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Double isobaric analog of ^{11}Li in ^{11}B

R. J. Charity,[1] L. G. Sobotka,[1] K. Hagino,[2] D. Bazin,[3] M. A. Famiano,[4] A. Gade,[3] S. Hudan,[5] S. A. Komarov,[1] Jenny Lee,[3] S. P. Lobastov,[3] S. M. Lukyanov,[3] W. G. Lynch,[3] C. Metelko,[5] M. Mocko,[3] A. M. Rogers,[3] H. Sagawa,[6,7] A. Sanetullaev,[3] M. B. Tsang,[3] M. S. Wallace,[3] M. J. van Goethem,[8] and A. H. Wuosmaa[4]

[1]*Departments of Chemistry and Physics, Washington University, St. Louis, Missouri 63130, USA*
[2]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[3]*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008, USA*
[5]*Department of Chemistry and Indiana University Cyclotron Facility, Indiana University, Bloomington, Indiana 47405, USA*
[6]*Center for Mathematics and Physics, University of Aizu, Aizu-Wakamatsu, Fukushima 965-8560, Japan*
[7]*RIKEN Nishina Center, Wako 351-0198, Japan*
[8]*Kernfysisch Versneller Institut, NL-9747 AA Groningen, The Netherlands*

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The ground state of ^{11}Li is the preeminent example of a two-neutron-halo nucleus and is part of an isobaric sextet. Another member of this sextet, the double isobaric analog of $^{11}\mathrm{Li}_{\mathrm{g.s.}}$ in ^{11}B, has been identified in the $^{12}\mathrm{Be}(p,2n)^{11}\mathrm{B}$ reaction. The state was discovered through its two-proton decay branch. From detected $2p + {}^{9}\mathrm{Li}$ events, its excitation energy was determined to be 33.57(8) MeV using the invariant mass method. With the known masses of ^{11}Li and its isobaric analog state in ^{11}Be, three members of the same sextet have measured masses for the first time, permitting the masses of the remaining members to be extrapolated using the isobaric multiplet mass equation. All members of this multiplet are expected to have a two-nucleon halo structure and this was found consistent with the evolution of the mass across the sextet. 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 are 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 wave functions of the loosely bound outer neutrons extend a considerable distance beyond the radius of the core [1]. The best known and most studied case is the ground state of ^{11}Li. On the other hand, proton-rich systems just beyond the proton drip line can have exotic decay modes such as two-proton emission (^{6}Be, ^{8}C, ^{12}O, ^{16}Ne, etc. [2]). These exotic states on either side of the $N = Z$ line are not unrelated; for instance, the two-neutron-halo nucleus ^{6}He is the mirror of the two-proton emitter ^{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 configurations are not just confined to 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 among the large density of lower T levels. So more generally, the region of high T is the frontier where similar exotic structures are to be found, not just nuclei with large isospin projections.

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 ($T = 5/2$). Most sextets have only one known member ($T_Z = T$), and only for $A = 11$ and 19 and some excited sextets in $A = 47$, 49, 53, and 65 [5] have two of the six masses been measured. In this work we will focus on the isobaric sextet containing $^{11}\mathrm{Li}_{\mathrm{g.s.}}$ ($T = T_Z = 5/2$, $J^{\pi} = 3/2^{-}$), a well-studied and the best known example of a 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.* [6] in 1997 using the invariant-mass method to determine its mass from its detected decay products. In this work we report on an observation of a third member of this sextet in ^{11}B which makes the $A = 11$ sextet unique because now three of the six masses are known.

In the halo and core model of Suzuki and Yabana [7], the wave functions of the three most neutron-rich members are expressed in terms of their core and halo components

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

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

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

For the $^{11}\mathrm{Be_{IAS}}$, the two-neutron-halo contribution (60%) is bound, but the $n+p$ contribution (40%) is unbound by 1.020(20) MeV explaining why $^{11}\mathrm{Be_{IAS}}$ was discovered through the $n + p + {}^9\mathrm{Li}$ 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, $^{11}\mathrm{B_{DIAS}}$, through the detection of its $2p + {}^9\mathrm{Li}$ exit channel.

The experimental data come from an earlier study 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. [8,9] 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 high-resolution array (HiRA) [10] 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 by 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 number of other states near this excitation energy due to the high selectivity of the decay channel. The other expected decay branch, $n + p + {}^9\mathrm{Be_{IAS}}$, is unstable by 1.14(8) MeV.

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. [9]. The dashed curve shows an estimate of the background and the fitted decay width of this peak is $\Gamma = 306(182)$ 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.

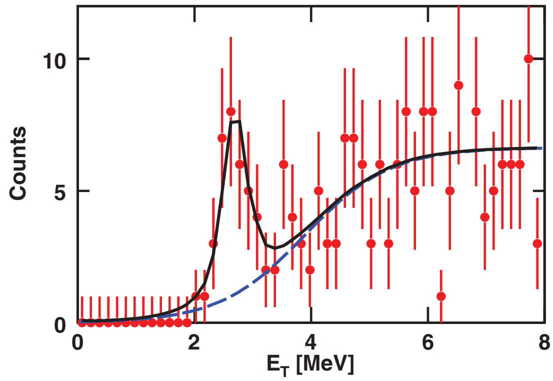

FIG. 1. (Color online) Distribution of total decay kinetic energy E_T determined from the detected $2p + {}^9\mathrm{Li}$ events. The solid curve shows a fit to the data with a single Breit-Wigner peak including the experimental resolution; the dashed curve indicates the estimated background.

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)	Ref.	a, b, c (keV)
Li	5/2	40.728 (1)	[14]	$a = 42795(150)$
Be	3/2	41.335 (20)	[6]	$b = -1193(170)$
B	1/2	42.24 (8)	This work	$c = 147(44)$

Most of these events in Fig. 1 were produced from interactions with the hydrogen component of the target because 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 $^{12}\mathrm{Be}(p, 2n)^{11}\mathrm{B}$ reaction. Correcting for the detector efficiency [9], we obtain a cross section of 72(21) μb for the detected exit channel.

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. When two-body forces are responsible for charge-dependent effects, Wigner found the mass excesses can be described by a quadratic dependence called the isobaric multiplet mass equation (IMME) [11]:

$$\Delta M(T, T_Z) = a + bT_Z + cT_Z^2. \tag{4}$$

The largest deviations from a quadratic behavior 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.

With a third member of the $A = 11$ sextet now found, we are able to determine the parameters of the corresponding 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 $^{11}\mathrm{O_{g.s.}}$ as $\Delta M = 46.70(84)$ 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 predicted decay energies of the isospin-allowed decay branches for the other members of the sextet are listed in Table II. Note that $^9\mathrm{Be_{IAS}}$ and $^9\mathrm{B_{IAS}}$ are produced in some of these decays and they themselves are unstable. They are both

TABLE II. Isospin-allowed decay branches of the members of the $A = 11$ sextet, with the total decay energy, and the final exit channel.

T_Z	Symbol	Decay branch	E_T (MeV)	Exit channel
3/2	$^{11}\mathrm{Be_{IAS}}$	$n + p + {}^9\mathrm{Li_{g.s.}}$	1.02(2)	$n + p + {}^9\mathrm{Li_{g.s.}}$
1/2	$^{11}\mathrm{B_{DIAS}}$	$2p + {}^9\mathrm{Li_{g.s.}}$	2.70(8)	$2p + {}^9\mathrm{Li_{g.s.}}$
		$n + p + {}^9\mathrm{B_{IAS}}$	1.14(8)	$p + 2n + 2\alpha$
$-1/2$	$^{11}\mathrm{C_{DIAS}}$	$2p + {}^9\mathrm{Be_{IAS}}$	3.11(24)	$n + 2p + 2\alpha$
		$n + p + {}^9\mathrm{B_{IAS}}$	1.00(24)	$n + 2p + 2\alpha$
$-3/2$	$^{11}\mathrm{N_{IAS}}$	$2p + {}^9\mathrm{B_{IAS}}$	3.27(50)	$3p + 2\alpha$
		$n + p + {}^9\mathrm{C_{g.s.}}$	0.65(50)	$n + p + {}^9\mathrm{C_{g.s.}}$
$-5/2$	$^{11}\mathrm{O_{g.s.}}$	$2p + {}^9\mathrm{C_{g.s.}}$	3.21(84)	$2p + {}^9\mathrm{C_{g.s.}}$

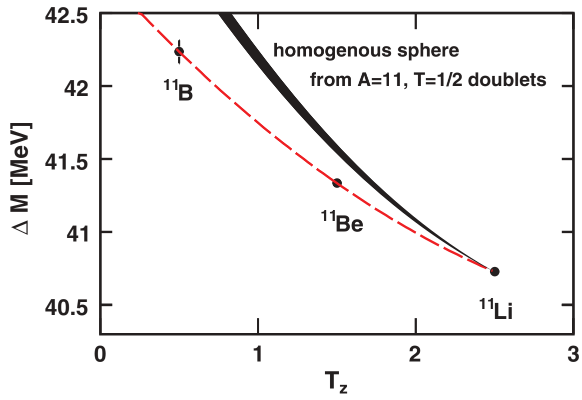

FIG. 2. (Color online) Mass excesses of the three known members of the $A = 11$ sextet plotted as a function of isospin projection. The solid band shows the prediction for a homogeneous sphere with the same radius as the $T = 1/2$, $A = 11$ doublet. The dashed curve shows the quadratic IMME curve which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

listed as having a ~4% γ-decay branch with the remaining strength leading to the production of two α particles and a nucleon [5]. The final exit channel, ignoring these small γ branches, are also listed in Table II. Apart from ^{11}O$_{\rm g.s.}$, the other unknown members of the sextet (^{11}C$_{\rm DIAS}$ and ^{11}N$_{\rm IAS}$) will be harder to measure with the invariant-mass technique since the final exit channel is five body and/or contains neutrons.

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 nucleus can be approximated as a homogeneous sphere of radius R, then the last two coefficients of the IMME are [11,15]

$$c = \frac{0.6e^2}{R}, \tag{5}$$

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

The mass excesses of isospin doublets ($T = 1/2$) for $A = 11$ were reproduced using a and R as fit parameters. We obtained $R = 3.125(1)$ and 3.261(1) fm for the lowest $J^\pi = 3/2^-$ and $1/2^-$ doublets, respectively. The solid band in Fig. 2 shows the predicted mass dependence for the $J^\pi = 3/2^-$ 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 these 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 halo wave functions are identical for each member of the sextet, then the last two coefficients of the IMME are

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

$$c = \tfrac{1}{20}(6c_{\rm core} + V_{pp} + 6\overline{V_{c-p}}), \tag{8}$$

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

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

For the core parameters $c_{\rm core}$ and $b^*_{\rm core}$, we have fit the $A = 9$ quartet ($T = 3/2$) assuming a homogeneous sphere obtaining $R_{\rm core} = 3.29$ 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, because 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 wave functions identical to the ^{11}Li neutron-halo wave functions 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

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

where r_b is constrained from the experimental charge radius of ^{9}Li [$\sqrt{\langle r^2_{\rm ch}\rangle} = 2.217(35)$ 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$_{\rm IAS}$ and ^{11}B$_{\rm DIAS}$ have similar halo structures to ^{11}Li$_{\rm g.s.}$.

As in Ref. [6], 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

$$\Delta(^{11}{\rm Be_{IAS}} - {}^{11}{\rm Li}) = \tfrac{3}{5}[M(^9{\rm Be_{IAS}}) - M(^9{\rm Li_{g.s.}})] + \tfrac{2}{5}V_{^9{\rm Li_{g.s.}}-p}, \tag{11}$$

$$\Delta(^{11}{\rm B_{DIAS}} - {}^{11}{\rm Be_{IAS}}) = \tfrac{3}{10}[M(^9{\rm B_{IAS}}) - M(^9{\rm Li_{g.s.}})] + \tfrac{3}{5}V_{^9{\rm Be_{IAS}}-p} - \tfrac{1}{5}V_{^9{\rm Li_{g.s.}}-p} + \tfrac{1}{10}V_{pp}. \tag{12}$$

With the calculated Coulomb energies, we obtain values of 1.375 and 1.797 MeV from Eqs. (11) and (12) 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 identical neutron and proton halo wave functions in the sextet will not be strictly correct, since the protons are more loosely bound and thus their wave functions should be more extended. In fact, ^{11}Li is the only member of the sextet not in the continuum. However, this may not mean we should see deviations from the quadratic behavior. In the $A = 12$ quintet, three of the five members are above the threshold for isospin-allowed two-proton decay, and no indication of deviations from the quadratic behavior was observed to the statistical accuracy of that work, 24 keV [4]. Also there is the three-body Thomas-Ehrman effect discussed

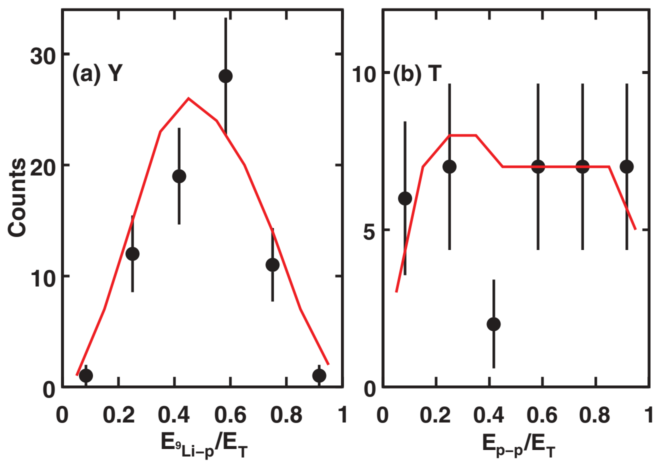

FIG. 3. (Color online) Three-body correlations displayed as energy distributions in the Jacobi (a) Y and (b) T systems. For comparison, the correlations measured for the two-proton decay of ^{6}Be [13], normalized to the same number of events, are shown by the curves.

for these $A = 12$ quintets by Grigorenko *et al.* which caused an increased s^2 contribution for the proton-rich members [19]. Significant s^2 is also present for the $A = 11$ sextet [20]. The Thomas-Ehrman effect also does not appear to cause deviations from the quadratic behavior [11,15] and like the continuum, its main effects are probably absorbed in the b and c coefficients. However, given the consistency of the measured b and c coefficients with the predicted wave functions of the bound ^{11}Li ground state, it does not appear that these continuum, Thomas-Ehrman, and other effects are large.

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 few 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 $E_{^9\text{Li}-p}/E_T = 0.5$ if the energies of the two protons are the same. Instead we observe one broad peak centered at $E_{^9\text{Li}-p}/E_T = 0.5$ (equal proton energies on average) similar to the results obtained for the two-proton decay of ^{6}Be [13] indicated by the solid curve. Such a distribution is expected for prompt two-proton decay because the product of the two proton barrier-penetration probabilities $[P(E_{^9\text{Li}-p})P(E_T - E_{^9\text{Li}-p})]$ 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 of 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 correlations are a reflection of the spacial configurations of the halo protons inside the ^{6}Be nucleus but which become smeared out in the barrier penetration process. The deduced internal diproton and cigar spatial 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 configurations. Based on the similarity of the experimental $^6\text{Be}_{\text{g.s.}}$ and $^{11}\text{B}_{T=5/2}$ correlations, one can then also argue that the neutrons in the halo of ^{11}Li also have similar magnitudes of these two types of configurations. Indeed this observation is consistent with the calculations of Hagino and Sagawa where 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 the two-neutron-halo system $^{11}\text{Li}_{\text{g.s.}}$ in ^{11}B produced via the $^{12}\text{Be}(p, 2n)^{11}\text{B}$ reaction. The state was identified from the detection of its $2p + {}^9\text{Li}$ 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 a sextet are now identified for the first time. With the isobaric multiplet mass equation, the masses of the three unknown proton-rich members of the $A = 11$ sextet were extrapolated. The extrapolated mass excess for $^{11}\text{O}_{\text{g.s.}}$ is 46.70(84) MeV. The T_Z dependence of the experimental masses for this sextet was found to be consistent with a halo structure. Proton-halo wave functions, taken to be identical to the ^{11}Li neutron-halo wave functions predicted by Hagino and Sagawa [16], were found appropriate in describing the member states in ^{11}Be and ^{11}B. Momentum correlations of the decay products suggest similar amounts of dinucleon and cigar type configurations.

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