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Near–threshold ηd resonance

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A remarkable feature of the η–nucleon interaction at low energies is that it is resonant. The resonance (the so-called S_{11}) lies only 48 MeV above the ηN threshold and is very broad, covering a wide low–energy region. Due to the very short life-time of η, we can only have this meson in final states of certain nuclear reactions where the S_{11}-resonance should manifest itself in the form of a strong final–state interaction. Moreover, at low energies the ηN interaction is attractive. A question immediately arises: Is this attraction strong enough to bind η inside a nucleus?

Being of interest by itself, the existence of η-nuclei would also shed new light on various fundamental problems of particle physics. For example, the study of η-nuclei would give a clue for understanding the possible restoration of chiral symmetry in a nuclear medium. A further aspect, which makes such systems interesting for other fields of nuclear physics, is the modification of the two-body ηN force by the nuclear medium.

First estimate, obtained in the framework of the optical potential theory, put a lower bound on the number of nucleons A which is necessary to bind the η–meson, namely, $A \geq 12$. Few years ago, by locating the S–matrix poles in the complex momentum plane, we showed[1] that even light nuclei, like helium isotopes, can bind η meson or at least an η–nucleus resonance may exist close to the threshold energy.

Since the ηN interaction is dominated by the S_{11} resonance, the two–body T-matrix can be parametrized in a simple form,

$$t_{\eta N}(k', k; z) = (k'^2 + \alpha^2)^{-1} \frac{\lambda}{z - E_0 + i\Gamma/2} (k^2 + \alpha^2)^{-1} , \tag{1}$$

with two vertex functions and the S_{11}–propagator in between. The strength parameter λ is chosen to reproduce the ηN scattering length. Unfortunately, this scattering length is known with very large uncertainties, namely,

$$\mathrm{Re}\, a_{\eta N} \in [0.27, 0.98]\,\mathrm{fm}, \qquad \mathrm{Im}\, a_{\eta N} \in [0.19, 0.37]\,\mathrm{fm} . \tag{2}$$

Practically all authors agree that the imaginary part is close to 0.3 fm. There is however a controversy concerning the real part, because an increase of it means strengthening of the ηN attraction and a question then arises: What is the minimal value of the real part, which is needed to bind the η inside a nucleus?

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Various approximate calculations give different answers to this question. To avoid all possible inaccuracies associated with few-body dynamics in the presence of a resonant two-body interaction, we performed exact calculations of the η-deuteron scattering by solving the AGS equations.

In doing these calculations we found[2] a very interesting behaviour of the η–deuteron scattering length when the potential becomes more attractive. By increasing $\mathrm{Re}\, a_{\eta N}$ from 0.25 to 1 fm, which means making the potential deeper, the corresponding three–body scattering length moves on the Argand diagram along a circular trajectory in the anti-clockwise direction. This implies that in the complex energy plane a three-body resonance pole exists and is not far from the threshold energy. At a certain value of $\mathrm{Re}\, a_{\eta N}$ within the uncertainty interval, this pole bypasses the point $E = 0$ from below and becomes a quasi–bound state.

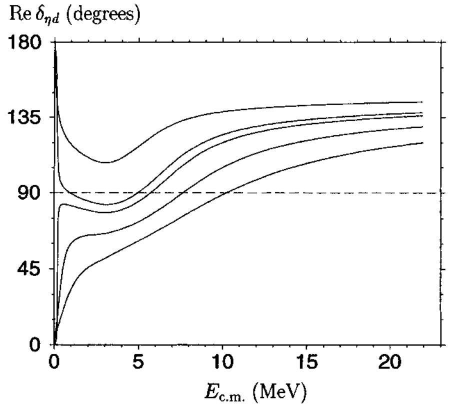

Figure 1

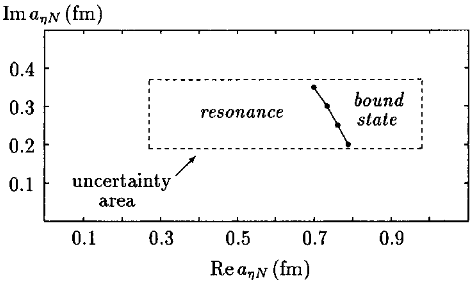

Figure 2

Using the same few–body integral equations, we calculated the elastic η–deuteron scattering in the collision–energy interval from zero up to 20 MeV. The energy dependence of the phase-shifts for five different choices of $\mathrm{Re}\, a_{\eta N}$ and $\mathrm{Im}\, a_{\eta N}$=0.3 fm is shown in Fig. 1. The sequence of the curves (from the bottom to the top) corresponds to $\mathrm{Re}\, a_{\eta N}$= 0.55, 0.65, 0.725, and 0.85 fm. The lower three curves start from zero, while the upper two curves, corresponding to the stronger attraction, start from π. According to Levinson's theorem, the phase shift at threshold energy is equal to the number of bound states n times π. We found that the transition from the lower family of the curves to the upper one occurs at the critical value of $\mathrm{Re}\, a_{\eta N}$=0.733 fm. Therefore, the ηN force, which generates $\mathrm{Im}\, a_{\eta N} = 0.3$ fm and $\mathrm{Re}\, a_{\eta N} > 0.733$ fm, is sufficiently attractive to bind η inside the deuteron.

For three other choices of $\mathrm{Im}\, a_{\eta N}$ within the uncertainty interval, namely, 0.20 fm, 0.25 fm, and 0.35 fm, the corresponding critical values of $\mathrm{Re}\, a_{\eta N}$ turned out to be 0.788 fm, 0.761 fm, and 0.698 fm. In the complex $a_{\eta N}$-plane (see Fig. 2) the corresponding points form a curve separating the uncertainty area into two parts. If $a_{\eta N}$ is to the right of this curve, the ηd-system can be bound. This is the first conclusion of our calculations.

The second conclusion concerns the peaks in the energy dependence of the total elastic cross-section (see Fig. 3), indicating that a resonance appears in the ηd-system. Of course, not every maximum of the cross-section is a resonance, but the corresponding Argand plots, shown in Fig. 4, prove that the maxima we found are resonances. Their positions and widths for $\mathrm{Im}\, a_{\eta N} = 0.3\,\mathrm{fm}$ and various choices of $\mathrm{Re}\, a_{\eta N}$ are given in Table 1.

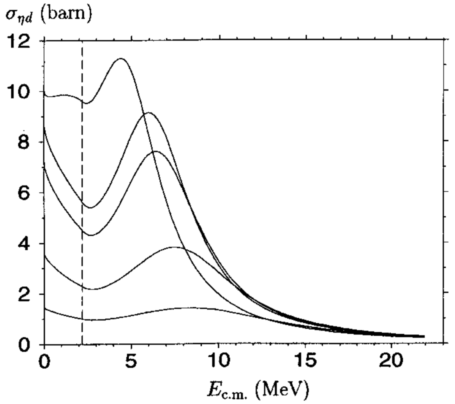

Figure 3

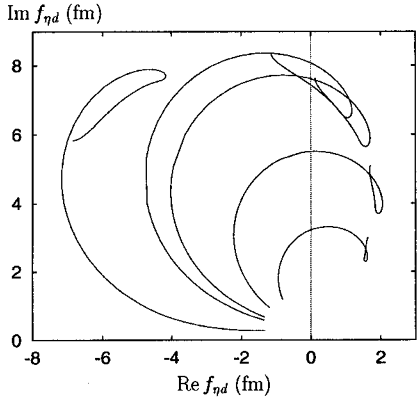

Figure 4

The presence of a resonance before a quasi-bound state appears is not surprising. With increasing attraction the poles of the S-matrix should move in the complex energy plane from the resonance area (fourth quadrant) to the quasi-bound state area (third quadrant). In Ref.[2] we showed that such transition of the pole happens when $\mathrm{Re}\, a_{\eta N}$ changes from 0.25 fm to 1 fm. In the present calculations, we found the corresponding critical value of $\mathrm{Re}\, a_{\eta N}$ exactly.

Table 1

$\mathrm{Re}\, a_{\eta N}$ (fm)	0.55	0.65	0.675	0.70	0.725	0.75	0.85	0.90
$E_{\eta d}^{\mathrm{res}}$ (MeV)	8.24	7.46	7.14	6.79	6.41	6.01	4.39	3.73
$\Gamma_{\eta d}$ (MeV)	9.15	8.45	7.61	6.90	6.31	5.87	5.79	6.81

In conclusion: Elastic ηd scattering is considered within the AGS formalism. A resonant state is found close to the ηd threshold. The position of the resonance moves towards the threshold when $\mathrm{Re}\, a_{\eta N}$ is increased, and turns into a quasi-bound state at $\mathrm{Re}\, a_{\eta N} \sim 0.7 \div 0.8\,\mathrm{fm}$ depending on the choice of $\mathrm{Im}\, a_{\eta N}$.

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