PHYSICAL REVIEW C VOLUME 47, NUMBER 5 MAY 1993

Effect of isospin on three nucleon pion absorption in light nuclei

Arthur Mateos and Neven Šimičević
Department of Physics and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 30 November 1992)

In this paper we present a model based solely on isospin for the determination of ratios of pion absorption cross sections on three nucleons. We then compare the results with the available experimental data for pion absorption on ^{3}He and ^{4}He, at the energies 120 and 165 MeV, and for ^{6}Li and ^{7}Li at 50, 100, 140, and 180 MeV. Good agreement was found between this simple model and experiment, suggesting that pion absorption on three nucleons in light nuclei may be described as a one-step process.

PACS number(s): 25.80.Ls

It is widely known that absorption on two nucleons is an important mechanism for pion absorption in nuclei. There is also evidence that absorption processes in which more than two nucleons take part are also of importance [1, 2]. Investigation of the absorption mechanism when more than two nucleons participate has been difficult because the data generally lack either kinematic completeness or large phase space acceptance [3]. Consequently, the contributions of various absorption mechanisms to the total absorption cross section is still uncertain.

To be specific about the issues involved in the process of $3N$ absorption, we will define a three nucleon event as one in which three nucleons participate substantially in sharing the momentum and energy of the absorbed pion. The following two descriptions represent limiting cases in describing three nucleon absorption.

(i) Pion absorption occurs in at least two steps. The pion is absorbed on two nucleons, and an additional nucleon is involved either through a pion-nucleon interaction prior to absorption, an initial state interaction (ISI), or through a nucleon-nucleon interaction after pion absorption, a final state interaction (FSI).

(ii) A pion is absorbed directly on three nucleons in a "genuine" one-step process.

There is no clear quantum mechanical distinction between the cases described above. In particular, the kinematic signatures of ISI and FSI are expected to be washed out when the steps occur within a short distance. Nevertheless, specific signatures of FSI and ISI have been looked for. In heavy nuclei there is evidence that FSI is important in absorption, and data have been corrected for this effect. In light nuclei, the importance of ISI and FSI is much less clear. It should be noted that in our discussion we are excluding FSI of the Migdal-Watson [4, 5] type. This effect is non-negligible and is clearly visible in many reactions with nucleons in the final state [2].

The most recent kinematically complete experimental results on three nucleon absorption in ^{3}He and ^{4}He agree on the following [3, 6–11].

(a) The contribution of $3N$ absorption processes to the total absorption cross section is significant, on the order of about 30 percent.

(b) There is no clear evidence that ISI or hard FSI are important in pion absorption on these nuclei.

Instead of looking at three nucleon absorption as a two nucleon absorption with initial or final state interactions, we will examine the consequences of three nucleon absorption as a one step process. Using isospin formalism one may be able to gain some understanding of three nucleon absorption without knowing the details of the reaction mechanism.

It is known that pion absorption on a nucleon pair depends strongly on the isospin of the pair [7, 8, 12]. The cross section for the absorption on the isovector $T = 1$ pair is an order of magnitude smaller than the absorption on an isoscalar $T = 0$ pair. For pion absorption on three nucleons in ^{3}He and in ^{4}He the cross sections for different isospin states are presented in Table I. For three nucleon pion absorption on ^{3}He the cross section shows very little or no dependence on the final isospin. For pion absorption on ^{4}He the cross section does not depend on the spectator isospin in the case of a deuteron in the final state, but there is apparently dependence in the case of free nucleons in the final state.

Ashery [13] proposed a mechanism, analogous to the two nucleon absorption mechanism, by which a pion can be absorbed on three nucleons. He used amplitudes F_T for absorption leading to a three nucleon final state with total isospin T. In his case, the cross section can be written in terms of the transition amplitude as follows:

$$\begin{aligned}\sigma(\pi^+\,{}^3\mathrm{He}\to ppp) &= \left\langle T_{\pi^+}=1, T^{(3)}_{\pi^+}=1; T_{^3\mathrm{He}}=\frac{1}{2}, T^{(3)}_{^3\mathrm{He}}=\frac{1}{2}\,\middle|\, T_{3\mathrm{p}}=\frac{3}{2}, T^{(3)}_{3\mathrm{p}}=\frac{3}{2}\right\rangle^2 |F_{3/2}|^2 \\ &= |F_{3/2}|^2, \end{aligned} \tag{1}$$

TABLE I. Experimental cross sections (mb) for pion absorption on three nucleons from kinematically complete experiments on ^{3}He and ^{4}He and their representations as a function of transition amplitudes leading to three nucleons with final isospin $\frac{1}{2}$ and $\frac{3}{2}$ [3, 10, 15].

Reaction	120 MeV	165 MeV	
$\pi^+\,{}^3\mathrm{He} \to ppp$	4.4±0.6	6.0±0.6	$\vert F_{3/2}\vert^2$
$\pi^-\,{}^3\mathrm{He} \to pnn$	4.0±0.6	5.0±0.6	$\frac{1}{3}\vert F_{3/2}\vert^2+\frac{2}{3}\vert F_{1/2}\vert^2$
$\pi^-\,{}^3\mathrm{He} \to dn$	0.8±0.2	Not measured	$\frac{2}{3}\vert F_{1/2}\vert^2$
$\pi^+\,{}^4\mathrm{He} \to (ppp)n$	2.1±0.4	4.8±1.0	$\frac{3}{4}\vert F_{3/2}\vert^2$
$\pi^+\,{}^4\mathrm{He} \to (ppn)p$	4.4±1.1	Not measured	$\frac{1}{4}\vert F_{3/2}\vert^2+\vert F_{1/2}\vert^2$
$\pi^+\,{}^4\mathrm{He} \to (dp)p$	1.49±0.22	Not measured	$\vert F_{1/2}\vert^2$
$\pi^-\,{}^4\mathrm{He} \to (nnn)p$	Not measured	Not measured	$\frac{3}{4}\vert F_{3/2}\vert^2$
$\pi^-\,{}^4\mathrm{He} \to (pnn)n$	Not measured	Not measured	$\frac{1}{4}\vert F_{3/2}\vert^2+\vert F_{1/2}\vert^2$
$\pi^-\,{}^4\mathrm{He} \to (dn)n$	1.51±0.26	Not measured	$\vert F_{1/2}\vert^2$

$$\begin{aligned}\sigma(\pi^-\,{}^3\mathrm{He}\to 2np) &= \left\langle 1,-1;\frac{1}{2},\frac{1}{2}\middle|\frac{3}{2},-\frac{1}{2}\right\rangle^2 |F_{3/2}|^2 + \left\langle 1,-1;\frac{1}{2},\frac{1}{2}\middle|\frac{1}{2},-\frac{1}{2}\right\rangle^2 |F_{1/2}|^2\\ &= \frac{1}{3}\,|F_{3/2}|^2+\frac{2}{3}\,|F_{1/2}|^2. \end{aligned} \tag{2}$$

In our model we reduce pion interaction with individual nucleons in the process of absorption to interaction with a group of nucleons defined by its total isospin. For example, the three nucleon absorption cross section on ^{4}He, when a proton is a spectator in the absorption, may be represented as a transition from the initial $\pi^+\,{}^4$He isospin state $|1,1;0,0\rangle$ into the two possible final $(ppn)p$ isospin states $|\frac{3}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\rangle$ and $|\frac{1}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\rangle$:

$$\sigma(\pi^+\,{}^4\mathrm{He}\to(ppn)p) = \left|\left\langle 1,1;0,0\middle|F\middle|\frac{3}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\right\rangle\right|^2 + \left|\left\langle 1,1;0,0,\middle|F\middle|\frac{1}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\right\rangle\right|^2. \tag{3}$$

By introducing a complete set of states, and making use of the fact the the proton is a spectator one can reduce the transition elements into the same amplitudes as for the three-nucleon absorption in ^{3}He multiplied by the Clebsch-Gordan coefficients corresponding to the different isospin couplings. The cross section then becomes

$$\begin{aligned}\sigma(\pi^+\,{}^4\mathrm{He}\to(ppn)p) = \;& \left|\left\langle 1,1;0,0\middle|\frac{3}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\right\rangle\left\langle\frac{3}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\middle|F\middle|\frac{3}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\right\rangle\right|^2\\ &+\left|\left\langle 1,1;0,0\middle|\frac{1}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\right\rangle\left\langle\frac{1}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\middle|F\middle|\frac{1}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\right\rangle\right|^2\\ =&\left\langle 1,1;0,0\middle|\frac{3}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\right\rangle^2\left\langle\frac{1}{2},\frac{1}{2}\middle|\frac{1}{2},\frac{1}{2}\right\rangle^2\left|\left\langle\frac{3}{2},\frac{1}{2}\middle|F\middle|\frac{3}{2},\frac{1}{2}\right\rangle\right|^2\\ &+\left\langle 1,1;0,0\middle|\frac{1}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\right\rangle^2\left\langle\frac{1}{2},\frac{1}{2}\middle|\frac{1}{2},\frac{1}{2}\right\rangle^2\left|\left\langle\frac{1}{2},\frac{1}{2}\middle|F\middle|\frac{1}{2},\frac{1}{2}\right\rangle\right|^2\\ =&\frac{1}{4}\,|F_{3/2}|^2+|F_{1/2}|^2.\end{aligned} \tag{4}$$

In the same way calculations may be performed for different nucleon configurations in the initial and final states in ^{3}He and ^{4}He. The results are summarized in Table I.

Experiments have shown that the cross sections for $3N$ absorption of π^+ and π^- on ^{3}He are approximately equal (Table I). This leads one to conclude [from Eqs. (1) and (2)] that $|F_{3/2}|^2$ and $|F_{1/2}|^2$ have roughly the same value. For the reactions $\pi^+\,{}^4\mathrm{He} \to (ppp)n$ and $\pi^+\,{}^4$He $\to (ppn)p$, one would expect the wave functions of the final states to differ only in their isospin. Assuming the equality of the amplitudes $|F_{3/2}|^2$ and $|F_{1/2}|^2$, our model gives the cross section ratio

$$\frac{\sigma(\pi^+\,{}^4\mathrm{He}\to(ppp)n)}{\sigma(\pi^+\,{}^4\mathrm{He}\to(ppn)p)} = 0.6. \tag{5}$$

TABLE II. Comparison of model with experiment for ^{3}He and ^{4}He [3, 10, 15].

Ratio	Model	Experiment
$\frac{\sigma(\pi^+\,{}^4\mathrm{He}\to(dp)p)}{\sigma(\pi^-\,{}^4\mathrm{He}\to(dn)n)}$	$\frac{\lvert F_{1/2}\rvert^2}{\lvert F_{1/2}\rvert^2}=1.0$	120 MeV $\Rightarrow 0.99\pm0.22$
$\frac{\sigma(\pi^+\,{}^4\mathrm{He}\to(ppp)n)}{\sigma(\pi^+\,{}^4\mathrm{He}\to(ppn)p)}$	$\frac{\frac{3}{4}\lvert F_{3/2}\rvert^2}{\frac{1}{4}\lvert F_{3/2}\rvert^2+\lvert F_{1/2}\rvert^2}=0.60$	120 MeV $\Rightarrow 0.48\pm0.15$
$\frac{\sigma(\pi^+\,{}^3\mathrm{He}\to ppp)}{\sigma(\pi^+\,{}^4\mathrm{He}\to(ppp)n)}$	$\frac{\lvert F_{3/2}\rvert^2}{\frac{3}{4}\lvert F_{1/2}\rvert^2}=1.33$	120 MeV $\Rightarrow 2.1\pm0.5$ 165 MeV $\Rightarrow 1.3\pm0.3$
$\frac{\sigma(\pi^-\,{}^3\mathrm{He}\to dn)}{\sigma(\pi^-\,{}^4\mathrm{He}\to(dn)n)}$	$\frac{\frac{2}{3}\lvert F_{1/2}\rvert^2}{\lvert F_{1/2}\rvert^2}=0.67$	120 MeV $\Rightarrow 0.5\pm0.2$

The experimental value for this ratio is 0.48 ± 0.15 [10]. To our knowledge there is no other existing explanation for the ratio between these competing $3N$ channels.

Assuming that the wave functions involved are not too dissimilar, the isospin predictions should remain valid for comparing the ratios of pion absorption reactions between similar channels in ^{3}He and ^{4}He. We find good agreement between our model predictions and existing experimental results (Table II).

As in the case for ^{3}He and ^{4}He, experiments on pion absorption on ^{6}Li have not shown evidence for initial and final state interactions [14]. Thus, one can perhaps apply the same isospin considerations to compute the $3N$ absorption cross sections as a function of amplitudes F_T for ^{6}Li and ^{7}Li. For example,

$$\begin{aligned}\sigma(\pi^+\,{}^6\mathrm{Li}\to(ppn)X) = & \left|\left\langle 1,1;0,0\left|F\right|\frac{3}{2},\frac{1}{2};\frac{3}{2},\frac{1}{2}\right\rangle\right|^2+\left|\left\langle 1,1;0,0,\left|F\right|\frac{3}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\right\rangle\right|^2\\ & +\left|\left\langle 1,1;0,0\left|F\right|\frac{1}{2},\frac{1}{2};\frac{3}{2},\frac{1}{2}\right\rangle\right|^2+\left|\left\langle 1,1;0,0,\left|F\right|\frac{1}{2},\frac{1}{2};\frac{1}{2},\frac{1}{2}\right\rangle\right|^2\\ & =\frac{13}{20}\,|F_{3/2}|^2+\frac{5}{4}\,|F_{1/2}|^2. \end{aligned} \quad (6)$$

The expressions for the other three nucleon absorption channels in ^{6}Li and ^{7}Li are shown in Table III.

The contributions of the various three nucleon absorption channels in ^{6}Li and ^{7}Li are not as well known as in ^{3}He and ^{4}He. However, the data which are available for three nucleon absorption on these nuclei (Table IV) are consistent with our model. According to our model, the

TABLE III. Cross sections of ^{6}Li and ^{7}Li represented as a function of the transition amplitude leading to three nucleon with final isospin $\frac{1}{2}$ and $\frac{3}{2}$.

Reaction	Amplitude
$\pi^+\,{}^6\mathrm{Li}\to(ppp)X$	$\frac{21}{20}\lvert F_{3/2}\rvert^2$
$\pi^+\,{}^6\mathrm{Li}\to(ppn)X$	$\frac{13}{20}\lvert F_{3/2}\rvert^2+\frac{5}{4}\lvert F_{1/2}\rvert^2$
$\pi^+\,{}^6\mathrm{Li}\to(pd)X$	$\frac{5}{4}\lvert F_{1/2}\rvert^2$
$\pi^+\,{}^6\mathrm{Li}\to(nd)X$	$\frac{3}{4}\lvert F_{1/2}\rvert^2$
$\pi^+\,{}^6\mathrm{Li}\to(pnn)X$	$\frac{3}{10}\lvert F_{3/2}\rvert^2+\frac{3}{4}\lvert F_{1/2}\rvert^2$
$\pi^+\,{}^7\mathrm{Li}\to(ppp)X$	$\frac{2}{3}\lvert F_{3/2}\rvert^2$
$\pi^+\,{}^7\mathrm{Li}\to(ppn)X$	$\frac{7}{9}\lvert F_{3/2}\rvert^2+\frac{56}{45}\lvert F_{1/2}\rvert^2$
$\pi^+\,{}^7\mathrm{Li}\to(pd)X$	$\frac{56}{45}\lvert F_{1/2}\rvert^2$
$\pi^+\,{}^7\mathrm{Li}\to(nd)X$	$\frac{34}{45}\lvert F_{1/2}\rvert^2$
$\pi^+\,{}^7\mathrm{Li}\to(pnn)X$	$\frac{22}{45}\lvert F_{3/2}\rvert^2+\frac{34}{45}\lvert F_{1/2}\rvert^2$

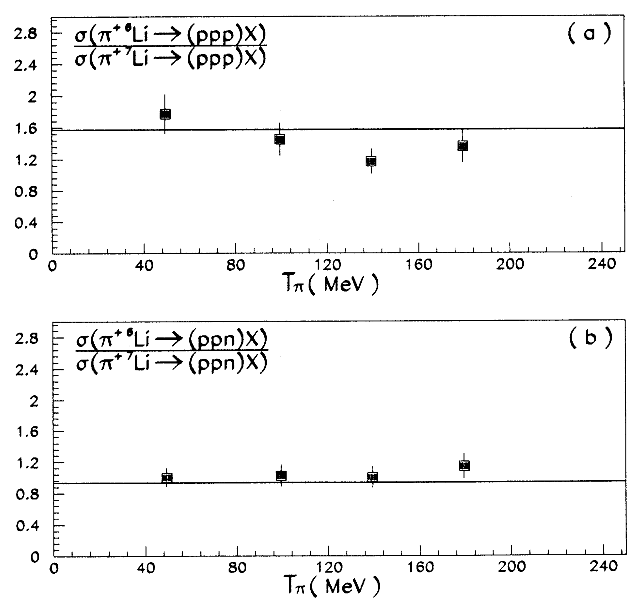

FIG. 1. Comparison of model with experiment for ^{6}Li and ^{7}Li: (a) for three protons in the final state and (b) for two protons and a neutron in the final state.

TABLE IV. Experimental cross sections for pion absorption on three nucleons in ^{6}Li and ^{7}Li (mb) with errors of 10%. The cross sections with a neutron in the final state are uncorrected for neutron detection efficiency [16].

Reaction	50 MeV	100 MeV	140 MeV	180 MeV
$\pi^+\,{}^6\mathrm{Li} \to (ppp)X$	0.23	1.0	2.1	3.4
$\pi^+\,{}^6\mathrm{Li} \to (ppn)X$	0.11	0.58	1.4	2.4
$\pi^+\,{}^7\mathrm{Li} \to (ppp)X$	0.13	0.69	1.8	2.5
$\pi^+\,{}^7\mathrm{Li} \to (ppn)X$	0.11	0.57	1.4	2.1

ratios of three nucleon absorption cross sections for the same channels on ^{6}Li and ^{7}Li should be as follows:

$$\frac{\sigma(\pi^+\,{}^6\mathrm{Li} \to (ppp)X)}{\sigma(\pi^+\,{}^7\mathrm{Li} \to (ppp)X)} = \frac{\frac{21}{20}|F_{3/2}|^2}{\frac{2}{3}|F_{3/2}|^2} = 1.58, \quad (7)$$

$$\frac{\sigma(\pi^+\,{}^6\mathrm{Li} \to (ppn)X)}{\sigma(\pi^+\,{}^7\mathrm{Li} \to (ppn)X)} = \frac{\frac{13}{20}|F_{3/2}|^2 + \frac{5}{4}|F_{1/2}|^2}{\frac{7}{9}|F_{3/2}|^2 + \frac{56}{45}|F_{1/2}|^2} = 0.94. \quad (8)$$

The agreement of the model with experimental results is shown in Fig. 1(a) for absorption leading to three protons in the final state and in Fig. 1(b) for two protons and one neutron in the final state. A direct comparison of the (ppp) and (ppn) channels of absorption on ^{6}Li or ^{7}Li cannot be performed at this point because the neutron detection efficiency is only roughly estimated in the reported experimental results [16]. If however one uses the estimated neutron efficiency of 25 percent, one finds reasonable agreement between the model and experiment.

Experiments have shown that the $3N$ contribution to the total absorption cross section is significant. In this paper, we looked for evidence that $3N$ absorption occurs as a coherent one-step process. Since the details of such an interaction are unknown, we assumed that the coupling of the isospin of the group of nucleons on which the absorption occurred with the isospin of the initial pion-nucleus system is the determining quantity in the absorption process. For the existing experimental results in the Δ-resonance region, our model shows remarkably good agreement. We therefore conclude that one-step coherent $3N$ absorption processes dominate over processes involving $2N$ absorption with final or initial state interactions.

We would like to thank R. Redwine, Q. Ingram, D. Rowntree, and K. Wilson for useful discussion. This work was supported in part by funds provided by the U. S. Department of Energy (DOE) under Contract No. DE-AC02-76ER03069.

[1] D. Ashery and J.P. Schiffer, Annu. Rev. Nucl. Part. Sci. **36**, 207 (1986).
[2] H.J. Weyer, Phys. Rep. **195**, 295 (1990).
[3] P. Weber, G. Backenstoss, M. Izycki, R.J. Powers, P. Salvisberg, M. Steinacher, H.J. Weyer, S. Cierjacks, A. Hoffart, B. Rzehorz, H. Ullrich, D. Bosnar, M. Furić, T. Petković, and N. Šimičević, Nucl. Phys. **A534**, 541 (1991).
[4] K.M. Watson, Phys. Rev. **88**, 1163 (1952).
[5] A.B. Migdal, Zh. Eksp. Teor. Fiz. **28**, 3 (1955) [Sov. Phys. JETP **1**, 2 (1955)].
[6] G. Backenstoss, M. Izycki, R. Powers, P. Salvisberg, M. Steinacher, P. Weber, H.J. Weyer, A. Hoffart, B. Rzehorz, H. Ullrich, D. Bosnar, M. Furić, and T. Petković, Phys. Lett. B **222**, 7 (1989).
[7] K.A. Aniol, A. Altman, R.R. Johnson, H.W. Roser, R. Tacik, U. Wienands, D. Ashery, J. Alster, M.A. Moinester, E. Piasetzky, D.R. Gill, and J. Vincent, Phys. Rev. C **33**, 1714 (1986).
[8] L.C. Smith, R.C. Minehart, D. Ashery, E. Piasetsky, M. Moinester, I. Navon, D.F. Geesaman, J.P. Schiffer, G. Stephens, B. Zeidman, S. Levinson, S. Mukhopadhyay, R.E. Segel, B. Anderson, R. Madey, J. Watson, and R.R. Whitney, Phys. Rev. C **40**, 1347 (1989).
[9] P. Weber, J. McAlister, R. Olszewski, A. Feltham, M. Hanna, D. Humphrey, R.R. Johnson, G.J. Lolos, Y. Mardor, S. May-Tal, D. Ottewell, Z. Papandreou, M. Pavan, C. Ponting, F.M. Rozon, M. Sevior, G. Sheffer, G.R. Smith, V. Sossi, R. Tacik, and D. Vetterli, Phys. Lett. B **233**, 281 (1989).
[10] M. Steinacher, G. Backenstoss, M. Izycki, P. Salvisberg, P. Weber, H.J. Weyer, A. Hoffart, B. Rzehorz, H. Ullrich, M. Džemidžic, M. Furić, and T. Petković, Nucl. Phys. **A517**, 413 (1990).
[11] F. Adimi, H. Breuer, B.S. Flanders, M.A. Khandaker, M.G. Khayat, P.G. Roos, D. Zhang, Th.S. Bauer, J. Konijn, C.T.A.M. de Laat, G.S. Kyle, S. Mukhopadhyay, M. Wang, and R. Tacik, Phys. Rev. C **45**, 2589 (1992).
[12] P. Weber, G. Backenstoss, M. Izycki, R.J. Powers, P. Salvisberg, M. Steinacher, H.J. Weyer, S. Cierjacks, A. Hoffart, H. Ullrich, M. Furić, T. Petković, and N. Šimičević, Nucl. Phys. **A501**, 765 (1989).
[13] D. Ashery, Phys. Rev. C **36**, 460 (1987).
[14] R.D. Ransome, V.R. Cupps, S. Dawson, R.W. Fergerson, A. Green, C.L. Morris, J.A. McGill, J.R. Comfort, B.G. Ritchie, J. Tinsley, J.D. Zumbro, R.A. Loveman, P.C. Gugelot, D.L. Watson, and C. Fred Moore, Phys. Rev. Lett. **64**, 372 (1990).
[15] P. Weber, J. McAlister, R. Olszewski, A. Feltham, M. Hanna, R.R. Johnson, M. Pavan, C. Ponting, F.M. Rozon, M. Sevior, V. Sossi, D. Vetterli, D. Humphrey, G.J. Lolos, Z. Papandreou, R. Tacik, D. Ottewell, G. Sheffer, G.R. Smith, Y. Mardor, and S. May-Tal, Phys. Rev. C **43**, 1553 (1991).
[16] R.D. Ransome, C.L. Morris, M.K. Jones, B.G. Ritchie, D.L. Watson, J.A. McGill, K. Pujara, D.B. Clayton, I. Brown, P. Campbell, and C. Fred Moore, Phys. Rev. C **46**, 273 (1992).