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Large-angle elastic scattering of π^+ and π^- from ^{16}O at 114 MeV

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Elastic cross sections have been measured for the scattering of π^+ and π^- from ^{16}O at 114 MeV in the angular range of 115°–175° (c.m.). Large cross sections and large π^+/π^- differences have been observed beyond 140° (c.m.). First-order optical model calculations fail to reproduce the large-angle data. Second-order effects generally improve the fits, but the details of the present data together with the results of earlier measurements at smaller angles have not been satisfactorily explained.

The pion is the only currently used probe of nuclei that exists in both positive and negative charge states within the same isospin multiplet. This means, for example, that the pion can be used to study details of Coulomb effects in hadronic scattering, as well as differences in neutron and proton distributions in nuclei. This latter sensitivity arises because of the difference in the isospin structure of the $\pi^+p(\pi^-n)$ and $\pi^+n(\pi^-p)$ systems. In the region of the $\Delta(1232)$ resonance this results in the well-known 9:1 ratio for the total elastic cross section. With measurements of $\pi^\pm$ scattering on self-conjugate nuclei, it has been possible to investigate various charge symmetry breaking effects in nuclei.[1,2]

Results of such studies are reliable only if the pion-nucleus interaction is adequately understood. This interaction has been the subject of intensive investigation for several years,[3] with work that has resulted in good fits by several models to scattering data which extend generally over the forward hemisphere. For scattering at backward angles, however, these models give strongly divergent predictions, indicating that higher-order effects are needed to explain the difference. These considerations have led us to begin a study of pion-nucleus scattering at large angles, using both π^+ and π^-, with the aim of improving our understanding of the pion-nucleus interaction.

To date, only two sets of $\pi^\pm$ elastic scattering data on a self-conjugate nucleus which extend out to 180° have been published, i.e., for ^{12}C at 162 (Ref. 4) and 100 MeV.[5] At 100 MeV, the π^+/π^- cross section ratio was found to be less than 1.5, and at 162 MeV it was smaller. In both cases the shapes of π^+ and π^- angular distributions were very similar at backward angles. The 100 MeV data were analyzed[5] within the delta-hole formalism,[6] but the $\pi^\pm$ difference could not be explained simultaneously for both elastic and inelastic scattering. We note that both of these data sets indicate a relative maximum near 180°. In this paper, we present data on ^{16}O at 114 MeV which indicate a minimum near 180°, with a π^+/π^- ratio of about 2.5. This is the largest such ratio that has been reported for a self-conjugate nucleus.

The experiment was performed at the Clinton P. Anderson Meson Physics Facility, using the Energetic Pion Channel and Spectrometer (EPICS). The EPICS spectrometer and the experimental setup for the back-angle measurements are described elsewhere.[7] The target used was in the form of beryllium oxide, with areal density 481 mg/cm^2. Typical energy resolution was of the order 1.0 MeV full width at half maximum (FWHM). It was limited by the target thickness, since reflection geometry was used for the target angle. Absolute normalizations were obtained by using a CH_2 target (of areal density 211 mg/cm^2) to determine π^+ and π^- elastic scattering yields from hydrogen. The $\pi^\pm$ cross sections for hydrogen were calculated using the phase shifts from Ref. 8. The normalization is believed to be accurate to $\pm 10\%$.

In Fig. 1 we have plotted the $\pi^\pm$ angular distributions between 115° and 175° measured in this experiment, along with the π^+ data of Albanese *et al.*[9] and the π^- data of Ingram *et al.*,[10] and Bason *et al.*[11] We note that in the overlap region the EPICS data are in some disagreement with the data of Ref. 9 from the Swiss Institute for Nuclear Research (SIN) as well as with the large-angle data of Ref. 11 from CERN. We have no explanations for the disagreement, but we observe that discrepancies between large-angle pion scattering data taken with SUSI spectrometer at SIN and the EPICS spectrometer system have been noted before.[12,13] We also observe that, unlike the system used at CERN,[14] the effective solid angle of our system is independent of scattering angle,[7] and we speculate that this may be one of the reasons for the discrepancy.

In an effort to understand both the $\pi^\pm$ differences and the large-angle behavior of the data, we have carried out a number of calculations employing several models[15–17] of varying degrees of sophistication. These models have in general given a reasonable representation of pion-nucleus scattering in the forward hemisphere throughout the 100–300 MeV energy region. The different approaches can be characterized by two categories: (1) phenomenological models which utilize zero-range pion-nucleon amplitudes and are calculated in coordinate space, and (2) microscopic

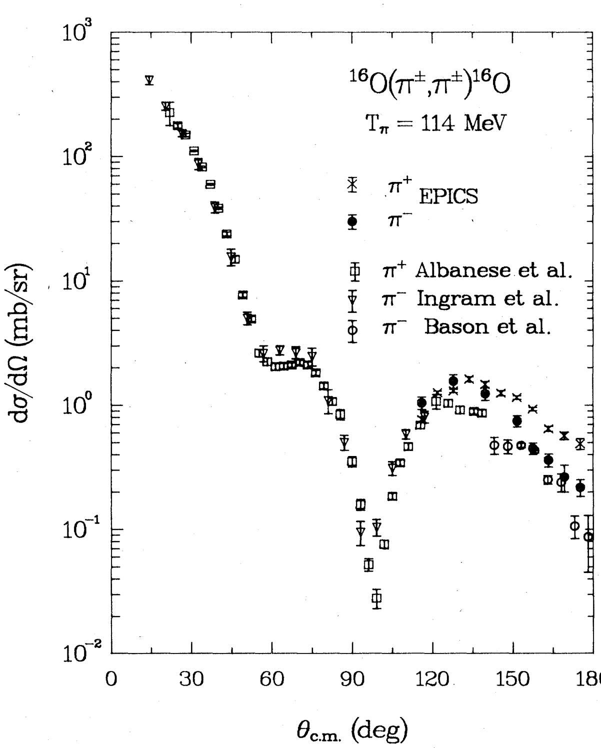

FIG. 1. The 114 MeV $\pi^\pm$ angular distributions on ^{16}O at large angles measured in this experiment, along with the π^+ data of Albanese *et al.*,[9] the π^- data of Ingram *et al.*,[10] and the large-angle π^- data of Bason *et al.*[11]

models which are calculated in momentum space. The first type of model follows the general form originally proposed by Kisslinger[18] but includes modern advances such as a relativistic frame transformation from the pion-nucleon to the pion-nucleus frame. The phenomenology is introduced via the addition of second-order terms proportional to ρ^2, and, sometimes, a phenomenological shift in the energy of the two-body amplitude which occurs in the first-order term. The more microscopic models assume an underlying dynamics for the pion-nucleon interaction and then expand the optical potential in a multiple-scattering series. The first-order, impulse approximation is then carefully calculated while the second-order terms are treated as the phenomenology of the theory.

In order to test the predictions of a fairly successful first-order zero-range model, we used the elastic scattering code PIRK,[15] as modified by Cottingame and Holtkamp,[19] to perform optical-model calculations. All calculations with this code used a modern version of the Kisslinger[18] optical potential and a ground-state density in the form of a three-parameter Fermi distribution. The density parameters, taken from electron scattering measurements,[20] were suitably modified to remove the finite size of the proton. We evaluated the pion-nucleon t matrix at an energy 30 MeV less than the incident pion energy. This procedure was found by Cottingame and Holtkamp to provide a good representation of resonance-energy data, but it may be questionable at 114 MeV. The results are shown in Fig. 2(a). Apart from the very forward angles, it is quite clear that the PIRK calculations bear little resemblance to the data.

Recently, Greene *et al.*[21] carried out a unified analysis of pion elastic scattering and single- and double-charge-exchange reactions on several nuclei at 164 MeV. These authors used the phenomenological model[17] of Johnson and Siciliano which is based on the isospin symmetry that exists between these three processes leading to isobaric analog states. The symmetry feature of the model allows for a general form of the optical potential, which is expressed as a series expansion in the nuclear density (retaining all terms up to ρ^2). The parameters of the model have been extracted from fits to elastic and charge-exchange data. Using the code PIESDEX,[22] we fitted the π^+ and π^- data of Albanese *et al.*[9] and Ingram *et al.*,[10] respectively, with the results displayed in Fig. 2(b). The relevant PIESDEX parameters are given in Table I. In order to investigate the sensitivity of the parameters to the angular range of the data set, we performed another fit to the π^+ and π^- data, with the back-angle data included. The results are shown in Fig. 2(c). It is noteworthy that not only have the shapes of the distributions changed at back angles, but the extracted parameters, also given in Table I, are dramatically different. Clearly this illustrates the need for large-angle measurements in disentangling higher-order terms in the potential and also at the same time serves as a warning to the dangers of extracting meaningful coefficients of these ρ^2 terms from partial angular distributions.

In addition to the two coordinate-space approaches discussed above, we have examined two microscopic momentum-space approaches. Some of the advantages of the momentum-space approach include an exact treatment of relativistic kinematics, the incorporation of the finite range of the pion-nucleon amplitude, an improved treatment of dispersive effects, and exact performance of the Fermi-averaging integral. This last feature allows the

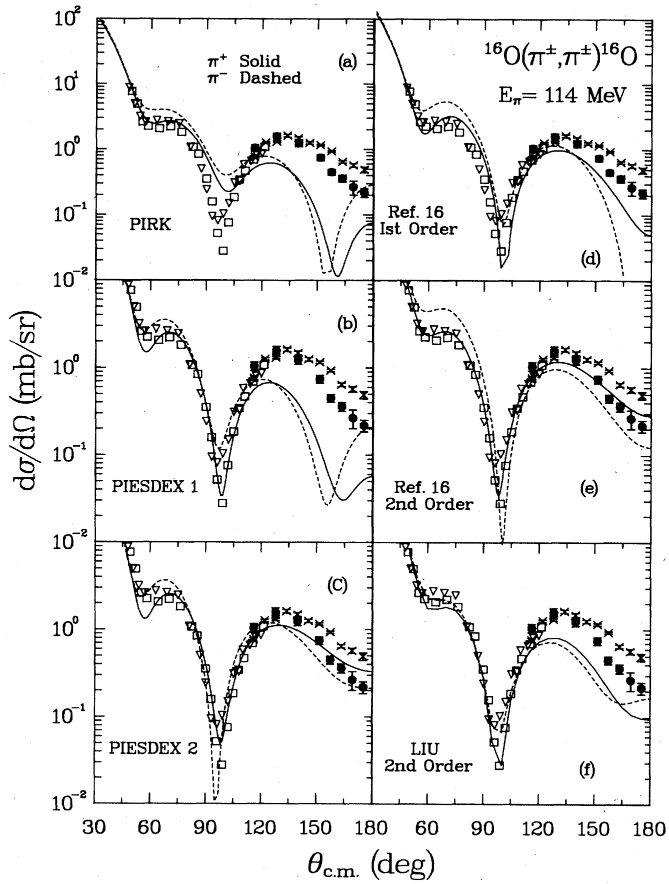

FIG. 2. Fits to the $\pi^{\pm}$ angular distributions using the models of (a) Ref. 19, (b) and (c) Ref. 21, (d) and (e) Ref. 16, (f) Ref. 23, as described in the text. The symbols for the experimental points are the same as in Fig. 1. For the purpose of clarity, the data for $\Theta > 120°$ from Refs. 9 and 10, shown in Fig. 1, are omitted.

models to incorporate exactly the formation, propagation, and decay of the delta. These models differ from the delta-hole model in that the phenomenology is incorporated through higher-order terms in the multiple-scattering theory rather than a phenomenological delta-hole interaction.

Shown in Fig. 2(d) are the results of calculations carried out with the field-theoretic momentum-space approach of Ref. 16. From Fig. 2(d) it is immediately obvious that the results from this model represent a considerable improvement over the PIRK calculations. Considering that there are no free parameters in this calculation, the agreement with the data (up to 140°) is fairly good, although the maximum at 70° is not well reproduced. Another feature of the result is that a sizable difference between π^+ and π^- distributions is predicted at large angles. In this model an option exists to introduce a second-order potential described by two complex energy-dependent parameters. Shown in Fig. 2(e) are the results from a search on these parameters by fitting only the π^+ distribution data and calculating the π^- distribution using the same parameters. Note that most of the improvement in the fit to the data occurs at back angles, indicating the sensitivity of large-angle measurements in the investigation of the second-order potential. It is also encouraging to note that the calculated π^+/π^- ratio at 175° is now about 2.0, which is very similar to the measured ratio. In this model, as was also the case with PIESDEX, the second-order phenomenology is only well determined if the data for the entire angular range are included.

A second momentum-space approach has also been examined. This is the approach of Liu and Shakin,[23] which differs from the field-theoretic model of Ref. 16 in that the underlying dynamics is taken to be a separable potential and the two-body energy in the impulse approximation is evaluated using the "three-body energy denominator" rather than the "mean-spectral" propagator of Ref. 16. The second-order phenomenology of these two momentum-space models is quite similar, and, at low energies, can be related to the true absorption channel. Predictions of this model are displayed in Fig. 2(f). The results up to 120° are quite impressive, particularly in view of the difficulty that all the other models have in this region. At the larger angles, however, this model predicts a negligible $\pi^{\pm}$ difference, in clear contradiction with the data.

In conclusion, the substantial differences in shape and magnitude of the $\pi^{\pm}$ elastic cross sections at 114 MeV on ^{16}O at large angles are, at this stage, not quantitatively understood. None of the models which were successful at resonance energies have given good fits to the data at 114 MeV. Calculations with coordinate-space models are totally inadequate at large angles. A first-order field-theoretic momentum-space model gives an improved, but still inadequate, representation. Second-order fits which include the large-angle data have varying success in reproducing either the $\pi^{\pm}$ difference at large angles or the shape of the cross sections near the first minimum, but not both. None of these is able to reproduce the magnitude of the angular distributions at the largest angles. These studies do clearly demonstrate, however, the need for back-angle data in the extraction of higher-order terms. An understanding of the $\pi^{\pm}$ data over the entire angular region is presently lacking, suggesting that our knowledge of the pion-nucleus interaction on the low-energy side of the (3,3) resonance is incomplete. A resolution of this problem should lead to an improved understanding of pion-nucleus dynamics.

TABLE I. $^{16}O(\pi^{\pm},\pi^{\pm})^{16}O$ at 114 MeV.

Model	ΔE [a]	$\lambda^{(2)}0$ [b]	Ref.
PIESDEX 1	$33.13-i7.55$	$3.26+i2.87$	21, 22
PIESDEX 2	$-6.05+i46.89$	$3.41-i6.97$	21, 22

[a] ΔE = energy shift in the Δ_{33} channel.
[b] $\lambda^{(2)}0=\rho^2$ term in the isoscalar potential.

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[1]T. G. Masterson *et al.*, Phys. Rev. C **30**, 2010 (1980).

[2]D. B. Holtkamp *et al.*, Phys. Rev. Lett. **45**, 420 (1980); C. L. Morris *et al.*, Phys. Lett. **99B**, 387 (1981).

[3]See, for example, R. Redwine, Nucl. Phys. **A434**, 239c (1985); C. H. Q. Ingram, *ibid.* **A374**, 319 (1982); R. H. Landau, *ibid.* **A335**, 289 (1980); *Proceedings of the Conference on Meson-Nuclear Physics, Houston, 1970,* edited by E. V. Hungerfold III, AIP Conf. Proc. No. 54 (AIP, New York, 1979).

[4]B. Chabloz *et al.*, Phys. Lett. **81B**, 143 (1979).

[5]L. E. Antonuk *et al.*, Nucl. Phys. **A420**, 435 (1984).

[6]F. Lenz, M. Thies, and Y. Horikawa, Ann. Phys. (N.Y.) **140**, 266 (1982); M. Thies, Nucl. Phys. **A382**, 434 (1982); Y. Horikawa, M. Thies, and F. Lenz, *ibid.* **A345**, 386 (1980); M. Hirata, J. H. Koch, F. Lenz, and E. J. Moniz, Ann. Phys. (N.Y.) **120**, 205 (1979); M. Hirata, F. Lenz, and K. Yazaki, *ibid.* **108**, 116 (1977).

[7]H. A. Thiessen and S. Sobottka, Los Alamos National Laboratory Report No. LA-4534-MS, 1970 (unpublished); G. R. Burleson *et al.*, Nucl. Instrum. Methods (to be published); W. B. Cottingame *et al.*, Los Alamos National Laboratory Report No. LA-10201-MS, 1984 (unpublished).

[8]G. Rowe, M. Salomon, and R. H. Landau, Phys. Lett. **18C**, 584 (1978).

[9]J. P. Albanese *et al.*, Nucl. Phys. **A350**, 301 (1980).

[10]Q. Ingram *et al.*, Phys. Lett. **76B**, 173 (1978).

[11]E. Bason *et al.*, Phys. Lett. **118B**, 319 (1982).

[12]C. J. Harvey *et al.*, Los Alamos National Laboratory Report No. LA-UR-84-1732, 1984 (unpublished).

[13]H. A. Thiessen *et al.*, Los Alamos Scientific Laboratory Report No. LA-7607-PR, 1979.

[14]A. Stanovnik *et al.*, Nucl. Instrum. Methods **177**, 369 (1980).

[15]R. A. Eisenstein and G. Miller, Comput. Phys. Commun. **8**, 130 (1974).

[16]M. B. Johnson and D. J. Ernst, Phys. Rev. C **27**, 709 (1983); D. L. Weiss and D. J. Ernst, *ibid.* **26**, 605 (1982); D. R. Giebink and D. J. Ernst (unpublished); D. J. Ernst, D. R. Giebink, and M. B. Johnson (unpublished).

[17]M. B. Johnson and E. R. Siciliano, Phys. Rev. C **27**, 730 (1983); **27**, 1647 (1983).

[18]L. S. Kisslinger, Phys. Rev. **98**, 761 (1955).

[19]W. B. Cottingame and D. B. Holtkamp, Phys. Rev. Lett. **45**, 1828 (1980).

[20]C. W. DeJager, H. DeVries, and C. DeVries, At. Data Nucl. Data Tables **14**, 479 (1974).

[21]Steven J. Greene *et al.*, Phys. Rev. C **30**, 2003 (1984).

[22]M. B. Johnson and E. R. Siciliano, PIESDEX (unpublished).

[23]L. C. Liu and C. M. Shakin, Phys. Rev. C **19**, 129 (1979).