PHYSICAL REVIEW C VOLUME 40, NUMBER 2 AUGUST 1989

Low energy pion-nucleus potentials from differential and integral data

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(Received 14 September 1988)

Total reaction cross sections were measured for 50 MeV $\pi^{\pm}$ on Si and Ni, 65 MeV $\pi^{\pm}$ on Ni, and 80 MeV $\pi^{\pm}$ on C, Ca, Zr, and Pb. Together with similar data measured previously for 50 and 65 MeV $\pi^{\pm}$ on several targets, these cross sections were used as constraints in optical-model analysis of the elastic scattering of pions by nuclei. Also analyzing data at 20 and 30 MeV, a pion-nucleus potential was constructed that is strongly linked with the free pion-nucleon interaction, has smooth variation with energy between 0 and 80 MeV, and is capable of describing very well, much better than any potential published so far, all available data on differential and integral cross sections for π^+ and π^- interactions with nuclei.

I. INTRODUCTION

The interaction of low-energy pions with nuclei is described quite well by a Kisslinger-type optical potential. Despite the wealth of data for strong-interaction effects in pionic atoms and for elastic scattering of low-energy pions by nuclei, the complicated structure of the potential has precluded the establishment of unique sets of potential parameters. The isospin conserving nature of the interaction was also sometimes questioned because of difficulties in describing the elastic scattering of π^+ and π^- with the help of the same potential. (See Refs. 1 and 2 for an extensive list of references.)

In Ref. 1 we discussed in some detail the need for integral data, such as total reaction cross sections to supplement the conventional differential data, in order to achieve better defined pion-nucleus potentials. In a preliminary analysis of differential and integral data it was shown[2] that most of the difficulties with previous sets of parameters could indeed be removed.

The present paper reports on global fits of optical potentials to very extensive data for the elastic scattering of 30–80 MeV pions by nuclei, using as additional information total reaction cross sections for pions, measured specifically for that purpose. The variation of potential parameters with energy received special attention and the connection between the scattering regime and pionic atoms is a key point in this work, that is a continuation of Refs. 1 and 2, where most earlier work is cited.

In Sec. II the role played by total reaction cross sections (σ_R) in removing ambiguities in the potentials is outlined, and in Sec. III we report additional experimental results for σ_R on nuclei of interest. The fit procedure is described in Sec. IV, where the values of the parameters are given. Section V contains examples of the predictive power of these potentials, and a summary.

II. THE ROLE OF TOTAL REACTION CROSS SECTIONS

In Ref. 1 we discussed at some length the unusual situation with the pion-nucleus interaction at low energies that causes the total reaction cross section to depend rather strongly, not only on the imaginary part of the potential, but also on the real one, thus making it a useful constraint in the analysis of elastic scattering data. That is a consequence of the complicated structure of the interaction, having both an attractive and a repulsive term.[3] The use of integral cross sections as a supplement to differential cross sections was advocated by several authors.[4–7] For reasons of accuracy and reliability we have chosen[1] the total reaction cross section as the additional quantity rather than the total cross section.

Table I shows, as an example (in addition to the discussion in Ref. 1), parameter values for the pion-nucleus potential (see Sec. IV) obtained from χ^2 fits to elastic scattering for 65 MeV π^- on ^{58}Ni. This is typical of the situation with pion-nucleus interaction, where even if one attempts to fit just five parameters of the potential (out of its 13 parameters) most of them are not really determined by the data. The first line shows results of a conventional fit whereas the second shows results of a fit with the σ_R constraint included. It is seen that the addition of the σ_R constraint makes it possible to select one of the two equivalent fits. It also reduces significantly the uncertainty in the value of Imc_0, with smaller effect on the other parameters. Figure 1 shows comparisons between those two different best-fit calculations and the data, and again it is clear that the elastic scattering data available cannot distinguish between the two. We have, therefore, demonstrated the problem of nonuniqueness with the pion-nucleus interaction and the importance of using the σ_R values as additional information.

TABLE I. Examples of parameter values from fits to elastic scattering of 65 MeV π^- on ^{58}Ni. See Sec. IV for notation.

σ_R constraint	Rec_0 (m_π^{-3})	Imc_0 (m_π^{-3})	ReB_0 (m_π^{-4})	ImB_0 (m_π^{-4})	ReC_0 (m_π^{-6})	χ^2/F	σ_R^{calc} (mb)
No	0.286±0.049	−0.003±0.160	−0.033±0.064	0.020±0.049	−0.131±0.125	11.7	553
Yes	0.283±0.070	0.083±0.036	−0.055±0.034	−0.001±0.038	−0.048±0.100	12.1	1078

III. EXPERIMENTAL RESULTS FOR σ_R

The present experiment was described in great detail in Ref. 1. Transmission measurements were performed for 50, 65, and 80 MeV positive and negative pions at the TRIUMF cyclotron. As these measurements were aimed at providing additional data for the analysis of elastic scattering of pions, the targets and energies were selected accordingly, i.e., the availability of high-quality elastic scattering data both for π^+ and π^- for the same target and at the same energy, preferably from the same experiment, was a precondition for choosing a target for our σ_R measurements. To the previous results at 50 and 65 MeV we have added results for Si and Ni. At 80 MeV the targets were C, Ca, Zr, and Pb. The measurements at 80 MeV were, in fact, easier to perform and to analyze, compared to the lower-energy ones, as the various corrections to the data due to effects such as the pion-decay muons and Coulomb multiple scattering, become less important with increasing energy. Table II summarizes these new experimental results together with those published earlier[1] to provide a comprehensive list of data.

IV. FITS AND RESULTS

The pion-nucleus potential used here is the Ericson-Ericson[8] version of the Kisslinger[9] potential, as modified for elastic scattering by the Michigan State University (MSU) (Refs. 10, 5, and 6) group. The potential that is used in the Klein-Gordon equation, where V_N^2 and $V_N V_C$ terms are neglected, is written as

$$2\omega V_N(r)=q(r)+\nabla\cdot\alpha(r)\nabla\ , \tag{1}$$

where V_C is the Coulomb potential due to the finite charge distribution of the nucleus and ω is the total pion energy in the pion-nucleus system. The s-wave (q) and p-wave (α) parts of the potential are given by ($\pm$ apply to $\pi^{\mp}$)

$$q(r)=-4\pi\left[\left\{1+\frac{\omega}{m}\right\}[b_0(\rho_n+\rho_p)\pm b_1(\rho_n-\rho_p)]\right.$$
$$\left.+\left\{1+\frac{\omega}{2m}\right\}4B_0\rho_n\rho_p\right]+\Delta q_{\text{at}}(r)\ , \tag{2}$$

$$\alpha(r)=\frac{\alpha_1(r)}{1+\frac{1}{3}\xi\alpha_1(r)}+\alpha_2(r)\ , \tag{3}$$

with $\Delta q_{\text{at}}(r)$ the so-called angle-transformation term,

$$\Delta q_{\text{at}}(r)=-4\pi\frac{\omega}{2m}\left[\left\{1+\frac{\omega}{m}\right\}^{-1}\nabla^2[c_0(\rho_n+\rho_p)\right.$$
$$\pm c_1(\rho_n-\rho_p)]$$
$$\left.+\left\{1+\frac{\omega}{2m}\right\}^{-1}2C_0\nabla^2(\rho_n\rho_p)\right]\ , \tag{4}$$

and

$$\alpha_1(r)=4\pi\left\{1+\frac{\omega}{m}\right\}^{-1}[c_0(\rho_n+\rho_n)\pm c_1(\rho_n-\rho_p)]\ , \tag{5}$$

$$\alpha_2=4\pi\left\{1+\frac{\omega}{2m}\right\}^{-1}4C_0\rho_n\rho_p\ . \tag{6}$$

ρ_n and ρ_p are the nuclear densities normalized to N and Z, respectively, and m is the mass of the nucleon. Note that some authors write $(\rho_n+\rho_p)^2$ instead of $4\rho_n\rho_p$. We prefer the latter form as it reflects the fact that most absorptions occur on neutron-proton pairs. Note also that the Ericson-Ericson Lorentz-Lorenz (EELL) effect is applied here only to the linear term of α, to emphasize the fact that the terms of the potential that are quadratic in the nuclear densities are to be obtained phenomenologically, whereas the linear terms may be associated with the free pion-nucleon interaction. This point is not crucial to the present work but it affects the values of some parameters.

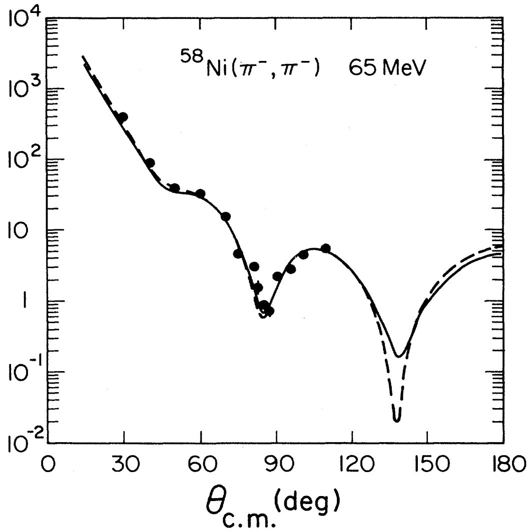

FIG. 1. Two equally good fits to the 65 MeV π^- on ^{58}Ni data, predicting widely different values of σ_R (see Table I). Data is from Ref. 33.

Pionic atoms, representing the pion-nucleus interaction at zero energy, served as the starting point for the analysis. It has been known for many years that strong interaction effects in pionic atoms are described very well (with the exception of a few "abnormal" states[11]) by the Ericson-Ericson potential. Very recently it was shown[11] that one could use for the linear terms b_0, b_1, c_0, and c_1 the corresponding free $\pi-N$ values, provided the EELL parameter ξ had the somewhat large value of 1.8.[12] The values of the complex parameters B_0 and C_0 were then obtained[11] from fits to pionic atom data. That procedure was also used in the present work. Proton densities were derived from electron-scattering data after correcting for the finite size of the proton charge. For the heavier nuclei, neutron densities were taken from proton or alpha-particle scattering or Hartree-Fock calculations, as done before.[13]

Turning next to elastic scattering, some additional problems arise. The linear terms are no longer real at positive energies and their imaginary parts generate inelastic scattering whereas $\mathrm{Im}B_0$ and $\mathrm{Im}C_0$ generate, as before, true absorption of pions. Fits to elastic scattering data are incapable of separating the two types of nonelastic processes and total reaction cross sections cannot help in this respect either, as they represent only the combined effect of these two processes. Information on true absorption of pions can help separate the two kinds of processes but, unfortunately, the data on true absorption of pions by nuclei is very limited. As fits to elastic scattering data determine only the combined effect of the two, correlations between the imaginary parts of the linear and the quadratic terms are unavoidable.[14] We have therefore used, as much as possible, data on true absorption of pions, and had to impose restrictions on the fits, for example, that the imaginary parts of both the s- and p-wave terms be nonnegative. The cross section for true absorption was calculated from

$$\sigma_{\mathrm{abs}} = -\frac{2\omega}{k}\int \chi^*(\mathrm{Im}V_N)\chi d\mathbf{r} \ , \tag{7}$$

where only the quadratic imaginary terms are retained in V_N, both in the integrand and when producing the pion-nucleus distorted waves χ. This expression differs from that of the MSU group[6] who used the full potential in generating the distorted waves, but it appears that although there is no unique prescription for calculating true absorption, the present procedure is preferred.[15,16] It expresses the intuitive expectation that inelastic scattering processes do not shadow true absorption.

The sources of the elastic scattering data used in the present work are summarized in Table III. Data for 20 and 30 MeV were included too, although experimental results for σ_R are available only for 50, 65, and 80 MeV (Table II). The reason for including the very low energies was the attempt to link the potentials at positive energies to the zero-energy pionic atom potentials.

The analysis of the scattering data began at 20 MeV, where it was found that calculations using pionic atom potentials were in excellent agreement with the data. However, at 30 MeV that was no longer the case and values of parameters had to be modified. At each energy, fits were made to all the data taken together, consisting usually of 250–300 data points. The values of $\mathrm{Im}C_0$ could be determined reasonably well by comparing calculations to experimental values of σ_{abs}. The latter were taken from interpolations between the experimental results of several groups.[17–19] Only data for π^+ were used for σ_{abs} because for π^- the differences between the experimental results of the various groups greatly exceed their quoted errors. The values of $\mathrm{Im}B_0$ could not be determined from σ_{abs}, and we eventually chose the largest values of $\mathrm{Im}B_0$ that did not lead to negative $\mathrm{Im}b_0$. With $\mathrm{Im}B_0$ and $\mathrm{Im}C_0$ fixed (at each energy) in this way, we eventually varied c_0, $\mathrm{Re}B_0$, and $\mathrm{Re}C_0$, keeping $\mathrm{Re}b_0$, $\mathrm{Re}b_1$, and $\mathrm{Re}c_1$ at the free $\pi-N$ values with their imaginary parts set to zero. The parameter c_0 is the most sensitive one and it was allowed to vary, but its real part did not depart much from the free $\pi-N$ value. Its imaginary part contains, phenomenologically, effects not included explicitly such as Pauli blocking. Thus, by varying four parameters we could obtain very good fits to 250–300 data points.

Table IV summarizes the values of the parameters for this potential (denoted by $J4$) and Table V shows, for comparisons, the free poin-nucleon values. Uncertainties are not quoted for the best-fit parameters in Table IV because the actual values depend on the type of fit performed. Typical uncertainties are generally about ±5%. (For pionic atoms the uncertainty in $\mathrm{Re}b_0$ is almost as large as this parameter itself.) It is more difficult to quote uncertainties for the free $\pi-N$ values of Table V, calculated from phase-shift values,[35] but from the scatter of results an estimated uncertainty of ±10% is obtained for $\mathrm{Re}b_1$, $\mathrm{Re}c_0$, and $\mathrm{Re}c_1$.

As can be seen in Table IV, the $J4$ parameters show a smooth variation with the energy of the incident pion. For the one-nucleon terms a general agreement with the free $\pi-N$ values is obtained. The real parts of b_0, b_1, and c_1 were held at the free $\pi-N$ values and setting their imaginary parts to zero had no effect on the quality of the fits as they were found to be relatively small in all cases (see also Table V). Both the real and the imaginary parts of c_0 increase with pion energy, where $\mathrm{Re}c_0$ and $\mathrm{Im}c_0$ are about 10% below and 50% above the free $\pi-N$ values, respectively. The absolute values of real and imaginary parts of the two-nucleon terms decrease with energy, and are close to zero around 80 MeV. The ratio of $\mathrm{Im}B_0$ to $\mathrm{Im}C_0$ is approximately constant for all energies. The decrease in the absorption parameters as a function of energy was obtained also by the MSU group[6] and is in contradiction to theoretical predictions derived from two-body operators adjusted to fit pion absorption on the deuteron.[36] This is not too surprising as the quadratic terms are, probably, the most phenomenological part of the potential and their values depend critically on the way that effects such as EELL, Pauli blocking, and Fermi averaging are handled (see, for example, Refs. 36–39). In particular, their real values are very hard to predict.

Figures 2–4 show examples of comparisons between calculations based on Table IV and the data. Very good agreement between calculation and experiment is ob-

TABLE II. Experimental values for total reaction cross sections (in mb).

	50 MeV		65 MeV		80 MeV	
	π^+	π^-	π^+	π^-	π^+	π^-
C	150±15	193±10	201±16	251±20	240±12	280±20
O	166±19	242±21				
^{18}O	179±31	272±20				
Si	335±31	557±60				
S	379±24	664±60				
Ca	439±36	770±50	600±43	765±50	690±30	950±50
Ni	554±50	1200±200	790±50	1100±70		
Zr	805±70				1180±50	1680±70
Pb					2120±100	3240±150

TABLE III. References for elastic scattering data used.

Target	20 MeV	30 MeV	50 MeV	65 MeV	80 MeV
C	20	22[a],23[b]	27	31	34
O		22[a],24[b]			7[a]
Si			28		
S			27		
Ca	21	22[a],21[b]	29	32	34
^{58}Ni		25	30	33	
^{60}Ni		25	30	33	
^{64}Ni		25	30	33	
Zr		22[a]	22[a]		34
Pb		22[a],26[b]	22[a]		34

[a] π^+ only.

[b] π^- only.

TABLE IV. *J*4 parameter values (Re;Im). Pion energies in MeV. $\xi=1.8$. Note that B_0 and C_0 multiply $4\rho_p\rho_n$ and not $(\rho_p+\rho_n)^2$. The LLEE effect applies to the linear term only.

T_π (MeV)	b_0 (m_π^{-1})	c_0 (m_π^{-3})	b_1 (m_π^{-1})	c_1 (m_π^{-3})	B_0 (m_π^{-4})	C_0 (m_π^{-6})
0–20	−0.009;0	0.220;0	−0.094;0	0.152;0	−0.113;0.058	0.074;0.053
30	−0.014;0	0.228;0.018	−0.093;0	0.160;0	−0.100;0.043	0.053;0.053
50	−0.021;0	0.231;0.051	−0.092;0	0.161;0	−0.075;0.036	0.036;0.053
65	−0.026;0	0.237;0.087	−0.092;0	0.165;0	−0.025;0.025	0.025;0.038
80	−0.031;0	0.250;0.117	−0.091;0	0.169;0	+0.006;0.020	0.013;0.023

TABLE V. Values of the one-nucleon terms (Re;Im) from $\pi - N$ phase-shift data (Ref. 35).

T_π (MeV)	b_0 (m_π^{-1})	b_1 (m_π^{-1})	c_0 (m_π^{-3})	c_1 (m_π^{-3})
0	−0.004;0	−0.094;0	0.231;0	0.152;0
30	−0.014;0.010	−0.093;−0.004	0.251,0.013	0.157;0.006
50	−0.021;0.014	−0.092;−0.004	0.267;0.032	0.161;0.016
65	−0.026;0.016	−0.092;−0.003	0.280;0.053	0.165;0.026
80	−0.031;0.018	−0.091;−0.003	0.292;0.083	0.169;0.041

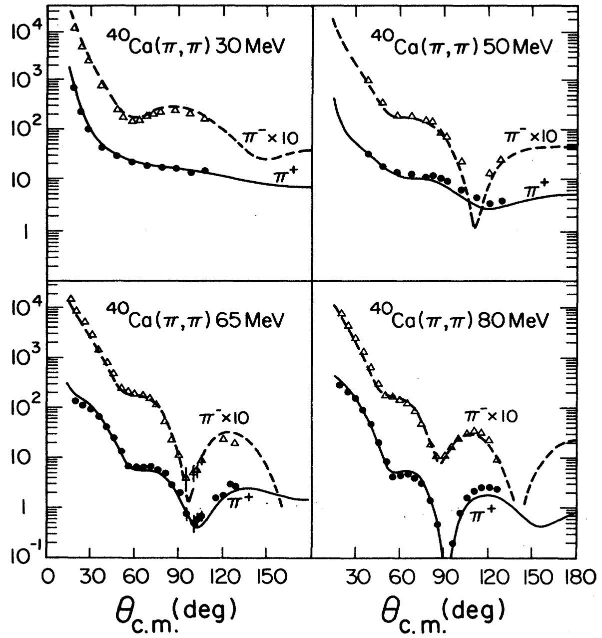

FIG. 2. Comparisons between $J4$ calculations and experiment for 30, 50, 65, and 80 MeV $\pi^{\pm}$ on ^{40}Ca. See Table III for references to the data. The 30 MeV π^{+} data in this figure is from Ref. 21.

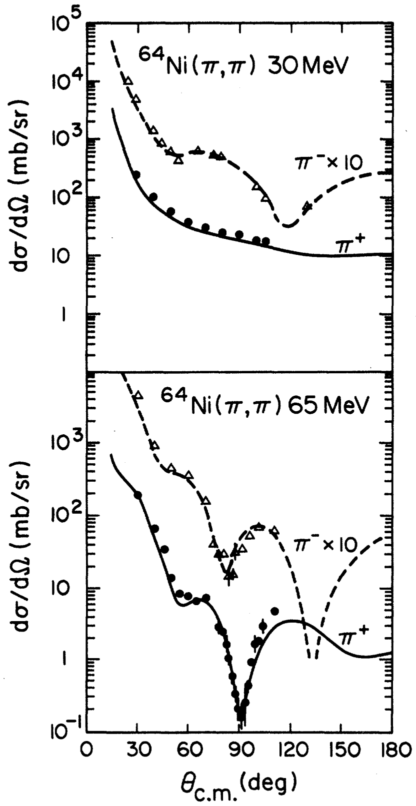

FIG. 3. Comparisons between $J4$ calculations and experiment for 50 and 65 MeV $\pi^{\pm}$ on ^{64}Ni. See Table III for references to the data.

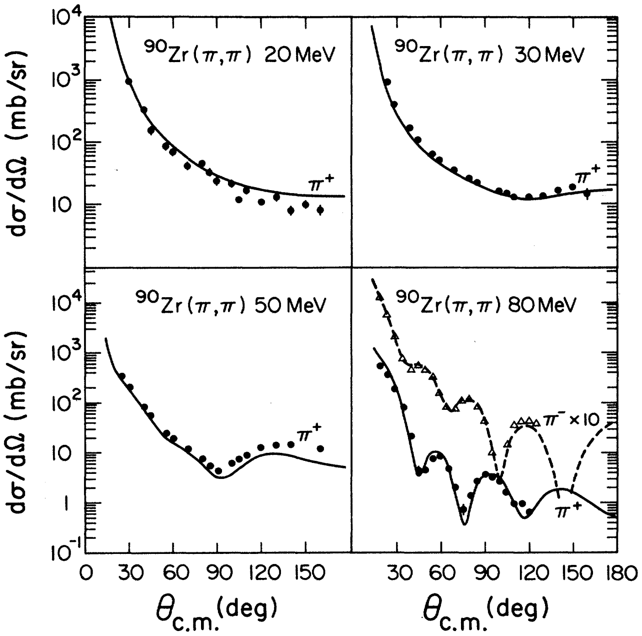

FIG. 4. Comparisons between $J4$ calculations and experiment for 20, 30, and 50 MeV π^{+} and 80 MeV $\pi^{\pm}$ on Zr. See Table III for references to the data.

tained also for the various integral cross sections mentioned above. At each energy the same set of parameters is used for all targets, both for π^{+} and π^{-}.

It is obvious that these parameters do not form a unique set. In particular, correlations exist between b_0 and B_0 and between c_0 and C_0. However, with the constraints of σ_R and the guidance by σ_{abs} and the free $\pi-N$ parameters, the $J4$ potential has many desirable features

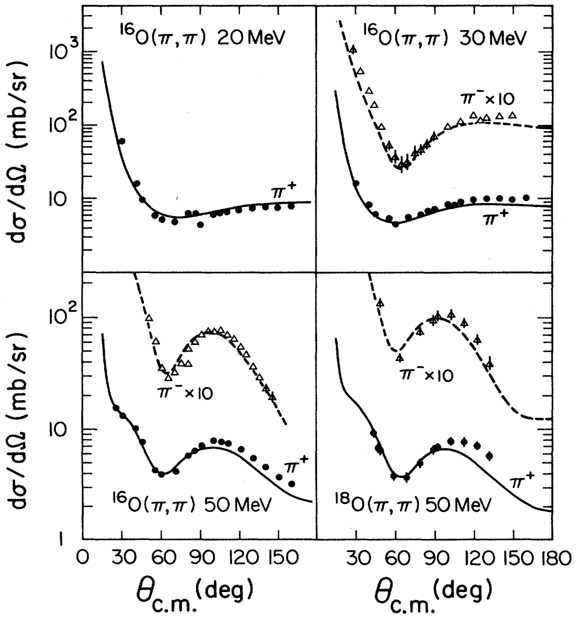

FIG. 5. Comparisons between $J4$ predictions and experiment for 20 (Ref. 40), 30 (Refs. 22 and 26), 50 MeV π^{+} (Ref. 22), and π^{-} (Ref. 41) on oxygen and 50 MeV $\pi^{\pm}$ on ^{18}O (Ref. 42). These data were not included in the data base.

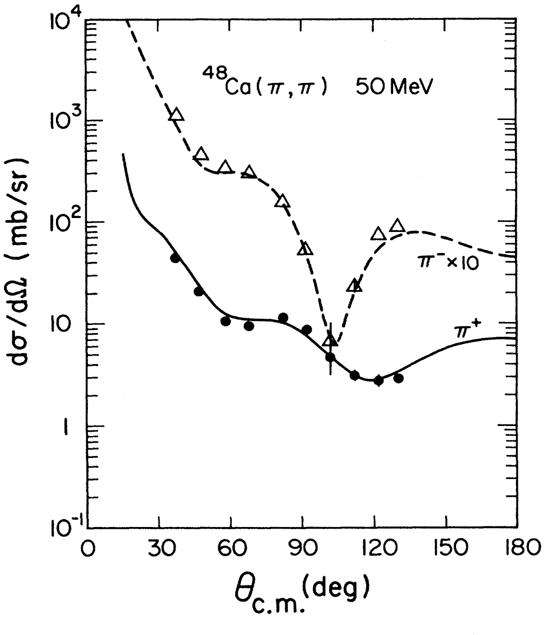

FIG. 6. Comparisons between $J4$ predictions and experiment (Ref. 29) for 50 MeV $\pi^\pm$ on ^{48}Ca. These data were not included in the data base.

not found in any published set of parameters. The superior fit to the data obtained with this potential as compared, for example, to the MSU (Ref. 6) potentials must be, at least partly, due to the broader data base of the present work, particularly with regard to π^- data.

V. SUMMARY

The $J4$ potential presented in this work is a theoretically motivated phenomenological potential. Its structure is based on theoretical arguments that lead to the well-known Kisslinger-Ericson-Ericson form, having far too many parameters to be determined by pion-nucleus elastic scattering data. By using total reaction cross sections as additional constraints it was possible to remove some of the ambiguities. Furthermore, by linking the potential to pionic atoms, to experimental results for true absorption of pions by nuclei and to the free $\pi-N$ interaction, we have constructed a potential that has many desirable features. Among these one should note the smooth dependence on energy and the validity of the potential both for π^+ and π^- [with the obvious change of sign of the isovector terms in Eqs. (2), (4), and (5)]. Several theoretical corrections such as Fermi averaging and Pauli blocking were not included, because most of the effects due to the nuclear environment enter, in any case, phenomenologically through the two-nucleon terms B_0 and C_0, and in that respect it is different from more fundamental approaches.[43]

A stringent test of the potential is its ability to predict angular distributions. Two such examples are shown in Figs. 5 and 6 where comparisons are made between predictions and experiment, for cases that were not included at all in the data base for the fit. The example with ^{48}Ca is most significant because of the relatively large isospin of the target. It is seen, therefore, that in the energy range of 0–80 MeV this potential is extremely successful in describing the elastic scattering of pions by nuclei and it could prove useful in calculations of other reactions too.

ACKNOWLEDGMENTS

We wish to acknowledge fruitful discussions with A. Gal and Z. Kalbermann. O. M. and E. F. acknowledge partial support by the Schonbrunn Endowment Fund.

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