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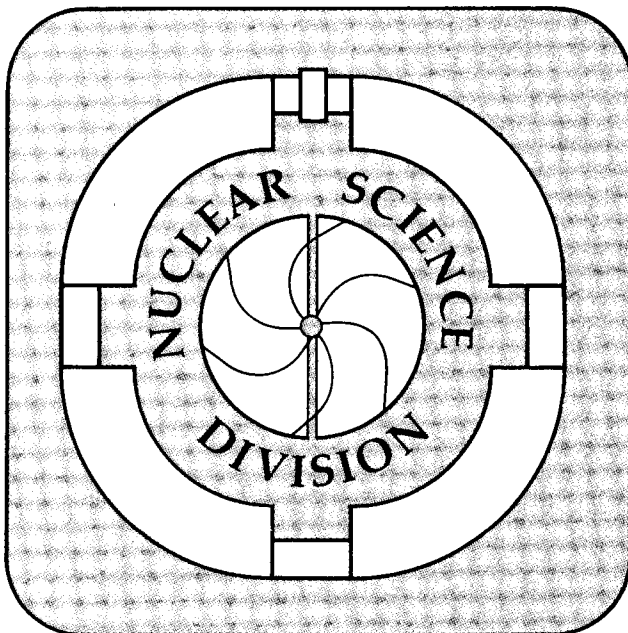
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NEUTRON DENSITY DISTRIBUTION IN ^{11}Li *

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ABSTRACT

The radial density distribution of neutrons in ^{11}Li is deduced from the measured perpendicular momentum distribution of ^9Li fragments coming from the interaction of ^{11}Li (790 MeV/A) with a carbon target and from the reaction cross section. The results confirm that the neutron density distribution in ^{11}Li extends to very large radii.

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The reaction of ^{11}Li (790 MeV/A) with a carbon target was studied by Tanihata et al. at the Berkeley Bevalac (1-3). The perpendicular momentum distribution of ^9Li coming from this reaction was found to contain two Gaussian components with widely different widths (23 ± 5 and 95 ± 15 MeV/c). The ratio of their areas (broad/narrow) is 1.73 ± 0.33 (2). The reaction cross section was found to be 1055 ± 14 mb(2), substantially larger than the value obtained for the interaction of ^{12}C with carbon (939 ± 49 mb)(4) at 870 MeV/A. Thus the ^{11}Li nucleus must be larger than ^{12}C even though it contains one less nucleon.

It was suggested by Migdal(5) that the dineutron might become bound in the field of a nucleus. Hansen and Jonson(6) applied this concept to ^{11}Li , which has two neutrons outside the closed $p_{3/2}$ shell, and suggested that the wave function of the outer neutrons in the force-free region should be proportional to $\exp(-r/L)/r$, where L is a decay length whose value was calculated to be 8.2 fm from the binding energy of the two neutrons to the ^9Li core.

The present calculation investigated the formation of ^9Li as a result of the collision of target nucleons with projectile nucleons. The method has already been described(7,8). The spatial coordinates of the ^{12}C target nucleons were chosen at random from a Fermi distribution with diffusivity a of 0.521 fm and half-density radius c of 2.222 fm. The coordinates of the projectile protons were chosen from a Fermi distribution with a of 0.583 fm, c of 1.79 fm, and those of the neutrons from the sum of a Fermi distribution and an exponential distribution:

$$\rho_n(r) = 0.08458 / \{1 + \exp [(r - 2.222) / a]\} + N \exp (-2r/L) / r^2 \quad (1)$$

where N is a normalization parameter which determines the contribution of the loosely bound neutrons to the exponential tail. In calculations in which less than the full two

loosely bound neutrons fell in the exponential tail, the balance was added to the Fermi distribution, keeping the central density and half-density radius at the values of ^{12}C (0.08458 N/fm^3 and 2.222 fm respectively), but allowing the diffusivity a to change so that the volume integral over the Fermi component was equal to the number of neutrons that it was assumed to contain. In all calculations, a value of 6 fm was assigned to the decay length L , and the exponential density contribution was added only at radii greater than 2.5 fm .

Having fixed the coordinates of all nucleons, the target and projectile nuclei were allowed to collide at a given impact parameter. When two nucleons approached each other with a minimum separation less than a collision distance given by the free nucleon-nucleon scattering cross sections, they were assumed to collide. The projectile nucleon was assumed to be scattered in the direction of the line between the two nucleons at the collision point. Therefore, in about half of the NN collisions, the projectile nucleon was scattered towards the projectile. A mean free path of 4 fm was assumed⁽⁸⁾ to determine the probability that this nucleon induced a secondary reaction in the projectile fragment or whether it escaped with no final state interaction (FSI). Harmonic oscillator wave functions were used to calculate the probability that the scattered nucleon came from the s -shell. If it did, the residual fragment was assumed to be too excited to survive as ^{10}Li or ^9Li .

The calculation was repeated at each of 151 different impact parameters in steps of 0.1 fm from 0 to 15 fm for a total of 100,000 nucleus-nucleus collisions. Only the larger impact parameters, though, contributed to the formation of ^{10}Li or ^9Li . The number of events in which ^{10}Li and ^9Li primary fragments were formed without FSI or s -shell hole were recorded, along with the identity of the lost neutrons, i.e. whether they came from the six tightly bound $p_{3/2}$ neutrons or from the two loosely bound neutrons.

Since ${}^9\text{Li}$ is so slightly bound against neutron decay, it was assumed, and confirmed by decay calculations⁽⁸⁾, that the decay of ${}^{11}\text{Li}$ or ${}^{10}\text{Li}$ nuclei that were formed in excited states by FSI or s-shell hole would contribute only a few percent to the final yield of ${}^9\text{Li}$. Thus ${}^9\text{Li}$ came from a) the removal of two tightly or loosely bound neutrons, or one of each, or b) by the removal of one tightly or one loosely bound neutron followed by neutron decay of the ${}^{10}\text{Li}$ thus formed. The ${}^9\text{Li}$ recoiled by the momentum (36.94 MeV/c) of the emitted neutron: this momentum was assumed to be isotropic in the projectile frame. Its perpendicular component was added to that of ${}^{10}\text{Li}$ arising from the loss of the first neutron.

Friedman has suggested⁽¹⁰⁾ that the width of the momentum distribution of a fragment formed by the removal of a nucleon is related to the separation energy of the lost nucleon. Thus the broad momentum component observed experimentally should contain those events in which one or more of the tightly bound neutrons were lost, and the narrow component to those in which all lost neutrons came from the loosely bound pair. The width σ of the Gaussian distributions is approximately related to separation energy ϵ by^(2,3):

$$\sigma^2 = \sigma_0^2 F(B-F) / (B-1)$$

with
$$\sigma_0^2 = M_n \epsilon / (B-1) / B \quad (2)$$

where B, F are the projectile and fragment masses and M_n is the neutron mass. The observed widths correspond to separation energies of about 0.34 MeV for the outer neutrons and 6.0 MeV for the $p_{3/2}$ neutrons⁽²⁾.

Since the separation energies have to be treated as parameters to fit the observed widths, nothing can be learned from them other than a general confirmation of Friedman's suggestion. The ratio of momentum peak areas, though, is a measure of the probability

that the lost neutrons came from the tightly or loosely bound groups, and therefore of the density ratio of these two groups in the tail of the ^{11}Li neutron distribution. The calculated value of the reaction cross section is sensitive to the total neutron density at large radii.

Table I shows a comparison of the experimental values⁽²⁾ of the reaction cross section and the ratio of broad/narrow peak areas with the values of these quantities calculated for several values of N (eq. 1) and the corresponding Fermi diffusivity a . Since Coulomb excitation is not included in the calculation, its estimated contribution to the experimental reaction cross section ($7 - 30 \text{ mb}^{(9)}$) has been subtracted. The nuclear part of the reaction cross section is therefore $1036 \pm 19 \text{ mb}$.

The best agreement is obtained for an exponential tail containing 1.0 loosely bound neutrons. Fig. 1 shows a comparison of the experimental and calculated perpendicular momentum distribution for this case. "Separation energies" of 5.0 and 0.15 MeV were used for the tightly bound and loosely bound neutrons respectively. These values are lower than those of ref. 2 because the present calculation contains the contribution to the ^9Li momentum from the neutron decay of ^{10}Li .

The calculation identifies the sources of the broad and narrow momentum distributions. 79.1% of the broad component comes from the removal of a single tightly bound neutron, 9.4% from removal of two tightly bound, and 11.5% from removal of one tightly bound and one loosely bound neutron. The narrow component comes from the removal of one loosely bound neutron (98.1%) or two loosely bound neutrons (1.9%). The last process is rare because the loosely bound neutron in the exponential tail of the density distribution is found only at large radii where the density is so low that a collision with a second neutron is improbable. The fit to a double Gaussian distribution is a reasonable approximation only because nearly all (85.8%) of the ^9Li comes from removal of either a tightly bound or a loosely bound neutron from ^{11}Li . Removal of two neutrons,

which would introduce components with additional widths, is responsible for only 14.2% of the total ${}^9\text{Li}$.

It is worth noting that a calculation in which the fragment recoiled with the Fermi momentum of the struck neutrons gave equally good results for the ${}^9\text{Li}$ momentum distribution. The Fermi momentum was assumed to be proportional to the cube root of the total density at the radius of the neutron (the local Fermi gas model⁽¹¹⁾). However, both broad and narrow momentum components were found when the method was applied to neutron distributions that did not contain an exponential tail to large radii, although the narrow component was reduced in amplitude. This result is in contradiction with the observation that ${}^6\text{He}$ from the interaction of ${}^8\text{He}$ with a carbon target has only a single broad component in its perpendicular momentum distribution⁽²⁾.

FIGURE CAPTION

Fig. 1. Comparison of experimental (filled circles) and calculated (bars) perpendicular momentum distribution of ${}^9\text{Li}$. The dots show the double Gaussian fit to the calculation. The ${}^{11}\text{Li}$ neutron distribution with $\text{No.N} = 1.0$ was used in the calculation. The parameters are given in Table I. The calculated distribution was normalized to the height of the experimental peak.

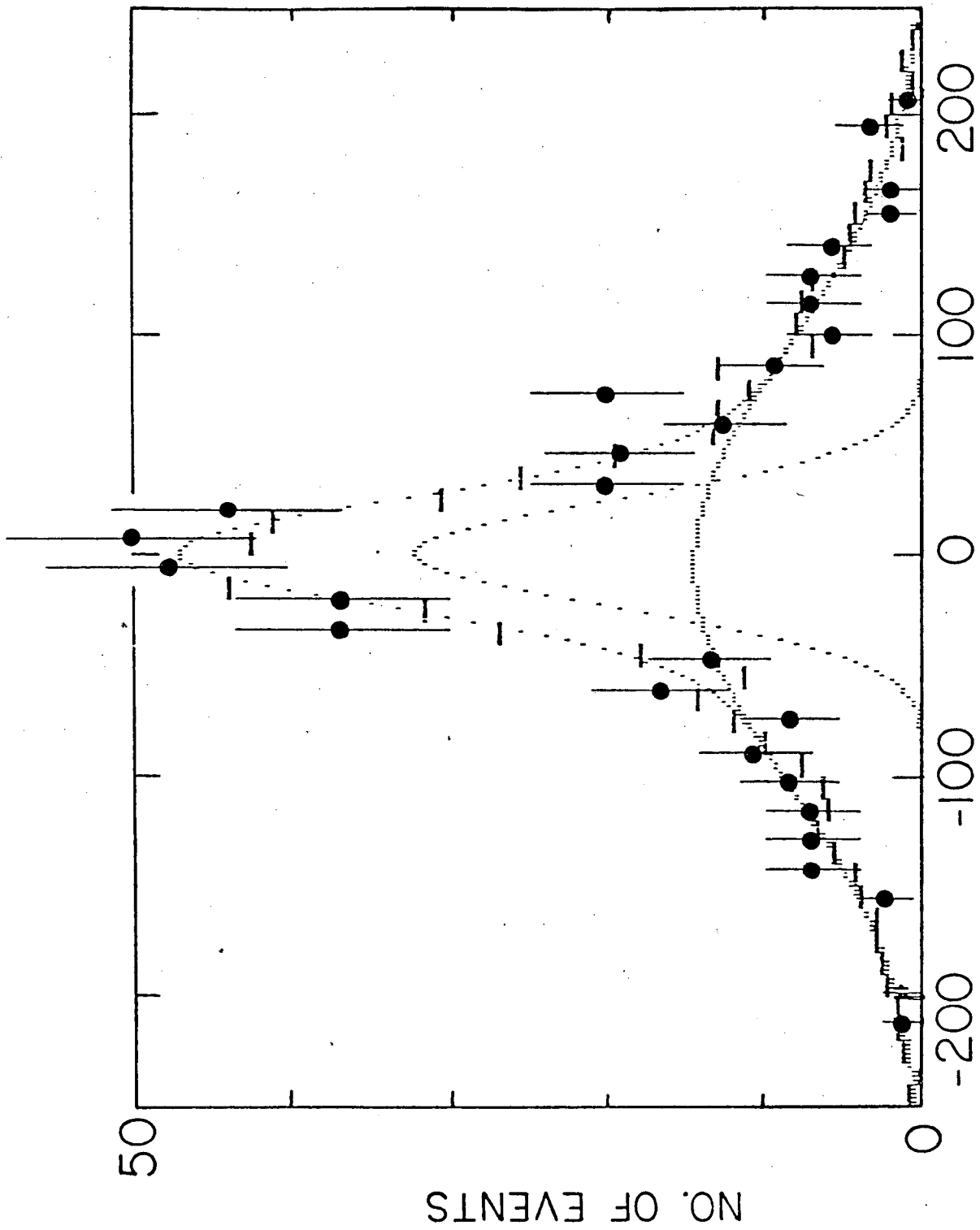
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TABLE 1. Comparison of calculated and experimental values of the reaction cross section σ_r and the ratio R of the areas of the broad and narrow peaks in the perpendicular momentum distribution. Calculations were made for different values of N and a (eq. 1) corresponding to different average numbers (No.N) of neutrons in the exponential tail of the density distribution beyond 2.5 fm.

No.N	a (fm)	N	σ_r (mb)	R
Expt.(a)	—	—	1036 ± 19	1.73 ± 0.33
Calculations:				
0.5	0.682	0.03052	1010	2.74
0.8	0.651	0.04883	1023	2.19
0.9	0.643	0.05494	1019	1.98
1.0	0.633	0.06104	1021	1.74
1.5	0.580	0.09155	1023	1.12

(a)Reference 2



XBL 895-1671

$p(\text{perp})$ (MeV/c)

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