Narrow component of momentum width and neutron halo in ^{11}Li

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Assuming that two neutrons in ^{11}Li form a "halo," we derive phenomenologically the narrow component of the width of the momentum distribution of ^{9}Li from the fragmentation of ^{11}Li using a diffractive excitation model. The binding energy of the two neutrons in the halo is estimated and the momentum widths of other heavy fragments are also given.

It has been suggested that some nuclei might have a neutron "halo,"[1,2] consisting of a few neutrons, in the far periphery which behave incoherently[2] with the rest of the nucleons in the nuclear distribution in the ordinary sense. Recently, distinctive structures have been observed in the momentum distribution of ^{9}Li produced from the fragmentation of the neutron-rich ^{11}Li beam in high-energy heavy-ion collisions.[3] On the other hand, we know empirically[4] that the energy required to breakup ^{11}Li into ^{9}Li$+2n$ is 0.156 MeV, which is smaller than the energy needed for breaking ^{11}Li into ^{10}Li$+n$ (1.030 MeV). It takes more energy to remove one neutron from ^{11}Li than to remove two neutrons. The existence of two extremely loosely bound neutrons suggests the existence of unusual structure such as a neutron halo in ^{11}Li.[5]

We show how the above two experimental facts are related by analyzing phenomenologically the widths of momentum distributions.

We assume two neutrons in ^{11}Li form a halo which behave independently in peripheral collisions from the ordinary nuclear distribution "^{9}Li." In other words, the halo and "^{9}Li" in ^{11}Li are so extremely loosely bound that the excitations of ^{11}Li nuclei by fast grazing collisions take place independently in the two parts. The two neutrons in the halo may be considered to be loosely bound to each other under the influence of the nuclear force exerted from "^{9}Li" (core henceforth). The binding energy between the two neutrons in the halo and the intercluster binding energy between the halo and the core must sum up to 0.156 MeV, the threshold energy for breaking ^{11}Li into ^{9}Ln$+2n$. Because of the smallness of this energy, the narrow component of the width of the momentum distribution of ^{9}Li stems out. We use the diffractive excitation model[6] (DEM) for the calculation of the momentum widths, which has been found capable of reproducing the experimentally observed widths of the momentum distributions of heavy nuclei produced by fragmentation of ^{16}O and ^{12}C in high energy periphercal collisions.

Upon high energy peripheral collisions, according to the DEM model, a nucleus A is excited in a way characterized by a diffractive excitation energy spectrum,

$$\rho_A(E)=\exp(-\beta_A/E)/E^2 , \tag{1}$$

where β_A is a constant depending only on the nucleus A which is approximately the average binding energy per nucleon of the nucleus A. The excited nucleus A^* then decays into various nuclear fragments carrying various energies and momenta. The conservation of total momentum ($=0$ in the rest system of A^*) and energy, and the conservation of total number of nucleons restrict the energies and momenta of the fragments and give the widths of the momentum distribution of a fragment as a statistical average. In the fragmentation of the excited nucleus A^{*6}, we denote the mass of the observed fragment by m_c, and the remaining mass by m_x (our main interest is for the case $A={}^{11}$Li and $c={}^{9}$Li, we use general expression). Energy conservation in the center of mass system of A^* implies

$$m_A^*=m_A+E=(m_c^2+P_c^2)^{1/2}+(m_x^2+P_c^2)^{1/2} . \tag{2}$$

In this case $P_c \ll m_c, m_x$, so we can expand Eq. (2) as

$$m_A^*=m_A+E=m_c+m_x+\frac{P_c^2}{2m_c}+\frac{P_c^2}{2m_x} ,$$

which gives

$$P_c^2=\frac{2m_c m_x}{m_c+m_x}(m_A-m_c-m_x+E) . \tag{3}$$

Next we express m_x in terms of kinematical quantities. To do this, we define a nucleon mass m in such a way that the projectile has no binding energy, namely $m_A=N_A m$, where N_A is the nucleon number in the nucleus A.

Denoting the nucleon number in the observed fragment C by N_C, we have $m_c=N_c m+\delta_c$, where δ_c is the binding energy of nucleus C. Suppose that the unobserved mass m_x fragments into K pieces whose nucleon numbers and masses are N_i, and $m_i=nN_i+\delta_i$ ($i=1,2,\ldots k$), respectively. As each one of these K fragments has momentum P_i, and energy-momentum conservation gives

$$m_x = \Sigma m_i + \Sigma P_i^2/2m_i - P_c^2/2m_x \ . \tag{4}$$

Since the δ_i's are less than 100 MeV, and $P_i^2/2m$ ($P_c^2/2m$) is of the order of a few MeV, whereas $m_i > 940$ MeV, we can safely make the following approximations for the analysis of ^{11}Li:

$$\begin{aligned} &m_c + m_x = m_A \ , \\ &(m_A - m_c - m_x) + E = mN_A - (mN_c + \delta_c) \\ &\qquad - \sum_{i=1}^{k} (mN_i + \delta_i) \\ &\qquad - \sum_{i=1}^{k} \left[\frac{P_i^2}{2m_i} \right] + \frac{P_c^2}{2m_x} + E \\ &\qquad = E - \delta_c - \Sigma \delta_i \ . \end{aligned} \tag{5}$$

We also used the nucleon number conservation $N_A = N_c + \sum_{i=1}^{k} N_i$ to derive the last expression. Substituting these approximate forms into Eq. (3) and averaging over the excitation energy, we obtain the following equation for the width of the momentum distribution for each component.

$$\sigma_\perp^2 = \left[E - \delta_c - \sum_{i=1}^{k} \delta_i \right] \frac{2m_c(m_A - m_c)}{3m_A} \ , \tag{6}$$

where the factor 3 in the denominator comes from the number of momentum vector components. The reduced width σ (σ° in Ref. 3) is defined is

$$\sigma \equiv \sigma_\perp \cdot \left[\frac{N_A - 1}{N_c(N_A - N_c)} \right]^{1/2} \ , \tag{7}$$

which gives from Eq. (6)

$$\sigma = \left[\frac{2}{3} m \left[E - \delta_c - \sum_{i=1}^{k} \delta_i \right] \frac{N_A - 1}{N_A} \right]^{1/2} \ . \tag{8}$$

Back to our main interest, in our model ^{11}Li is made of two parts: the ordinary nuclear distribution "^{9}Li," the core consisting of three protons and six neutrons, and a halo consisting of two neutrons which are loosely bound to each other. The binding between the halo and the core is so weak that we can assume that the "^{9}Li" retains its usual structure of ^{9}Li and that the two parts may receive independently the amounts of energy transfers unique to their structures. Accordingly the neutron rich ^{11}Li can be excited in two distinctive ways depending on which part of the nucleus is excited by peripheral collisions. It may aquire excitation energy with the excitation spectrum $\rho_H(E)$ through the interaction of the neutrons in the halo with the target (we call this halo excitation). The halo excitation energy spectrum $\rho_H(E)$ is characterized by a parameter β_H. The core, "^{9}Li," may also be excited (core excitation); this excitation is characterized by a parameter β_A, which is approximately the binding energy per nucleon in ^{9}Li. Both excitation energy spectra have the same functional form of energy E as the one in Eq. (1) and have a peak at approximately $E = \beta/2$.

When halo excitation occurs, the excitation energy spectrum is

$$\rho_H(E) = \rho_H \exp(-\beta_H/E)/E^2 \ , \tag{9}$$

where ρ_H is the normalization constant. In order to produce ^{9}Li fragment, it is necessary for ^{11}Li* to receive energy transfers larger than the threshold energy for production of the fragment. The final state for ^{9}Li is unique, ^{9}Li$+2n$ for which the threshold energy is equal to the binding energy $\delta = \delta_c + 2\delta_n$ where $c = {}^9$Li and δ_n is the binding energy for a neutron. δ is 0.156 MeV.

Using Eqs. (6), (8), and (9), we obtain the reduced width of the transverse momentum distribution of ^{9}Li in terms of the average excitation energy $\bar{E}$ and δ for this channel,

$$\sigma_H = \left[\frac{2}{3} m (\bar{E} - \delta) \frac{N_A - 1}{N_A} \right]^{1/2} \ , \tag{10}$$

where m is the nucleon mass and

$$\bar{E} = \frac{\int_\delta^{m_\pi} E \rho_H(E)/N(E) dE}{\int_\delta^{m_\pi} \rho_H(E)/N(E) dE} \ , \tag{11}$$

$N(E)$ is the number of open channels at an available energy E. As before,[5] we choose the cutoff energy at the pion mass m_π, but $\bar{E}$ depends weakly on the cutoff energy because the number of open channel $N(E)$ increases as energy increases.

We performed numerical calculation of Eqs. (10) and (11) using all conceivable decay channels of ^{11}Li* for $N(E)$.[7] Little is known about the excitation energy parameter β_H except that it is about the binding energy of the neutrons in the halo which is less than 0.156 MeV. We very β_H as a parameter in the vicinity. Figure 1 shows σ_H as a function of β_H. The horizontal lines are the upper and lower experimental boundaries and the arrows are drawn at the experimental median value of the narrow component of the momentum width $\sigma_N^{\exp} = 17$ MeV/c. It determines the value of the halo excitation energy parameter, $\beta_H = 0.140$ MeV. This implies that the binding energy of the two neutrons in the halo is approximately 0.140 MeV which should be compared with $\beta = 8$ MeV used for the ^{16}O and ^{12}C excitation energy spec-

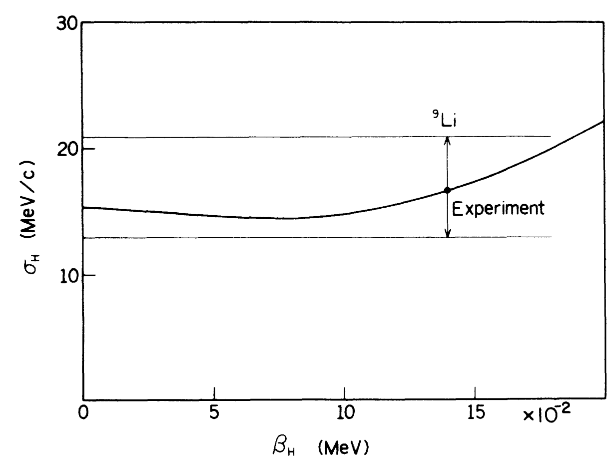

FIG. 1. The reduced width of the momentum distribution of the ^{9}Li fragment as a function of the excitation energy parameter of the halo β_H. The arrows at 0.14 MeV indicate the range of the experimental uncertainty in the width.

trums in the similar analysis[5] (their average binding energies per nucleon are 7.966 and 9.680 MeV, respectively).

Because of the facts that we need 0.156 MeV to remove two neutrons from ^{11}Li, and that this is equal to the sum of the binding energy of the two neutrons in the halo and the intercluster binding energy between the halo and the ordinary nuclear distribution "^{9}Li," we obtain the intercluster binding energy between the halo and the ordinary nuclear distribution "^{9}Li," $\epsilon=0.016$ MeV. This is 2 orders of magnitude smaller than the average binding energy of a nucleon in the usual nuclear distribution of ^{9}Li. The remark remains the same even if the binding energy of two neutrons is 30% less than β_H. At present, by the limitation of experimental uncertainty, both the effective binding energy of the two neutrons in the halo and ϵ can be any value smaller than 0.156 MeV with the restriction that their sum is less then this value. Nevertheless, the result that the magnitude of β_H needed to reproduce the narrow component of the momentum is within the restriction means that the existance of the neutron halo is responsible for the narrow component of the momentum width.

We perform a similar calculation for the excitation of the ordinary nuclear distribution using the binding energy per nucleon for ^{9}Li, β_A (to simplify the notation, we write A' in place of ^{9}Li). For this case the excitation energy spectrum is given by

$$\rho_{A'}(E)=\rho_{A'}\frac{\exp(-\beta_{A'}/E)}{E^2}\ , \tag{12}$$

where $\beta_{A'}=5.038$ MeV and $\rho_{A'}$ is a normalization constant. Substituting $\rho_{A'}(E)$ for $\rho_H(E)$ in Eq. (11) and substituting the result for the average energy $\bar{E}$ in Eq. (10), we obtain the reduced width $\sigma=59$ MeV/c. This has the expected magnitude for the width of the momentum distribution for fragments from ordinary light nuclei. The experimental value of the wide component of the momentum width of ^{9}Li is $\sigma_w^{\rm exp}=71\pm9$ MeV/c.

Using the values $\beta_{A'}$ and β_H which are obtained from the analysis of the production of ^{9}Li, we calculate the widths of the momentum distributions for the other heavy fragments such as ^{8}Li, ^{8}He, etc. For ^{8}Li there is only one possible final fragmentation channel, namely $^{11}\text{Li}\to{}^{8}\text{Li}+3n$. So the threshold energy δ for ^{8}Li production is uniquely determined to be 4.064 Mev. For other cases there are several possible channels. For instance, ^{8}He can be produced in three final states, He$+t$, He$+d+n$, He$+P+2n$. The binding energies for the three channels are 5.618, 11.875, 14.110 MeV, respectively. Statistical considerations of the decay mechanism of the excited nuclei renders us a justification for using the lowest binding energy configuration as the dominant fragmentation channel. Thus, for the production of ^{8}He, $\delta=5.618$ MeV. The relative probability for an excited nucleus to decay into a specific channel is proportional to $\exp(-\delta/T)$ where δ is the threshold energy (binding energy) for that channel and T is the temperature of the excited nucleus. The typical temperature appropriate for peripheral collisions is $\sim$4 MeV, estimated from Fermi motion, which is in good agreement with fragmentation data.[9] According to these arguments alone, the decay rate into the aforementioned three channels are in the ratio 1:0.05:0.03. By similar arguments, we find the dominant final state for the production of ^{6}He is ^{6}He$+t+2n$ ($\delta=7.749$ MeV).

In Table I we summarized the calculated reduced momentum widths for the experimentally observed nuclear fragments. The final states and the interfragment binding energies (the threshold energies) used in the calculation are also tabulated, along with the measured momentum widths. We have also calculated the widths of the fragments by varying $\beta_{A'}$. To show the typical dependence of the momentum widths on the excitation energy spectrum, we list the widths obtained at $\beta_{A'}=8.0$ MeV. In Fig. 2 we show the calculated reduced momentum widths of various fragments along with the experimental values of the fragments as functions of the interfragment binding energies δ for the two excitation energy spectrums for "^{9}Li" and for the halo. The sharp variation of the curve for $\beta=0.140$ MeV as a function of δ is due to the discrete nature of the numbers of the open channels $N(E)$. We notice that the two energy spectra give two distinguishable widths for the fragments having lower interfragment binding energy while the two components converge as the binding energy increases. At first sight, the calculated momentum widths for ^{8}Li disagree greatly with the experimental values. But the

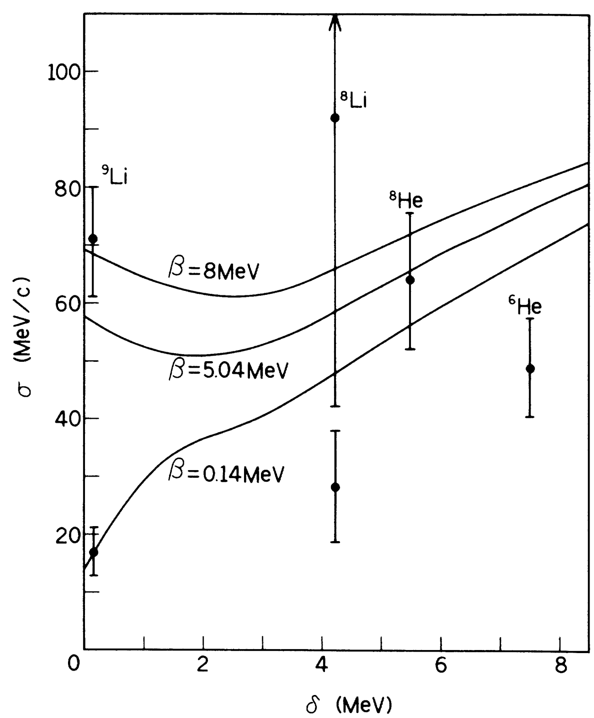

FIG. 2. The widths of the momentum distribution calculated for the three excitation energy parameters, $\beta=0.14$, 5.04, and 8.00 MeV. The experimental points (Ref. 3) with the error bars for the fragment of ^{9}Li, ^{8}Li, ^{8}He, and ^{6}He are drawn in at the lowest possible interfragment binding energies of the production channels.

TABLE I. The calculated momentum widths of all the measured fragments obtained from halo excitation, and two different core excitation energy spectra characterized by β_H and $\beta_{A'}$, respectively. The specific decay channels and their threshold (binding) energies used for the calculation are given. The experimental values of the narrow and wide components of width are also listed (Ref. 3).

	σ (MeV/c)			
Fragment $^{11}Li \rightarrow$	^{9}Li	^{8}Li	^{8}He	^{6}He
channel $^{11}Li \rightarrow$	$^{9}Li+2n$	$^{8}Li+3n$	$^{8}He+t$	$^{6}He+t+2n$
binding energy (MeV)	0.156	4.220	5.618	7.749
Theory				
$\beta_H=0.140$	16	45	54	64
$\beta_{A'}=5.04$	55	56	59	68
$\beta_{A'}=8.00$	65	64	69	77
Experiment				
Narrow	17±4	27±11		
Wide	71±9	92±76	64±12	47±7

data are extracted from the Gaussian fits to the momentum distribution of ^{8}Li. They have such large error bars that it is possible[9] to fit equally well the momentum distribution with another set of momentum widths which are consistent with the calculated ones. However, this simple extension of the DEM model fails to give an explanation to the relatively narrow width of ^{6}He.

We have shown phenomenologically that the narrow components of the momentum width of ^{9}Li fragments can result from the excitation of the halo consisting of two neutrons which are loosely bound to each other under the influence of an ordinary nuclear core. The fact that we need such a small halo excitation energy parameter β_H in order to reproduce the narrow component of the momentum width for ^{9}Li justifies the assumption of the existences of the neutron halo and of the relation between the two experimental facts. The extremely small intercluster binding energy ϵ gives a support to the independence of the halo and the core. This independent behavior of the two parts in ^{11}Li during peripheral collisions will more directly be manifested in the beam rest system as the difference in the displacements[5,10] of the center of the Gaussian distributions in the longitudinal direction: The Gaussian distribution of the narrow component should have smaller displacement compared to that of the wider component in the rest system of the beam nucleus because of the smaller effect recoil mass of the halo in comparison with that of the core, "^{9}Li."

[1]H. A. Bethe and P. J. Simens, Nucl. Phys. **B21**, 589 (1970); C. B. Dover, Proceedings of the Summer Study Meeting on Nuclear and Hypernuclear Physics with Kaon Beams, Brookhaven National Laboratory Report BNL-18335, 1973, and references therein.

[2]F. Uchiyama, Phys. Lett. **153B**, 363 (1985).

[3]T. Kobayashi *et al.*, Proceedings of the Eleventh International Conference on Particles and Nuclei, Kyoto, Japan, 1987, edited by S. Homma *et al.* [Nucl. Phys. **A478**, 1c-914c (1988)]; Phys. Rev. Lett. **60**, 2599 (1988).

[4]F. Ajzenberg-Selves, Nucl. Phys. **A320**, 1 (1979).

[5]P. G. Hansen and B. Jonson, Europhys. Lett. **4**, 409 (1987).

[6]N. Masuda and F. Uchiyama, Phys. Rev. C **15**, 972 (1977); **15**, 1588 (1977); F. Uchiyama, *ibid.* **23**, 935 (1981).

[7]We obtained $N(E)$ by calculating the binding energies for all the decay channels for which all the fragments in the channels have measured binding energies listed in the *Table of Isotopes,* C. M. Lederer and V. S. Shirley (Wiley-Interscience, New York, 1978).

[8]A. S. Hirsch *et al.*, Phys. Rev. C **29**, 508 (1984).

[9]T. Kobayashi, private communication.

[10]D. E. Greiner *et al.*, Phys. Rev. Lett. **35**, 152 (1975). See also, A. S. Goldhaber and H. H. Heckman, Annu. Rev. Nucl. Sci. **28**, 161 (1978), pp. 177–185.