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Physics Letters B 654 (2007) 92–96
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Is there an $\eta\,^3$He quasi-bound state?

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Received 10 July 2007; received in revised form 22 August 2007; accepted 22 August 2007

Available online 24 August 2007

Editor: D.F. Geesaman

Abstract

The observed variation of the total cross section for the $dp \to {}^3\text{He}\,\eta$ reaction near threshold means that the magnitude of the s-wave amplitude falls very rapidly with the η centre-of-mass momentum. It is shown here that recent measurements of the momentum dependence of the angular distribution imply a strong variation also in the phase of this amplitude. Such a behaviour is that expected from a quasi-bound or virtual $\eta\,^3$He state. The interpretation can be investigated further through measurements of the deuteron or proton analysing powers and/or spin-correlations.

PACS: 13.60.Le; 14.40.Aq; 25.45.-z

Keywords: Eta production; Quasi-bound states

New and very precise data on the $dp \to {}^3\text{He}\,\eta$ reaction near threshold [1,2], taken at the COSY accelerator of the Forschungszentrum Jülich, confirm the energy dependence of the total cross section found in earlier experiments [3,4], but with much finer steps in energy over an extended range. The measurements at the lowest excess energy Q (the centre-of-mass kinetic energy in the $\eta\,^3$He system) are of especial interest. The very rapid rise and levelling off of the cross section in this region, shown in Fig. 1 for the COSY–ANKE data [1], suggests that there is a nearby bound or virtual state of the $\eta\,^3$He nucleus [5,6].

The concept of η-mesic nuclei was introduced by Liu and Haider [7]. Since the η-meson has isospin-zero, the attraction noted for the η-nucleon system should add coherently when the meson is introduced into a nuclear environment. On the basis of the rather small η-nucleon scattering length $a_{\eta N}$ assumed, they estimated that the lightest nucleus on which the η might bind would be ^{12}C. Experimental searches for the signals of such effects have generally proved negative, as for example in the $^{16}\text{O}(\pi^+, p)^{15}\text{O}^*$ reaction [8]. The larger $\text{Re}(a_{\eta N})$ subsequently advocated [9] means that the η should bind tightly with such heavy nuclei, generating large and overlapping widths, and thus

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0370-2693/$ – see front matter
doi:10.1016/j.physletb.2007.08.041

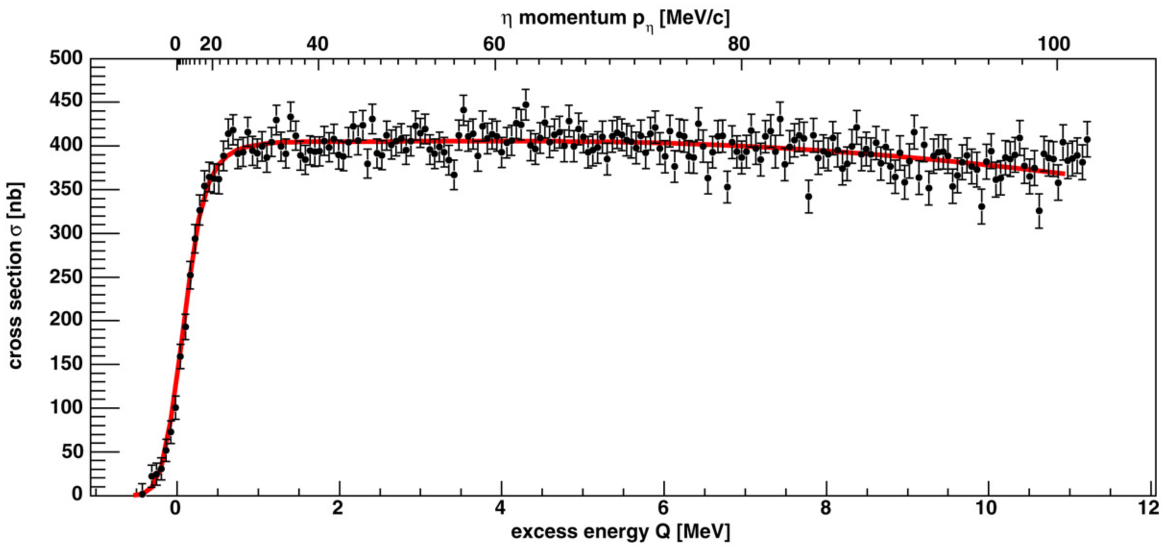

Fig. 1. Total cross section for the $dp \to {}^3\mathrm{He}\,\eta$ reaction measured at COSY–ANKE [1] in terms of the excess energy Q and η c.m. momentum p_η. The fits with and without the p-waves, as discussed in the text, are indistinguishable and so they are not presented separately.

be hard to detect [10]. On the other hand, it also leads to the possibility of binding even in light systems, such as $\eta\,{}^3\mathrm{He}$.

A quasi-bound state leads to a pole of the $\eta\,{}^3\mathrm{He} \to \eta\,{}^3\mathrm{He}$ scattering amplitude in the complex momentum p plane with $\mathrm{Im}(p) > 0$ and in the complex Q plane with $\mathrm{Im}(Q) < 0$.[1] Since such a state can decay via the emission of pions or nucleons, it can only be described as being quasi-bound. If the η-nucleus force is not attractive enough, the signs of these imaginary parts are reversed and the state is called virtual. When a pole is close to $Q = 0$ it distorts strongly the energy dependence of the $dp \to {}^3\mathrm{He}\,\eta$ total cross section at low energies. This is precisely what is seen in the experimental data [1–4], with all experiments identifying a pole with $|Q|$ less than a couple of MeV. The ANKE data [1] shown in Fig. 1 include many points in the threshold region and, after taking into account the finite momentum spread of the beam, a pole was identified at $Q_0 = [(-0.30 \pm 0.15_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}) \pm i(0.21 \pm 0.29_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}})]$ MeV, where the sign of the imaginary part cannot be determined even in principle from such η production data.

The properties of any $\eta\,{}^3\mathrm{He}$ nucleus should be largely independent of the production process but the backgrounds will be reaction-dependent. The only other evidence for the existence of the $\eta\,{}^3\mathrm{He}$ nucleus has come from photoproduction [11]. Though a sharp energy dependence has been seen in the $\gamma\,{}^3\mathrm{He} \to \eta\,{}^3\mathrm{He}$ amplitude, the limited statistics meant that a coarser binning had to be used than for the $dp \to {}^3\mathrm{He}\,\eta$ reaction [1]. A significant improvement in this is to be expected from the new MAMI data, which are currently being analysed [12]. The MAMI–TAPS group also found an anomalous behaviour in the photoproduction of back-to-back (π^-, p) pairs. It was suggested that this is consistent with the existence of a quasi-bound $\eta\,{}^3\mathrm{He}$ state [11], though the interpretation is somewhat controversial [13].

In order to prove that a nearby pole in the complex Q plane is indeed responsible for the unusual energy dependence of the $dp \to {}^3\mathrm{He}\,\eta$ cross section, it is necessary to show that the pole induces a change in the phase as well as in the magnitude of the s-wave amplitude. Since the cross section is proportional to the absolute square of the amplitude, much phase information is thereby lost. However, it is the purpose of the present Letter to point out that the interference between the s- and p-waves, as seen in the newly published angular distributions [1,2], leads to the required confirmation.

The $dp \to {}^3\mathrm{He}\,\eta$ differential cross sections were found to be linear in $\cos\theta_\eta$, where θ_η is the c.m. angle between the initial proton and final η. Throughout the range of the new COSY measurements, $Q < 11$ MeV [1,2], there is no sign of the $\cos^2\theta_\eta$ term that is needed for the description of the angular distributions at higher energies [14]. The angular dependence may therefore be summarised in terms of an asymmetry parameter α, defined as

$$\alpha = \frac{\mathrm{d}}{\mathrm{d}(\cos\theta_\eta)} \ln\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)\Bigg|_{\cos\theta_\eta = 0}. \tag{1}$$

The variation of the ANKE measurements of α with the η momentum p_η is shown in Fig. 2.

On kinematic grounds, the angular dependence near threshold might be expected to develop like $\vec{p}_p \cdot \vec{p}_\eta = p_p p_\eta \cos\theta_\eta$, where $\vec{p}_p$ and $\vec{p}_\eta$ are the c.m. momenta of the incident proton and final η-meson, respectively. However, one striking feature of Fig. 2 is that, although α rises sharply with p_η, it only does so from about 40 MeV$/c$ instead of from the origin, as one might expect on the basis of the above kinematic argument. At low values of p_η the error bars are necessarily large and α might even to go negative in this region. This feature is not inconsistent with the results of other measurements [2,4] that have different systematic uncertainties and so it is possibly a gen-

[1] The time evolution of the wave function of the state involves a factor $\exp(-iQ_0t) = \exp(-i\,\mathrm{Re}(Q_0)t)\exp(+\mathrm{Im}(Q_0)t)$. A quasi-bound state must decay in time, which thus requires that $\mathrm{Im}(Q_0) < 0$. In contrast, a virtual state has $\mathrm{Im}(Q_0) > 0$ and is also on the second (unphysical) sheet.