Title: Dynamics of Pion-Nucleus Systems

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Dynamics of Pion-Nucleus Systems

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Abstract

The prospects for using high-energy pions to examine modifications of baryon resonances in nuclei, nuclear structure, exchange currents, short-range correlations, and to characterize pion propagation are discussed.

Pion-nucleus scattering experiments at the meson factories have 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 at next-generation meson factories having high-quality beams of pions up to energies of several GeV and high-resolution spectrometers. Here, I will 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 [2].

Microscopic approaches [3, 4] have become successful descriptions of pion-nucleus scattering in the vicinity of the $\Delta_{33}$ resonance. Beyond the $\Delta_{33}$ resonance, these approaches become computationally intensive and prohibitively inefficient. This is because more and more partial waves are needed in the pion-nucleon two-body amplitudes as the energy increases. The middle panel of Fig. 1, which shows the resonances in the pion-nucleon scattering amplitude that come into play at energies below 1600 MeV. Note that 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, $G$-waves and $H$-waves above 700 MeV, etc. At the same time, the number of pion-nucleon partial waves is increasing at a rate proportional to the pion momentum. On the other hand, semi-classical theory, which becomes an increasingly quantitative description for a local interaction at high energies, is much simpler to compute. However, for a highly nonlocal interaction, such as that expected for the pion-nucleus optical potential [3, 4] the semi-classical approach is not guaranteed to be a good approximation to the exact theory. Thus, how reliable is the semi-classical method for quantitative study of baryon resonances and other issues of the physics of pion-nucleus scattering?

We show our [2] answer to this question for $\pi^{+}^{40}$Ca at 800 MeV/c in Figs. 2(a) and (b). We compare a microscopic optical model calculation using the code ROMPIN [3] to the eikonal model [5] using the same target wave functions, which are obtained from Hartree-Fock calculations, and the same on-shell pion-nucleon two-body amplitudes, which are from Arndt's and Hohler's phase-shifts. The location of the minima and the magnitude of the cross section at the forward angles are in good agreement for 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 energies above about 300 MeV. Below this energy, the agreement is considerably worse, which can be traced to the increasing importance of Fermi averaging, the pion-nucleus form factor, and the large size of finite-wave corrections to the eikonal theory.
Figure 1: Energy dependence of the two-body $\pi N$ scattering amplitude, from Ref.
Figure 2: Results of the eikonal theory and momentum-space optical model ROMPIN$^3_4$ for 800-MeV/c data for $\pi^\pm$-$^{40}\text{Ca}$ scattering. Experiment is from Ref. [6].
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. One implication of this weaker amplitude is that the pion is able to penetrate deeper into the nucleus. 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 pion in the energy region from 500 MeV to 1 GeV is one of the most penetrating of the strongly interacting particles. Another implication of the weaker two-body cross section is that multiple-scattering theory becomes increasingly convergent. A simple estimate of the convergence parameter \([7]\) of multiple-scattering theory for the optical potential to the first-order optical potential \(U^{(1)}\) (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 \(U^{(1)}\), \(R \equiv U^{(2)}/U^{(1)} = \sqrt{\sigma(t_c/k)}\rho\), where \(\sigma\) is the total two-body cross section, \(t_c\) is the correlation length, \(k\) is the incident pion momentum, and \(\rho\) is the nuclear density. On resonance we find \(R \approx 1\), 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, \(R \approx 0.02\). Thus, 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. If one wants to look for ingredients that belong in \(U^{(2)}\), one will have to look at experiments that are sensitive to second-order terms, such as pion double charge exchange.

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.

Resonance Properties 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 \([8]\) 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 (on the order of 50 MeV) 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.

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.

In the high-energy region \((300 \text{ MeV} \leq T_\pi \leq 1 \text{ GeV})\), 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,
Figure 3: 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.

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 groundstate and transition densities.

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].

Hadron Dynamics in 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. 3. One place to do this is in the double-charge-exchange reaction, where the leading single-scattering term is absent, 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. An example is the determination of the \( \Delta_{33} \)-nucleon interaction shown in Fig. 3. The \( \Delta_{33}-N \) interaction effect (called DINT when it was used earlier as a mechanism for pion double charge exchange [9]) 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. From a comparison between theory and experiment, 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 [10] have studied pion double charge exchange at high energy. They have shown recently that the double-charge-exchange data taken at LAMPF is well described by the Glauber theory. They find at $T_\pi = 700$ 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. 3 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.

Reaction Mechanism. 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.

In summary, we have additionally argued that many applications of importance to nuclear physics can be pursued with high-energy pions.

References


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