Reaction mechanism of the coherent η meson production in the isovector nucleus

Swapan Das*
Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai - 400085, INDIA

The availability of several data sets for the η production reactions (from various laboratories [1]) provides opportunities to learn many exciting physics. The ηN scattering length near threshold is large and attractive, which predicts the existence of a new type of hadronic atom, i.e., bound or quasi-bound eta mesic nucleus [2]. Large charge symmetry violation in the $\pi^0-\eta$ mixing [3] provides a way to estimate the mass difference between u and d quarks. Being an isoscalar particle, the η meson can excite a nucleon to a $I = \frac{1}{2}$ nucleonic resonance. Specifically, the η meson strongly couples only to $N^*(1535)$, a $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ nucleonic resonance. Therefore, the η meson production in the nuclear reaction can be considered as a potential tool to investigate the propagation of the $N^*(1535)$ resonance in the nucleus, in addition to the study of the η meson nucleus interaction in the final state [4].

Sometime back, Alvaredo and Oset [5] studied the coherent η meson production in the (p,p') reaction in the spin-isospin saturated nucleus: $p + A(gs) \to p' + A(gs) + \eta$. The elementary reaction in the nucleus had been assumed to proceed as $pN \to pN^*$; $N^*(1535) \to N\eta$. The $N^*(1535)$ resonance produced in the intermediate state due to the η meson (a psuedoscalar-isoscalar meson) exchange interaction only, specifically, for the forward going proton and η meson. The contributions from other meson exchange interactions vanish in this reaction.

It should be mentioned that both π and η mesons are pseudoscalar particles but pion can't contribute to above reaction. This occurs since pion is an isovector meson and this reaction involves isoscalar nucleus. Contrast to this, both π and η meson exchange interactions contribute to $N \to N^*(1535)$ excitation in the spin-saturated isospin-one nucleus. We, therefore, consider the coherent η meson production in the scalar-isovector nucleus through the (p,p') reaction, and study the contributions due to the π^0, η meson exchange interactions and the interference of these interactions.

The Lagrangian densities describing the πNN, πNN^*, ηNN and ηNN^* interactions [6] are given by

$$\begin{aligned}
\mathcal{L}_{\pi NN} &= -ig_\pi F_\pi(q^2)\bar{N}\gamma_5 \tau N \cdot \pi \\
\mathcal{L}_{\pi NN^*} &= -g^*_\pi F^*_\pi(q^2)\bar{N}^* \tau N \cdot \pi \\
\mathcal{L}_{\eta NN} &= -ig_\eta F_\eta(q^2)\bar{N}\gamma_5 N\eta \\
\mathcal{L}_{\eta NN^*} &= -g^*_\eta F^*_\eta(q^2)\bar{N}^* N\eta, \qquad (1)
\end{aligned}$$

where $g_{\pi(\eta)}$ and $g^*_{\pi(\eta)}$ denote the $\pi(\eta)NN$ and $\pi(\eta)NN^*$ coupling constants respectively. The values for them are $g_\pi = 13.536$, $g^*_\pi = 0.79$, $g^*_\eta = 2.22$ and $g_\eta = 7.927$ [7]. $F_{\pi(\eta)}$ and $F^*_{\pi(\eta)}$ are the $\pi(\eta)NN$ and $\pi(\eta)NN^*$ form factors which are given by

$$F_M(q^2) = F^*_M(q^2) = \frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - q^2}; (M = \pi^0, \eta). \qquad (2)$$

$q^2[= q_0^2 - \mathbf{q}^2]$ is the four-momentum transfer from pp' vertex to the nucleus, i.e., $q_0 = E_p - E_{p'}$ and $\mathbf{q} = \mathbf{k}_p - \mathbf{k}_{p'}$. Values for the length parameters are $\Lambda_\pi = 1.3$ GeV and $\Lambda_\eta = 1.5$ GeV. m_M denotes the mass of the pseudoscalar meson: $m_{\pi^0} \simeq 135$ MeV and $m_\eta \simeq 548$ MeV.

The $N^*(1535)$ resonance produced due to the interactions given in Eq. (1) propagates certain distance before it decays. The form

*Electronic address: swapand@barc.gov.in

for its propagator, i.e., $G_{N^*}(m, \mathbf{r})$ is given by

$$G_{N^*}(m, \mathbf{r}) = \frac{2m_{N^*}}{G^{-1}_{0N^*}(m) - 2E_{N^*}V_{ON^*}(\mathbf{r})},$$

where

$$G^{-1}_{N^*}(0m) = m^2 - m^2_{N^*} + im_{N^*}\Gamma_{N^*}(m). \quad (3)$$

with $m_{N^*} = 1.535$ GeV. E_{N^*} is the energy of N^* resonance. m represents the invariant mass of the η meson and nucleon. $V_{ON^*}(\mathbf{r})$ is the optical potential which describes the interaction taking place between the N^* resonance and nucleus. $\Gamma_{N^*}(m)$ denotes the total width of N^* for its mass equal to m. It consists of the partial decay widths due to the $N^* \to N\pi(\sim 40\%)$, $N^* \to N\eta(\sim 50\%)$ and $N^* \to N\pi\pi(\sim 10\%)$.

The distorted wave functions for protons and η meson are described by Glauber model [8]. For the beam proton p, this wave function can be written as

$$\chi^{(+)}(\mathbf{k}_p, \mathbf{r}) = e^{i\mathbf{k}_p\cdot\mathbf{r}} exp[-\frac{i}{v_p}\int_{-\infty}^{z} dz' V_{Op}(\mathbf{b}, z')], \quad (4)$$

where v_p is the velocity of the proton. $V_{Op}(\mathbf{b}, z')$ describes the optical potential for it. For outgoing particles, the form for their distorted wave functions is given by $\chi^{(-)^*}(\mathbf{k}, \mathbf{r})$ [9]. The optical potentials appearing in the above equations describe the initial and final state interactions. They are evaluated by using "$t\varrho$" approximation.

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