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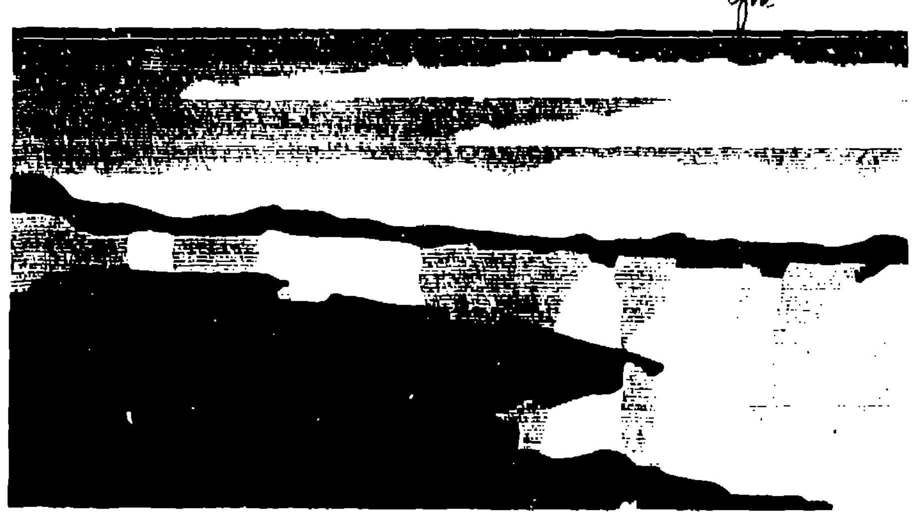

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# HADRON DYNAMICS IN HIGH-ENERGY PION-NUCLEUS SCATTERING

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## ABSTRACT

It is argued that pion-nucleus scattering at high energy (above 300 MeV) is likely to be easier to interpret than it has been at lower energies where the $\Delta_{33}$ resonance dominates. We establish this by examining the relative importance of various dynamic ingredients of scattering theory for high-energy pions and comparing different versions of the theory: a "model-exact" microscopic optical model and an eikonal approximation. For nuclei as heavy as Ca, the eikonal theory is an excellent approximation to the full theory for the angular distribution out to the position of the second minimum in the cross section. The prospects for using high-energy pions to examine modifications of nucleons and baryon resonances in nuclei, nuclear structure, exchange currents, short-range correlations, and to characterize pion propagation are discussed.

## I. INTRODUCTION

Pion-nucleus scattering at the meson factories has concentrated on the energy range up to several hundred MeV incident pion kinetic energy. These results have provided a variety of insights into how mesons interact with nuclei as well as about nuclear structure. What can be learned from higher-energy pion-nucleus scattering? This question is of some interest because next-generation meson factories will have the capability of high-quality beams of pions up to energies of one or more GeV.

In this talk, I would like to attempt to provide some answers that have come out of recent studies of this question at LAMPF, including a study by the LAMPF users group.[1] I will also mention some of the work that I have done recently on the problem with my collaborators Jasson Chen, Dharam Ahluwalia, and David Ernst.[2]

Let me begin by noting that there are two ways in which high-energy pion scattering data can be helpful. One is to provide data with which specific dynamical models of general interest can be tested. This includes models of nuclear structure and hadron dynamics, the latter including short-range correlations, isobar-nucleon interactions, and exchange currents. The other is to provide data needed for interpretation of experiments in related areas of nuclear physics such as high-energy electron scattering, heavy-ion collisions, and hypernuclear physics through the $(\pi,K)$ reaction. Pion scattering data is essential, because in high-energy collisions of any type pions are a prominent feature of the initial, intermediate, and final states. Both require data in specific reaction channels, including double charge exchange, true absorption, quasi-elastic scattering, pion-production, elastic scattering, and inelastic scattering. Typically, these channels can be characterized experimentally in great detail given the high intensity and large array of detectors available at the meson factories.

For the most part, I will concentrate here on investigations that aim at a microscopic understanding of phenomena. The talk will be organized as follows: In Sec. II, I will discuss the theoretical tools for studying high-energy pion scattering. It will be argued that pion physics is likely to be simpler in the energy region above the $\Delta_{33}$ resonance. I will show by comparing to exact calculations how well one can expect the semi-classical theory to work. In Sec. III, I will indicate some of the issues that might be studied with high-energy pions. In Sec. IV, I will draw my conclusions.

## II. THEORETICAL TOOLS

In order to test models using pion scattering data, one would like a flexible theoretical framework that is capable of providing a simple answer to specific questions. Ultimately, suitable methods should be available to analyze all reactions mentioned in the introduction. In this section, we will establish that semi-classical methods are of this character. We will do this by comparing the results of the semi-classical theory for elastic scattering to a "model-exact" momentum-space optical model calculation for elastic scattering.

In the study of high-energy pion-nucleus scattering, more and more partial waves are needed in the pion-nucleon two-body amplitudes as the energy increases. This can be inferred from the middle panel of Fig. 1, which illustrates resonances in the pion-nucleon scattering amplitude that come into play at energies below 1600 MeV. Below 300 MeV, only $S$-waves and $P$-waves are needed. Above 300 MeV, $D$-waves become important. $F$-waves become significant above 500 MeV, and $G$-waves and $H$-waves above 700 MeV. At the same time, the number of pion-nucleus partial waves is increasing at a rate proportional to the pion momentum. Thus, at high energies the momentum-space approach, which is computationally intensive, becomes prohibitively inefficient.

On the other hand, a semi-classical theory, which becomes increasingly quantitative at high energies, is much simpler to compute. In addition, the simpler character of the theory can more easily reveal physical insights. As the wavelength of the projectile becomes shorter, the semi-classical theory would eventually become a good approximation if the optical potential were local. The pion-nucleus optical potential is highly nonlocal, as are our model-exact calculations, so it is not *a priori* clear that one is justified in using the semi-classical theory to simplify the calculation of pion-nucleus scattering observables.

In our comparisons, both the optical and the eikonal models use the same target wave functions, which are obtained from Hartree-Fock calculations. We also use the same on-shell pion-nucleon two-body amplitudes, which are from Arndt's and Höhler's phase shifts.

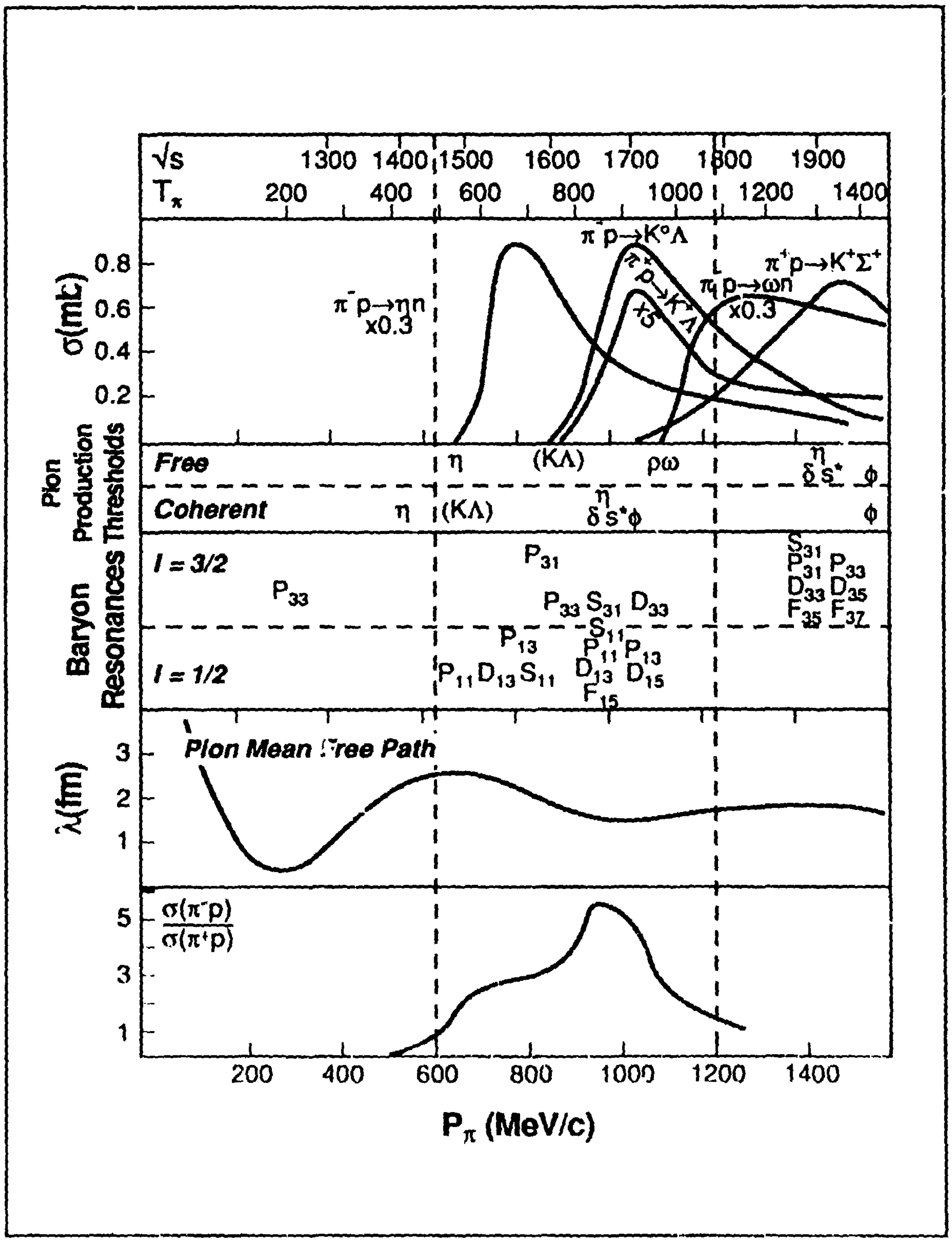


*Fig. 1. Energy dependence of the two-body πN scattering amplitude, from Ref. i*

Working in momentum-space presents the opportunity to calculate the scattering from a lowest-order optical potential, which includes the following features: (1) exact Fermi-averaging integration, (2) fully covariant kinematics, normalizations, and phase-space factors, (3) invariant amplitudes, and (4) finite-range, physically motivated two-body off-shell amplitudes. The program ROMPIN,[3] which we used in solving the scattering problem in the region of the $\Delta_{33}$ resonance[4] includes these features and is used as the basis of the calculations. We exploit it and make exact calculations with the lowest-order optical potential. A brief review of this approach will be given here; we refer the reader to Ref. 4 for a complete list of references to earlier work.

The relativistic first-order optical potential can be written in the impulse approximation as

$$\left\langle \bar{P}_1'\bar{P}_A' \middle| U(E) \middle| \bar{P}_1\bar{P}_A \right\rangle = \sum_{\alpha_3}\int \frac{d^3\bar{P}_3}{2\bar{E}_3}\left\langle \psi'\left(\bar{P}_A'\right) \middle| \bar{P}_2'\bar{P}_3\alpha_3 \right\rangle \left\langle \bar{P}_1'\bar{P}_2' \middle| T\left(E^{cm}\right) \middle| \bar{P}_1\bar{P}_2 \right\rangle \left\langle \bar{P}_2\bar{P}_3\alpha_3 \middle| \psi\left(\bar{P}_A\right) \right\rangle , \quad (1)$$

where $\bar{P}_1$, $\bar{P}_2$, and $\bar{P}_3$ are the momenta of the incident particle, the struck nucleon and the $A-1$ residual nucleons, respectively. $E^{cm}$ is the center-of-momentum (CM) energy at which the pion-nucleon $t$-matrix is to be evaluated,

$$E^{cm} \approx E_\pi^0 + E_B - \frac{\left(\bar{k}_\pi + \bar{k}_N\right)^2}{2\left(m_N + E_\pi^0\right)} , \quad (2)$$

where $E_\pi^0$ is the energy of the pion in the pion-nucleus center-of-momentum frame, $E_B$ is the binding of the struck nucleon, and $\alpha_3$ is a set of quantum numbers that specifically label the nuclear bound state. Note that from the conservation of momentum, $\bar{P}_A' = \bar{P}_1' + \bar{P}_3$ and $\bar{P}_A = \bar{P}_1 + \bar{P}_3$.

For the off-shell pion-nucleon two-body $T$-matrix we choose a simple separable form for each spin, isospin channel $\alpha$:

$$\left\langle p'l's' \middle| T(\omega) \middle| pls \right\rangle = \frac{v(p')}{v(p_{on})}\left\langle p_{on}l's' \middle| T_\alpha(\omega) \middle| p_{on}, ls \right\rangle \frac{v(p)}{v(p_{on})} , \quad (3)$$

where $\omega$ and $p_{on}$ are the total energy and the on-mass-shell momentum in the pion nucleon two-body center-of-mass frame, respectively. The $T$-matrix is Lorentz invariantly normalized, and thus avoids any kinematics singularity. The on-shell values are taken from experiment as we have indicated. The function $v(p)$ has a Gaussian form, $e^{-p^2/\beta^2}$.

The optical potential, after being calculated, is inserted in the Klein-Gordon Lippmann-Schwinger equation. The pion-nucleus reaction matrix is obtained using matrix inversion techniques. The reaction matrix is converted to the $T$-matrix, which is then converted to the differential cross section. The theory works very well in the region of the $\Delta_{33}$ resonance, as shown in Fig. 2, when various medium modifications are included as explained in Ref. 4. Especially important is the shift of the $\Delta_{33}$ mass in the nucleus; to incorporate this, a constant (whose value is very close to the average binding potential of a nucleon in the nucleus) is added to the right-hand side of Eq. (2).

Although the Fermi-averaging integration is quite important in the region of the $\Delta_{33}$ resonance, we have found that for high-energy pion-nucleus scattering (above about 300-MeV incident pion energy) it does not significantly affect the elastic differential cross section out to the position of the second minimum in the angular distribution. This means that we get essentially the same results doing the full Fermi averaging or making the closure approximation, in which the $E_B$ and $\bar{k}_N$ in the last term on the right-hand side of Eq. (2) are dropped. This is the case even though the pion-nucleon amplitude is, partial wave by partial wave, rather energy dependent, exhibiting resonances in various partial waves as was already pointed out in the discussion of Fig 1. We also made calculations varying the form-factor range $\beta$ from 500 MeV to 4 GeV, where we see similar levels of insensitivity. We conclude from these studies that at least two sources of nonlocality are of minor importance at forward angles for the higher energy pions, contrary to what one might have expected. This opens the possibility that a simple eikonal approximation might be valid.

We developed a semi-classical model, the eikonal approximation, which includes the Coulomb interaction, the Wallace corrections, and is based on a simple local potential calculated from the same pion-nucleon two-body amplitudes as used by the exact optical potential theory. Wallace has shown that the semi-classical theory can be improved if the corrections that bear his name are added. The results of this section were adapted from Ref. 5, and we refer the reader to that paper for references to earlier work.

In the eikonal approximation, we take the scattering amplitude to be written as

$$F(q) = F_{pt}(q) + F_{CN}(q) \ , \tag{4}$$

where $q$ is the momentum transfer. $F_{pt}$ represents the Coulomb amplitude. $F_{CN}$ denotes the nuclear and the finite size Coulomb amplitude, and is written as

$$F_{CN}(q) = ik\int_0^\infty b\,db\,J_0(qb)\,e^{i\chi_{pt}(b)}\,\Gamma_{CN}(E,b) \ , \tag{5}$$

where $k$ is the momentum of the incident particle in the projectile-nucleus CM frame, $b$ is the impact parameter, $\chi_{pt}$ is the point Coulomb phase, and $\Gamma_{CN}$ is the profile function.

To incorporate the distortion and energy shift caused by the Coulomb interaction, we write the profile function as

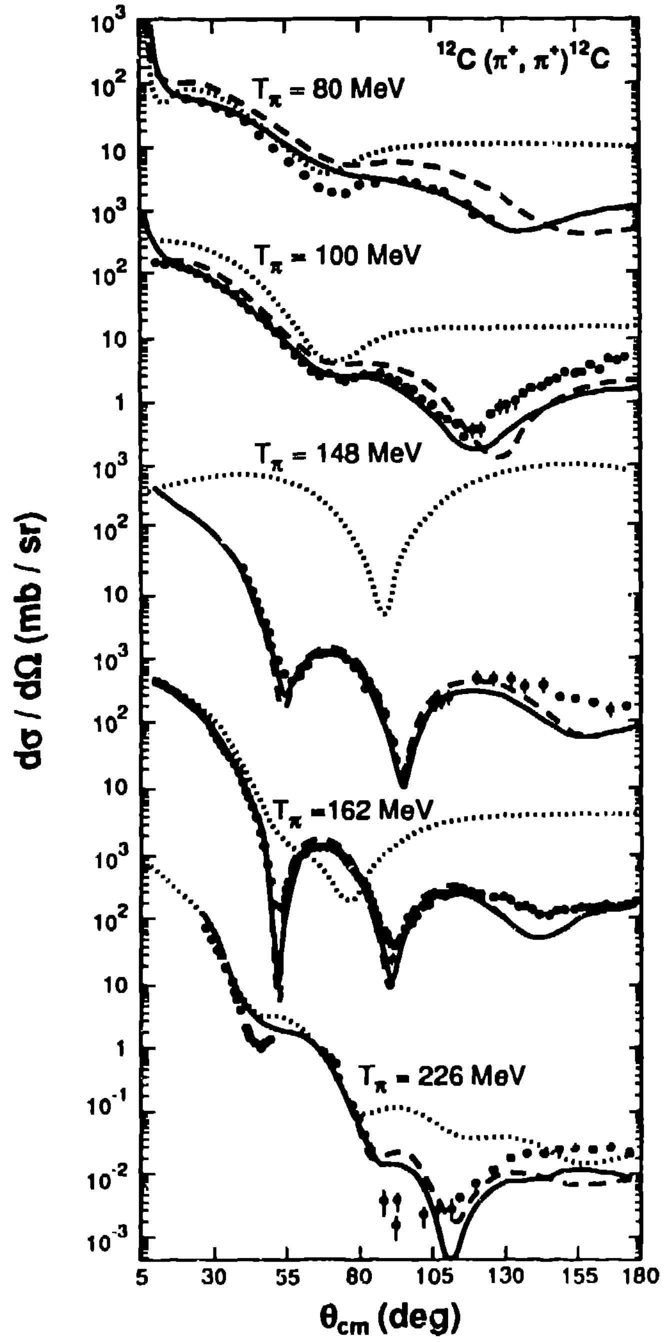


*Fig. 2. The results of a zero-parameter description of pion-nucleus scattering data in the region of the $\Delta_{33}$ resonance using the momentum-space theory of Ref. 4. The dashed curve is the lowest-order potential; the dotted curve includes, in addition, Pauli effects; and the solid curve is the final result, including the spreading interaction.*

$$\Gamma_{CN}(E,b)=1-\exp\{i\chi_{CN}(E,b)\}$$
$$=1-\exp\left\{i\chi_N\left[E-V_c(b),b\left(1+EV_c(b)/k^2\right)\right]+i\chi_c(b)-i\chi_{pt}(b)\right\}\,, \qquad (6)$$

where $\chi$ is the phase shift caused by a uniformly charged sphere, $V_c$ is the Coulomb potential, and the nuclear phase shift $\chi_N$ is written as

$$\chi_N(E,b)=-\frac{1}{2k}\int_{-\infty}^{\infty}dz\,U\left[E,\left(b^2+z^2\right)^{1/2}\right]. \qquad (7)$$

A local, strong-interaction potential $U$ is obtained from the pion-nucleon two-body forward scattering amplitude with a small-angle expansion correction, and can be expressed as

$$U(E,r)=-Z\left[f_p(0)\rho_p+\frac{f_p'(0)}{2k^2}\nabla^2\rho_p\right]-N\left[f_n(0)\rho_n+\frac{f_n'(0)}{2k^2}\nabla^2\rho_n\right], \qquad (8)$$

where $Z$ and $N$ are the proton number and the neutron number respectively, $f(0)$ is the forward, on-shell pion-nucleon scattering amplitude in the pion-nucleus CM frame, and $f'(0)$ is the derivative of $f(0)$ with respect to the square of the momentum transfer.

To improve the eikonal model representation of the solution from a Klein-Gordon equation, we utilize the Wallace correction in the strong potential, which is written as

$$U(E,b)=U+\frac{U^2}{4k^2}\left(1+\frac{2b^2}{r}\frac{d}{dr}\ln U\right). \qquad (9)$$

As the eikonal theory becomes a better approximation to the exact solution of the Klein-Gordon equation, the Wallace corrections become smaller. We have found that the Wallace corrections are small but nonnegligible at energies above about 300 MeV, but that close to the $\Delta_{33}$ resonance they can be unacceptably large.

For a highly nonlocal interaction, such as that expected for the pion-nucleus optical potential, the eikonal theory is not guaranteed to be a good approximation to the exact theory. This is because the eikonal approximation is derived assuming a local potential. In order to calibrate the eikonal theory for high-energy pion-nucleus scattering, we must make numerical comparisons. The insensitivity of the cross section to the off-shell range $\beta$ and to Fermi averaging, which we established earlier, is a necessary but not a sufficient condition for the validity of the eikonal representation.

We show our results for $\pi^+$-$^{40}Ca$ at 800 MeV/c in Figs. 3(a) and (b). The location of the minima and the magnitude of the cross section at the forward angles are in good agreement for

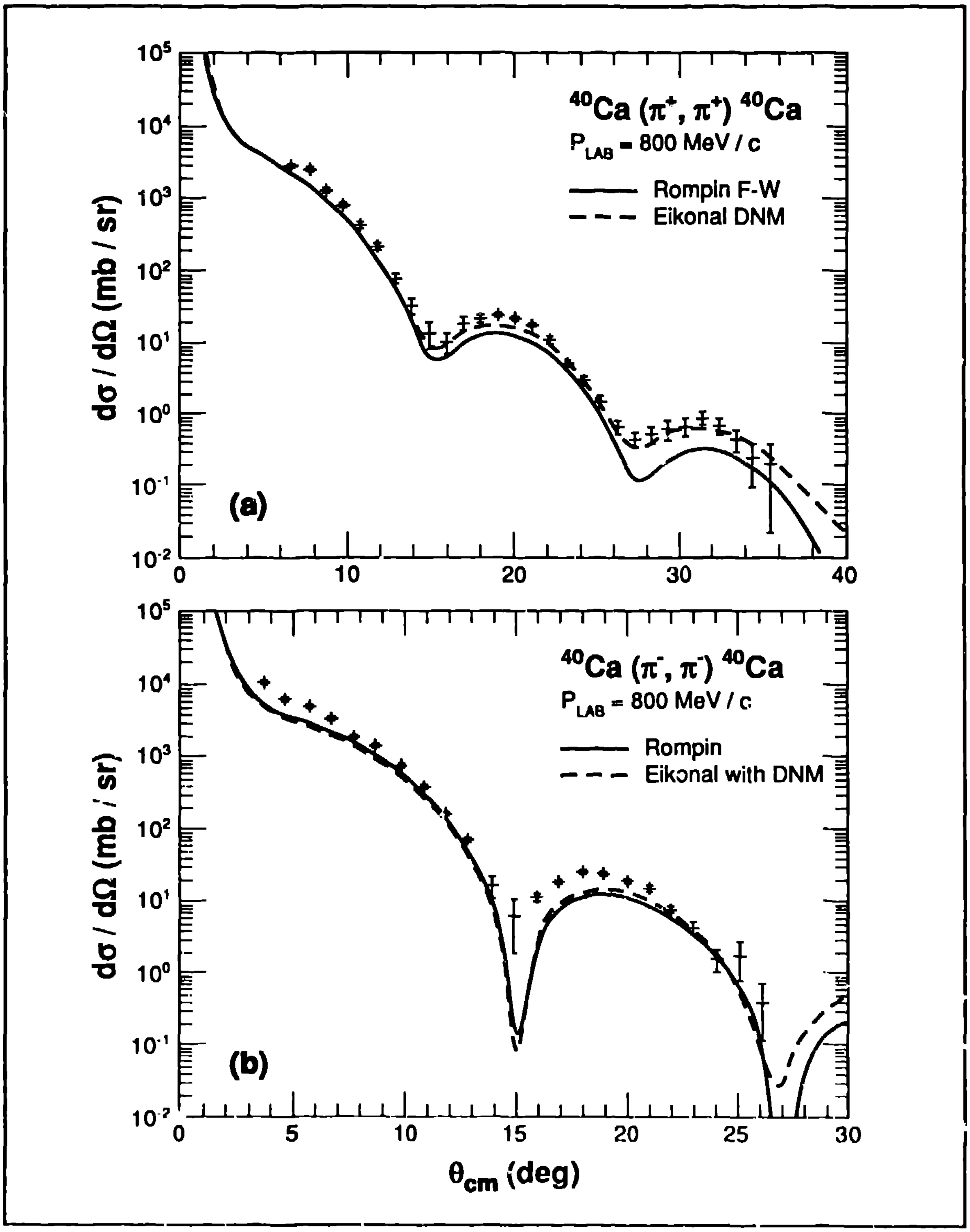


*Fig. 3. Results of the eikonal theory and momentum-space optical model for 800-MeV/c data for $\pi^{\pm}$-$^{40}$Ca scattering. Experiment is from Ref. 6.*

the two calculations. We find similarly good agreement for other heavy nuclei, but for a light nucleus like $^{12}C$ the results are slightly inferior to this. These results justify the use of the eikonal representation for pions at high energy.

Knowing that the eikonal theory is a semi-quantitative approach to pion-nucleus scattering at energies above about 300 MeV makes possible the study of a variety of issues with high-energy pions. These include nuclear structure, pion propagation in the medium, and hadron dynamics. The latter, which includes the study of exchange currents and nucleon-nucleon correlations, may be investigated using pion double charge exchange.

Other work, utilizing full Glauber theory can be found in Ref. 7. Some comparisons between the Glauber theory and the optical model have been made, showing that the Glauber theory is a good approximation to the optical model tested. However, it is not clear that the good agreement is from the lack of the Fermi averaging in their optical model or not. On the other hand, compared with our simple and straightforward eikonal approximation, the full Glauber theory was more complicated and the important Wallace corrections in the previous section were not considered. Our work strongly supports their conclusion that the semi-classical model is a quantitatively good approximation to the optical model, even when sources of nonlocality are included.

## III. ISSUES

In this section we will mention the prospects for studying a variety of issues with high-energy pions. This includes modifications of the baryon resonance masses and their couplings to mesons in the medium, the use of pions to study nuclear structure, the study of pion propagation in the medium, and the use of pions to study obtain further information about hadron dynamics, such as exchange currents and nucleon-nucleon correlations.

In the high-energy region (300 MeV $\leq T_\pi \leq$ 1 GeV), the pion clearly has a much shorter wavelength. For example, the wavelength at resonance is about 4 fm (about the size of the nucleus) while at 1 GeV the wavelength is 1 fm (about the size of a single nucleon). The shorter wavelength implies that elastic and inelastic data at the higher energies can probe finer details of the spatial dependence of the ground-state and transition densities.

Moreover, the pion-nucleon two-body interaction becomes much weaker as one goes to energies above the $\Delta_{33}$ resonance. The two-body total cross section becomes less than 30 mb, which is about 15% of that on the $\Delta_{33}$ resonance. The first implication of this weaker amplitude is that the pion is able to penetrate deeper into the nucleus. A simple estimate from total reaction cross section studies finds that a projectile can penetrate into a target to a radius that is equal to the impact parameter at which the profile function equals one mean-free path. The mean-free path of a pion as deduced from the free pion-nucleon scattering amplitude is shown in the fourth panel of Fig. 1. The same information is conveyed in a slightly different form in Fig. 4, where the

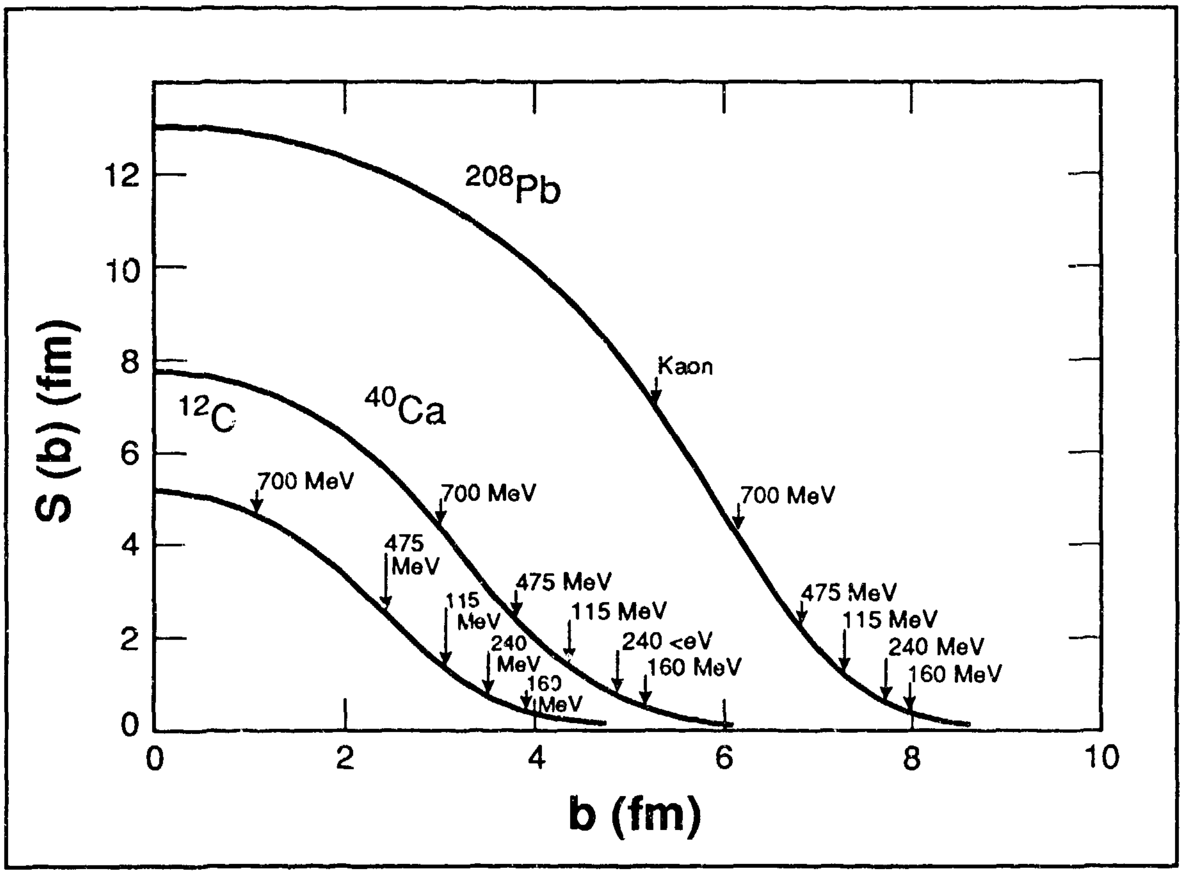


*Fig. 4. Profile function S(b) for $^{12}C$, $^{40}Ca$, and $^{208}Pb$. The arrows indicate the depth to which the pion (labeled by its energy) can penetrate.*

profile function for $^{12}$C, $^{40}$Ca, and $^{208}$Pb are pictured and the arrows indicate approximately how far into a nucleus a pion of the labeled energy can penetrate. The pion in the energy region from 500 MeV to 1 GeV is one of the most penetrating of the strongly interacting particles.

The second implication of the weaker two-body cross section is, when combined with an increasing energy (decreasing propagator), that multiple-scattering theory becomes increasingly convergent. A simple estimate of the convergence parameter[8] of multiple-scattering theory for the optical potential is obtained by comparing the relative size $R$ of an important term in the second-order optical potential $U^{(2)}$ (in the case considered here, it is correlations coming from the short-range repulsion in the nucleon-nucleon interaction) to the first-order optical potential $U^{(1)}$,

$$R \equiv \frac{U^{(2)}}{U^{(1)}} = \sqrt{\sigma}\,\frac{\ell_c}{k}\,\rho \ , \qquad (10)$$

where $\sigma$ is the total two-body cross section, $\ell_c$ is the correlation length, $k$ is the incident pion momentum, and $\rho$ is the nuclear density. On resonance we find $R \approx 0.1$, but $R < 1$ only because the density at which the pion interacts is so small. At 500 MeV, we find $R \approx 0.04$ and at 1 GeV, $R \approx 0.02$. This says that at high energies, the conventional lowest-order multiple scattering theory expression for $U$ becomes increasingly accurate for elastic scattering. It also suggests that the largest types of corrections would be those that would influence the lowest-order optical potential, such as modifications of the resonance parameters (masses, couplings, and widths) in the medium. We will explore these effects in more detail in Sec. III.A below. If one wants to look for ingredients that belong in $U^{(2)}$, one will have to look at observables that are sensitive to second-order terms, such as pion double charge exchange. We discuss some of these possibilities in Sec. III.B.

## A. Modifications of Nucleons and Baryon Resonances in Nuclei

In recent years, it has become increasingly clear that the energy shifts of baryons in nuclei are connected to very fundamental ideas of how interactions arise both in quantum chromodynamics (QCD) and in meson theory. The so-called QCD sum rules[9] have been evaluated for the mass of a nucleon and a $\Delta_{33}$ resonance in free space, and recent studies of nuclear matter indicate that the shift of these and higher-lying resonances in nuclear matter might be similarly evaluated. Empirically, we know that the mass shift (in a nonrelativistic sense) of a $\Delta_{33}$ in the nuclear medium is nearly equal to that of a nucleon[4] in nuclear matter. It would be quite interesting to learn something empirically (and ultimately understand it theoretically) about the mass shift of other baryons in nuclear matter.

We[2] have made preliminary calculations to test the sensitivity of our theory of elastic scattering to the energy of the resonances in nuclear matter. We found that modest energy shifts of the resonances in nuclear matter would show up as shifts of the minima of the elastic angular distributions of pion-nucleus scattering. The energy location of the deepest minima compared to the calculation of their location in the absence of medium modifications shows them to be rather sensitive to in-medium energy shifts of baryon resonances. Phenomenological determination of the energy at which the minima of the elastic scattering angular distribution are the deepest would then reflect the energy shifts of the resonances in nuclear matter.

There has been much discussion about the possibility of nucleons swelling in nuclear matter. The swelling is presumably just another manifestation of the same physics that would also alter the mass (and perhaps also the meson-baryon coupling constants).

In order to study meson-nucleus scattering theoretically in more detail at high energy, it would be useful to develop an effective meson theory. Such a theory would need as a starting point an appropriate unperturbed description of high-spin fields. A phenomenology of high-spin fields based on the Weinberg equations has been has been developed by Ahluwalia and Ernst.[10] This work might be used as the basis of a hadron dynamics description of interacting pions and nucleons at high energy.

The problem of separating the shifts for the individual resonances may require the full nonlocal optical-model theory in combination with data out to rather large angles. Data other than elastic scattering might likewise be required, such as $\eta$ meson production, which is particularly sensitive to the $S_{11}(1535)$ resonance. The fact remains that the problem of determining the medium modifications of baryons is a problem ideally suited to exploration at high-intensity pion facilities with pion energies of one or more GeV.

## B. Nuclear Structure

The simple eikonal model provides a straightforward method for studying nuclear structure easily at high energies. The weakness of the interaction implies that the pion penetrates into the nucleus, becoming more sensitive to structure in the nuclear interior. The simplicity of its form at high energy makes the possibility of studying nuclear structure with pions very attractive.

The pion has a strong isospin dependence, which makes it possible to separate neutron and proton components of densities. It has often been remarked that the changing character of the pion-nucleon interaction (the $\pi^+$ becomes more sensitive to neutrons as the energy is raised, in contrast to the region of the $\Delta_{33}$ resonance, see the bottom most panel of Fig. 1) makes the high-energy region particularly interesting for the purposes of determining neutron and proton distributions. The pion-nucleon amplitude also has a strong spin-dependence, which makes the pion a promising probe of spin-dependent effects in nuclei.[1]

## C. Hadron Dynamics in Pion Double Charge Exchange

One would like to study the effects of dynamical correlations, exchange currents and meson-baryon couplings, some examples of which are shown in Fig. 5. One place to do this is in the double-charge-exchange reaction, because the leading piece of the reaction is of second-order, since two charges must be exchanged between the projectile and the nucleus.

Such studies have been made using data in the vicinity of the $\Delta_{33}$ resonance. I give one example here of the determination of the $\Delta_{33}$-nucleon interaction, which was shown in Fig. 5. The $\Delta_{33}$-$N$ interaction effect (called DINT when it was used earlier as a mechanism for pion double charge exchange[11]) is quite pronounced in the region of the $\Delta_{33}$ resonance for some special types of nuclear transitions (the ground-state nonanalog transitions) for which the conventional sequential double-charge-exchange process is strongly suppressed. Figure 6 shows a comparison of the theoretical calculation of DINT to data, showing the good agreement for a variety of nuclei.[11] From this comparison, the strength of the $\pi\Delta\Delta$ coupling can be inferred. Similar studies might be possible for the higher-mass resonances, as shown in Fig. 1.

Oset and Strottman[12] have studied pion double charge exchange at high energy. They used the Glauber theory, which we believe from our previous remarks is suitable for study at high energy, particularly if semi-classical corrections of Wallace are incorporated. They have shown recently that the double-charge-exchange data taken at LAMPF is well described by the Glauber

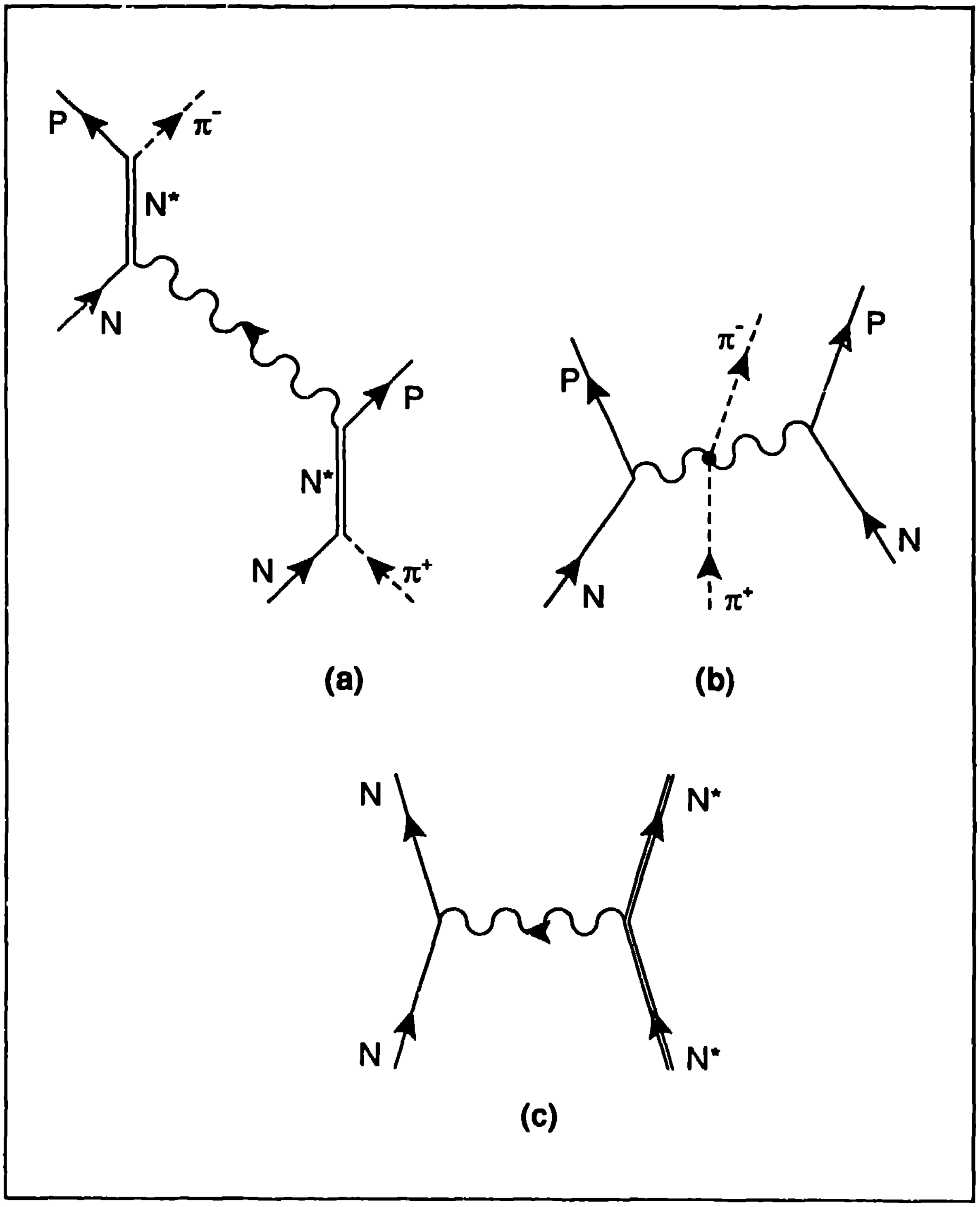


*Fig. 5. Examples of second-order effects that may influence pion double charge exchange: (a) sequential DCX mediated by heavy mesons; (b) DCX from the meson cloud in nuclei; and (c) the baryon-nucleon interaction.*

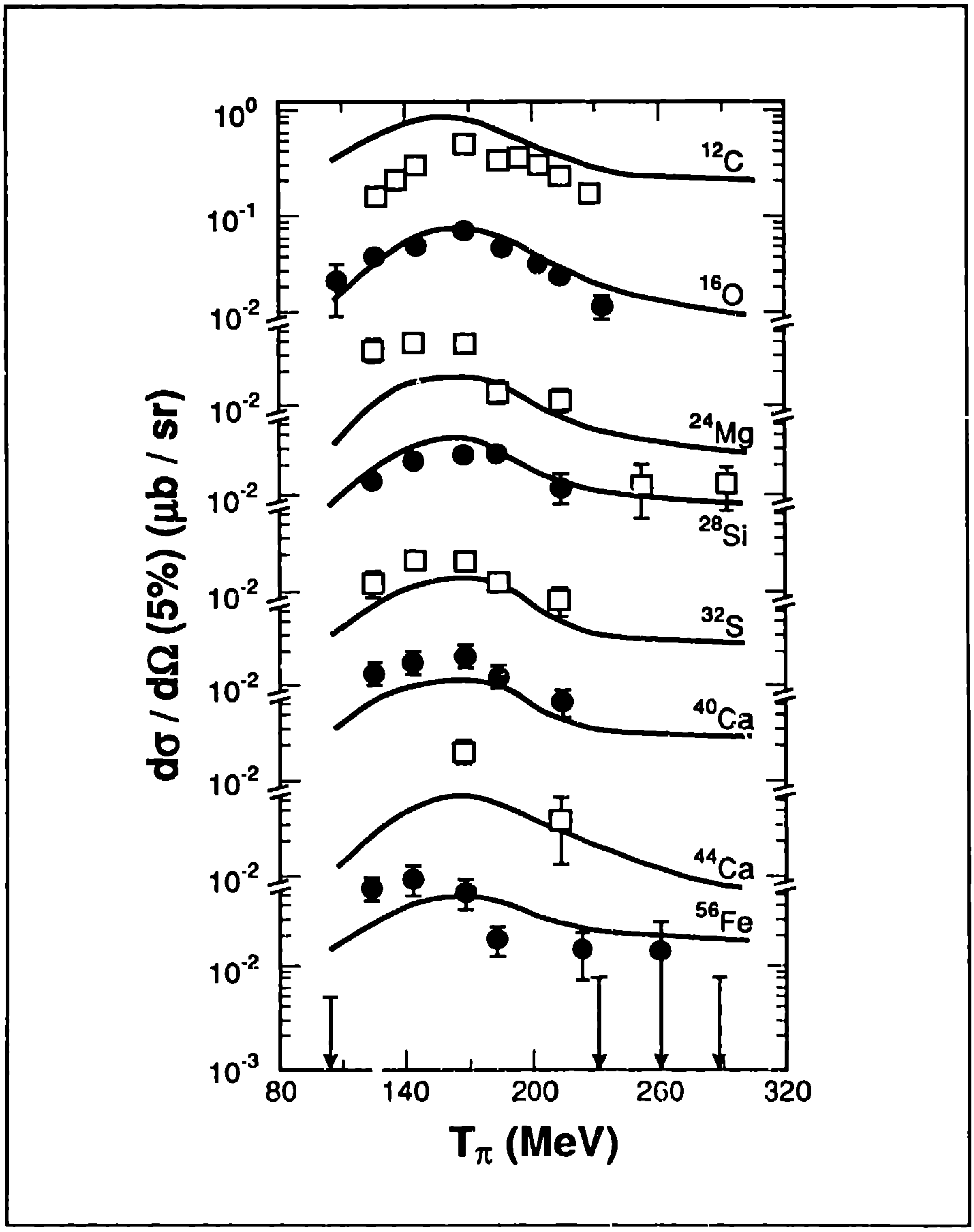


*Fig. 6. An example of the sensitivity to the $\Delta_{33}$-nucleon interaction on double charge exchange at current meson-factory energies for a case where sequential scattering is suppressed.*

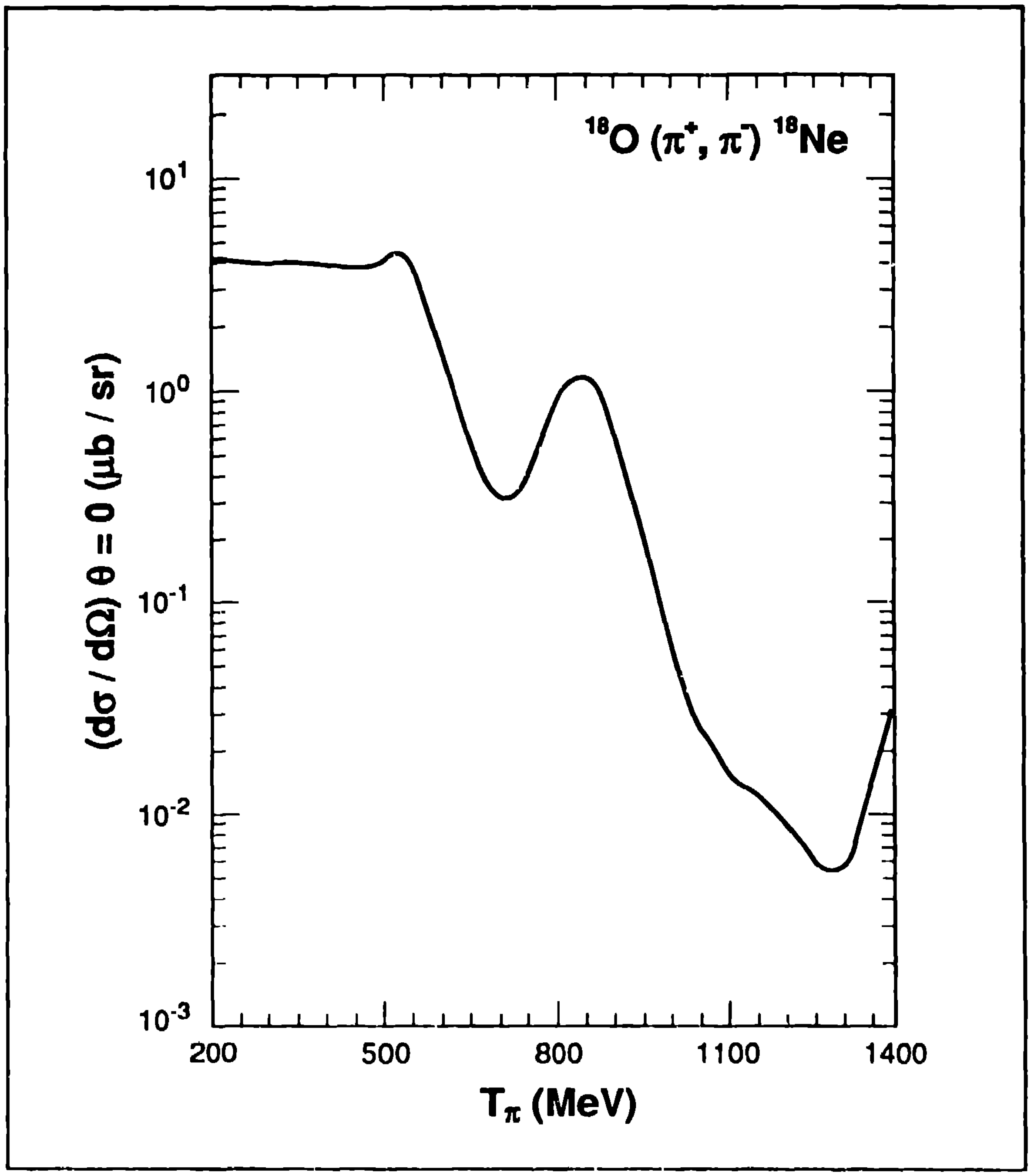


*Fig. 7. A calculation by Oset and Strottman[12] showing that the sequential-scattering cross section is suppressed in the region of 700 and 1300 MeV.*

theory. A result is shown in Fig. 7. They find at $T_\pi \approx 700$ MeV that the DCX cross section has a dip. This occurs near the middle of the group of resonances shown in Fig. 1. This dip provides a window through which to view processes such as those in Fig. 5 in the same way that the nonanalog cross sections provided a window for the $\Delta$-$N$ interaction as discussed above. A perhaps more promising opportunity occurs for higher energies, about $T_\pi = 1300$ MeV.

### D. Pion Propagation and Reaction Mechanisms

The study of pion-nucleus reactions is important for the understanding of other reactions. For example, some of the cross sections, such as true absorption and pion-production, will be needed as input to transport models of heavy-ion collisions. The range of energies up to 1 GeV is particularly important for the heavy-ion reactions.

## IV. SUMMARY, CONCLUSION AND FUTURE PROSPECTS

We have compared the full microscopic lowest-order optical potential to the eikonal theory. It seems to be quantitatively valid at high energy, at least for the first several minima in the differential elastic cross section. This makes possible a simpler reaction theory than the one familiar from the experience at lower pion energies (near the $\Delta_{33}$ resonance). At high energy and/or for heavy nuclei, use of the full optical model becomes very time-consuming and sometimes computationally impossible. In contrast, the eikonal theory is relatively simple and fast on the computer. It therefore becomes a matter of considerable practical importance to realize that the physics is faithfully reproduced by the simple version of the theory.

We have additionally argued that many applications of importance to nuclear physics can be pursued with high-energy pions. Chief among these is the study of properties of baryon resonances in nuclear matter. These derive much of their interest from the connections to QCD through QCD sum rules.

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