Is there a bound dineutron in ^{11}Li?

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Photodisintegration of ^{11}Li was accomplished by sending a beam of ^{11}Li at 28 MeV/nucleon through the equivalent photon field of a lead target. By measuring the complete kinematics of the disintegration products, $^{9}\mathrm{Li}+n+n$, we constructed the correlation of the angle between the two neutrons in the rest frame of the ^{11}Li. The correlation is independent of angle. This result argues against the existence of a bound dineutron in the ground state of ^{11}Li. [S0556-2813(96)01210-1]

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^{11}Li is the archetypal exotic nucleus—a light, neutron-dripline nucleus that may be viewed as a core (^{9}Li) plus two valence neutrons. The pairs—core plus neutron and neutron plus neutron—do not bind, but the three-body system is bound. In addition, the low binding energy, only 0.3 MeV [1], of the two valence neutrons gives them a relatively large radial extent; they form a neutron halo. Finally, it has been suggested that the main structure of ^{11}Li may be even simpler than core-plus-two-neutrons; it may be core-plus-dineutron [2,3]—a pair of strongly correlated neutrons.

In two similar experiments [4–6], ^{11}Li was dissociated by photon absorption into $^{9}\mathrm{Li}+n+n$, and the ^{9}Li and both neutrons were detected. A ^{11}Li target being unattainable, two ingenious developments were used—a radioactive beam facility [7,8] and the method of equivalent photons [9,10]. ^{11}Li became the projectile, and the electric field of a Pb target nucleus was the photon source. Each event was transformed back into the ^{11}Li rest frame, where various histograms were constructed. The two experiments agree with each other, as shown in Fig. 1, except for the partition of the decay energy between the $^{9}\mathrm{Li}$-$2n$ and the n-n systems. The data of [6] are interpreted in terms of an extended dineutron model. This work is based on a histogram of the neutron-neutron angular correlation contained in data of the experiment of [4,5]. As we will show below, that correlation gives no evidence for a dineutron in the ground state of ^{11}Li.

The difficulty in seeing the ground-state structure is reminiscent of the Heisenberg microscope: the process of examining the system destroys it. We see two neutrons in the final state, but where were they in the initial state? Fortunately, a

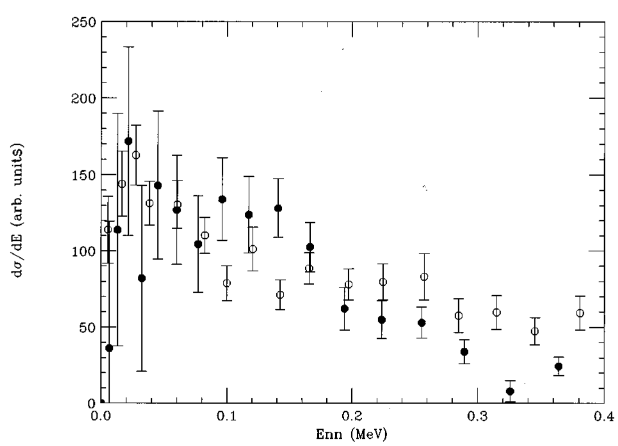

FIG. 1. Comparison of relative energy (E_{nn}) spectra of the two neutrons between two experiments. The open circles are from [6] and the solid circles are from [5].

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conclusion of both experiments [4–6] was that the photon absorption led to a direct, rather than to a resonant, breakup. With a direct transition to continuum states, the equivalent photon method is a very good way to look at the ground-state structure of ^{11}Li if two requirements are met: (1) The momentum of the absorbed photon should not significantly perturb the initial correlation of the system. This will be true if the photon momentum is small compared to the momentum of the ^{9}Li core and of each neutron. The perturbation should be *gentle*. (2) The photon absorption process should take place so quickly that the positions of the three constituents are not significantly changed; it should be a *sudden* absorption. If these requirements are met, no elaborate theory is required to see in the final state the *n-n* correlation that existed in the ground state.

The first requirement is met because [4,5] show that a typical ^{9}Li momentum is about 30 MeV/c and a typical neutron momentum is about 20 MeV/c, whereas the peak in the photon absorption cross section is around $p_\gamma = 1$ MeV/c. So the perturbing photons do not appreciably disrupt the system. The second condition is also met. At our beam velocity, $c/4$, the ^{11}Li projectile pathlength over which most of the photon absorption occurs is about 25 fm, which, at the projectile velocity of $c/4$, results in an interaction time of ~ 100 fm/c. The orbital period of a halo neutron is much greater. To estimate the latter, we note that a halo neutron has an rms radius of about 6 fm [11] and a momentum of about 20 MeV/c, hence a period of almost 2000 fm/c, about 20 times the interaction time.

Because both the gentle and sudden requirements are met, we can expect that a dineutron in the ground state would show itself in the final state. With that expectation, we look for evidence for a dineutron in our data.

If the Coulomb dissociation is indeed both gentle and sudden, a dineutron structure in the ground state results in a *two*-body breakup in the first instance. The two neutrons are assumed to be strongly correlated, i.e., relative momentum between them is zero. Thereafter, the angle θ between the momenta of the two neutrons in the ^{11}Li center of mass system should be zero, or $\cos\theta$ should be 1.0. This is the suggestion made by Tanihata *et al.* [12] from an evaluation of average momentum distributions of ^{9}Li at a beam energy of 790 MeV/nucleon and of neutrons at 29 MeV/nucleon, respectively. Note that the assumption of zero relative momentum does not necessarily mean that the dineutron is ''pointlike.'' On the other hand, the two neutrons may extend to a significant distance in coordinate space as is the case of the deuteron.

Our measured distribution of $\cos\theta$, the first to be published, along with some model distributions are given in Fig. 2. In that figure the points are from our experiment. They are indeed peaked toward $\cos\theta = 1.0$, but that peaking is a distortion caused by the differential response of the neutron detection system [4,5]. That detection system had a rather limited angle coverage, the maximum neutron angle with respect to the ^{11}Li projectile direction being only 5°. For very low decay energies, 5° is sufficient to encompass neutrons emitted under all kinematically possible conditions in the ^{11}Li rest frame, but for higher decay energies neutrons near 90° in the rest frame will miss the detector. The effect of the differential response on the $\cos\theta$ distribution can be understood by consideration of a simple example involving two extreme decay modes. For decays in which the two neutrons recoil together against the ^{9}Li, the neutrons have the minimum possible velocity for a given decay energy. For decays in which one recoils back-to-back against the other neutron and the ^{9}Li, the first neutron has the maximum possible velocity. If the decay energy is 0.52 MeV, for example, both neutrons in the first, parallel, category will have laboratory angles below 5°, but in the second, antiparallel, category only 1/4 of the time will both neutrons have angles below 5°.

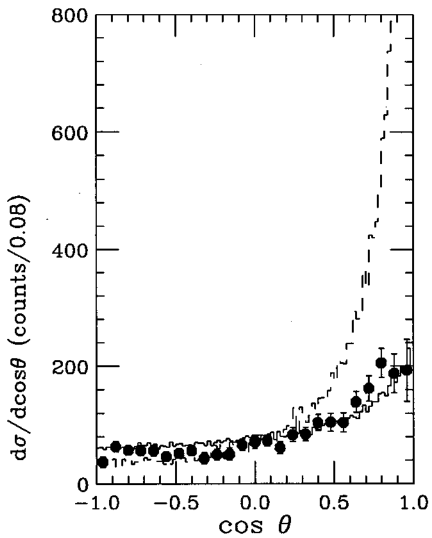

FIG. 2. Angle distribution of the two neutrons when ^{11}Li decays into $^{9}\mathrm{Li}+n+n$. The angle between the momenta of the neutrons is θ. The points are from our experiment. The histograms are Monte Carlo simulations of two decay models: solid, standard three-body phase space; dashed, two-body dineutron. The dashed histogram rises above 2000 at $\cos\theta = 1$.

To take this effect and other geometry effects into account, we calculated $\cos\theta$ distributions for two decay models and included the detector response by Monte Carlo simulations. The solid histogram in Fig. 2 is for the standard three-body phase-space model [13]. Were it not for detector response effects, this histogram would be a constant. Since the data have the same distribution, we can conclude that the neutrons are emitted with no angular correlation between them. The good agreement between the data and the three-body phase-space model also suggests that the final state interaction between the two neutrons does not manifest itself significantly in the present data.

The dashed histogram is for the simple dineutron model in which the two neutrons are emitted with equal velocities and with $\cos\theta = 1$. This histogram is at wide variance with the data. We conclude that there is no evidence here for the dineutron model and good evidence against it.

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[1] B.M. Young, W. Benenson, M. Fauerbach, J.H. Kelley, R. Pfaff, B.M. Sherrill, M. Steiner, J.S. Winfield, T. Kubo, M. Hellström, N.A. Orr, J. Stetson, J.A. Winger, and S.J. Yennello, Phys. Rev. Lett. **71**, 4124 (1993).
[2] A.B. Migdal, Yad. Fiz. **16**, 427 (1972) [Sov. J. Nucl. Phys. **16**, 238 (1973)].
[3] P.G. Hansen and B. Jonson, Europhys. Lett. **4**, 409 (1987).
[4] K. Ieki, D. Sackett, A. Galonsky, C.A. Bertulani, J.J. Kruse, W.G. Lynch, D.J. Morrissey, N.A. Orr, H. Schulz, B.M. Sherrill, A. Sustich, J.A. Winger, F. Deák, Á. Horváth, Á. Kiss, Z. Seres, J.J. Kolata, R.E. Warner, and D.L. Humphrey, Phys. Rev. Lett. **70**, 730 (1993).
[5] D. Sackett, K. Ieki, A. Galonsky, C.A. Bertulani, H. Esbebsen, J.J. Kruse, W.G. Lynch, D.J. Morrissey, N.A. Orr, B.M. Sherrill, H. Schulz, A. Sustich, J.A. Winger, F. Deák, Á. Horváth, Á. Kiss, Z. Seres, J.J. Kolata, R.E. Warner, and D.L. Humphrey, Phys. Rev. C **48**, 118 (1993).
[6] S. Shimoura, T. Nakamura, M. Ishihara, N. Inabe, T. Kobayashi, T. Kubo, R.H. Siemssen, I. Tanihata, and Y. Watanabe, Phys. Lett. B **348**, 29 (1995).
[7] B.M. Sherrill, D.J. Morrissey, J.A. Nolen, and J.A. Winger, Nucl. Instrum. Methods B **56/57**, 1106 (1991).
[8] T. Kubo, M. Ishihara, N. Inabe, H. Kumagai, I. Tanihata, K. Yoshida, T. Nakamura, H. Okuno, S. Shimoura, and K. Asahi, Nucl. Instrum. Methods B **70**, 309 (1992).
[9] B. Baur, C.A. Bertulani, and H. Rebel, Nucl. Phys. **A458**, 188 (1986).
[10] C.A. Bertulani and G. Baur, Phys. Rep. **163**, 299 (1988).
[11] N.A. Orr, N. Anantaraman, S.M. Austin, C.A. Bertulani, K. Hanold, J.H. Kelley, D.J. Morrisey, B.M. Sherrill, G.A. Souliotis, M. Thoennessen, J.S. Winfield, and J.A. Winger, Phys. Rev. Lett. **69**, 2050 (1992).
[12] I. Tanihata, T. Kobayashi, T. Suzuki, K. Yoshida, S. Shimoura, K. Sugimoto, K. Matsuta, T. Minamisono, W. Christie, D. Olson, and H. Wieman, Phys. Lett. B **287**, 307 (1992).
[13] M.M. Block, Phys. Rev. **101**, 796 (1956).