Pion-Helium Scattering above the (3,3) Resonance

J. Källne, J. F. Davis, J. S. McCarthy, R. C. Minehart, and R. R. Whitney
University of Virginia, Charlottesville, Virginia 22901

and

R. L. Boudrie
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

and

J. McClelland
University of California, Los Angeles, California 90024

and

A. Stetz
Oregon State University, Corvallis, Oregon 97331

(Received 8 May 1980)

Differential cross sections are reported for $\pi^+ + {}^{3,4}$He elastic scattering at 260, 295, and 310 MeV and $\pi^- + {}^{3,4}$He at 295 MeV. The angular distributions (except for $\pi^- + {}^3$He) confirm the fixed angle ($\theta \approx 75°$) minimum seen at lower energies [caused by the (3,3) $\pi + N$ resonance dominance] and show a deep minimum at $\theta \approx 110°$. Comparisons are made to $\pi + d$ and the current discussion of pion excitation of intermediate dibaryon and ΔN states.

PACS numbers: 25.80.+f, 25.10.+s

Pion scattering from the few-body nuclei ^{2}H and ^{3,4}He has provided the most stringent standard against which to judge our understanding of pion-nucleus processes. Characteristic features of measured angular distributions have been interpreted in terms of $\pi + N$ scattering and reaction amplitudes in different kinds of microscopic calculations. Systematic differences between π^+ and π^- scattering from ^{3}He at resonance energies have been ascribed to the importance of $\pi + N$ spin-flip amplitudes on the unpaired neutron.[1-3] Such amplitudes are suppressed for $\pi + {}^4$He scattering which makes it the best example of single partial-wave dominance, i.e., through the (3, 3) resonance; a characteristic feature of $\pi + {}^4$He is the fixed angle ($\theta \approx 75°$) minimum which is a reflection of the angular dependence of the elementary $\pi + N$ scattering.[1,4] Such features of the elementary $\pi + N$ interaction together with the nuclear form-factor dependence dominate the forward-angle scattering of both $\pi + d$ and $\pi +$ He. Large-angle scattering at energies above the resonance has just recently begun to be explored. This is the region of large momentum transfer, and hence a generally smaller cross section, so that measurements are harder and calculations more complex. The cases where theory has been confronted with data indicate that there are some significant pion-scattering effects that are not understood. A broad minimum observed[5] in $\pi + d$ scattering around $\theta = 100°$ has defied explanation in terms of otherwise successful theories[6] and stimulated the discussion of new effects in pion scattering.[7,8] Similarly, the cross section of large-angle single-charge-exchange (SCE) scattering on ^{3}He indicates little variation with energy between 200 and 300 MeV, contrary to theoretical predictions.[9] Here we report new and unpredicted features of π^+ and π^- elastic scattering on ^{3,4}He from measurements at 260, 295, and 310 MeV.

The experiment was done using the EPICS channel and spectrometer system of the Clinton P. Anderson Meson Physics Facility. Standard procedures were followed except for the use of a cryostat[10] for liquid-helium targets. It contained two cells ($15.2 \times 12.7 \times 2.5$ cm^3) for ^{3}He and ^{4}He which were kept at a temperature of 1.5° K. The target thickness over the beam spot size was measured with help of x-ray photographs from which the effective target densities were determined to better than ± 5%. The $\pi + {}^{3,4}$He elastic scattering cross sections were measured relative to known $\pi + p$ cross sections[11] giving an overall uncertainty of $\lesssim \pm 10\%$ in the absolute scale of the cross sections determined. The error given for each point includes the uncertainty due to counting statistics, background subtraction (contributions come from scattering in the 25-mg/

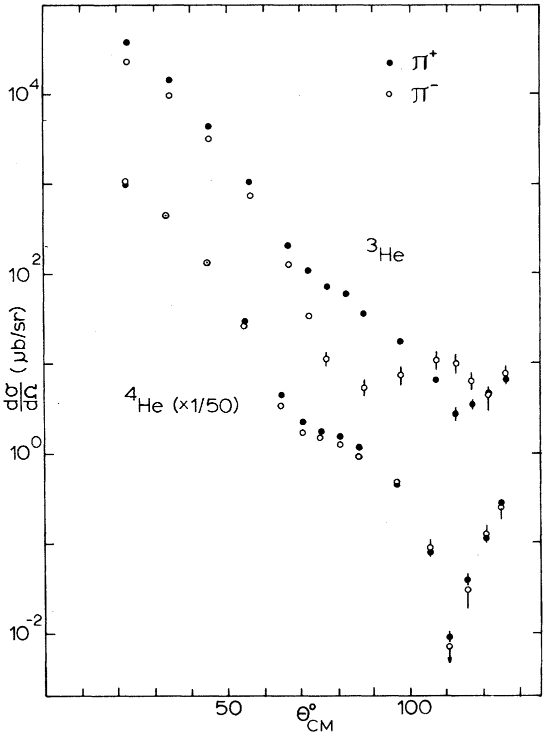

FIG. 1. Differential cross sections for π^+ and π^- (solid and open symbols) elastic scattering from ^{3}He and ^{4}He at $T_\pi = 295$ MeV.

cm^2 thick cell windows of aluminum), and the spectrometer acceptance correction.

Our results on elastic $\pi + {}^{3,4}$He scattering consist of angular distributions at 295 MeV (Fig. 1) and partial ones at 260 and 310 MeV. The forward-angle scattering shows a rapid and continous falloff with increasing angle and hence momentum transfer which is indicative of a strong nuclear form-factor dependence in this angular range. The $\pi^- + {}^3$He cross section is weaker than that of $\pi^+ + {}^3$He which is in line with an expected $T = \frac{3}{2}$ dominance in the $\pi + N$ scattering. A striking similarity is found for $\pi^+ + {}^3$He and $\pi^\pm + {}^4$He scattering which again can be understood from the $T = \frac{3}{2}$ dominance of the $\pi + N$ amplitudes and the documented similarity[10] of the ^{3}He and ^{4}He charge form factors. Apart from a 10% to 20% difference in the region $\theta = 65°$–$80°$, the π^+ and π^- data for ^{4}He overlap over the entire angular range observed ($\theta \approx 22°$–$125°$). The angular region $\theta > 70°$, however, shows features that signal effects beyond isospin-dependent $\pi + N$ amplitudes and nuclear structure.

The inflection point in our angular distributions at $\theta \approx 75°$ is reminiscent of the strong minimum seen at lower energies[1,4] but is rapidly being filled in between 260 and 295 MeV. It remains at fixed angle from as low energies as $T = 100$ MeV indicating that the signature of the (3, 3) resonance is still present at 300 MeV despite likely contributions from higher partial waves. Our data, however, indicate no minimum at 75° but one appears at 90° instead. Previous $\pi^\pm + {}^3$He data at $T_\pi < 160$ MeV show that a principal difference between $\pi^\pm$ scattering lies in the depth of the 75° minimum. It is partly filled in for π^- which is taken as evidence of principal spin-flip amplitudes in the $T = \frac{3}{2}$ channel[2,3] and hence dominant for π^- scattering on the unpaired neutron in ^{3}He. Such differences might be important also at higher energies but amplitude interference effects may change the simple picture of low-energy scattering dominated by incoherent contributions from isospin dependent spin-flip and non-spin-flip terms.

The most conspicuous feature of our results is the very deep minimum at $\theta = 110°$ in $\pi + {}^4$He scattering. It is observed at fixed angle for the energies studied ($T_\pi = 260$, 295, and 310 MeV) with a rapid increase in depth between 260 and 295 MeV. Although not so prominent, there is also a minimum in the $\pi^+ + {}^3$He angular distribution at a nearby angle ($\theta \approx 115°$). The $\pi^- + {}^3$He cross section does not show this feature which is also true for SCE scattering[9] ^{3}He(π^-, π^0)^{3}H; SCE is closely related to elastic scattering being the difference between π^+ and π^- elastic-scattering first-order amplitudes. It is likely that the minima in the $\pi^+ + {}^3$He and $\pi + {}^4$He are related but spin-flip amplitudes from scattering on the unpaired neutron fill in the minimum for $\pi^+ + {}^3$He. For $\pi^- + {}^3$He, the later effects would be even stronger, overwhelming the amplitudes primarily responsible for the minimum.

To display the significance of the observed second minimum in the $\pi +$ He angular distributions we reason as follows. We observe (Fig. 2) that it occurs in a region of large momentum transfer (q) where the charge form factors of ^{3}He and ^{4}He have the first minimum[10] ($q = 630$–670 MeV/c). If this were to show up in pion scattering it would be because of predominant single $\pi + N$ scattering. Therefore, this region of the $\pi +$ He cross section provides for a test of the leading terms of multiple $\pi + N$ scattering contribitions to pion-nucleus scattering. The fact that the $\pi +$ He minimum is observed at a nonfixed momentum transfer is indication against nuclear structure or diffractive origins of this phenomenon and that mul-

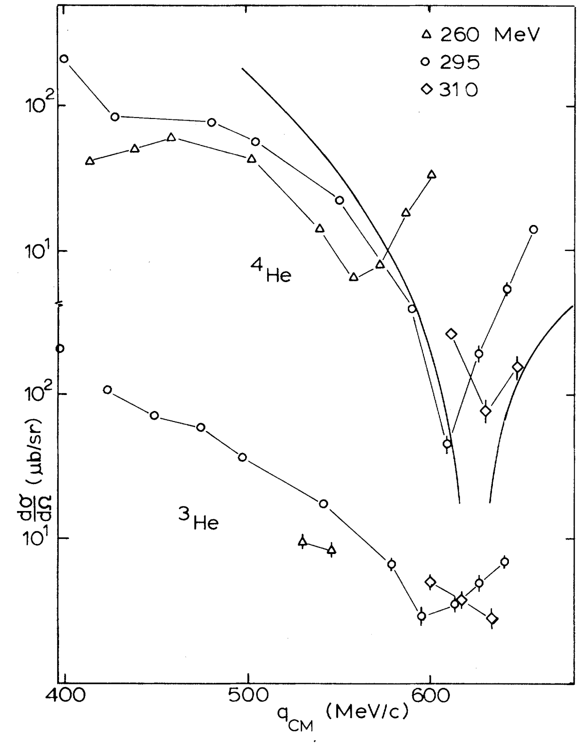

FIG. 2. Differential cross sections vs $q_{\mathrm{c.m.}} = 2p \sin(\theta/2)$ for π^+ elastic scattering from ^{4}He and ^{3}He at $T_\pi = 260$, 295, and 310 MeV. The ^{4}He data are compared with the square of the ^{4}He charge form factor (Ref. 10) normalized at $\theta = 22°$.

tiple scattering or other second-order effects dominate the cross section. This leads us to believe that what we observe is an interference minimum due to cancellation of such scattering amplitudes.

The $\pi + d$ scattering[5] shows a similar behavior in the same angular and energy range. The cross section around $\theta = 100°$ decreases rapidly between 230 and 320 MeV while it remains fairly steady at more backward angles; the angular distribution at 320 MeV shows a pronounced minimum at $\theta = 100°$. It is possible that these features of $\pi + d$ and π + He scattering originate from the same effects.

$\pi + d$ scattering has been the objective for many theoretical calculations. Different approaches give similar results which means that they reproduce the data except for $\theta \gtrsim 90°$ and $T \gtrsim 250$ MeV; the minimum around 100° in $\pi + d$ has defied all attempts of interpretation in terms of amplitudes generally believed to be important in pion-nucleus scattering. In this situation, the interest has been directed towards certain intermediate N^*N and $(NN)^*$ states which can couple to the $\pi + d$ scattering channel.[7,8] The largest effects seen so far come from the inclusion of dibaryon resonances[8] [for instance $^3F_3$ $(NN)^*$ at 2.16 GeV] which give rise to a desirable interference minimum around $\theta = 100°$. These contributions are still hypothetical and π + He in terms of a quasideuteron scattering model could provide a further test. The zero-spin ground state of ^{4}He would freeze the spin direction of the quasideuteron during the scattering process and hence block contributions of certain spin-flip amplitudes. This might enhance the possibility to observe N^*N and dibaryon resonance effects although the nuclear form factor suppresses quasideuteron amplitudes in π + He. Guided by the observed similarity in angular distributions of $\pi + d$ and $\pi + {}^{3,4}$He scattering, calculations should be pursued to assess the importance of intermediate dibaryon resonances and N^*N interactions relative to other $\pi + 2N$ interactions.

In summary, we have reported angular distributions for $\pi + {}^{3,4}$He scattering. We find a pronounced similarity between $\pi^+ + {}^3$He and $\pi^\pm + {}^4$He. The (3, 3) resonance of $\pi + N$ is still present at 295 MeV and imprints its signature in the angular distributions as an inflection point at $\theta \approx 75°$. The $\pi^- + {}^3$He scattering differs from the other cases probably reflecting the influence of $\pi^- + n$ spin-flip amplitudes. The most remarkable result of our experiment is the deep minimum seen in the angular distributions for $\pi^\pm + {}^4$He at $\theta \approx 110°$ and also for $\pi^+ + {}^3$He. We point out the apparent similarity to previous $\pi + d$ data with the possibility of common π-NN interactions in both $\pi + d$ and $\pi + {}^{3,4}$He. The present data should be useful in the current discussion of NN dibaryon resonances or N^*N interactions in pion scattering.

This work was supported by the U. S. Department of Energy.

---

[1] A. Shcherbakov *et al.*, Nuovo Cimento 31A, 249, 262 (1976).

[2] R. H. Landau, Phys. Rev. C 15, 2127 (1977), and Nucl. Phys. A335, 289 (1980).

[3] B. M. K. Nefkens, in *Few Body Systems and Nuclear Forces II*, edited by H. Zingl, M. Haftel, and H. Zankel, Lectures Notes in Physics Vol. 87 (Springer-Verlag, Berlin, Heidelberg, and New York, 1978), p. 189.

[4] F. Binon *et al.*, Nucl. Phys. A298, 499 (1978).

[5] R. H. Cole, J. S. McCarthy, R. C. Minehart, and E. A. Wadlinger, Phys. Rev. C 17, 681 (1978).

[6] A. S. Rinat, E. Hammel, Y. Starkland, and A. W.

Thomas, Nucl. Phys. A239, 285 (1979); N. Giraud, Y. Avishai, C. Fayard, and G. H. Lamot, Phys. Rev. C 19, 465 (1979).

[7] R. Händel, M. Dillig, and M. G. Huber, Phys. Lett. 73B, 4 (1978).

[8] K. Kanai, A. Minaka, A. Nakamura, and H. Samiyoshi, to be published, and in Proceedings of the Eighth International Conference on High-Energy Physics and Nuclear Structure, Vancouver, Canada, August 1979, Abstracts of contributed papers (to be published); K. Kubodera, M. P. Locher, F. Myrer, and A. W. Thomas, J. Phys. G 6, 171 (1980).

[9] J. Källne *et al.*, Phys. Rev. Lett. 42, 157 (1979).

[10] J. S. McCarthy, I. Sick, and R. R. Whitney, Phys. Rev. C 15, 1396 (1977).

[11] P. J. Bussey *et al.*, Nucl. Phys. B58, 363 (1973).

Determination of the Asymptotic Ratio of the Deuteron *D*- and *S*-State Amplitudes

K. Stephenson[(a)] and W. Haeberli

University of Wisconsin, Madison, Wisconsin 53706

(Received 20 June 1980)

The value $0.026\,49 \pm 0.000\,43$ is deduced for the deuteron asymptotic D- to S-state ratio from measurements of the $^{208}\mathrm{Pb}(d,p)^{209}\mathrm{Pb}$ tensor analyzing powers at sub-Coulomb bombarding energies $E_d = 7$, 8, and 9 MeV. The quoted uncertainty includes statistical errors, beam-polarization measurement errors, and systematic errors which result from a choice of optical-model parameters used to describe the reaction. The result is compared to several theoretical deuteron wave functions.

PACS numbers: 21.40.+d, 13.75.Cs, 24.70.+s, 25.50.Gx

In spite of years of experimental effort, many properties of the deuteron are still poorly determined. A continued study of the deuteron is required if stringent tests of n-p interaction theories are to be possible. Although the measurability of the deuteron D-state probability has recently been called into question,[1] the asymptotic ratio of the D- and S-state amplitudes (η) is accepted as a well-defined measurable quantity. Two methods have been proposed in the literature to measure η.

It has been suggested[2] that the tensor analyzing powers in p-d elastic scattering are sensitive to η. The sensitivity is a result of a pole in the scattering amplitude at an unphysical angle θ_p, where $\cos\theta_p < -1$. The extraction of η requires an extrapolation of tensor analyzing power and cross-section angular distributions to θ_p. Such extrapolations have been performed.[3,4] Of course, in any experiment designed to measure a fundamental quantity to high accuracy, an accurate error analysis is most important. The difficulties in performing a rigorous error analysis of the extrapolation method have been discussed by Colby and Haeberli.[5]

The other method to measure η was proposed in a recent Letter by Knutson and Haeberli.[6] This method is based on the observation that distorted-wave Born-approximation (DWBA) calculations predict that the tensor analyzing powers of (d,p) stripping reactions have a strong (essentially linear) dependence on η. Moreover, at bombarding energies below the Coulomb barrier, the fundamental assumptions in DWBA are particularly well satisfied and the dependence on parameters in the theory other than η is drastically decreased. Specifically, the dependence on the nuclear optical-model parameters which describe the incoming deuteron and outgoing proton scattering waves decreases because the scattered particles do not penetrate into the nuclear interior. As a result, the scattering waves are perturbed Coulomb wave functions. By adjusting the value of η to fit measured tensor analyzing power angular distributions of $^{208}\mathrm{Pb}(d,p)\,^{209}\mathrm{Pb}$ at $E_d = 9$ MeV, Knutson and Haeberli determined that[7] $\eta = 0.0234 \pm 0.0017$. This value of η is smaller than that of many published deuteron wave functions. For example, the wave functions of Refs. 8–10 predict $\eta = 0.0262$, 0.0260, and 0.0260, respectively. Unfortunately, because of the large error bar, the measurement is unable to conclusively rule out these wave functions and a measurement with a smaller error is desired.

The sources of error in Ref. 6 were primarily from uncertainties in the beam polarization measurement and uncertainties in the nuclear optical-model parameters. The former error can be re-