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Complete Isobaric Quintet*

R. G. H. Robertson and W. S. Chien
Cyclotron Laboratory and Physics Department, Michigan State University, East Lansing, Michigan 48824

and

D. R. Goosman†
Brookhaven National Laboratory, Upton, New York 11973
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By experimental observation of the lowest $T=2$ states in ^{8}B and ^{8}Li, an isobaric quintet has been completed for the first time. The $T=2$ state in ^{8}B, populated via the reaction ^{11}B(^{3}He,^{6}He)^{8}B, lies at 10.619 ± 0.009 MeV excitation, and its analog in ^{8}Li, found in ^{10}Be(p,^{3}He)^{8}Li, lies at 10.8222 ± 0.0055 MeV. The excitation of the previously known $T=2$ state in ^{8}Be was measured by ^{10}Be(p,t)^{8}Be to be 27.4922 ± 0.0027 MeV. A significant departure from the isobaric-multiplet mass equation is indicated.

Until recently no more than three members of any isobaric quintet ($T=2$ multiplet) were known, because $T=2$ states had not been observed in nuclei with a proton excess. However with the observation[1] of the $T_z=-2$ nuclides ^{8}C and ^{20}Mg, prospects for completing a quintet have been much improved. The isobaric-multiplet mass equation (IMME), which predicts that the mass excesses ΔM of analog states should be described by a three-parameter quadratic equation

$$\Delta M = a + bT_z + cT_z^2,$$

has been shown to apply to a high degree of precision in a large number of isobaric quartets ($T=\frac{3}{2}$). Nevertheless, when sufficient experimental accuracy can be brought to bear, deviations become apparent which substantially exceed the small theoretical corrections arising from known effects.[2,3] If we represent the deviations by additional terms, dT_z^3, eT_z^4, etc., two such terms can be determined in a quintet, but only one in a quartet. One might hope, therefore, by completing a quintet to test the IMME more rigorously, and, in the event of a violation, to gain some insight into the mechanisms causing it. In particular, the explicit nature of many-body charge-dependent forces could be tested in a quintet. We wish to report the identification and precise mass measurements of the lowest $T=2$ states in ^{8}B, ^{8}Be, and ^{8}Li, which, with the known masses of ^{8}C [1] and ^{8}He,[4-6] form a complete isobaric quintet.

Although it has long been recognized that the (^{3}He, ^{6}He) reaction could in principle be employed to reach $T=2$ states in $T_z=-1$ nuclei by an isospin-allowed process, in practice the reaction also unselectively populates $T=1$ states in the same region of excitation. For this reason, it might be expected that the most favorable case would be a very light nucleus where the $T=1$ states (which can decay by isospin-allowed nucleon emission) would be so broad that a sharp $T=2$ state would stand out clearly on a continuum of $T=1$ states. Our experiments on ^{11}B(^{3}He, ^{6}He)^{8}B show that this is indeed the case.

Beams of 72-MeV ^{3}He ions from the Michigan State University cyclotron impinged on targets enriched to 97.2% in ^{11}B. Emergent ^{6}He particles were analyzed in an Enge split-pole spectrograph and detected with a position-sensitive propor-

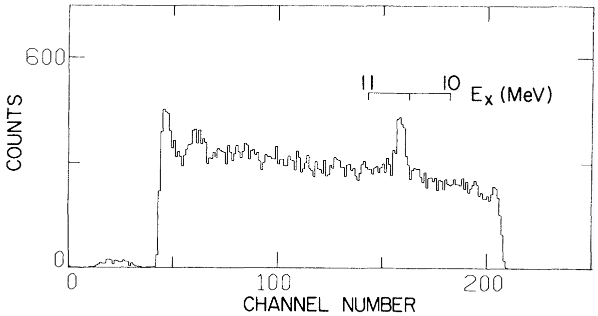

FIG. 1. Spectrum of $^{11}B(^3He,^6He)^8B$ at 72 MeV and 9° (lab) showing $T=2$ state in ^8B.

tional counter backed by a plastic scintillator for time-of-flight identification.[7] Spectra taken at 9° (see Fig. 1), 10°, 11°, and 13° (lab) reveal a sharp state (of width <60 keV) at 10.619(9) MeV excitation in ^8B, close to the energy, 10.720(70) MeV, predicted by the IMME for the lowest $T=2$ state.[8,9] At 9° it is populated with a cross section of 190 nb sr^{-1} (lab). Since there are no other states within ±2.4 MeV, and the kinematic signature is unambiguous, we infer that the state observed is the lowest $T=2$ level in ^8B.

In order to find the remaining member of the quintet, the $T=2$ state in ^8Li, we have employed the reaction $^{10}Be(p,\,^3He)^8Li$. The reaction $^{10}Be(p,t)^8Be$ was also studied to verify the identification of a narrow resonance seen by Black *et al.*[10] in ^6Li+d as the $T=2$ state in ^8Be. Target material[11] enriched to 94% in 1.6-My ^{10}Be was produced by $^{13}C(n,\alpha)^{10}Be$ in the Oak Ridge high-flux isotope reactor. A target, prepared in the form of 114 $\mu g\ cm^{-2}$ of ^{10}BeO on a 1-mg-cm^{-2} Pt backing, was bombarded with 45-MeV protons from the Michigan State University cyclotron. Reaction products analyzed by the spectrograph were detected in a Si position-sensitive detector.

Spectra from the (p,t) and $(p,\,^3He)$ reactions to the appropriate regions of excitation in ^8Be and ^8Li are shown in Fig. 2. In both cases sharp states are clearly seen, and are identified as the $T=2$ states sought.

Angular distributions to those states are shown in Fig. 3, with the (p,t) cross sections multiplied by a factor 1.53. The $(p,\,^3He)$ and (p,t) cross sections to the $T=2$ states should bear that ratio to each other if charge-dependent effects are small,[12] and the test is seen to be rather well satisfied. Also shown is a local, zero-range, distorted-wave Born-approximation calculation, with optical-model parameters (set AX) taken

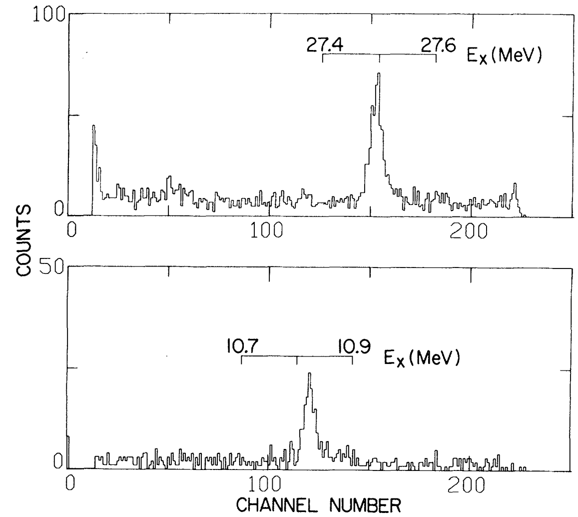

FIG. 2. Spectra resulting from 45-MeV proton bombardment of ^{10}Be, showing $T=2$ state in ^8Be (top) and ^8Li (bottom).

from Fleming *et al.*,[13] and the agreement is sufficient to confirm that the angular momentum transfer is 0.

The Q values were obtained through an extensive calibration procedure in which particle groups with accurately known Q values were placed on the detector by varying the spectrograph field. The magnet calibration of Trentelman, Preedom, and Kashy,[14] now extended to lower fields, was used. For the proton-induced

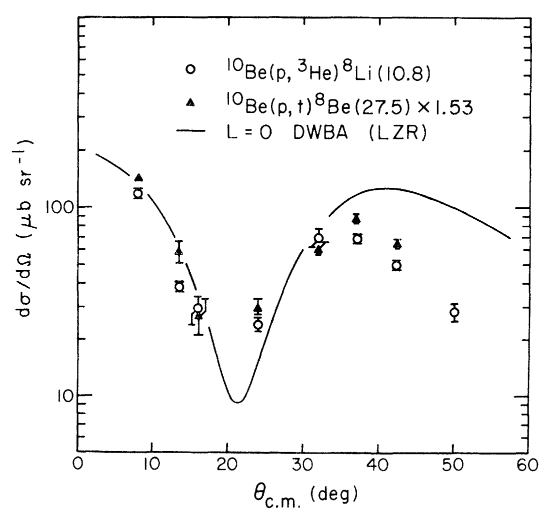

FIG. 3. Angular distributions for (p,t) and $(p,\,^3He)$ reactions on ^{10}Be to $T=2$ states in ^8Be and ^8Li. For comparison, the (p,t) data have been multiplied by 1.53. Also shown is a local, zero-range, distorted-wave Born-approximation calculation.

TABLE I. Summary of properties of $A=8$ isobaric quintet.

	T_z	M (MeV)	E_x (MeV)	Q_{1p} (MeV)[a]	Q_{2p} (MeV)[a]	Width $\Gamma_{c.m.}$ (keV)
^8C [b]	−2	35.36(17)	0.0	0.13	2.41	222^{+80}_{-140}
^8B [c]	−1	33.542(9)	10.619(9)	−0.49	1.31	32(25)
^8Be [d]	0	32.4340(27)	27.4922(26)	−1.02	0.28	12(3)
^8Li [c]	+1	31.7697(54)	10.8222(55)	−1.63		< 12
^8He [e]	+2	31.597(13)	0.0			Bound

[a]Energies for one-proton and two-proton isospin-allowed decays. Five-body channels are also open for ^8C and $^8B(T=2)$.

[b]Ref. 1, corrected for new ^8He mass (Refs. 4–6).

[c]Present work.

[d]Present work averaged with results of Ref. 8. $\Gamma_{c.m.}$ (present) is 17(4) keV.

[e]ΔM is the average of 31.57(3) MeV (Ref. 4), 31.606(18) MeV (Ref. 5), and 31.600(25) MeV (Ref. 6).

reactions, the beam energy was measured by a generalized momentum match[14] between (p,p) and (p,t) groups, and the reaction angle via proton scattering from hydrogen. The primary calibration reactions (which were consistent among themselves to ~1 keV) were for (p,t), $^{12}C(p,t)^{10}C(3.35)$ and $^{16}O(p,t)^{14}O(0.0)$, and for $(p,{}^3He)$, $^{12}C(p,{}^3He)^{10}B(0.0)$ and $^{16}O(p,{}^3He)^{14}N(0.0)$. These reactions were assumed to have Q values of −26.7139(15),[2] −20.4065(5),[15] −19.6948(5),[15] and

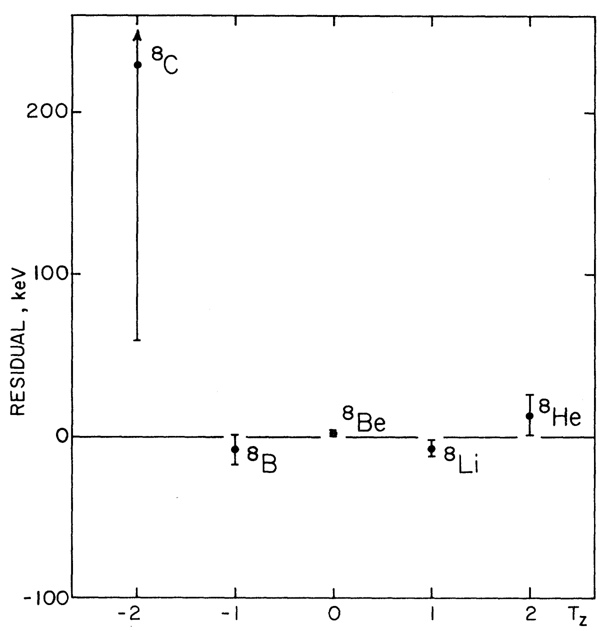

FIG. 4. Amounts by which individual masses exceed those predicted by a weighted fit of an equation quadratic in T_z to the masses of the $A=8$ quintet. The even-order alternation indicative of a nonzero $T_z{}^4$ term is discernible.

−15.2430(3) MeV,[15] respectively. The Q values found for (p,t) and $(p,{}^3He)$ to the $T=2$ states in ^8Be and ^8Li are −27.4876(26) and −26.8041(54) MeV, respectively. The corresponding excitation energy for the ^8Be level, 27.4927(27) MeV, is in agreement with the result (corrected for revised masses[15] of ^8Be and ^6Li) of Black *et al.*,[10] 27.485(10) MeV.

Table I summarizes the known properties of the members of the $A=8$ quintet. Fitting the five masses with a five-parameter IMME yields coefficients d and e of −18(14) and 13(7) keV, respectively. It appears that e, at least, differs appreciably from zero. A three-parameter fit gives an unnormalized χ^2 of 5.9 and in Fig. 4 are plotted the residuals in this fit. There is clearly a need to reduce the experimental uncertainty in the ^8C mass, which at present leads to a large correlation coefficient between d and e (−0.96).

Although several effects, particularly increasing Coulomb repulsion in the neutron-deficient members of the quintet, could cause deviations from the IMME, the known presence of isospin mixing of the $T=2$ state in ^8Be with $T=0$ states[10] produces an effect which is readily calculable. Using the model of Barker and Kumar[16] one finds in the full quintet that $d\equiv 0$ and $e\sim -1$ keV. With the constraint $d=0$, experiment gives $e=+4(2)$ keV, and $\chi^2=1.6$, an acceptable fit. It would appear that the character of the observed deviation from the IMME is consistent with the effects of isospin mixing, but that the detailed model of Barker and Kumar predicts somewhat less mixing than is observed. There is, furthermore, a difference in sign, which suggests that the perturbing isoscalar strength lies below the $T=2$ state rather than above as in Barker and Kumar's calculation. It may be remarked that, in general, quintets are much more likely to contain mixing-induced higher-order terms than are quartets, because cancelations due to approximate mirror symmetry do not occur. In quartets, mixing with $T=\frac{1}{2}$ states contributes chiefly to the T_z^2 term, but in a quintet, mixing with $T=0$ or 1 states immediately causes a T_z^4 dependence.

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†Present address: Lawrence Livermore Laboratory, Livermore, Calif. 94550.

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Are the New Particles Baryon-Antibaryon Nuclei?

Alfred S. Goldhaber
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794*

and

Maurice Goldhaber
Physics Department, Brookhaven National Laboratory,† Upton, New York 11973

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Baryon-antibaryon bound states and resonances could account for the new particles, as well as narrow states near nucleon-antinucleon threshold, which were reported earlier.

The recent discoveries of exceedingly sharp particles decaying to e^+e^-, probably $\mu^+\mu^-$, and multihadron final states[1-4] draw attention to earlier reports of narrow states in the nucleon-antinucleon ($N\overline{N}$) channel.[5-7] Could these phenomena be connected? If so, a possible common explanation would be that all of these are primarily baryon-antibaryon ($B\overline{B}$) bound states or resonances.

There are three main predictions which follow from such a model. (1) Branching ratios for decay to channels including a baryon pair should be high. (2) Such states should be found in the vicinity of every $B\overline{B}$ threshold. (3) There should be many new states which do not couple to e^+e^-.

Some of the new states might be produced in the reaction $K^\pm, \pi^\pm + $"$\gamma$"$\to X$, where the virtual γ comes from the Coulomb field of a high-Z target. Using 400-GeV meson beams, resonance states with masses up to 3 GeV would be open to study.

Shapiro and co-workers[8] have proposed just such bound states to explain relatively broad bumps in meson spectra, and later[9] have argued that the widths in some cases could be as small as a few MeV. Their width estimates seem hard to reduce further, in view of the observed large cross section for $\bar{p}p$ annihilation at low energies.[10] Therefore, if these narrow states are $B\overline{B}$ bound states, there is something about their dynamics which is not revealed in the free cross sections. Somehow the internal coordinates of the baryons