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Comparison of inclusive inelastic scattering of π^+ and π^- from nuclei at 100 MeV

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Inclusive inelastic scattering spectra from C, Ca, Sn, and Pb were measured for 100-MeV pions at a number of angles. The observed ratios of the π^- and π^+ total inelastic cross sections for the different targets are explained in terms of a simple model which is based on the assumption that the scattered pion has interacted with only one nucleon. This model also accounts for the ratio between normal and charge-exchange scattering cross sections at 100 MeV.

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By comparing the quasielastic scattering of a projectile from a nucleus with its scattering from a free nucleon one can presumably learn about effects that stem from a nucleon's immersion in nuclear matter. Such effects arise from the momentum distribution of the nucleons in nuclei, from Pauli blocking, from the coupling of struck nucleons to their immediate neighbors, and possibly from modifications of the projectile-nucleon interaction in nuclear matter. Among the strongly interacting particles, pions of about 100 MeV are a particularly suitable projectile for studies of such medium effects because they cannot be confused with ejected nuclear constituents and because they generally scatter only once before they escape. Multiple scatterings are relatively improbable at this energy since the pion-nucleon scattering is mostly backwards. Backward scattering gives rise to large pion energy loss, and at 100 MeV, where the pion-nucleon cross section is decreasing rapidly with decreasing pion energy, the quasielastically scattered pions have a substantially longer mean free path in nuclei than the incident pions.

An additional advantage of pions for quasielastic studies is that both π^+ and π^- beams are readily available and one can observe π^+, π^-, and π^0 in the exit channel. This makes it possible to distinguish effects which depend on electric charge and isospin from other effects. However there have been relatively few studies of inclusive π^- scattering compared with the number of π^+ experiments [1–3], and the π^- studies which have been reported [4, 5] do not give consistent results. We have therefore compared the inclusive scattering of π^+ and π^- directly by using a magnetic spectrometer to study the full scattering spectra and angular distributions using a set of targets which span the Periodic Table.

I. EXPERIMENTAL DETAILS

We measured the double differential cross sections $d^2\sigma/d\Omega dE$ for 100-MeV π^+ and π^- inelastically scattering from natural C, Ca, Sn, and Pb with thicknesses of 0.51, 1.01, 0.79, and 1.22 g/cm^2, respectively. The measurements were made at angles of 50°, 75°, 100°, 120°, and 140°. Although it was not possible to obtain data for each combination of projectile charge, target, and angle in this list, enough information was obtained to make the general patterns clear. The measurements were made using the clamshell spectrometer [6] on the LEP channel at LAMPF. The overall observable energy range for scattered pions extended from 20 MeV to slightly beyond the incident pion energy. This broad range was achieved by running the spectrometer at three contiguous momentum ranges with ample overlap at their boundaries. Relative efficiencies as a function of position in the focal plane were determined by scattering pions from hydrogen in a CH_2 target. This target was also used, for both π^+ and π^-, to normalize the beam flux monitors: an ionization chamber in the pion beam and a toroid around the primary proton beam. Pions were distinguished from muons and electrons by measuring the flight time through the spectrometer and by pulse-height measurements in a pair of scintillators in the focal-plane array. Electrons were easily eliminated by either technique at all angles. The muon contamination was reduced to negligible levels at all angles but 50° where it may have remained as high as 10%.

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II. RESULTS

Figure 1 shows the measured double differential cross sections for C, Ca, Sn, and Pb at a common angle, 100°. It is easy to understand some of the more apparent features of these spectra, at least qualitatively. For example, the broad width of the spectra stems from the fact that the nucleons in the target nuclei have momenta comparable with that of the incident pions. The π^- and π^+ spectra are found to be nearly identical in Ca and especially in C, reflecting the effect of charge symmetry. For the heavier targets where N is no longer equal to Z and where Coulomb effects begin to play a role, the ratio of the π^- and π^+ cross sections is found to increase rapidly with mass number. These ratios will be discussed in detail in the next section. One also sees from Fig. 1 that π^- spectra become significantly softer than those for π^+ as the target mass number increases. This relative displacement of the spectra arises mainly from the fact that, inside the nucleus, the kinetic energies of incident 100-MeV negative pions are at least two Coulomb-barrier heights higher ($\sim$ 40% higher for Pb) than those of incident positive pions. The π^- therefore lose proportionally more energy in a quasielastic collision.

To obtain a value for the energy-integrated inelastic cross section at each angle, it was necessary to extrapolate the measured spectra to pion energies below our 20-MeV threshold. We used linear extrapolations, with π^- spectra going to zero at $T_\pi = 0$ and π^+ spectra going to zero at the Coulomb-barrier height. The energy-integrated differential cross sections obtained with other reasonable extrapolation procedures did not differ from the simple linear extrapolations by more than 5–10%.

The energy-integrated cross sections so obtained are plotted as a function of angle for Ca and Pb in Fig. 2. The observed backward peaking of the cross sections is

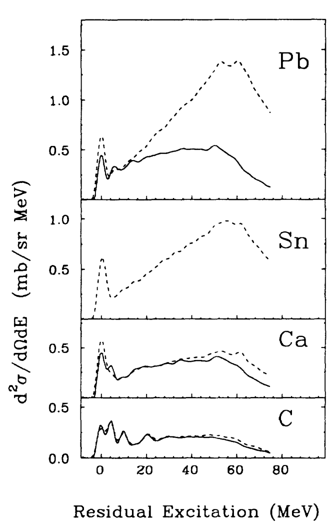

FIG. 1. Measured double differential cross sections for inclusive pion scattering from four nuclei at 100 MeV. The solid curves are for π^+, the dashed ones for π^-. They were made by smoothing the measured data over a 4 MeV interval. The statistical uncertainties of the ordinates for a 4 MeV interval are typically less than 3%.

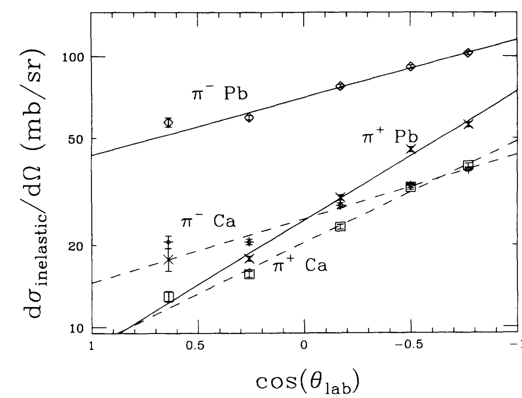

FIG. 2. Differential cross sections for the inclusive scattering of π^+ and π^- on Ca and Pb at 100 MeV. The points were obtained by integrating over outgoing pion energy of curves like those in Fig. 1. Least-square fits have been drawn in to show the differences in mean slopes of the angular distributions. The uncertainties shown result from statistical and systematic sources.

due to the short mean free path for pions of this energy in nuclear matter and to the backward peaking of the elementary pion-nucleon cross section. The backward peaking of this distribution also leads one to expect an increase in the π^-/π^+ ratio toward forward angles, especially in heavy nuclei, because the Coulomb field deflects negative pions forward, on their way in and out of the nucleus, while it deflects positive pions backward. An increase of this kind is clearly present in the data.

To obtain values for the total or angle-integrated inclusive inelastic scattering cross sections from data like those in Fig. 2, it is necessary to extrapolate the measured data to cover the full angular range. The total inclusive cross sections so determined for π^+ were found to agree with the earlier determinations of Aniol *et al.* [1] to better than 10% for C, Ca, and Pb. Since we did not, in this experiment, obtain π^+ data for Sn, the level of our agreement with Ref. [1] for the other three targets suggests that we can use their result for π^+ on Sn in our examination of the systematics of the total π^+ and π^- inclusive inelastic cross sections. Our measured cross sections along with those of Aniol *et al.* for π^+ on Sn are recorded in Table I. For later consideration, we also

TABLE I. Total inclusive inelastic cross sections for 100 MeV pions (mb). The typical uncertainty of these cross sections is 15%. The relative uncertainties of cross sections in any one row should be better than that.

	C	Ca	Sn	Pb
$\pi^+ \to \pi^{+'}$ [a]	152	291	359	388
$\pi^- \to \pi^{-'}$ [a]	173	334	652	915
$\pi^+ \to \pi^0$ [b]	49	84	196	251

[a]Results of the present experiment except for $\pi^+ \to \pi^{+'}$ on Sn which was taken from Ref. [1].

[b]These cross sections are interpolations of those measured by Bowles *et al.* [7], who quote a 15% uncertainty.

include the $\pi^+ \to \pi^0$ cross sections of Bowles *et al.* [7] at 100 MeV.

III. DISCUSSION OF THE INTEGRATED CROSS SECTIONS

It is generally accepted that pion inelastic scattering from nuclei is dominated by quasielastic scattering from individual nucleons. To probe this perception quantitatively, we compare the measured cross sections with the implications of a straightforward model in which the observed pions are attributed to a single scattering from a nucleon. In this model an incident pion joins a nucleon to make a short-lived complex, resembling a Δ, just as it might do with a free nucleon. In the nucleus, however, there is also a possibility for the absorption of the pion. We assume that before the pion-nucleon complex decays there is a chance that absorption can occur when an appropriate nucleon is nearby. True pion absorption is known to become increasingly likely at lower energies [8–11] and we consequently assume that those pions which do not escape from the nucleus following their first interaction with a nucleon will eventually be absorbed.

Instead of trying to compare model predictions of specific cross sections with individual measurements, we restrict our comparisons to particular *ratios* of cross sections. The comparisons then depend only on a few well-defined factors since other factors in the cross sections, both those in the model and those in the measurements, tend to cancel.

The model cross sections are taken to be a product of five factors, the first three having to do with the probability for the creation of a particular pion-nucleon complex, and the last two relating to the break-up of this complex and the escape of the pion. The factors are the following:

(1) An effective geometrical cross section of the target nucleus. At our energy, all but the smallest nuclei are black to pions and this effective cross section can be thought of as that for a plane wave of electrically neutral pions.

(2) The factor by which Coulomb refraction of the incoming pion modifies the effective cross section.

(3) The probability that when the pion finally interacts, it does so with the appropriate species of nucleon. For $\pi^+ \to \pi^0$ a neutron is required. For $\pi^+ \to \pi^{+'}$ we assume that a proton is required. Although $\pi^+ \to \pi^{+'}$ can also take place on neutrons, at our energy this cross section is small and strongly forward peaked. The scattered pions would therefore be strongly absorbed. Their contribution to our measurements is assumed to be negligible.

(4) The probability that the pion avoids absorption and emerges in the charge state of interest. We assume that initially the pion engages with a single nucleon and that this system either decays back into a nucleon plus a pion or that the pion is absorbed.

(5) Finally, the chance that the decay pion from the pion-nucleon complex manages to avoid further interactions on its way out of the nucleus. Any such interactions are assumed to lead to eventual absorption. In this connection, the incident energy, 100 MeV, was well chosen since it is on the steep low side of the (3,3) resonance and scattered pions consequently have substantially longer mean free paths than do the incident pions.

When we compare the magnitudes of different quasielastic cross sections using average values for these five factors, we are ignoring possible correlations between the factors. Rough estimates of possible correlation effects indicate that, at the level of precision of the present experiment, they remain negligible.

A. Comparing $\pi^+ \to \pi^{+'}$ with $\pi^+ \to \pi^0$

We begin our examination of cross-section ratios by comparing our $\pi^+ \to \pi^{+'}$ results with those of Bowles *et al.* [7] for $\pi^+ \to \pi^0$. The latter measurement was also done at 100 MeV. Although it did not involve the same set of targets that we used, the $\pi^+ \to \pi^0$ cross sections for our targets can be obtained by interpolating their results. Bowles *et al.* [7] found that $d\sigma/d\Omega$ for $\pi^+ \to \pi^0$ at a given angle varies smoothly with target mass and that the ratios of $d\sigma/d\Omega$, 120° to 40°, are independent of the target mass. This suggests that $d\sigma/d\Omega$ at any angle is proportional to the integrated $\pi^+ \to \pi^0$ cross section. The proportionality constant is available from their measurements of integrated cross sections for a few of their targets (beryllium, oxygen, and nickel). We were therefore able to estimate, from their differential cross-section curves, the $\pi^+ \to \pi^0$ total cross sections for our targets.

The factors 1 and 2 above are identical for all scatterings starting with a π^+ beam and therefore cancel in the cross-section ratios for $\pi^+ \to \pi^{+'}$ and $\pi^+ \to \pi^0$. We have estimated the escape probabilities (factor 5) for π^+ and π^0 averaged over the reaction sites for the initial interaction of the incident pion with a nucleon. The distribution of reaction sites is found by assuming that pions pass into the nucleus along straight line trajectories with a local attenuation length set by the local nucleon density and the pion-nucleon cross sections. The (angle-dependent) escape probability is obtained by assuming that the quasielastic pions are emitted from this distribution of sites and are attenuated at a rate depending on their energy as they pass out of the nucleus along straight paths in the direction of interest. We find that the average attenuations of π^+ and π^0 are within 5% of each other and therefore ignore factor 5 in estimating the ratio of $\pi^+ \to \pi^{+'}$ to $\pi^+ \to \pi^0$ cross sections. That leaves only factors 3 and 4 to consider.

Since we are assuming that the contribution of neutrons to $\pi^+ \to \pi^{+'}$ is negligible, we write factor 3 for this scattering on a target with Z protons and N neutrons in the form

$$\frac{\sigma_p Z}{\sigma_n N + \sigma_p Z} = \frac{1}{1 + (\frac{\sigma_n}{\sigma_p})\frac{N}{Z}} ,$$

where σ_p is the total scattering cross section for a 100-MeV π^+ by a free proton and σ_n is its scattering cross section, including charge exchange, on a free neutron. (We use for the latter the cross section of π^- on protons.)

Our expression reflects the assumption that neutrons and protons have similar spatial distributions in the nucleus.

For $\pi^+ \rightarrow \pi^0$, the π^+ must interact with a neutron, so the corresponding factor is obviously $\sigma_n N/(\sigma_n N + \sigma_p Z)$. It is seen that these factors depend on σ_n and σ_p only through their *ratio.* Even though there are a number of reasons for σ_n and σ_p to differ inside nuclei from their free nucleon value, the ratio of these cross sections should remain substantially unchanged from the free nucleon value, 0.38 [12].

For $\pi^+ \rightarrow \pi^{+'}$, we write factor 4 in the form $\Gamma_d/(\Gamma_d + \Gamma_a)$, where Γ_d is the width for the decay of the π-nucleon complex into a pion and a nucleon. We assume that absorption occurs predominantly on *n*-*p* pairs [8–11] and that Γ_a, the absorption width, is therefore proportional, for $\pi^+ \rightarrow \pi^{+'}$, to the local neutron density, N/A. Factor 4 is then $(1 + \gamma N/A)^{-1}$ where γ is a constant which we take to be independent of the target nucleus. We choose a value of 2.0 for γ, to be in accord with available estimates of the total π^+ reaction cross sections at this energy. The reaction cross section deduced from our data is the measured scattering cross section divided by factors 3, 4, and 5. The average escape probability for the scattered pion, factor 5, was estimated from the geometry to vary from 0.85 in C to 0.73 in Pb for positive pions. The reaction cross sections which we estimate, using $\gamma = 2.0$, are found to be in reasonable accord with other estimates and measurements of these cross sections [1, 4, 13]. If we divide the reaction cross sections by the Coulomb refraction factor 2, we obtain effective geometrical cross sections, πR_{eff}^2. The values of R_{eff} so determined for our heaviest three targets can be approximated by $R_{\text{eff}} = 1.4A^{1/3} + 1$ fm. (As one might expect, carbon is small enough to be somewhat transparent to 100-MeV pions and its reaction cross section is smaller than this πR_{eff}^2.) The model predictions of the ratios are fortunately not very sensitive to values of γ over the range of reasonable values for this parameter. For example, for values of γ between 1 and 3, the implied reaction cross sections vary by a factor of 1.6, but the predicted $\pi^+ \rightarrow \pi^{+'}$ to $\pi^+ \rightarrow \pi^0$ cross-section ratio is changed by less than 10%.

For the $\pi^+ \rightarrow \pi^0$ reaction, the absorption factor 4 is modified in two ways from that for $\pi^+ \rightarrow \pi^{+'}$. Assuming again that absorption occurs overwhelmingly on *n*-*p* pairs, the average local neutron density N/A must be replaced by Z/A. (We assume that the value of γ is the same for both reactions.) The second modification of factor 4 is to multiply it, for $\pi^+ \rightarrow \pi^0$, by the branching factor f for decay to charge exchange rather than to a π^+ final state. The value of f at 100 MeV is approximately 0.76 [12].

In Table II we give the values for factors 3 and 4 and for their product for both $\pi^+ \rightarrow \pi^{+'}$ and $\pi^+ \rightarrow \pi^0$. According to our model the ratio of the product of factors 3 and 4 should give the ratio of the observed inclusive scattering cross sections. In this model, there is only one parameter, γ, which is not obtained from free π-nucleon scattering. It should be emphasized that the predicted ratio is rather insensitive to the value of γ. The predicted cross-section ratios are seen to match the measured ones to within about 15% with no obvious trends in the disagreement as a function of mass number. Considering the uncertainties in the raw data, this must be viewed as encouraging support for a model which attributes all of the observed scattering to single encounters with individual nucleons.

It is seen from Table II that factor 3 is much more influential than factor 4 for the dependence of the $\pi^+ \rightarrow \pi^0$ cross section on mass number A. Its relative importance is naturally even greater for double charge exchange. Indeed, Gram *et al.* [14] have given a good account of inclusive double charge-exchange cross sections at 180 and 240 MeV in terms of factor 3 alone. At their higher energies, the Coulomb refraction factor 2 is less important than it is at our energies and acts in a direction to cancel the relatively small effects of the pion absorption factor 4.

TABLE II. Ratios of total inelastic cross sections $\pi^+ \rightarrow \pi^{+'}$ to $\pi^+ \rightarrow \pi^0$.

Factor	C	Ca	Sn	Pb
	$\pi^+ \rightarrow \pi^{+'}$			
3 · Partner choice	0.72	0.72	0.66	0.63
4 · Decay branch	0.50	0.50	0.46	0.45
Product (3 × 4)	0.36	0.36	0.31	0.29
	$\pi^+ \rightarrow \pi^0$			
3 · Partner choice	0.28	0.28	0.34	0.37
4 · Decay branch	0.38	0.38	0.41	0.42
Product (3 × 4)	0.106	0.106	0.140	0.16
Ratio of product factors $(\pi^+ \rightarrow \pi^{+'})/(\pi^+ \rightarrow \pi^0)$	3.4	3.4	2.2	1.8
Ratio of measured cross sections[a] $(\pi^+ \rightarrow \pi^{+'})/(\pi^+ \rightarrow \pi^0)$	3.1	3.5	1.8	1.5

[a]For both experiments, normalizations are based on π^+-proton phase shifts and separately have 15% uncertainties. These normalization uncertainties probably cancel to a large extent when ratios are taken.

TABLE III. Ratios of total inelastic cross sections $\pi^- \to \pi^{-'}$ to $\pi^+ \to \pi^{+'}$.

Factor	C	Ca	Sn	Pb
	$\pi^- \to \pi^{-'}$			
2 · Coulomb refraction	1.04	1.09	1.15	1.20
3 · Partner choice	0.72	0.72	0.78	0.80
4 · Decay branch	0.50	0.50	0.54	0.56
Product (2 × 3 × 4)	0.37	0.39	0.49	0.53
	$\pi^+ \to \pi^{+'}$			
2 · Coulomb refraction	0.96	0.91	0.85	0.80
3 · Partner choice	0.72	0.72	0.66	0.63
4 · Decay branch	0.50	0.50	0.46	0.45
Product (2 × 3 × 4)	0.35	0.33	0.26	0.23
Ratio of product factors $(\pi^- \to \pi^{-'})/(\pi^+ \to \pi^{+'})$	1.08	1.20	1.87	2.34
Ratio of measured cross sections[a] $(\pi^- \to \pi^{-'})/(\pi^+ \to \pi^{+'})$	1.14	1.15	1.82	2.36

[a] Aside from normalization uncertainties, these ratios have uncertainties of 7%.

B. Comparing $\pi^- \to \pi^{-'}$ with $\pi^+ \to \pi^{+'}$

The ratios of these two inelastic cross sections depend on the Coulomb refraction factors 2, as well as on factors 3 and 4. Like the ratio in Sec. III A, the ratio between π^+ and π^- inelastic scattering is also rather insensitive to the ratios of factor 5, the escape factor for the two reactions. We also assume that factor 1 has the same value for π^+ and π^-. (This assumption ignores the fact that nuclei are slightly blacker at their diffuse edges to π^- than to π^+, especially for heavier nuclei, since incident π^- kinetic energies are shifted upward toward the resonance peak by the nuclear Coulomb attraction, whereas the π^+ kinetic energies are shifted downward.) The ratio of observed $\pi^- \to \pi^{-'}$ to $\pi^+ \to \pi^{+'}$ inclusive cross sections should therefore be equal to the ratios of the products of model factors 2 × 3 × 4.

Factor 2 can be written $(1 - R\frac{B}{T})$, where T is the incident pion kinetic energy and B is the height of the Coulomb barrier. The factor R is the relativistic correction factor $(2E + B)/(E + m_0c^2)$, where E is the total energy of the incident pion and m_0c^2 is its rest energy. It is easily derived from the requirements of energy and angular momentum conservation. The values for factors 2, 3, and 4 for $\pi^+ \to \pi^{+'}$ and $\pi^- \to \pi^{-'}$ as well as the value of their product is given in Table III. We also give the ratios of the three product factors for π^- to π^+ inelastic scattering since these ratios are expected to reproduce the ratios of the π^- to π^+ measured cross sections of Table I. These measured ratios appear in the last row of Table III. Once again, the model predictions are seen to match the measurements to well within the measurement uncertainties.

We call attention to the rather large ratio between the total inelastic scattering cross sections for π^- to π^+ on heavy targets. This asymmetry for + and − pions is due to sizable contributions from each of the factors 2, 3, and 4. An excess of the π^- over the π^+ cross section comparable to the one we observe in Pb (~ 140%) was reported earlier by McKeown *et al.* [5] The rather smaller excess (~ 20%) reported by Navon *et al.* [4, 15] in the same energy range probably arises from the high threshold of their pion detectors and the difference between the shapes of the π^+ and π^- energy spectra (Fig. 1).

In summary, we have seen that a very simple version of a single-collision model for pion interactions in nuclei at 100 MeV gives a creditable account of the observed ratios of total inelastic scatterings. The success of the elementary model speaks for the assumed dominance of single quasielastic collisions in these scatterings and encourages a more detailed description of the pion-nucleon collisions in nuclear matter. One would now like to see how well a single-collision model which specifically includes the effects of nucleon motion in the nucleus, Pauli blocking, refraction, etc., would account for those features of the spectra and angular distributions which were described only qualitatively earlier in this paper. We have been applying such a model to the more differential aspects of the pion scatterings and expect to publish some of these results in the near future.

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[1] K. A. Aniol, D. T. Chiang, K. G. R. Doss, I. Halpern, M. A. Khandaker, D. W. Storm, D. R. Tieger, P. D. Barnes, B. Bassalleck, N. J. Colella, S. A. Dytman, R. A. Eisenstein, R. Grace, C. Maher, D. Marlow, P. Pile, R. Rieder, F. Takeutchi, W. R. Wharton, J. F. Amann, and J. Julien, Phys. Rev. C **33**, 208 (1986).

[2] S. M. Levenson, D. F. Geesaman, E. P. Colton, R. J. Holt, H. E. Jackson, J. P. Schiffer, J. R. Specht, K. E. Stephenson, B. Zeidman, R. E. Segel, P. A. M. Gram, and C. A. Goulding, Phys. Rev. C **28**, 326 (1983).

[3] C. H. Q. Ingram, P. A. M. Gram, J. Jansen, R. E. Mischke, J. Zichy, J. Bolder, E. T. Boschitz, G. Pröbstle, and J. Arvieux, Phys. Rev. C **27**, 1578 (1983).

[4] D. Ashery, I. Navon, G. Azuelos, H. K. Walter, H. J. Pfeiffer, and F. W. Schlepütz, Phys. Rev. C **23**, 2173 (1981).

[5] R. D. McKeown, S. J. Sanders, J. P. Schiffer, H. E. Jackson, M. Paul, J. R. Specht, E. J. Stephenson, R. P. Redwine, and R. E. Segel, Phys. Rev. C **24**, 211 (1981).

[6] J. H. Mitchell, J. T. Brack, R. J. Peterson, R. A. Ristenen, J. L. Ullmann, R. L. Boudrie, B. G. Ritchie, and J. Escalante, Phys. Rev. C **37**, 710 (1988); see also J. H. Mitchell, Ph.D. thesis, University of Colorado at Boulder, 1987.

[7] T. J. Bowles, D. F. Geesaman, R. J. Holt, H. E. Jackson, J. Julien, R. M. Laszewski, J. R. Specht, E. J. Stephenson, R. P. Redwine, L. L. Rutledge, Jr., R. E. Segel, and M. A. Yates, Phys. Rev. C **23**, 439 (1981).

[8] D. Ashery and J. P. Schiffer, Annu. Rev. Nucl. Part. Sci. **36**, 207 (1986).

[9] K. Stricker, H. McManus, and J. A. Carr, Phys. Rev. C **19**, 929 (1979).

[10] D. Mack, Nucl. Phys. **A527**, 451c (1991).

[11] D. J. Mack, P. G. Roos, H. Breuer, N. S. Chant, S. D. Hyman, F. Khazaie, B. G. Ritchie, J. D. Silk, G. S. Kyle, P. A. Amaudruz, Th. S. Bauer, C. H. Q. Ingram, D. Renker, R. A. Schumacher, U. Sennhauser, and W. J. Burger, Phys. Rev. C **45**, 1767 (1992).

[12] Estimated at 100 MeV from phase shifts from G. Rowe, M. Salomon, and R. H. Landau, Phys. Rev. C **18**, 584 (1978).

[13] E. J. Moniz, Nucl. Phys. **A354**, 535c (1981); J. R. Carter, D. V. Bugg, and A. A. Carter, Nucl. Phys. **B58**, 378 (1973).

[14] P. A. M. Gram, S. A. Wood, E. R. Kinney, S. Hølbråten, P. Mansky, J. L. Matthews, T. Soos, G. A. Rebka, Jr., and D. A. Roberts, Phys. Rev. Lett. **62**, 1837 (1989).

[15] I. Navon, D. Ashery, G. Azuelos, H. J. Pfeiffer, H. K. Walter, and F. W. Schlepütz, Phys. Rev. Lett. **42**, 1465 (1979).