structure with similar magnitudes of "dineutron" and "cigar" correlation types. Based on the similarity of the experimental $^6\mathrm{Be}_{g.s.}$ and $^{11}\mathrm{B}_{T=5/2}$ correlations, one can then also argue that the neutrons in the halo of ^{11}Li also have similar magnitudes of these two correlations. Indeed this is consistent with the calculations of Hagino and Sagawa where these their predicted relative magnitudes are 51% and 49%, respectively (see Fig. 4 in Ref. [16]). However more quantitative comparisons with the data should await future higher-statistics measurements.

In summary we have observed the double isobaric analog state of ^{11}Li in ^{11}B produced via the $^{12}\mathrm{Be}(p,2n)^{11}\mathrm{B}$ reaction. The state was identified from the detection of its $2p$+^{9}Li exit channel in the HiRA array. From the invariant mass method, the total decay kinetic energy was determined to be 2.70(8) MeV giving a mass excess of 42.24(8) MeV and an excitation energy of 33.57(8) MeV. With the previously known masses of ^{11}Li and its isobaric analog in ^{11}Be, three members of the A=11 sextet are now identified permitting one to extrapolate the masses of the three unknown proton-rich members using the isobaric multiplet mass equation. The extrapolated mass excess for $^{11}\mathrm{O}_{g.s.}$ is 46.70(84) MeV. The T_Z dependence of experimental masses for the sextet was found consistent with a halo structure assuming the ^{11}Li halo wavefunctions predicted by Hagino and Sagawa [16] are frozen along the sextet. Momentum correlations of the decay products suggest similar amounts of "dinucleon" and "cigar" type configurations.

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