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Kinematically complete measurements for Coulomb dissociation of ^{11}Li into ^{9}Li+2n were made at 28 MeV/nucleon. Consistent with the concept of a neutron halo, the n-n correlation function indicates a source for the two valence neutrons much larger than the ^{9}Li core. The electromagnetic excitation spectrum of ^{11}Li implies a long lifetime for the anticipated low-energy dipole resonance, but a large post-breakup Coulomb acceleration of the ^{9}Li fragment is observed, indicating a much shorter lifetime and favoring direct breakup as the dissociation mechanism.

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The structure of "Li presents one of the most intriguing questions in nuclear physics. This nucleus has an interaction cross section which is large compared to those of its neighbor nuclei[1]. In its dominant reaction channel, dissociation into ^{9}Li plus two neutrons, both the neutrons and the fragment have been separately found to have sharply forward-peaked angular distributions[2–5]. These results have been interpreted to mean that "Li should be thought of as having a ^{9}Li core immersed in a halo of two neutrons, perhaps correlated as a di-neutron[6]. Furthermore, the large dissociation cross section of ^{11}Li by a high-Z target may then be the result of an electric dipole excitation to a "soft" dipole resonance located at an excitation energy much lower than the universal giant dipole resonance[7, 8]. While the giant dipole resonance may be thought of as an oscillation of all the neutrons against all the protons, in the proposed soft dipole the ^{9}Li core slowly oscillates in the diffuse cloud, or halo, of two neutrons. This new collective mode may also occur in other light neutron-rich nuclei, such as ^{6}He, ^{8}He and "Be. The fact that ^{10}Li is unbound whereas ^{11}Li is *bound* means that the interaction between the two valence neutrons in ^{11}Li is vital to its stability. The nature of the correlation between the two neutrons is not known. This paper is a report on the first measurement of the electromagnetic excitation spectrum of ^{11}Li and of a correlation between the decay neutrons.

For collective motion, such as a soft-dipole resonance, a large electric dipole strength is expected[8]. Since E2 strength is much smaller than El at our beam energy[9], the dipole strength function dB(El)/dE is related to the Coulomb dissociation cross section $d\sigma/dE$ for two-neutron removal as follows:

$$\frac{d\sigma}{dE} = \frac{16\pi^3}{9\hbar c}\frac{dB(E1)}{dE} N(E)$$

Here, N(E) gives the number of virtual photons and E is the ^{11}Li excitation energy. A thorough discussion is given in Ref. 10. Using the above formula, the dipole strength function can be determined by measuring the Coulomb dissociation cross section as a function of ^{11}Li excitation energy.

The excitation energy of the ^{11}Li is related to the decay energy E_d by $E=E_d+S_{2n}$, where S_{2n}(=0.34±0.05 MeV[3]) is the two-neutron separation energy. To calculate the decay energy from the experimental data, we extend the technique used by Heilbronn *et al.*[11] to the case of a 3-body problem. Using a relative velocity $\vec{V}_{2n-9}$ between the ^{9}Li and the two-neutron center of mass and a relative velocity $\vec{V}_{n-n}$ between the two neutrons, the decay energy of the ^{11}Li can be expressed as:

$$E_d = \frac{1}{2}\mu_1\, V_{2n-9}^2 + \frac{1}{2}\mu_2\, V_{n-n}^2$$

$$\text{with } \mu_1 = \frac{m_9\,(2m_n)}{m_9 + (2m_n)} \;\text{ and } \mu_2 = \frac{m_n}{2}.$$

Here, m_9 is the ^{9}Li mass and m_n is the neutron mass. Thus, the excitation energy of ^{11}Li can be determined by measuring the three velocities—of ^{9}Li and of two neutrons.

A ^{11}Li beam was produced by projectile fragmentation of ^{18}O from the K1200 Cyclotron and analyzed by the A1200 Fragment Separator at Michigan State University. The main elements of the experiment are shown in Fig. 1. A detailed description will be given in Ref. 12. The energy at the center of the Pb target was 28 MeV/nucleon. At this energy, Coulomb dissociation on Pb is known to dominate over nuclear dissociation due to the large number of low-energy virtual photons[13, 14]. Also the coincidence requirement of two neutrons at small angles diminishes the nuclear contribution. The ^{9}Li momenta were measured with a Si double-strip/CsI(Tl) telescope, which also served as the Faraday cup for the beam of about 400 ^{11}Li /sec. Dissociation of ^{11}Li in the silicon and CsI(Tl) detectors accounts for ~ 50% of the coincidence events. Since most of these events are indistinguishable from true events, they were measured separately with the target removed and the beam energy reduced by the 4 MeV/nucleon target thickness. Neutron velocities were measured via the time-of-flight method using the fragment signal in the Si detector as the stop.

The geometry was chosen to permit the detection of events with small relative momenta between the neutrons. Cross-talk events, events in which one neutron makes a false coincidence signal by scattering from one detector into another detector, were identified by their scattering kinematics and rejected event-by-event.

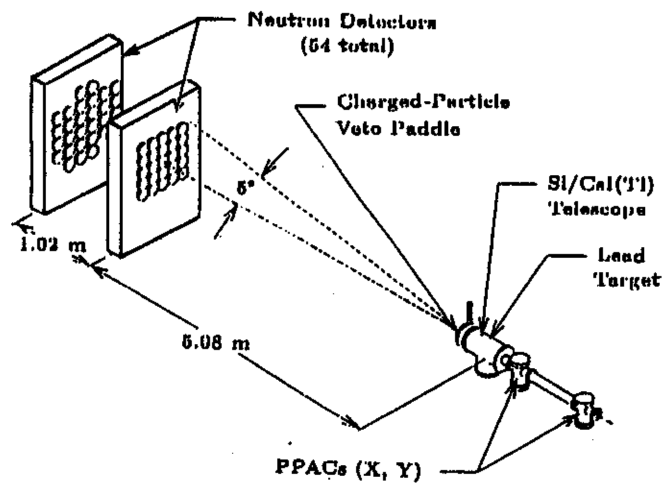

FIG. 1. Schematic drawing of the experimental set up.

First we deduced the correlation function[15]

$$C(q) \propto \frac{\sum \sigma(q)}{\sum \sigma(p_1)\sigma(p_2)}, \text{ with } q = \frac{1}{2}\,|\,\vec{p_1} - \vec{p_2}\,|$$

from the relative momentum spectrum between two neutrons in coincidence with a ^{9}Li fragment. This quantity is sensitive to the spatial extent of the source emitting the neutrons. The correlation function is displayed in Fig.2. To get a simple estimate of the source size, we compared the correlation data with a model in which each of the two neutrons is assumed to be distributed independently within the source, that is, the model neglects a possible correlated state, such as a bound dineutron state, for the two neutrons. The model also assumes a Gaussian radial shape for the neutron distribution. The curve in Fig.2 results from the model calculation with 5.3 fm for the radius parameter of the Gaussian; the corresponding rms

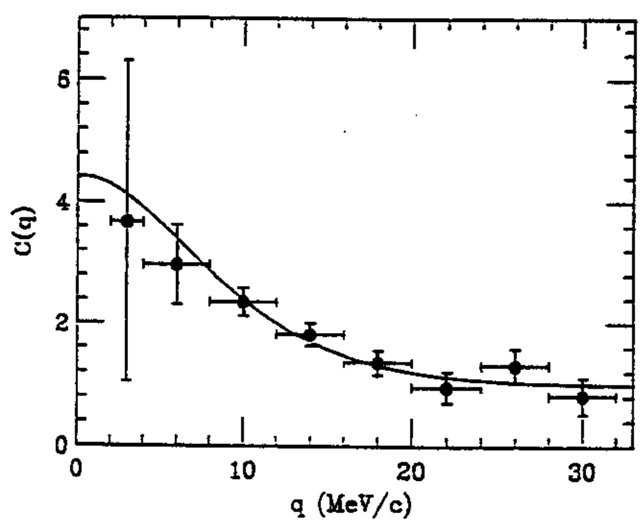

FIG. 2. Correlation function between the two neutrons. The curve represents a calculation based on a spherical Gaussian source with radius parameter 5.3 fm.

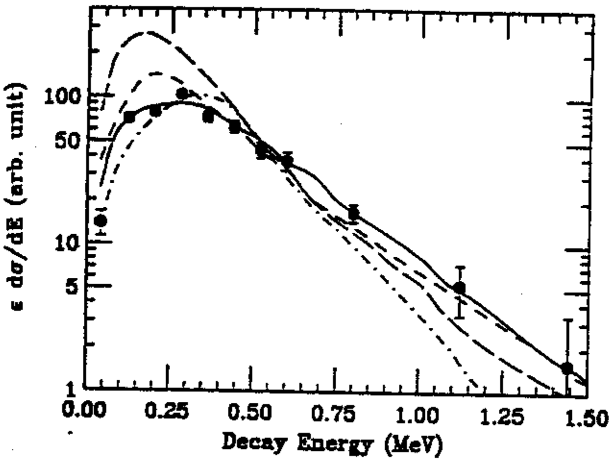

FIG. 3. The decay energy spectrum for ^{11}Li → ^{9}Li + n+n. ϵ is the energy-dependent efficiency of the detection system. The curves are results of Monte Carlo simulations for Breit-Wigner type photo-nuclear cross sections(solid for E_0=0.70 MeV, Γ_0=0.80 MeV, dot-dashed for E_0=0.40 MeV, Γ_0=0.23 MeV), a correlated-state model[16](dashed) and a dineutron-cluster model[17](long dashes).

radius is 9.2 fm. Although the shape of the halo-neutron distribution may not be Gaussian, this large radius compared with that of ^{9}Li (r_{rms}=2.3 fm[1]) supports the halo structure of the valence neutrons in ^{11}Li.

The measured decay energy spectrum is shown in Fig.3 (solid circles). The contribution from reactions in the telescope has been subtracted. To get the cross section dσ/dE, we would have to correct for the energy-dependent efficiency and resolution of the detection system. However, this is not feasible for a complicated neutron detection system. Instead, we start with a model dipole strength function and, for comparison with the data, make Monte Carlo calculations that simulate the detection system.

The dashed and long-dashed curves in Fig.3 show results of the Monte Carlo simulations with dB(E1)/dE predictions of a correlated-state model[16] and of a dineutron-cluster model[17]. Although these models reproduce the overall features of the spectrum, they overestimate the yield at low decay energy. This is partly because of the low peak positions of their dipole strength functions. It should be noted that the parameters in the correlated-state model were chosen with S_{2n} = 0.2 MeV, rather than 0.34 MeV[3].

As an alternative model, we introduced an empirical soft-dipole resonance model, in which the Coulomb-dissociation cross section is related to a Breit-Wigner type photo-nuclear cross section $\sigma_{E1}(E)$ by:

$$\frac{d\sigma}{dE} = \sigma_{E1}(E)\,\frac{N(E)}{E}.$$

The width parameter of the Breit-Wigner function has the energy dependence of s-wave neutron transmission. The solid curve in Fig. 3 displays the best-fit result of the simulations; it has resonance decay energy E_0 = 0.70 MeV and width Γ_0 = 0.80 MeV at E_0. With these parameters the Coulomb dissociation cross section is 3.6 ± 0.4 b and B(E1) is 1.00 ±0.11 $e^2 fm^2$. It is important to note that the narrow width of the ^{9}Li momentum distribution[4] and the forward peaking of the neutron angular distribution[5], both in agreement with our data[12], are also reproduced by the values of E_0 and Γ_0 with the assumption that the decay energy is shared by ^{9}Li and the neutrons according to 3-body phase space.

The good Breit-Wigner fit might be thought to reinforce the idea of the soft-dipole resonance mode in the excitation of ^{11}Li. However, a collective resonance with an excitation energy $\hbar\omega$ of only 1 MeV would have an oscillation period T = 1240 fm/c, whereas the lifetime τ of the resonance deduced from the width parameter of 0.80 MeV is 250 fm/c, only 1/5 of an oscillation. For the concept of a collective resonance to be meaningful, its lifetime should be longer; we suggest $\tau \geq T/2$. The dot-dashed curve in Fig.3, with E_0 = 0.40 MeV and Γ_0 = 0.23 MeV(τ=860 fm/c), obeys this constraint. However, the χ^2 of its fit to the data is 2.4 times the best-fit value. Hence, to describe the excitation spectrum with a resonance model, a lifetime of ~860 fm/c and some compromise on quality of fit would be necessary.

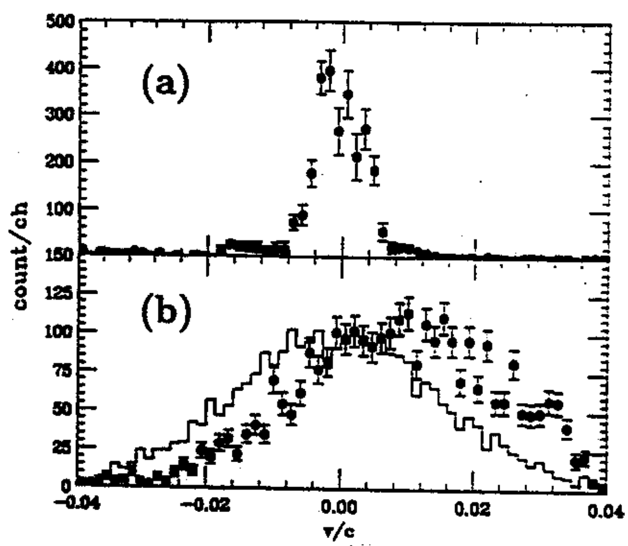

FIG. 4. (a) Spectrum of the longitudinal component of the center-of-mass velocity of ^{9}Li and two neutrons in the frame of the incident ^{11}Li. (b) Spectrum of the longitudinal component of the relative velocity $\vec{V}_9 - \vec{V}_{2n}$. The histogram shows the result of a Monte Carlo simulation assuming no Coulomb acceleration effects.

Quite a different constraint on lifetime was deduced from some velocity comparisons. In Fig.4(a), the spectrum of the longitudinal component of the center-of-mass velocity of the three-body system ^{9}Li + 2n is shown in the frame of the incident ^{11}Li. This figure, from its near-zero centroid, demonstrates the conservation of total momentum of the three body system and, from its width, gives us the experimental velocity resolution —about 0.008 c (FWHM). However, the distribution of the longitudinal component of relative velocity $\vec{V}_9 - \vec{V}_{2n}$ (Fig.4 (b)) is clearly not centered on zero; in general, ^{9}Li has a larger velocity than the neutrons. As shown by the histogram, there is no significant instrumental asymmetry. The velocity difference is understood by considering that the ^{9}Li is accelerated by the Coulomb field of the Pb target after the breakup, whereas the neutrons are not. As the absorption of a virtual photon occurs close to the Pb nucleus, a large Coulomb acceleration will result if the breakup also occurs close to the Pb nucleus, i.e., if the lifetime of the excited ^{11}Li is short. The observed velocity difference indicates that breakup occurs within a 30 fm distance of the lead nucleus. This distance limits the lifetime of the soft dipole state of ^{11}Li to less than about 85 fm/c, a factor of ten below that required for a meaningful (but marginal) fit to the excitation spectrum. It would seem that only a direct breakup process, perhaps a variant of the dineutron-cluster model, could satisfy the large Coulomb acceleration[18].

In summary, we have measured the electromagnetic excitation of ^{11}Li. The size of the neutron source estimated from two-neutron correlation function is consistent with a halo structure of the two valence neutrons in ^{11}Li. A correlated-state model and a dineutron-cluster model both overpredict the peak yield of the decay energy spectrum. In the resonance picture, the narrow width implies a long-lived state of ^{11}Li. However, an observed ^{9}Li-2n velocity difference implies a large post-breakup Coulomb acceleration, which means a short lifetime of the excited state. This contradiction indicates that the "soft-dipole resonance" is not suitable for the description of the electromagnetic excitation of ^{11}Li and suggests a direct breakup process.

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