Elastic Scattering of Negative Pions from ^{16}O in the Region of the (3, 3) Resonance

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The elastic differential cross sections for π^--^{16}O scattering have been measured for pions with kinetic energies 160, 170, 220, 230, and 240 MeV at laboratory angles from 15° to 77°. The cross sections are compared with the results of an optical-model calculation.

Studies of low-energy pion-nucleus elastic scattering[1] and analyses of π^--atom x-ray energies[2,3] have been consistent with predictions based on a pseudopotential of the form proposed by Kisslinger.[4] The Kisslinger potential is momentum dependent, because of the important p-wave pion-nucleon scattering, and the parameters of the potential have been successfully related to the elementary processes $\pi + N \to N + \pi$ and $\pi + 2N \to 2N$, especially in the pion-atom studies.[2]

An important question is whether or not the pion-nucleus effective potential will have as transparent an interpretation at higher energies and in particular in the interesting energy region near the pion-nucleon (3, 3) resonance. Recently, elastic and inelastic π^--^{12}C cross sections in this energy region were measured by Binon *et al.*[5] The observed cross sections are characteristic of a strongly absorptive interaction and have been analyzed using the diffractive scattering theory of Glauber[6] and the Kisslinger-model pseudopotential.[7] The agreement between theory and experiment is good, but discrepancies exist which may be due in part to the fact that ^{12}C is deformed in the ground state, as well as to difficulties associated with the construction of an effective potential in this energy region.

In this Letter we present our measurements of π^--^{16}O elastic scattering for pion kinetic energies between 160 and 240 MeV (lab). Oxygen is particularly favorable since, while it has spin zero, unlike carbon it is not deformed in the ground state. In addition, the first excited state is at 6.05 MeV, assuring an easy separation of elastic events.

The experimental arrangement is shown in Fig.

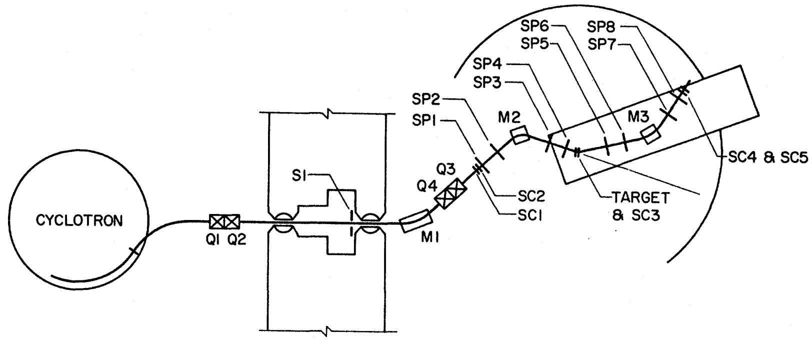

FIG. 1. Experimental setup. SC_1–SC_5 are scintillation counters, SP_1–SP_8 are sonic spark chambers, M_1–M_3 are bending magnets, Q_1–Q_4 are quadrupole magnets, and S_1 is a beam-defining slit.

1. The pion beam was produced with the 600-MeV synchrocyclotron of the National Aeronautics and Space Administration Space Radiation Effects Laboratory, and a beam transport system was designed to focus the maximum flux of pions onto a water target. The energy spread in the beam was approximately 30 MeV and neutral particles were cleared from the beam with a bending magnet (M_1). Two spectrometers, each consisting of four sonic spark chambers (SP_1–SP_4 or SP_5–SP_8) and a bending magnet (M_2 or M_3) were used to measure the pion momentum before and after scattering. Each chamber consisted of two aluminum foils 0.0025 cm thick separated by 1 cm of a 90% Ne, 10% He gas mixture. Effects of multiple scattering were reduced by helium-filled bags placed between chambers. The second spectrometer was mounted on a large table which could be rotated to vary the scattering angle.

The number of incident particles was defined as the number of coincidences in scintillation counters SC_1–SC_3. A scattering event, defined by an SC_1-SC_5 coincidence, triggered the sonic chambers. For each sonic-chamber microphone (four per chamber) the time of propagation of the sound wave from the spark to the microphone was digitized and transferred to the on-line IBM 360/44 computer at the Space Radiation Effects Laboratory. Reconstruction of spark location was performed along with preliminary data reduction on the computer to monitor the experiment. To obtain accurate values of momenta from the particle trajectories, the magnetic field shapes in magnets M_2 and M_3 were determined by measuring relative field values at 4480 points with an accuracy of 0.5%. The field maps were used in conjunction with computer programs[8] to calculate the momentum giving a best fit to the spark coordinates. The absolute magnitudes of the magnetic fields were obtained from measurements at the center of each magnet with a nuclear magnetic resonance probe.

Events were binned according to the incident energy and the scattering angle. For each bin an energy-loss spectrum was constructed using the incident and scattered momenta, and elastic events were identified. The experimental energy resolution was between 3 and 4 MeV because of multiple scattering and uncertainties in the location of sparks, but was sufficient to separate elastic and inelastic scattering. The energy-loss spectrum was used to determine the fraction of elastic events in each energy-angle bin. The solid angle subtended by the second spectrometer was calculated as a function of the energy loss for each incident energy and scattering angle using a Monte Carlo procedure.

In order to obtain absolute cross sections we used (1) the measured counter efficiencies, (2) the number of particles incident in each energy bin, and (3) the fraction of pions in the incident beam as determined from a time-of-flight measurement. As an alternate method of normalization we took data for π^- scattering on ^{12}C at $\theta_{lab} =$ 25°, 27°, 29°, and compared the resulting cross sections with the CERN results.[5] The normalizations were in agreement within the experimental errors. Since the time-of-flight resolution for 220- to 240-MeV pions was poor, we used the alternate method of normalization in this energy region. We estimate that our normalization may be in error by as much as 15%.

Our experimental results are shown in Fig. 2 The cross sections range over five decades for $15° \leq \theta_{lab} \leq 77°$ with minima at $\theta_{lab} \simeq 47°$ for 160–170-MeV pions and at $\theta_{lab} \simeq 40°$ for pion energies between 220 and 240 MeV. The minimum at 170 MeV [our energy nearest the (3, 3)-resonance energy] is quite deep. The positions of the minima, together with the shift to smaller angles with an increase in energy, are in good agreement with predictions based on diffractive scattering from a "black sphere" with a radius equal to that of the ^{16}O matter radius. The angular positions of the minima do not agree with the zeros of the elastic form factor which on a harmonic oscillator model occur at $\theta_{lab} \simeq 63°$–$70°$. This is characteristic of a strongly absorptive interaction.

To get a more detailed interpretation of the experimental results, we have calculated the cross sections numerically with an approximately relativistic Schrödinger equation:

$$(\nabla^2 + k^2)\psi = 2m(V_C + V_{opt})\psi,$$

where k is the center-of-mass momentum, m is the relativistic reduced mass [$m = E_\pi/(1 + E_\pi/E_{nucl})$, in the c.m. frame)], and V_C is the Coulomb potential. The strong pion-nucleus interaction is represented by a Kisslinger-model potential

$$-2mV_{opt} = k^2 b_0 \rho(r) - \nabla \cdot c_0 \rho(\boldsymbol{r}) \nabla,$$

where $\rho(r)$ is the matter density.

The optical-model parameters b_0 and c_0 are complex numbers that are simply related to the π-nucleon s- and p-wave scattering amplitudes in the single-scattering impulse-approximation.

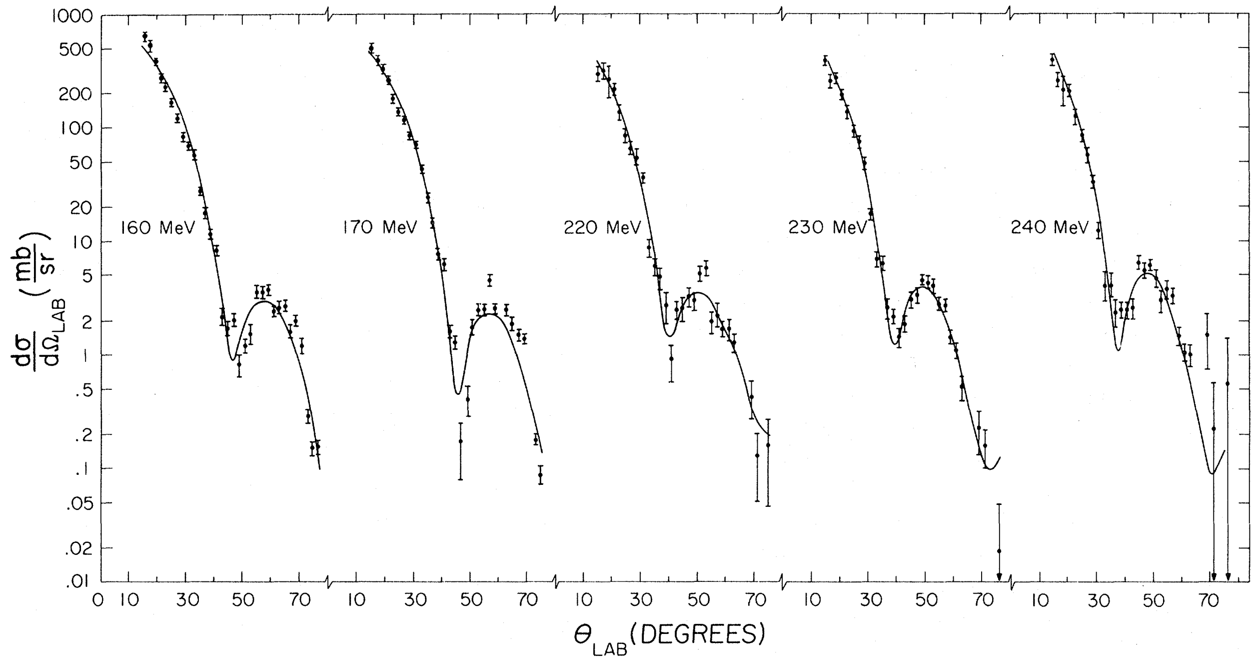

FIG. 2. Experimental cross sections in millibarns per steradian versus laboratory scattering angle. The error bars indicate only the statistical uncertainty in each point. The solid curves are best fits to the data obtained by adjusting the Kisslinger-model parameters b_0 and c_0.

However, this first approximation does not include binding effects, multiple scattering, or the pion-two-nucleon interaction. Therefore, we have adjusted the model parameters to fit the experimental data. A comparison with theoretically predicted parameters can then be used to judge the success of the model.

The calculated and experimental results are compared in Fig. 2. The charge distribution used in the calculations was composed of the appropriate harmonic-oscillator wave functions and had parameters equal to those found in electron scattering[9] $[\langle r_{ch}^2\rangle^{1/2} = 2.75\ \mathrm{F}]$. The matter density had the same shape, but its radius was corrected for the finite size of the nucleon $[\langle r^2\rangle^{1/2} = 2.64\ \mathrm{F}]$. The potential parameters were adjusted by means of a least-squares search program.

The best-fit parameters and their uncertainties as given by the search program's error matrix are collected in Table I. They are not well determined, and contrary to assumptions made in previous studies with the Kisslinger potential,[7] the parameters are found to be strongly correlated.

TABLE I. Best-fit Kisslinger-model potential parameters for oxygen together with their estimated uncertainties. Parameters set equal to zero were excluded from the analysis.

T_π (MeV)	$\mathrm{Re}b_0$ (F^3)	$\mathrm{Im}b_0$ (F^3)	$\mathrm{Re}c_0$ (F^3)	$\mathrm{Im}c_0$ (F^3)
160	-0.04 ± 2.4	-2.9 ± 2.0	0.5 ± 4.6	17 ± 3
	0.0	0.0	5.2 ± 2.3	13 ± 2
170	-0.70 ± 1.6	-2.0 ± 1.0	2.2 ± 2.9	13 ± 1
	0.0	0.0	4.2 ± 2.0	10 ± 1
220	5.80 ± 2.5	2.1 ± 0.9	-5.3 ± 1.6	5.5 ± 1.0
	0.0	0.0	-0.3 ± 0.6	7.8 ± 0.4
230	3.20 ± 1.4	1.4 ± 0.9	-3.2 ± 1.1	5.9 ± 0.9
	0.0	0.0	-0.1 ± 0.5	7.6 ± 0.3
240	1.50 ± 2.3	2.8 ± 1.4	-1.1 ± 1.8	5.1 ± 1.4
	0.0	0.0	-0.3 ± 0.6	8.0 ± 0.4

In particular, we find at all energies that $\mathrm{Re}(b_0 + c_0) \simeq 0$ and that $\mathrm{Im}(b_0 + c_0)$ is large, reflecting the highly absorptive nature of the scattering process. The imaginary parameters are less strongly correlated than the real. A relatively large value of $\mathrm{Im}(c_0)$ is always required to give the correct depth of the minimum in the cross sections. The best-fitting parameters for a purely nonlocal potential ($b_0 = 0$) are also shown in Table I. The fit is distinguishable only by a slightly higher χ^2 than the one obtained by varying all four parameters, and illustrates the strong correlations discussed above. Fits obtained with a local potential ($c_0 = 0$) are distinctly inferior. Typically, the first minimum is located correctly, but it is much too deep.

In general, satisfactory fits to the data can be obtained using a Kisslinger-model potential, but the potential parameters will certainly have to be more accurately determined before a meaningful comparison with theoretically predicted parameters can be made. This will require more accurate cross-section measurements over the entire angular range. Hopefully, high-intensity accelerators now being constructed will allow these difficult experiments to be performed.

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