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FORWARD AMPLITUDE IN PION DEUTERON SCATTERING

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ABSTRACT. ~~We analyse~~ the data on total cross section for πd scattering in terms of a single scattering calculation with Fermi motion dependence, in order to obtain a criterion to fix the value of the energy entering the two body meson nucleon amplitude. ~~We find~~ that the prescription derived from the non-reletivistic three body kinematics gives reasonable results. The introduction of a shift in the energy value, possibly representing nuclear binding effects, leads to a very good fitting of the data. ~~Our~~ results are compared with those obtained in direct calculations of Faddeev equations and with the Brueckner model of fixed scatterers.

RESUMO. Analisamos os dados experimentais de seção de choque total para espalhamento πd em termos de um cálculo de espalhamento simples com dependência em movimento de Fermi, com o objetivo de obter um critério para determinar o valor da energia em que a amplitude meson nucleon deve ser calculada. Obtivemos que o critério derivado da cinemática não-relativística de três corpos dá resultados razoaveis. A introdução de um deslocamento no valor da energia, possivelmente causado por efeitos de ligação nuclear, leva a um ajuste excelente dos dados. ~~Nossos~~ resultados são comparados com aqueles obtidos em resolução direta de equações de Faddeev e também com o modelo de espalhadores fixos de Brueckner.

1. INTRODUCTION

The evaluation of the differential cross section for pion-deuteron scattering at low and intermediate energies (below and about the P_{33} resonance region) has been performed mainly with two methods of calculation, namely the solution of three-body Faddeev-type equations and the evaluation of a few terms of the multiple scattering expansion. In general lines[1,2] the two approaches perform equally well, and equally badly, in the description of experimental data. The main failure of both methods rests in their unability to describe the elastic differential cross section at large angles for energies around and above 200 MeV. On the other hand, the elastic differential cross section for angles in the forward hemisphere is satisfactorily reproduced by both kinds of calculation. However, due to the large experimental errors in the available data on πd differential cross section, tests comparing the outputs of these different methods do not lead to definite conclusions. Technical questions involved in all calculations, such as the choice of prescription adequate to deal with kinematical ambiguities, or the proper recipe to perform the off-the-energy-shell extension of two-body amplitudes, cannot be solved in these circumstances.

Recent experimental measurements of total cross section for the interactions of pions (both π^+ and π^-) with deuterons[3] have set higher standards of accuracy in experiments of this kind. The experiment consisted of the measurement of πd total cross section as a function of the energy, in the range from 70 to 370 MeV incident pion kinetic energy. The accuracy is better than 0.5 percent in many points of the range. From the measurements of the total cross section, the imaginary part of the forward scattering amplitude f(0) is obtained through the optical theorem. With Imf(0) as an input, the real part Ref(0) was obtained by the same authors using forward dispersion relations. The authors estimate that the error in the value obtained for Ref(0) is not more than ± 0.1 fm in the whole energy range. The experiment was performed with unpolarized deuterons, so that the quantities obtained are averages and sums taken over the three initial and final polarization sates.

We thus have, directly derived from the experiments, the energy dependence of the forward elastic amplitude, with the imaginary part of the amplitude determined to higher accuracy than the real part. These are valuable pieces of information, as forward scattering offers the simplest and most favorable conditions for tests of some basic details of calculations of πd scattering. Contributions of second and higher order scatterings, Fermi motion and binding effects, and the influence of the specific form of the deuteron wavefunction, are much smaller in forward than in large angle scattering. On the contrary, due to strong cancellations then occurring in the integrals over the momentum distribution of the nucleons, backward elastic scattering is extremely sensitive to those and other effects. We may recall, for example, that Fermi motion effects changes by a factor two the backward scattering differential cross section at energies above 180 MeV[1]. Similar remark can be made about the presence of a d wave component in the deuteron wavefunction. Also, in the evaluation of the contributions of the multiple scattering terms of πd elastic process, it is seen that forward scattering is strongly dominated by the single scattering term. The double scattering contribution to forward scattering is more important below than above the resonance energy, but in no case changes the cross section by more than 3 percent. This is an important simplification, as it permits a closer study of the dominating single scattering term. In particular, these circumstances allows us to examine the kinematical and dynamical arbitrarinesses affecting the evaluation of the two body pion nucleon amplitudes which determine the single scattering contribution.

The experimental information described above has been analysed by Butterworth[4] in the framework of the Brueckner model of fixed scatterers with non-overlapping potentials. In his calculations, for energies below the resonance the contribution of the P_{33} wave is summed over all orders of multiple scattering, while the contributions of the other waves are evaluated up to double scattering. For energies above the resonance all waves are evaluated up to second order. These calculations show that all terms beyond single scattering give contributions to the cross section which are of the order of 10 percent. This is more than the 3 percent we obtain, and the larger value is possibly due to the assumption of fixed scatterers. Butterworth shows that his model gives good results for the forward amplitude, as seen through plots of the total cross section and of Ref(0), as compared to the experimental values. He also presents the results obtained from the Glauber model, which are not very different from those obtained in his calculations.

In the present paper we obtain Imf(0) and Ref(0) in a multiple scattering calculation, with allowance for nucleon recoil and Fermi motion effects, using several different kinematical prescriptions for the value of energy to be used in the evaluation of the two body pion nucleon amplitude. Some of these prescriptions have been used before[1] to obtain and compare values of the elastic differential cross section at all energies where experimental data are available.

The basis for one of these prescriptions consists in considering π-d scattering as a three-body problem governed by non-relativistic Faddeev equations. The exact amplitude is then expanded in the form of a multiple scattering series. In the explicit evaluation of the terms of the expansion, the matrix elements of operators defined in the three-body Hilbert space must be related to the usual two-body quantities. A shift appears in the value of the effective energy for the two body collision, which must then be calculated as equal to the total center of mass kinetic energy of the three particles minus the energy (calculated in the same system) of the particle which is not participating in that two body collision (the spectator particle for that term). This prescription will be hereafter called prescription A.

In most calculations performed in the past in the framework of the multiple scattering series, the adopted recipe for the kinematics governing the two body collision assumes that the incident particle collides with a nucleon which is on its mass shell, moving with a momentum probability fixed by the deuteron wavefunction. According to this choice, hereafter referred to as prescription B,the overall energy balance puts the spectator particle off the mass shell.

Another simple choice, which we call prescription C in what follows, assumes that the spectator nucleon behaves as an on shell particle, moving with the momentum distribution determined by the deuteron wavefunction. Correspondingly, the struck nucleon is now off the mass shell, with the same momentum as the spectator, and with energy determined by the difference between the deuteron mass and the total energy carried by the on-shell spectator.

In the calculations of the simplest kind, which ignore Fermi motion effects, the nucleon momentum is put equal to zero in the evaluation of the relative energy for the πN collision, so that the value of the two body amplitude is taken outside the integral over the deuteron wavepacket. For our future reference, this will be called prescription D.

Prescriptions A and C are similar to each other, as in both the effective energy for the πN collision is obtained subtracting the kinetic energy of the <u>on-shell</u> , spectator from the total energy. The difference rests in that the spectator energy is evaluated in the center of mass system for case A, while in case C the lab system value is taken.

Details of these kinematical prescriptions, and of the method of calculation, can be found elsewhere[1]. Among the above mentioned choices, prescription A, based on the three-body kinematics supporting Faddeev equation, has been shown the most adequate to describe πd elastic differential cross section near and below the resonance region. The non-relativistic three-body kinematics determines that the πN two-body collision operator evaluated between three-particle states appears in the calculations with a shift in the argument, given by the value of the kinetic energy of the nucleon which acts as spectator in each term of the multiple scattering expansion. Thus, if E is the value of the total kinetic energy of the πd system in the center of mass system, $\vec{P}(\vec{P}')$ is the initial (final) lab momentum of the struck nucleon, and $\vec{p}(\vec{p}')$ is the initial (final) meson momentum in lab system, then the matrix element to be evaluated is

$$\langle \vec{P}', -\vec{P}', \vec{p}' | t(E) | \vec{P}, -\vec{P}, \vec{p} \rangle = \delta(\vec{q}' - \vec{q})\,\delta(\vec{K}' - \vec{K}) \langle \vec{k}' | \hat{t}(E - \frac{\vec{q}^{\,2}}{2\mu}) \vec{k} \rangle \qquad (1)$$

where $\vec{K}(\vec{K}')$ is the total initial (final) momentum of the three particles, $\vec{q}(\vec{q}')$ is the initial (final momentum of the spectator nucleon with respect to the center of mass, and $\vec{k}(\vec{k}')$ is the initial (final) momentum of the meson relative to the center of mass of the interacting meson-nucleon system. The reduced mass μ is given by

$$\mu = m_N(m_N + m_\pi)/(2m_N + m_\pi) \qquad (2)$$

and $\tilde{t}$ is the usual two-body collision operator. The argument of the two-body transition operator then reads

$$E - \frac{\vec{q}^{\,2}}{2\mu} = E - \frac{[(2m_N + m_\pi)\vec{P} + m_N\vec{p}]^2}{2m_N(m_N + m_\pi)(2m_N + m_\pi)} \qquad (3)$$

We must be aware that pions are relativistic in the energy region of our interest, while the formalism leading to Eqs (1)-(3) is non-relativistic. In a fully relativistic formalism the total center of mass energy is not linear in the energy of the particles, and the energy of the spectator particle cannot be removed from the matrix element of the two-body collision operator evaluated in the three-body Hilbert space. However, the only result of consequence in our evaluation of cross sections is Eq (1), and the approximations involved in its use is expected to be very reasonable, a. the spectator particle, whose energy is subtracted from the total energy available, is always a non-relativistic nucleon. Of course pions individually are treated as relativistic particles in the sense that its energy and momentum are connected by the relativistic formula. As an attempt to account for the relativistic behaviour of the pions[5,6] an additional modification can be introduced in prescription A, substituting the value of the pion energy evaluated in the center of mass system for the mass m_π in Eq (3).

Several effects which are relevant for large angle scattering, and which are not under complete control in the calculations, such as those resulting from unknown details of deuteron structure, off-energy-shell extrapolation of two body matrix elements, multiple scattering contributions, and so on, affect strongly the results and have not allowed us to define a preference among the different kinematical prescriptions, based on the presently available measurements of differential cross sections. The comparative importance of these disturbing effects is minimized in forward scattering, where the kinematical prescriptions can then be more clearly studied. This study is the motivation for our calculations of the forward amplitude, whose results are presented in the next section.

II. RESULTS OF CALCULATIONS

a) The Total Cross Section

Fig. 1 shows the experimental results[3] on the πd total cross section, together with the theoretical values obtained from Im f(0) through the optical theorem, using different kinematical prescriptions. As the contribution of double scattering is of the order of magnitude of the experimental errors, and less than the difference between prescriptions, our calculations are limited to the single scattering terms. We are thus avoiding to introduce complications before the question of the kinematical ambiguities is settled. Moravcsik deuteron wavefunction with 7 percent d wave is used everywhere in our calculations. It is seen from the figure that prescription B (struck nucleon on shell, with Fermi motion effects included) and prescription

D (no allowance for Fermi motion dependence) perform badly, remarkably more so in the resonance region. The three-body inspired kinematics, represented by case A, and prescription C (with on-shell spectator), both give reasonable results in the whole energy range. At this point it may be inferred that, similarly to what has been found in the application of the multiple scattering method to the calculation of the differential cross section[1], the usual calculations in the impulse approximation framework, made with on shell struck nucleon, including or not including Fermi motion effects (prescriptions B and D respectively), do not give the best results. According to Fig 1, the distinction between prescriptions A and C cannot be based on the comparison of calculations and data on total cross section . The choice can perhaps be made, favoring case A, examining the behaviour of the elastic differential cross section at large angles[1]. The situation is not completely clear, mainly due to the low accuracy of the data, but we can also rely on theoretical grounds to justify a preference towards prescription A.

A limitation of a multiple scattering calculation such as ours is that the pion deuteron interaction is described in terms of a sequence of two-body pion nucleon and nucleon nucleon collisions. These two-body amplitudes used here are purely elastic, not allowing for pion production or absorption. Thus there are kinds of reactions which are included in the measured value of the total cross section, but which are not included in our model. It is not easy to evaluate precisely the influence of these processes of pion creation and re-absorption in our simple model for the forward scattering amplitude. However we may estimate its possible magnitude by subtracting from the observed values of σ_{total} the experimental values of the cross sections for reactions involving pion absorption ($\pi^+ d \to pp$, for example). This subtraction is shown in Fig 1, where the values of $\sigma_{total} - \sigma_{absorption}$ are shown for a few selected energy values where data are available[7]. It is seen from the figure that for energies below the resonance the subtraction of $\sigma_{absorption}$ brings the experimental points closer to the theoretical curve for prescription A. At 200 and at 230 MeV the subtracted cross section becomes rather too low, lying almost 10 mb below the theoretical curve. Above 250 MeV the cross section for processes with pion absorption is negligible.

Looking at Fig 1 we find the remarkable feature that the theoretical curves for prescriptions A and C seem to be shifted along the axis of the energy variable with respect to the experimental data. In Fig 2 we show the curve for the total cross section evaluated in case A with a shift of - 7 MeV in the value of the total center of mass energy used to determine the value of the meson nucleon amplitude in the single scattering calculation. The argument of the collision operator $\hat{t}$ in Eq (1) then becomes $E - \frac{\vec{q}^{\,2}}{2\mu} - \varepsilon$, where $\varepsilon = 7$ MeV in Fig 2. The curve obtained with the introduction of this constant shift fits almost perfectly the data. The value of σ_{total} at the peak, which is too low before the shift is introduced, appears now correct. The shift changes the amount of energy, carried by the spectator, which is subtracted from the total kinetic energy in the evaluation of the two-body amplitude. We may say that this shift represents a simulation for binding corrections, and possibly some other unknown effects, which are not incorporated in the simple model. Unfortunately we do not have a quantitative justification for the numerical value $\varepsilon =$ 7 MeV which we have chosen to fit the data. We have observed that the fitting is very sensitive to the constant numerical value of the energy shift. At the high energies the sensitivity is not pronounced, but in the resonance region hardly another value of ε can be adopted (for example, a shift of 10 Mev is remarkably too large). In the low energy region (below 150 Mev) the reccommended shift for single scattering calculation could be a little higher ($\varepsilon \simeq 10$ Mev for example) than the value of 7 MeV chosen as adequate for the resonance region.

The separation of the spectator energy shown in Eq (1) is carried out in a non-relativistic framework. As mentioned in the introduction, it has been suggested[5,6] that m_π be changed into $E_\pi = (m_\pi^2 + k^2)^{1/2}$, the pion energy in the center of mass system, in order to account for relativistic effects. We have made calculations of σ_{total} introducting this change, and verified that the change acts in the correct sense, moving the theoretical curves towards the experimental data in the whole energy range. However the improvement is too small, being noticeable only in the resonance region, where the cross section value is increased by 5 mb (less than 3 percent). In the low energy end the change introduced by this relativization is negligible, due to the small value of the pion momentum, while above the resonance the change is too small due to the insensitivity of the cross section. In other words, the relativistic correction is an improvement, but does not eliminate the requirement of a shift in the effective energy for the meson nucleon amplitude. The value of the shift should now be a little smaller, say $\varepsilon = 5$ MeV.

b) Real Part of the Forward Amplitude

The values of Ref(0) obtained[3] applying forward dispersion relations to the data on total cross section are shown in Fig 3. Since the estimated error in the evaluation of Ref(0) amounts to $\pm$ 0.1fm, we have drawn as a shaded area the band of values implied by this determination. In the same figure we plot the curves for Re f(0) obtained with different kinematical prescriptions. The curves are given for prescription A, with and without additional shift $\varepsilon =$ 7 MeV, and with prescription C. It is seen that these theoretical curves based on single scattering calculations reproduce the general features of the data represented by the shaded band. The curve obtained with shifted energy ($\varepsilon =$ 7 MeV) is clearly more satisfying than the others.

c) Differential and Integrated Elastic Cross Section

The calculations of differential cross sections for elastic πd scattering[1] in the multiple scattering framework have shown that in the resonance region prescription A gives the best results. We have now repeated these calculations, introducing the additional shift $\varepsilon = 7$ MeV in the argument of the πN amplitude at the energies 142, 182 and 256 Mev for which experimental data are available[8,9,10]. The calculations show that the effect of the shift is very small at large angles, and maximum in the forward direction. At 142 and 182 MeV the influence of the shift over the forward differential cross section is such as to bring the theoretical values closer to the experimental points. At 256 MeV the shift has very little effect, even in the forward direction. These results are clearly illustrated in Table I, where the forward scattering amplitude f(0) and the forward differential cross section obtained in several different calculations are confronted with the experimental data.

The existing data on differential cross sections for elastic πd scattering are not so accurate as those for the total cross section obtained in the recent SIN experiment[3], and do not allow a clear distinction among different theoretical calculations. Table I shows the values for the integrated elastic cross section obtained theoretically and in experiments at 142[8], 182[9] and 256[10] Mev. It is clear that better data of this sort are strongly needed.

III. CONCLUSIONS

Analysing the new data[3] on πd total cross section we find that a single scattering calculation with allowance for Fermi motion effects is able to describe the real and imaginary parts of the forward scattering amplitude in the energy range from 70 to 370 MeV. Taking advantage of the circumstance that several complications (multiple scattering contributions and details of deuteron structure) occurring in πd interaction have their influence reduced to a minimum in the forward direction, we have concentrated our attention on the determination of the value of the energy entering in the evaluation of the two-body pion nucleon amplitude. We have shown that the standard kinematical recipes, which treat the struck nucleon as an on-shell particle, with or without consideration for Fermi motion effects (these are called by us prescriptions B and D respectively), do not give good description of the total cross section data. We have shown that prescription A, derived from the non-relativistic three-body kinematics, and prescription C, which puts on-shell the spectator nucleon, reproduce fairly well the experimental results. The theoretical curves for the total cross section obtained in these two cases C present as a common feature the same shape of the experimental curve, but are displaced by a few MeV towards higher values along the energy axis. The subtraction of a constant amount ε = 7 MeV from the value for the effective two body collision energy generated by the three body kinematics (prescription A) leads to a very good fitting of the data. In the low energy region (below 140 MeV) a larger value of ε would be more appropriate, but from 150 to 230 MeV the shift should not be larger than 7 MeV. At higher energies the cross section values do not change appreciably with introduction of the 7 MeV shift. A natural interpretation for the requirement of a shift in the energy can be given considering that it provides an effective way to correct for binding effects, increasing the amount of energy carried by the spectator nucleon.

With the purpose of accounting for the relativistic nature of the pions, we have tested an alternative modification in the kinematics, following a recipe[5,6] according to which the pion total energy is substituted for the pion mass in the evaluation of the effective energy for the πN collision. We found that this procedure introduces minor improvements, and does not play the same role as the parametric shift.

Comparison of the results of our single scattering model with direct calculations of Faddeev equations[5,6] and with the results from the Bruckener model of fixed scatterers[4] is shown in Table I. As far as the forward scattering amplitude and the integrated elastic cross section are concerned, there is no strong discrepancy among these different calculations, and to distinguish among them we require good data on angular distributions.

As for the differential elastic cross section, the existing data in the energy range below the resonance are very poor and do not provide information able to test the theoretical calculations. For energies above the resonance we enter into the problem of the backward angle scattering, which has resisted all attempts made up to now. The shift in the energy in the evaluation of the πN amplitude does not help in solving this problem.

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FIGURE CAPTIONS

Fig. 1 - Results of single scattering calculations of πd total cross section, obtained from Im f(0) through the optical theorem. Each curve corresponds to a different criterion fixing the value of the energy in the πN amplitude. The solid curve represents prescription A (see text) obtained from non-relativistic three body kinematics. The dotted line is obtained with spectator nucleon on mass shell (prescription C). The dashed curve (case B) and the dot-dashed curve (case D) are obtained with struck nucleon on shell, respectively with and without Fermi motion dependence in the amplitudes. The experimental points on the total cross section are from Ref. 3. The circled points are obtained subtracting the absorption cross section, which is not accounted for in a multiple scattering calculation.

Fig. 2 - Results of single scattering calculations of πd total cross section, obtained from Im f(0) through the optical theorem. The solid curve is the same as in Fig. 1, corresponding to prescription A. The dashed curve is obtained introducing a shift $\varepsilon =$ $= 7$ MeV in the energy value used to evaluate the πN amplitude (see text).

Fig. 3 - Real part of the foward amplitude for πd scattering.

The dashed band represents the values, with ± 0.1 Fermi errors, obtained in Ref. 3 applying dispersion relations to the data on total cross section. The solid and the dotted curves represent the single scattering calculation using prescriptions A and C respectively. The dashed line is obtained as in Fig. 2 introducing a 7 MeV shift in the energy.

TABLE I

Comparison of Calculations and Data

a) Forward Amplitude f(0) Averaged over Polarizations (fm)

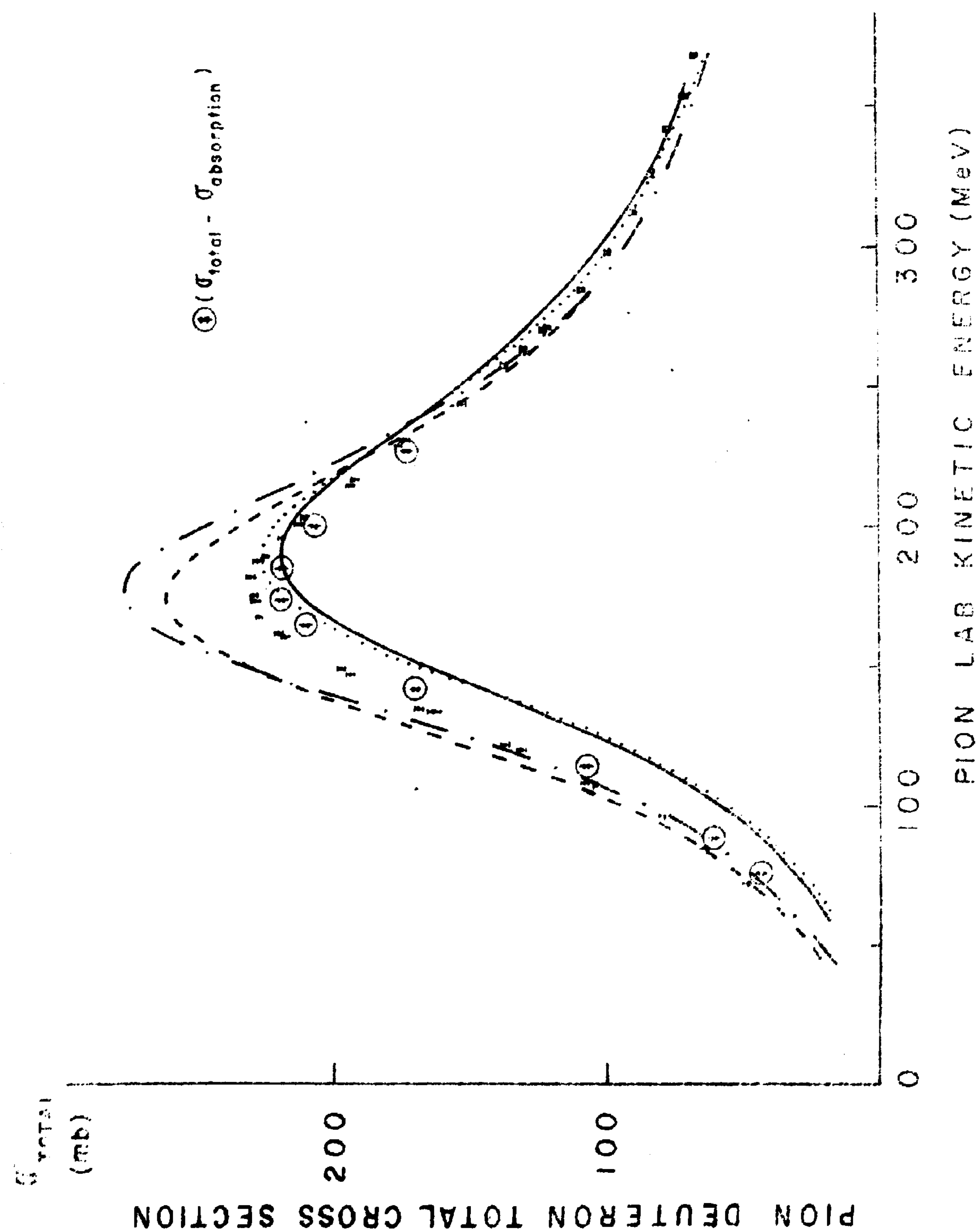
Energy (Mev)	Single Scattering (A)	Single Scattering with 7 MeV shift	Fixed Scatterers Ref 4	Faddeev Equations Ref 6	Faddeev Equations Ref 5	Experimental Ref 3
142	1.06+i1.25	1.06+i1.56	1.07+i1.61	1.40+i1.44	1.09+i1.38	1.00+i1.57
182	0.42+i2.18	0.16+i2.35	0.42+i2.12	0.60+i2.29	0.63+i2.34	0.04+i2.31
256	-0.98+i1.82	-1.07+i1.75	-0.77+i1.57	-0.76+i1.68		-1.27+i1.73

b) Forward Differential Cross Section $\left(\frac{d\sigma}{d\Omega}\right)^{c.m.}_{\theta = 0}$ (mb/strd)

Energy (MeV)	Single Scattering (A)	Single Scattering with 7 MeV shift	Fixed Scatterers Ref 4	Faddeev Equations Ref 6	Faddeev Equations Ref 5	Experimental Ref 3
142	26.9	35.7	37.4	40.3	29.8	34.3
182	49.2	55.5	46.7	56.0	56.2	52.3
256	42.7	42.1	30.7	34.0		46.0

c) Integrated Elastic Cross Section σ_{el} (mb)

Energy (MeV)	Single Scattering (A)	Single Scattering with 7 Mev shift	Faddeev Equations Ref 5	Experimental values
142	47.1	56.6	50.3	Ref 8 47.0 ± 3.2
182	60.1	69.9	69.2	Ref 9 65.0 ± 3.0
256	35.8	-		Ref 10 35.1



(σ_total - σ_absorption)
0
100
200
300
PION LAB KINETIC ENERGY (MeV)
σ_total (mb)
100
200
PION DEUTERON TOTAL CROSS SECTION

Fig. 1

PION DEUTERON TOTAL CROSS SECTION

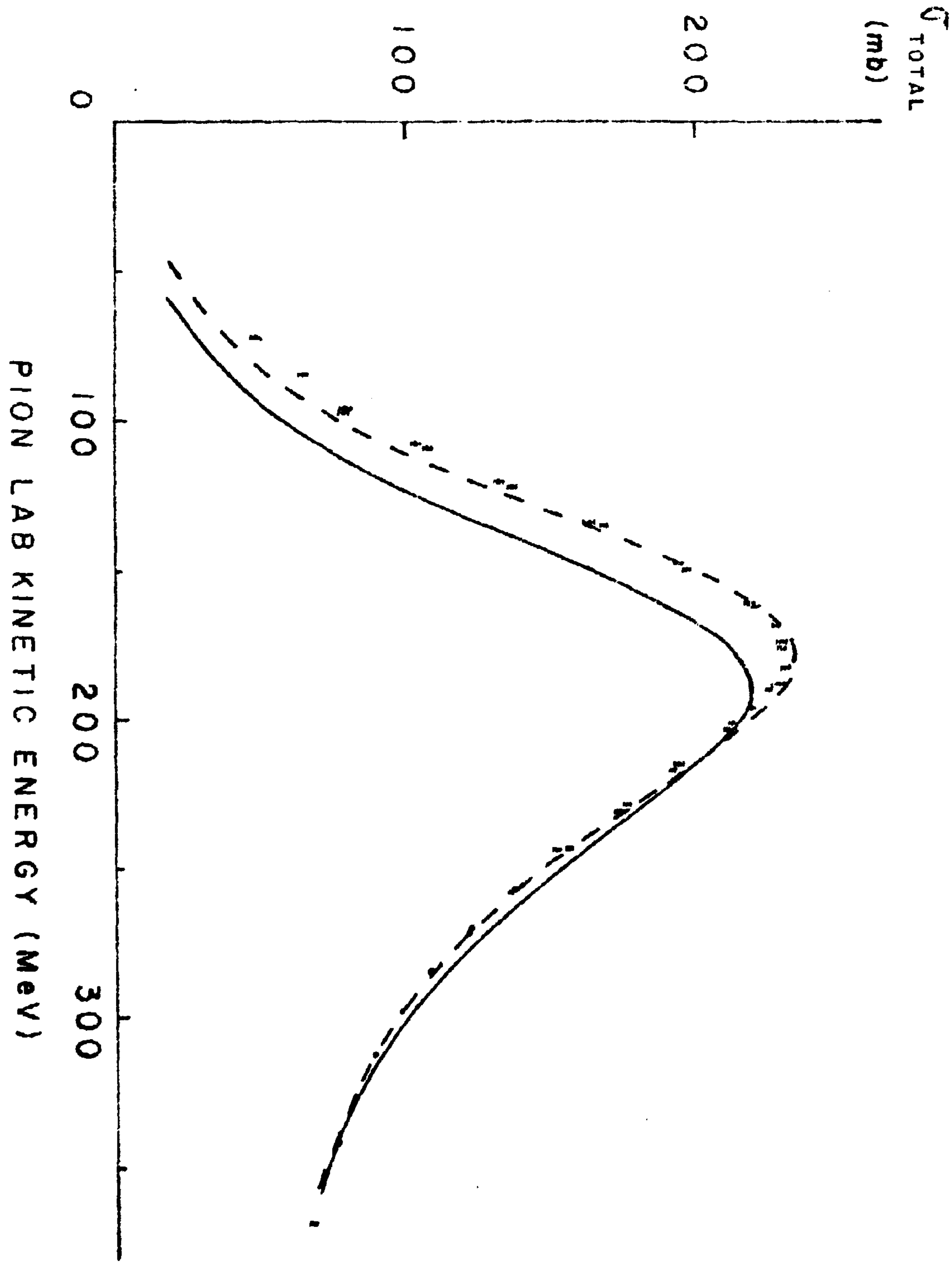


Fig. 2

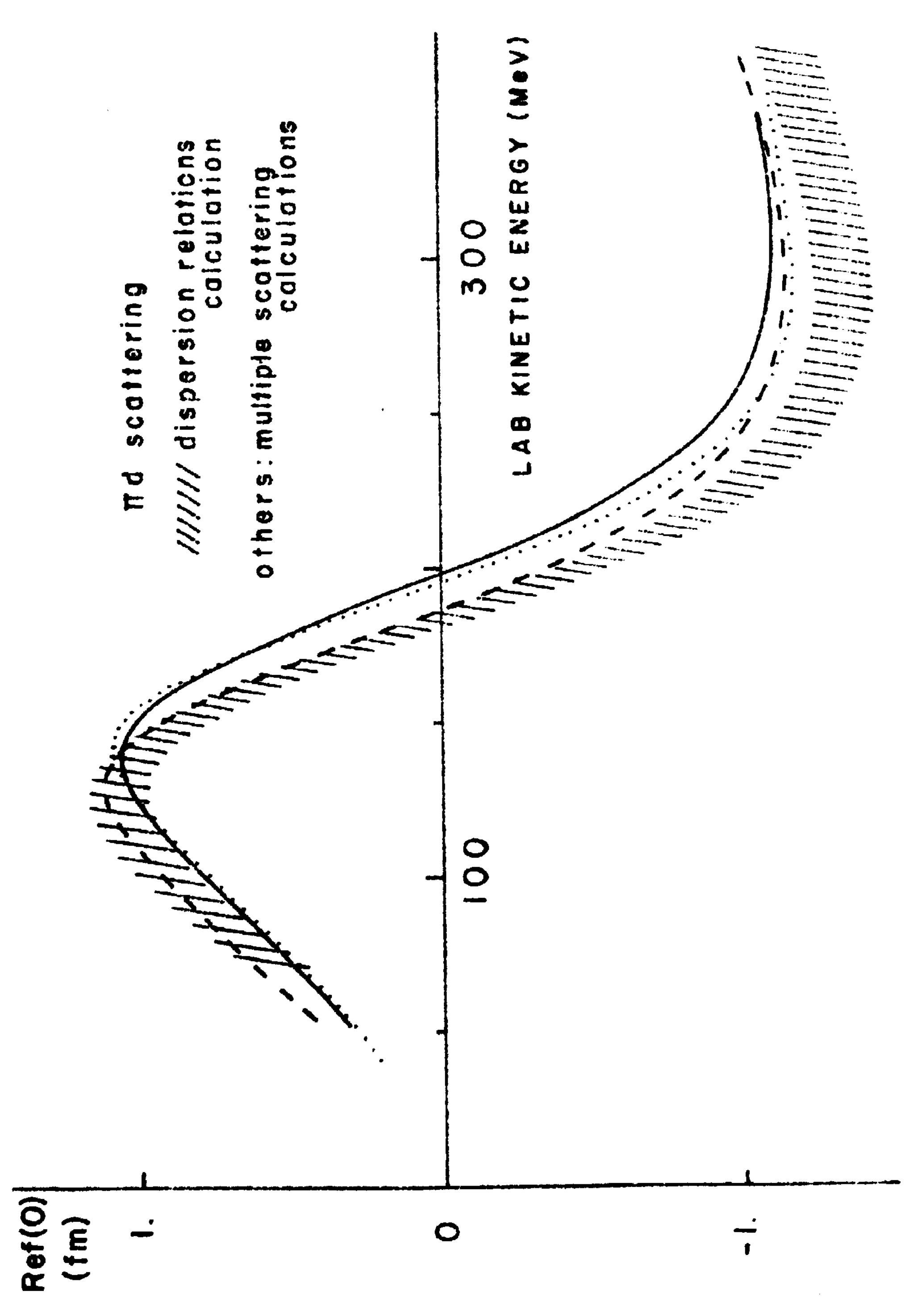

πd scattering
/////// dispersion relations calculation
others: multiple scattering calculations
LAB KINETIC ENERGY (MeV)
100
300
Ref(O) (fm)
1.
0
-1.

Fig. 3