ETA-NUCLEON INTERACTION AND NUCLEAR PRODUCTION OF ETA MESONS*

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Eta-nucleon interaction and eta-nucleus dynamics are discussed. The possibility of using η to probe unnatural-parity nuclear states and to study spin-isospin correlations between two nucleons are demonstrated.

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1. Introduction

As the energy of hadronic beams increases, mesons will be produced in greater varieties and quantities in hadron-nucleus and nucleus-nucleus collisions. Understanding meson production and propagation in a nuclear environment is essential to the understanding of the physics to be studied at future multi-GeV hadron beam facilities. Eta meson is of particular interest because of its hidden strangeness. Furthermore, near-threshold η meson production from nuclei is entirely dominated by the formation and subsequent decay of the baryon resonance $N^*(1535)$. Consequently, near-threshold nuclear η production can be used to tag the *nuclear* dynamics of the $N^*(1535)$, for which the present knowledge is next to nil.

Another important feature of the nuclear production of η is that it involves high momentum transfers. Thus, nuclear η production provides a new opportunity for studying nucleon-nucleon correlations in nuclei.

Because the $\pi N \rightarrow \eta N$ and $\eta N \rightarrow \eta N$ interactions are the basic ingredients to the modeling of the dynamics of nuclear production of etas,

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they will be examined at first. The next topics I will discuss is the special role played by η in nuclear structure studies. In particular, I will show the unique opportunity provided by the $(p, p'\eta)$ reaction for studying unnatural parity nuclear states. Finally, I will demonstrate the importance of multi-nucleon effects in coherent η production from nuclei in the threshold region, using the $^3\mathrm{He}(\pi^-, \eta)t$ reaction as an example.

2. Eta-nucleon interaction

The first coupled-channel model for pion-induced eta production on a nucleon was proposed by Bhalerao and Liu [1]. It treats the $\pi N \to \pi N$, $\pi N \to \eta N$, and $\eta N \to \eta N$ interactions on an equal footing and satisfies off-shell unitarity constraints. The s-, p-, and d-wave meson-nucleon interactions were assumed to be mediated, respectively, by the baryon resonances $N^*(1535)$, $N^*(1441)$, and $N^*(1520)$. The model parameters were then determined from fitting the corresponding πN phase shifts in the S_{11}, P_{11}, and D_{13} channels, Because only three low-lying N^*'s were considered, the model is only good for the energy region $\sqrt{s} \leq 1600$ MeV.

In spite of the fact that only the pion-nucleon phase shifts were used in the fit, very good prediction for the $\pi^- p \to \eta n$ cross sections was obtained [1], lending support to the soundness of the theoretical approach. The model predicted a s-wave ηN scattering length of $a_0 = 0.27 + i0.22$ fm. One notes that the predicted sign of the real part of a_0 is positive, indicating that the low-energy eta-nucleon interaction is attractive. The attraction is consistent with the fact that the threshold (1488 MeV) is just situated below the $N^*(1535)$ resonance. Implications of this attractive interaction on the existence of a new nuclear species, the η-mesic nuclei, were discussed in Refs. [2–5] and will not be repeated here. Recently, Wilkin used a first-order K-matrix theory to fit very low-energy $\pi p \to \eta n$ cross-section data. He obtained [6] $a_0 = 0.55 \pm 0.20 + i0.30$ fm. (The sign of the real part of his a_0 was chosen after Ref. [1].) At this time the model only applies to η production at energies situated within about 10 MeV of the threshold. Furthermore, it does not indicate how to make off-shell extensions in nuclear calculations.

In the threshold region, ηN scattering is dominated by a s-wave baryon resonance denoted N^*. The total decay width of the N^* is given by $\Gamma(\sqrt{s}) = \gamma^{\eta N}(\sqrt{s}) + \gamma^{\pi N}(\sqrt{s}) + \gamma^{\pi\pi N}(\sqrt{s})$. Here, $\gamma^{\eta N}$ denotes the partial width associated with the $N^* \to \eta N$ decay. (A similar notation holds for the other γ's.) It can be shown that $\gamma^{\pi N}$ is related to the imaginary part of the self-energy associated with the $N^* \to \eta N \to N^*$ process. For the s-wave

η-nucleon interaction, one has the relation [5]

$$\frac{\tilde{g}_\eta^2}{4\pi} = \frac{\gamma^{\eta N}(E_r)}{2} \frac{M^*}{M_N k_r}, \tag{1}$$

where $E_r = M^*$ is the s-wave resonance energy, and k_r the corresponding momentum in the ηN c.m. frame. (Note that because of the use of the different normalization conventions, the $\tilde{g}_\eta$ of Ref. [5] is related to the g_η of Ref. [1] by $g_\eta^2 = 2\pi^2[\Lambda^2 + k_r^2)]^2(\omega(k_r)/E_r)\tilde{g}_\eta^2$.) Here, ω is the total energy of the η and Λ is the range parameter. The T-matrix of ηN elastic scattering is then given by

$$\frac{\exp[2i\delta(k)] - 1}{2ik} = -\frac{\tilde{g}_\eta^2}{4\pi} \frac{E_N(k)}{\sqrt{s}} \frac{1}{\sqrt{s} - M^* + i\Gamma(\sqrt{s})/2}, \tag{2}$$

with $\sqrt{s} = E_N(k) + \omega(k)$. In the limit $k \to 0$, this last equation becomes

$$a_0 = -\frac{\tilde{g}_\eta^2}{4\pi} \frac{M_N}{M_N + m_\eta} \frac{1}{M_N + m_\eta - M^* + i\Gamma(E_0)/2}, \tag{3}$$

where $\Gamma(E_0)$ is the full width at the threshold energy $E_0 = M_N + m_\eta$. Let

$$b = \frac{\gamma^{\eta N}(E_r)}{\Gamma(E_r)} \tag{4}$$

be the branching ratio for the decay of N^* into the ηN channel at the resonance energy E_r. Although $\gamma^{\eta N}$ decreases to zero rapidly as $E_r \to E_0$, our calculations [1] show that $\gamma^{\pi N}$ and $\gamma^{\pi\pi N}$ vary only slightly between E_0 and E_r. It is, therefore, a good approximation to assume that $\Gamma(E_0) = \gamma^{\eta N}(E_r) + \gamma^{\pi\pi N}(E_r)$. Hence, by virtue of Eq. (4),

$$\Gamma(E_0) \simeq (1 - b)\Gamma(E_r). \tag{5}$$

Combining Eqs. (1), (3), (4) and (5), one can express the s-wave scattering length a_0 in terms of M^*, $\Gamma(E_r)$, and b.

It is, therefore, possible to infer from the s-wave scattering length the resonance energy M^*, full width Γ, and the branching ratio b of $N^* \to \eta N$ decay. The experimental values [7] for these quantities are $M^* = 1520-1555$ MeV, $\Gamma = 100-250$ MeV, and $b = 0.3-0.5$. The scattering of Bhalerao–Liu gives $M^* = 1530 - 1555$ MeV, $\Gamma = 100 - 174$ MeV, and $b = 0.32 - 0.37$, which are consistent with the data [7]. The lower limit of the a_0 of Wilkin gives $M^* = 1525 - 1555$ MeV, $\Gamma = 100 - 200$ MeV, $b = 0.36 - 0.43$, which are also compatible with the data. However, the upper limit of his a_0 leads in all cases to a branching ratio $b = 0.65 - 0.70$, well outside the range of the data. The use of his median value gives $M^* = 1531 - 1555$ MeV, $\Gamma = 100 - 176$ MeV, and $b = 0.53 - 0.58$, which correspond again to a branching ratio higher than the data. The above situation suggests that the large experimental error bars of the very low-energy $\pi^- p \to \eta n$ data used in the analysis of Ref. [6] need to be significantly reduced. Otherwise, these data can lead to an incompatibility with the πN scattering data used in the dispersion-relation analyses that had led to the published resonance energy, width, and branching ratio [7]. A definite answer to this question also requires a new pion-nucleon phase shift analysis that takes into account these recent close-to-threshold pion production data.

3. Study of unnatural-parity nuclear states

In this section, I would like to demonstrate that the $A(p,p'\eta)A^*$ reaction in the threshold region represents a unique tool for studying nuclear excitations leading to unnatural-parity states. Consequently, nuclear η production can greatly benefit nuclear structure studies.

Our experience with the nuclear pion production has led us to believe that the $(p,p'\eta)$ reaction proceeds through a quasifree $pN \to pN\eta$ process, as shown in Figs. 1(a)–1(d). In this quasi free process, the exchanged virtual pion interact either with the incoming proton or with a target nucleon to form the $N^*(1535)$ resonance that subsequently decays into a proton and an η, leaving the nucleus in an excited state. The amplitudes 1(a) and 1(d) represent an excitation mechanism mediated by an intermediate pion. Because pion has spin-parity $J^\pi = 0^-$, it follows that these amplitudes allow only transitions to unnatural-parity nuclear states. On the other hand, the amplitudes 1(b) and 1(c) are unrelated to such transitions. If all four amplitudes are important, then there will be no simple relations between the $(p,p'\eta)$ cross section and the transitions to unnatural-parity states. Fortunately, in the threshold region the amplitude 1(a) predominates and contributions from all other three amplitudes are negligible [9]. Consequently, the $(p,p'\eta)$ cross section is a direct measurement of nuclear transitions to unnatural parity states.

I emphasize that such ideal situation does not occur in the $(p,p'\pi)$ reaction. This is because in this latter reaction, the intermediate isobar is the $\Delta(1232)$, which is a p-wave resonance. This p-wave interaction introduces higher powers of momentum transfer dependence into amplitudes 1(b)–1(d), making them no longer negligible with respect to amplitude 1(a). Hence, the $(p,p'\pi)$ reaction depends on all four amplitudes and does not provide a one-to-one correspondence between the cross sections and nuclear transitions to unnatural-parity states. In this respect, η is a unique probe for studying unnatural-parity nuclear states [9].

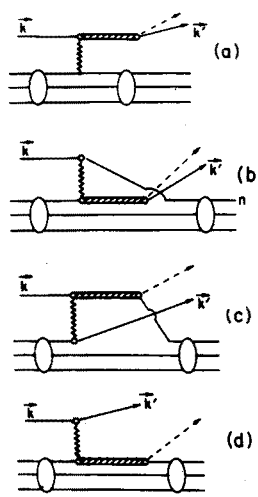

Fig. 1. Reaction amplitudes of the $(p, p'\eta)$ reaction: (a) "projectile excitation" amplitude; (b) "target excitation" amplitude; (c) interchanged projectile excitation amplitude; (d) interchanged target excitation amplitude. The solid, wavy, and dashed lines denote, respectively, the nucleons, virtual pions, and etas. The $N^*(1535)$ is represented by the shaded bar. The ovals denote the nuclear interactions that bound the nucleons. The initial and final proton momenta are denoted by k and k'.

4. Eta production in ^{3}He

The reaction $\pi^- +^3 He \rightarrow \eta + t$ was studied by Peng *et al.* at LAMPF, using pions having laboratory momenta between 590 and 680 MeV/c [8]. The kinetic energies of the produced eta vary between 7 and 135 MeV, corresponding to eta momenta between $\sim$ 88 and 408 MeV/c. This reaction offers two major advantages for theoretical studies. Firstly, pion induced eta production involves high momentum transfers. The fact that the charge form factors of ^{3}He and triton have been measured experimentally for momentum transfers up to $\sim$ 4.5 fm^{-1} eliminates theoretical undertainties caused by the lack of the knowledge of the high-momentum content of the nuclear wave functions. Secondly, ^{3}He and triton have only three nucleons. Hence, multiple scatterings of π and η can be calculated to all orders. This allows the nuclear medium effects on the πN, ηN elastic scattering amplitudes and on the $\pi N \rightarrow \eta N$ production amplitude be taken into account exactly.

The first theoretical calculation was carried out in the framework of the distorted-wave impulse approximation (DWIA) [8]. Although the DWIA calculation reproduces the angular dependence, it underestimated the data by factors ranging from 1.5 to 2.9 (Fig. 2). Large discrepancies between data

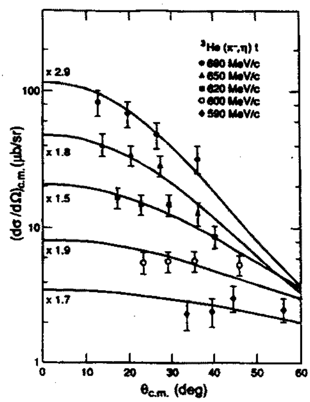

Fig. 2. Cross sections for the ^{3}He(π^-, η) reaction. Calculated cross sections were multiplied by the factors given in the parentheses.

and DWIA calculations were equally noticed for the inclusive ^{12}C(π, η) reaction, and for the $pd \rightarrow \eta^3$He reaction [10–12]. The universal discrepancies indicate that dynamics beyond the one-nucleon process (Fig. 3) must be considered.

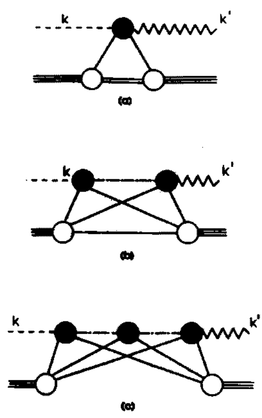

Fig. 3. Diagrams for the ^{3}He(π^-, η) reaction: (a) one-nucleon process; (b) two-nucleon processes; (c) three-nucleon processes. The dashed and wavy lines represent, respectively, π^- and η. The dashed-dotted line denotes the intermediate meson that can be either π or η. The nucleon and nucleus are shown as single and multiple lines. The shaded circles denote the meson-nucleon amplitude while the open circle denote nuclear vertices. Similar diagrams hold for $\pi \rightarrow \pi$ and $\eta \rightarrow \eta$ diagrams.

Two-nucleon processes are important not only because they favor the sharing of large momentum transfers between the nucleons, but also because the πN elastic scattering amplitude $t_{\pi\pi}$ is much stronger than the production amplitude $t_{\eta\pi}$. While the one-nucleon process depends on $t_{\eta\pi}$, the two-nucleon process depends on the quantity $\int t_{\eta\pi} G_\pi t_{\pi\pi} dy$. Here G_π denotes the pion propagator and y all the relevant dynamical variables. Because $|t_{\pi\pi}| \gg |t_{\eta\pi}|$, $\int t_{\eta\pi} G_\pi t_{\pi\pi} dy$ can be of the same order of magnitude as $t_{\eta\pi}$. This anticipation is indeed correct. Theoretical cross sections [13] obtained with the inclusion of two-nucleon processes are shown as the dotted curves in Fig. 4. There are six two-nucleon processes which correspond to the following interacting meson sequences: $\pi \to \pi \to \eta$, $\pi \to \eta \to \eta$, $\pi \to \pi \to \pi$, $\pi \to \eta \to \pi$, $\eta \to \eta \to \eta$, and $\eta \to \pi \to \eta$. All these processes were included in the calculations.

The importance of two-nucleon processes makes the investigation of three-nucleon processes indispensable. There are in total 12 three-nucleon processes. In terms of the interacting meson sequence, the four $\pi \to \eta$ processes can be denoted as $\pi\pi\pi\eta$, $\pi\pi\eta\eta$, $\pi\eta\eta\eta$, and $\pi\eta\pi\eta$. In a similar manner, the four $\pi \to \pi$ processes can be denoted as $\pi\pi\pi\pi$, $\pi\pi\eta\pi$, $\pi\eta\pi\pi$, and $\pi\eta\eta\pi$; and the four $\eta \to \eta$ processes as $\eta\eta\eta\eta$, $\eta\eta\pi\eta$, $\eta\pi\eta\eta$, and $\eta\pi\pi\eta$. An inspection of the solid curves in Fig. 4 indicates that the net effect of these three-nucleon processes is very small.

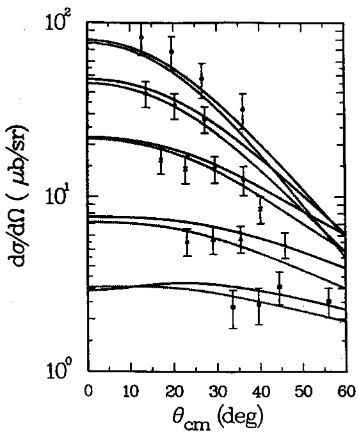

Fig. 4. Cross sections for the $^3He(\pi,\eta)t$ reaction. From bottom to top are the data at $p_{\pi,lab}$ = 590, 600, 620, 650, 680 MeV/c, respectively. The solid curves (upper ones of each set) are the theoretical results obtained with the inclusion of one-, two-, and three-nucleon processes. The dotted curves (lower ones of each set) are the results given by one- and two-nucleon processes only. Normalization for the theoretical results is absolute.

For the purpose of illustrating the relative strength of each individual process, I show in Fig. 5 the real part of the potentials due to the one-, two-, and three-nucleon processes, respectively. As one can see, the total two-nucleon contribution represents $a \geq 50\%$ additive correction to the one nucleon contribution, which is responsible to the large enhancement of the

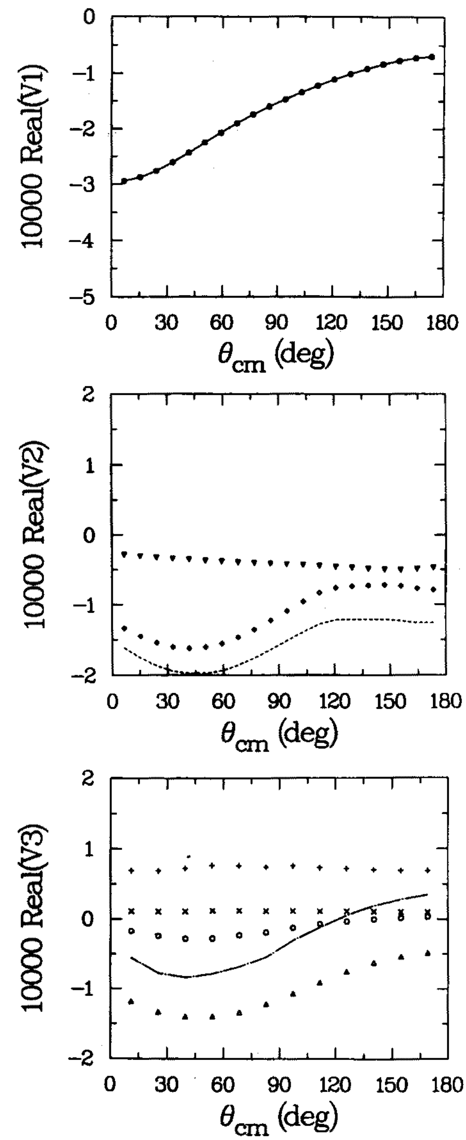

Fig. 5. Real parts of the potentials $V(\pi \to \eta)$ at $p_{\pi,\rm lab} = 620$ MeV/c. (a) One-nucleon contribution. (b) The $\pi\eta\eta$ ($\bigtriangledown$), $\pi\pi\eta$ ($\Diamond$), and summed (dash) two-nucleon contributions. (c) The $\pi\eta\eta\eta$ (+), $\pi\eta\pi\eta$($\times$), $\pi\pi\pi\eta$ ($\bigcirc$, $\pi\pi\eta\eta$ ($\triangle$), and summed (dot-dash) three-nucleon contributions.

calculated cross sections (the dotted curves in Fig. 4). Fig. 5 further shows that the net small contribution by the three-nucleon processes is a result of the large cancellations (or destructive interferences) among the various processes.

It has been further noted that [13] threshold nuclear production of η has a high spin-isospin selectivity. For the $^3\mathrm{He}(\pi^-,\eta)t$ reaction the dominant two-nucleon amplitude is the one associated with the spin-nonflip transition $J = 0(T = 1) \rightarrow J' = 0(T' = 1)$ while the spin-flip $J = 1(T = 0) \longleftrightarrow J' = 0(T = 1)$ transitions are negligible in the threshold region. The origin of this selectivity is discussed in Ref. [13], which I summarize as follows. The two-nucleon processes involve a product of two meson-nucleon amplitudes: $t_{\eta N \leftarrow \pi N} t_{\pi N \leftarrow \pi N}$ in the $\pi\pi\eta$ process; and $t_{\eta N \leftarrow \eta N} t_{\eta N \leftarrow \pi N}$ in the $\pi\eta\eta$ process. Consequently, the $J = 0 \leftrightarrow J' = 1$ transitions must involve a spinflip in one of the two meson-nucleon amplitudes. On the other hand, the $J = 0 \rightarrow J' = 0$ transition can take place without involving spinflip in both elementary meson-nucleon amplitudes. Since the threshold η production is dominated by the s-wave that cannot cause spinflip, it follows that the $J \neq J'$ amplitudes are extremely small. It is the spin non-flip part of the $J = J'$ amplitude that contributes to the bulk of the observed (π, η) cross sections.

4. Conclusions and suggestions

The DWIA is shown to be inadequate for (π, η) reactions. The inadequacy is due to the large momentum transfers involved in the reaction. It is also due to the inequality $|t_{\pi\pi}| \gg |t_{\eta\pi}|$. More generally, two-nucleon processes must be included in the modeling of reaction dynamics whenever the elementary amplitude for the DWIA process is very weak with respect to the other elementary amplitudes that can participate in second-order processes. This rule has been shown to be true in (π, η) reactions and is expected to be true in (π, K) reactions as well.

I must emphasize that the two-nucleon processes discussed here include all intermediate nuclear intermediate states. It is this latter feature that brings into play the nucleon-nucleon correlation aspect of the reaction dynamics. We have seen that the pion-induced η production in the threshold region can provide information about the correlation between the two nucleons in the $J = 0(T = 1)$ pairs.

With the dynamics of the nuclear eta production understood in the main, I suggest that we should now embark on the study of hadronic eta production in medium-mass nuclei. Such studies would provide us valuable information about nucleon-nucleon correlations and high-momentum contents of the nuclear wave functions in many nuclei.

The η meson is equally valuable to nuclear structure studies. I have shown that the $(p, p'\eta)$ reaction represent a unique tool for studying nuclear transitions to unnatural-parity states. I am convinced that the η meson, when used in concert with other mesons, can provide us many new pieces of information about hadron dynamics and nuclear structure.

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