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TITLE: THE ^{11}Li NEUTRON HALO RADIUS FROM PION DOUBLE CHARGE EXCHANGE

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The ^{11}Li Neutron Halo Radius from Pion Double Charge Exchange

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Abstract

We have analyzed the pion double charge exchange data for the direct population of the ground state of ^{11}Li by the $^{11}B(\pi^-,\pi^+)^{11}Li$ reaction and find that the measured cross section determines the rms radius of the last two neutrons in ^{11}Li to be $5.1^{+0.6}_{-0.8}$ fm. It is shown that the pion cross-section falls off as the sixth power of the assumed neutron halo radius, so that a radius greater than about 6 fm is ruled out. Indeed, pion double charge is found to act as an unusually sensitive probe of the properties of this exotic neutron rich nucleus.

Recently, there have been a number of experiments strongly suggesting that the neutron-rich nucleus ^{11}Li exhibits a 'neutron halo', in which the radius of the last two neutrons is several fermi larger than the radius of the ^{9}Li core. The existence of the halo has been inferred from the anomalous total reaction cross-section on various light targets[1], which is usually interpreted as arising from an anomalously large matter radius for the system. Furthermore, very narrow momentum distributions of the outgoing ^{9}Li[2] and neutron[3] fragments in (^{11}Li,^{9}Li) dissociation experiments confirm the large neutron radius and support the idea that it is indeed the last two neutrons which are largely responsible for the halo. However,the necessary model dependence involved in extracting the size of the halo from these experiments leaves a large uncertainty as to its magnitude, and results for ^{11}Li range from an total neutron rms radius[1] of 3.21 ± 0.17 fm to a neutron halo with a radius[3]of 12 fm. In this paper I report on calculations of the DCX cross-section for the $^{11}B(\pi^-,\pi^+)$ reaction which show that the recent LAMPF data[4] can be used to make a very accurate determination of the radius of the neutron halo in ^{11}Li.

The DCX cross-section is determined by the wave functions of the exchanged neutrons and protons, and thus acts as a direct probe of the neutron halo. In particular, the cross-section for the $^{11}B(\pi^-,\pi^+)^{11}Li$ reaction will be significant (or measurable) only if the transition density, obtained from the overlap of the wave functions for the initial protons and final neutrons, is sizeable. There is a very large difference in the binding energies of the last two (exchanged) protons of ^{11}B and the exchanged neutrons of ^{11}Li, and the resulting difference in the shape of the radial wave functions in the two cases causes the DCX cross-section to be quite sensitive to size of the neutron halo.

At a pion energy of T_π=164 MeV, the DCX reaction is dominated by two sequential single charge exchanges. We have performed calculations of the DCX reaction using finite range distorted waves and a closure approximation for the intermediate states. The calculational technique has already been described elsewhere[5]. The nuclear structure input was expressed in term of shell model two-body density matrix elements derived from a p-shell calculation[6]. In a p-shell model $^{11}Li_{g.s.}$ is described as a single $p_{3/2}$ proton with the neutrons forming a closed shell. The magnetic moment is then just the Schmidt $p_{3/2}$ value, 3.79 μ_n, which is in reasonable agreement with the measured value of $3.667\mu_n$. The wave function for $^{11}B_{g.s.}$, obtained by diagonalizing the Cohen-Kurath (8-16)2BME effective interaction, reproduces the ground state magnetic and quadrupole moments reasonably well.

In calculating the DCX reaction the rms radius of the last two neutrons in ^{11}Li (R_{2n}) was varied in order to determine the value giving the best representation of the data[4]. This was done by adjusting the size of the Woods-Saxon well used to obtain the single particle wave functions, while keeping the binding energy of the ^{11}Li neutrons fixed at 200 keV. The rms radius of the two protons on which the reaction proceeds was held fixed at 2.65 fm, a value suggested by the difference in charge radius between ^{11}B and ^{9}Li. The ^{11}B protons were bound by 11 MeV.

As the volume in which the exchanged neutrons are to be found increases the cross section deceases since the reaction only has significant strength when the overlap of the wave function of the final neutrons with the initial protons is large. In the limit as the radius of the two final neutrons becomes very large, it is the initial wave function alone which controls the volume over which the reaction takes place. When this limiting situation is reached the shape of the transition density no longer changes and the cross section scales as the inverse volume squared or as $1/R^6_{2n}$. The results of the calculation are shown in Figure 1 for a range of rms radii covering those that have been suggested in the literature. We note that a radius of 12 fm, as suggested by Anne *et al.*[3], would imply a cross section 3 orders of magnitude smaller than that observed.

We estimated the uncertainty in the calculated cross sections from systematic studies of nuclear structure and DCX for nuclei in this mass region. The use of p-shell wave functions may be too restrictive, particularly in the case of the ^{11}Li nucleus where di-neutron clustering is important. The description of a di-neutron cluster state in a harmonic oscillator shell model basis would require a large multi-$\hbar\omega$ calculation. The inclusion of states of very high excitation is necessary in order to give a realistic description of the relative motion wave function. While the problem is mitigated by our use of Woods-Saxon single-particle wave functions, and by the fact that our p-shell neutrons are strongly correlated[7], additional correlations can be introduced by increasing the model basis to allow sd-shell or higher excitations, and these have been shown to give up to a factor of two in the DCX cross sections between isobaric analog states. In the present non analog transition these effects will be reduced by roughly $\sqrt{2}$ since two nucleon clustering is important only in the final (^{11}Li) wave function.

The second source of possible error lies in the calculation of the distortions of the pion. We can estimate the accuracy of the calculated distortions by comparing with the analog state transition in ^{14}C. Using wave functions obtained by diagonalizing the same Cohen-Kurath interaction we find that the data for the $^{14}C(\pi^+,\pi^-)^{14}O$ reaction are correctly reproduced around 20^0 but are over estimated by almost a factor of 2 at 5^0. Thus we assign a factor of $\sqrt{2}$ error from the distortion. The corrections from nuclear structure and pion dynamics have approximately equal but opposite effect, with the former increasing and the latter decreasing the calculated cross section. Combining the two we estimate that the the uncertainty in the calculated cross sections has a one standard deviation error of 40%. Allowing this uncertainty we conclude that the measured cross section determines the radius of the last two neutrons in ^{11}Li to be $5.1^{+0.6}_{-0.8}$ fm.

We now turn to a comparison of the present extracted radius with other determinations. Bertsch *et al.*[8] find a matter radius of ^{11}Li to be 2.846 fm and that of ^{9}Li to be 2.224 fm leading to an R_{2n} of 4.72 fm, a value consistent with the present result. From the neutron radii of Tanihata *et al.*[1] determined from interaction cross section measurements, assuming that the ^{9}Li core neutron radius remains fixed at 2.39 fm, we find R_{2n} to be 4.91 fm. The dissociation experiments tend to show a larger radius but they are not inconsistent with our result if we use a cluster model for the last two neutrons. Consider a di-neutron bound to the ^{9}Li core and assume that the two neutrons are produced at zero relative momentum in the dissociation process. We implemented this model by solving for the bound state wave function of a particle with a two-nucleon mass in a Woods-Saxon potential holding the binding energy fixed at 190 keV, and varying the size of the well to allow the choice of different rms radii for the di-neutron.

If we compare the recoil distribution measured by Kobayashi *et al.*[2] with the transverse momentum obtained from the di-neutron wave function described above the result is in basic agreement for either of the 5.4 or 6.2 fm cases shown in Figure 2a. Note that if the ^{9}Li were recoiling against two independent neutrons the width of the peak would be narrower by $1/\sqrt{2}$. We also show a comparison with the results of Anne *et al.* [3] in fig. 2b for the angular distribution of the neutrons arising from dissociation. Because of the di-neutron assumption used above, each neutron carries half of the momentum of the ^{9}Li so that there should be a factor of 2 between the widths of the distributions in Ref. 2 and 3, while if the neutrons were uncorrelated there would be a factor of $\sqrt{2}$. The agreement is marginally satisfactory, except for the first point. Hüfner and Nemes[9] point out that for a reliable extraction of a momentum distribution the energy/nucleon should exceed 500 MeV/u, a condition met in ref 2 but not in ref. 3.

In summary, an analysis of the DCX reaction on ^{11}B leading to the ground state of ^{11}Li shows that the measured cross section places a strong limit on the size of the neutron halo in ^{11}Li: $R_{2n} = 5.1^{+0.6}_{-0.8}$ fm. For sufficiently large neutron radii the calculated cross section falls off as $1/R^6_{2n}$, so that an rms radius for the last two neutrons greater than about 6 fm is ruled out. We emphasize that this is not a model dependent statement, but can be understood in terms of geometric arguments alone. The extracted radius is in agreement with results from the interaction cross section measurements[1], and with Hartree-Fock calculations[8] which explicitly take account of the loose binding of the last neutrons. Agreement with the dissociation experiment of Ref. 2 (and to a lesser extent of ref. 3) is achieved if and only if we assume that the last two neutrons behave as a di-neutron cluster.

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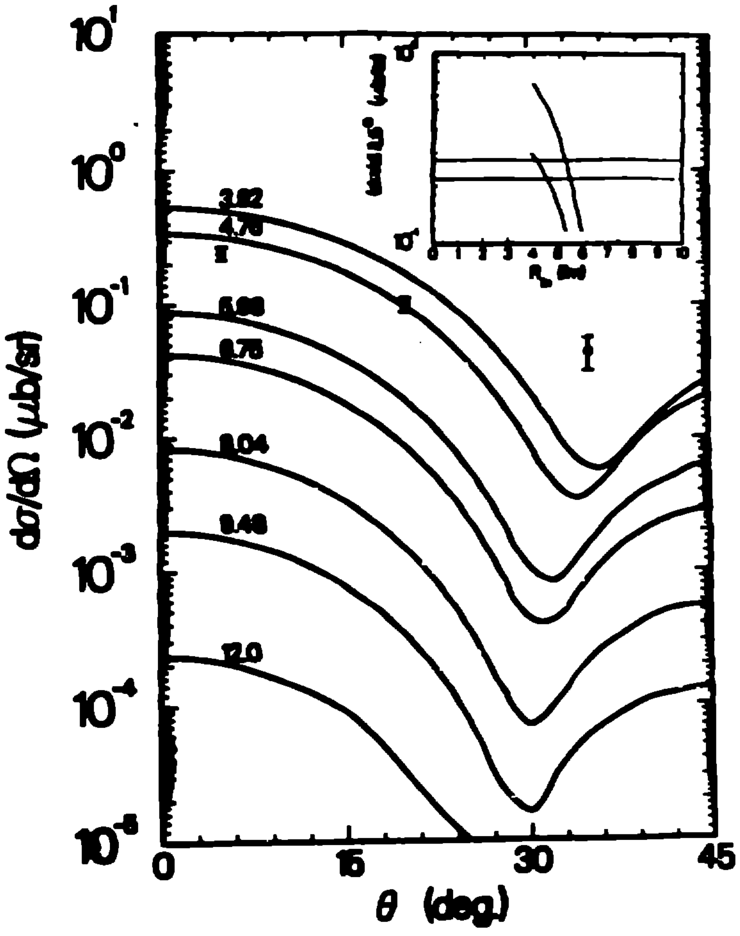

Figure 1. The angular distribution of the cross section for the DCX reaction for several values of R_{2n}. The insert shows the comparison of the 5° cross section (band defined by the dotted horizontal lines) with the theoretical calculation (band defined by the solid lines).

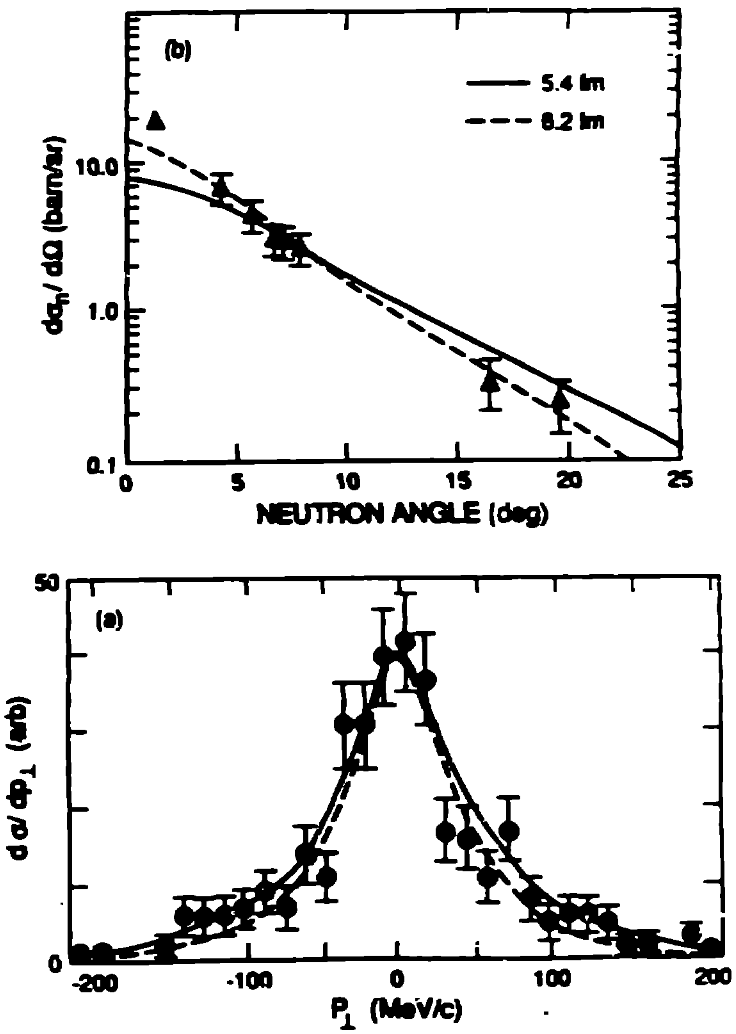

Figure 2. Comparison of the model described in the text with the data of Ref. 2(a) and Ref. 3(b).