Pion-nucleus optical potential valid up to the DELTA-resonance region

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The purpose of this work [1] is to provide a π-nucleus optical potential valid up to the Δ-resonance region that can be used in various studies involving the π-nucleus interaction. Specifically, we supply a potential that can provide an integral component in the analysis of several future and past experiments in pion photo- and electro-production processes from nuclei at Thomas Jefferson National Accelerator Facility (Jefferson Lab) and Mainz.

The π-nucleus elastic scattering has enjoyed significant investigation from a variety of theoretical perspectives. Our approach here is to extend the prominent work of Stricker, Carr, and McManus [1] on the low energy π-nucleus optical potential to higher energies so that it covers the Δ resonance region. Indeed, our treatment here follows structure-wise the analysis of Stricker *et al* but extends their treatment to higher energies by not using any low energy approximation and by invoking a fully covariant kinematics including the nucleus recoil.

We begin from where Stricker *et al* started by taking the elementary amplitude of the process $\pi N \rightarrow \pi N$ and using it, along with the impulse approximation, to develop the amplitude for the π-nucleus interaction. We arrive then at what is known as the impulse approximation form of the optical potential. Such a form however still lacks two classes of corrections: kinematical and physical ones. The kinematical ones arise from transforming the $\pi - N$ elementary amplitude from the $\pi - N$ center of mass (c.m.) frame to the π-nucleus c.m. system. The physical corrections however arise from the fact that the impulse approximation picture clearly does not encompass distinct many-body interactions that appear only in the π-nucleus channel. These effects include multiple scattering, pion absorption, Pauli blocking, and Coulomb corrections. They are of second and higher orders in strength compared to the first-order expression given by the impulse approximation.

The starting point for our derivation is the $\pi - N$ scattering amplitude. The s- and p-wave parameters are determined from the phase shifts of the interaction. In earlier treatments, these parameters were determined initially from a phase shift analysis but then were slightly modified to obtain the best fit for the π-nucleus scattering and pionic atom data. Our treatment differs in two respects: first, we extract the parameters from the state-of-the-art experimental measurements and phase shift analysis of Arndt, Strakovsky, Workman, and Pavan from the Virginia Tech SAID program [2]. Second, we keep these parameters intact by not attempting to change them to fit any specific data. In doing so we have maintained the theoretical basis for the optical potential unblemished. This is particularly important here as these parameters dominate the optical potential in the Δ-resonance region

After adopting the $\pi - N$ amplitude in the $\pi - N$ c.m. frame, the next step in the derivation is to transform the amplitude to the π-nucleus c.m. system. This is done using the relativistic potential theory which establishes a relationship between $\pi - N$ transition matrix (t) in the $\pi - N$ c.m. frame and the $\pi - N$ amplitude in the π-nucleus c.m. frame [1]. Next we express the arguments of $\pi - N$ amplitude in terms of the appropriate kinematical quantities in the π-nucleus c.m. frame. This is done using what is referred to as the angle transformation through a Lorentz transformation [1].

By invoking the impulse approximation, the resultant form for the amplitude is then sandwiched between bound-nucleon states and the expression is summed over all occupied states of the nucleus. Hence, one obtains the π-nucleus interaction amplitude in momentum space. Now taking the Fourier transform, we obtain an expression for the optical potential form. This form still lacks physical corrections arising from many-body processes, which alter the scattering amplitude parameters and add new terms to the optical potential. Thus we incorporate the second order corrections to the small (nearly zero) s-wave terms that play an important role only at low energies. This is a consequence of the fact that the p-wave role is still small in the low-energy regime. Since the p-wave terms are the crucial ones in the Δ resonance region, we include higher order corrections by summing the multiple scattering series to all orders. This introduces the Ericson-Ericson effect which adds a nonlocal term to the potential of the form $\boldsymbol{\nabla} \cdot f(r)\boldsymbol{\nabla}$ t [1].

We still need to include other physical mechanisms such as processes leading to absorption terms in the optical potential. There are two types of such terms: the first one arises from the fact that there are many open inelastic channels in the π-nucleus interaction such as nucleon knock-out. Accordingly, a portion of the incoming flux is absorbed by these processes leading to an imaginary part in the potential. This kind of absorption is naturally included in the impulse-approximation form for the potential. The second type of absorption originates from many-body mechanisms such as the two-nucleon absorption where the pion is scattered from one nucleon but then absorbed by another. This is in fact the dominant many-body absorption mechanism and has been incorporated in the potential. Another less important mechanism is the quasi-elastic charge exchange process. All of these many-body absorption mechanisms are referred to as true absorption to distinguish them from the inelastic (type one) absorptions. Ironically, the Δ-resonance formation that drives strongly the elementary process $\pi N \to \pi N$, dampens it in the nuclear medium through absorption channels.

Another alteration to the potential is the Pauli correction. Due to the Pauli principle, the number of available final states for the struck nucleon in the nuclear medium is reduced by Pauli blocking leading to this kind of correction. An additional correction is the Coulomb one stemming from the fact that the incoming charged pion (in π-nucleus scattering) is accelerated or decelerated depending on its charge, by the long-range Coulomb field of the nucleus before interacting through the short-range strong interaction. Finally, it is noteworthy to mention that there are also other kinematic corrections springing from transformations to the π-nucleus c.m. frame from many-body subsystems such the $\pi - 2N$ subsystem, when we consider $\pi - 2N$ interaction mechanisms. These small kinematic corrections have also been included in the potential.

By implementing all of these corrections to the impulse-approximation expression, we arrive at a π-nucleus optical potential—applicable from threshold through the delta-resonance region—of the form:

$$2\omega U \;=\; -4\pi\Big[p_1 b(r)+p_2 B(r)-\boldsymbol{\nabla}\ Q(r)\cdot\boldsymbol{\nabla}\ \ \frac{1}{4}p_1 u_1\nabla^2 c(r)-\frac{1}{4}p_2 u_2\nabla^2 C(r)+p_1 y_1\widetilde{K}(r)\Big]\ .(1)$$

Detailed information about the various terms and parameters in this expression can be found in Ref. [1].

References

[1] L.J. Abu-Raddad, Phys. Rev. C **(66)**, (2002) 064601, and references therein.

[2] Richard A. Arndt, Igor I. Strakovsky, Ron L. Workman, and Marcello M. Pavan, Phys. Rev. **C52**, (1995) 2120-2130; solution SP98 from the Virginia Tech SAID program.