LIGHT η-MESIC NUCLEI*

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(Received January 7, 2014)

Data on the production of η mesons on light nuclei near threshold are surveyed. The photoproduction of η^3He and elastic scattering from this nucleus are modelled in a multiple scattering scheme and the positions of the poles both here and in the scattering from neighbouring light nuclei are studied in an optical potential approach. The production of η^7Li is compared to that of η^3He within a cluster model. The decay of light η-mesic nuclei through pion or nucleon emission is also considered.

DOI:10.5506/APhysPolB.45.603
PACS numbers: 21.85.+d, 25.10.+s, 21.45.–v

1. Introduction

Although the idea of quasi-bound states of an η meson with a nucleus has been around for a quarter of a century [1], no experiment has yet shown incontrovertible evidence for their existence. By definition, in the bound state region the η meson does not have enough energy to escape and so the searches there have involved looking for other decay modes, such as the semi-inclusive $\pi^0 pX$ [2, 3]. The lack of a convincing positive signal may be due to a large non-η background. However, a more insidious effect for a complex nucleus is the fact that, in a single-channel optical potential calculation, an η would bind to a nuclear excited level in much the same way as it would to the ground state. The suspicion, therefore, has to be that it would be difficult to detect an η-mesic quasi-bound state if its width were larger than the nuclear level spacing.

The alternative approach [4] is to study η production just above the threshold and, from the measured energy dependence, try to extrapolate below the threshold. Looking at the energy spectrum of a nucleon–nucleon final state, one can *easily* deduce that there is a nearby S-wave pole but the big drawback is that such a measurement will never tell you that you have

* Presented at the II International Symposium on Mesic Nuclei, Kraków, Poland, September 22–25, 2013.

a bound state (like the $^3S_1$ deuteron) or a virtual state (like the $^1S_0$ singlet). On the other hand, the detection of an η-meson emerging from a reaction certainly cuts down the severe background problem.

2. Simple optical potential approach

There have been measurements of the production of ηd [5], η^3He [2, 3, 6–10], η^4He [11–14], and η^7Li/^{7}Be [15–17] systems near threshold. The most detailed $dp \to {}^3\text{He}\,\eta$ data [9] show an enormous threshold enhancement corresponding to a very large η^3He scattering length and a pole in the excess energy plane with $|Q| < 1$ MeV. The real and imaginary parts are strongly coupled in the fits and so the exact location of the pole is pretty uncertain. However, strong evidence for its existence is found from the anomalous dependence of the slope of the $dp \to {}^3\text{He}\,\eta$ differential cross section on the excess energy [18].

If the threshold enhancement is really due to a final state interaction, then a broadly similar FSI behaviour must be present for all entrance channels that lead to the s-wave η^3He system. Such features are indeed seen in the $\gamma^3\text{He} \to \eta^3\text{He}$ reaction [3]. Even more compelling are the measurements of the $\vec{d}p \to {}^3\text{He}\,\eta$ reaction with a tensor polarised deuteron beam [10]. The near constancy of the average value of the t_{20} analysing power with Q means that the η^3He pole has to be in more or less the same position for the spin $S = 1/2$ and $S = 3/2$ initial states. The pole must, therefore, be a consequence of η^3He dynamics. Very little angular dependence was observed for t_{20} and this suggests the assumptions that should be made in the amplitude analysis [18]. The other important point to note is that any threshold enhancement that may exist for ηd, η^4He, or η^7Li/^{7}Be has to be significantly weaker than that of η^3He.

I want to insist that nobody yet knows how to estimate the binding of an η meson to a light nucleus. In the simplest approach, one constructs an η-nucleus potential $V_{\eta A}(r) \propto f_{\eta N}\rho(r)$, where $\rho(r)$ is the nuclear density and $f_{\eta N}$ is the s-wave η-nucleon scattering amplitude. The major controversy is what to assume here for $f_{\eta N}$. In the most recent detailed calculations [19], it has been stressed that the ηN scattering amplitude has a very strong energy dependence due to the dominance of the $N^*(1535)$ isobar and its value is influenced by the nuclear as well as by the η binding energy. The required effective energy was then evaluated in a much more self-consistent way than in earlier approaches. However, the major drawback when trying to include the energy dependence seriously is that we do not really know how the $N^*(1535)$ itself behaves inside a nucleus. Is it more bound or less bound? Until we know this we really do not know how to include the energy dependence of $f_{\eta N}$ reliably.

If one neglects the energy dependence of $f_{\eta N}$ and just tries to fit the available data with a one-body optical potential based upon a scattering length $a_{\eta N}$, this seems to require an unbelievably small value of the imaginary part of the potential. Thus with $a_{\eta N} = (0.55 + 0.03i)$ fm, one gets $a_{\eta^3\mathrm{He}} = (-10.0 + 2.4i)$ fm, $a_{\eta^4\mathrm{He}} = (-2.8 + 0.20i)$ fm, and $a_{\eta^7\mathrm{Li}} = (-2.7 + 0.19i)$ fm, with corresponding energies of $Q_{\eta^3\mathrm{He}} = -(0.36 + 0.18i)$ MeV, $Q_{\eta^4\mathrm{He}} = -(5.0 + 0.7i)$ MeV, and $Q_{\eta^7\mathrm{Li}} = -(5.3 + 0.8i)$ MeV. Of course, it is very *ambitious* (or foolhardy) to use a simple potential model for such very light nuclei but, if we do, we seem to require a very small imaginary part to get scattering lengths that bear any relation to the η^3He production data. If we neglect this obvious drawback, then we find that the $^4_\eta$He pole lies in the quasi-bound part of the complex plane. I think that this raises the really crucial question. Is there any model capable of giving a pole with a small imaginary part for η^3He that does not require an input with a very small imaginary part?

As I have earlier stated, if instead of estimating the binding to the ground state of a nucleus, one looked rather at an excited state then, in a simple one-body optical potential approach, the binding would be similar. Hence, as soon as the widths become comparable to the nuclear level spacing, there is really no hope of finding meaningful peaks corresponding to quasi-bound states in sub-threshold reactions. If one believes the above numbers, then perhaps this is not too crucial for the very lightest nuclei but larger widths are given in the literature [19, 20], where the problem seems more serious.

A more intrinsic problem lies in the use of a one-body effective potential. If, for example, one takes the case of ^{12}C, can one safely neglect the coupling η^{12}C to η^{12}C*, where C* is the famous 0^+ Hoyle state at 7.6 MeV? In other words, is it justified to factorise out the nuclear and mesonic degrees of freedom?

3. Multiple scattering approach

The MAMI data on $\gamma^3\mathrm{He} \to \eta^3\mathrm{He}$ [3], in addition to showing the strong FSI associated with a possible $^3_\eta$He state of some kind, yielded some very interesting information on the angular dependence. Away from threshold, the data are sharply peaked towards the forward direction, where the momentum transfer between the initial and final ^{3}He is minimised, and this general behaviour is well reproduced in a single scattering calculation. Nearer to threshold the data flatten out and there is even a tendency for more of the cross section to lie in the backward hemisphere. This variation is very similar to that noted for $dp \to {}^3\mathrm{He}\,\eta$ [9], which was ascribed to the interference (mainly) of the p-wave with the rapidly changing s-wave amplitude associated with the η^3He pole [18]. It would be highly desirable to construct a photoproduction model that built a distorted-wave impulse approximation together with the η multiple scatterings. The toy one that I present today has many very serious defects but it serves to illustrate some of the inherent difficulties associated with the problem.

Suppose that the η-nucleon interaction is of very short range so that the interactions in ^{3}He do not overlap, in which case only the on-shell part of the ηN scattering amplitude f is relevant [21, 22]. As a second simplifying assumption, let us suppose that the ^{3}He nuclear density is represented by nucleons placed at the vertices of an equilateral triangle of side length ℓ [23]. The η^3He elastic scattering operator then becomes [24]

$$\mathcal{F}\left(\vec{k}',\vec{k}\right) = \frac{3f}{D}\left\{\left(1-f\,\frac{e^{ik\ell}}{\ell}\right)S\left(\vec{k}',\vec{k}\right)+2f\,\frac{e^{ik\ell}}{\ell}T\left(\vec{k}',\vec{k}\right)\right\}, \qquad (1)$$

where $\vec{k}$ and $\vec{k}'$ are the initial and final η momenta of magnitude k and the denominator function

$$D = \left(1+f\,\frac{e^{ik\ell}}{\ell}\right)\left(1-2f\,\frac{e^{ik\ell}}{\ell}\right). \qquad (2)$$

The form factors are the expectation values over the orientation of the triangle

$$S\left(\vec{k}',\vec{k}\right) = \left\langle e^{-i\left(\vec{k}'\cdot\vec{r}_A-\vec{k}\cdot\vec{r}_A\right)}\right\rangle \qquad \text{and} \qquad T\left(\vec{k}',\vec{k}\right) = \left\langle e^{-i\left(\vec{k}'\cdot\vec{r}_A-\vec{k}\cdot\vec{r}_B\right)}\right\rangle,$$

where $\vec{r}_A$ and $\vec{r}_B$ are two of the vertices of the triangle.

Although the expression for $S(\vec{k}',\vec{k})$ can be evaluated simply in closed form, the same is not true for $T(\vec{k}',\vec{k})$ except in colinear kinematics. However, the full scattering operator can be developed straightforwardly in partial waves

$$\mathcal{F}\left(\vec{k}',\vec{k}\right) = \sum_n (2n+1)\mathcal{F}_n(k)P_n(\cos\theta), \qquad (3)$$

where θ is the scattering angle and

$$\mathcal{F}_n(k) = \frac{3f}{D}\left\{\left(1-f\,\frac{e^{ik\ell}}{\ell}\right)+2f\,\frac{e^{ik\ell}}{\ell}P_n\left(-\frac{1}{2}\right)\right\}\left[j_n\left(k\ell/\sqrt{3}\right)\right]^2. \qquad (4)$$

It is interesting to look at the structure of the s- and p-wave amplitudes, for which the curly brackets become

$$\left\{\cdots\right\}_{n=0} = \left\{1+f\,\frac{e^{ik\ell}}{\ell}\right\} \qquad \text{and} \qquad \left\{\cdots\right\}_{n=1} = \left\{1-2f\,\frac{e^{ik\ell}}{\ell}\right\}. \qquad (5)$$

Thus, for the two lowest partial waves, different zeros of the denominator of Eq. (2) are cancelled. There can, therefore, be a significant variation in the relative phase between the s- and p-wave amplitudes near threshold.

Nevertheless, one disease of the rigid triangle model is immediately obvious. There are poles in the scattering amplitudes for *all* partial waves. The s-wave pole is at $k_0 = -(i/\ell)\ln(\ell/2f)$. Since $\ell \approx 2.7$ fm, in order to get the pole within 1 MeV of threshold, one requires $f \approx \ell/3 \approx 0.9$ fm. Taking into account the fact that the reduced masses are different in the ηN and η^3He systems, one still needs a scattering length of the order of 0.7 fm to get even a virtual state pole in such a model and much larger to make it quasi-bound. Having an imaginary part in the scattering length makes things a bit harder for, if we take $a_{\eta N} = (0.6 + 0.3i)$ fm, the imaginary part of the pole energy dominates and we find the pole energy at $Q_0 = (0.28 + 2.27i)$ MeV. The p-wave pole at $k_1 = -(i/\ell)\ln(-\ell/f)$ is <u>much</u> further away, primarily because of the minus sign in the logarithm.

In order to get a better description of the electromagnetic form factor in this nuclear model, one has to smear the triangle lengths with a weight function that gives an *average* value of $\langle\ell\rangle \approx 2.7$ fm [23]. The poles then get converted into short cuts, which illustrates yet another defect of this very naïve model.

The model can be easily transformed into one for $\gamma^3\text{He} \to \eta^3\text{He}$. The partial wave amplitude then becomes

$$\mathcal{F}_n(k) = \frac{3f_{\gamma N\to\eta N}}{D}\left\{\left(1 - f\,\frac{e^{ik\ell}}{\ell}\right) + 2f\,\frac{e^{ik\ell}}{\ell}P_n\left(-\frac{1}{2}\right)\right\} j_n\left(\frac{k\ell}{\sqrt{3}}\right) j_n\left(\frac{k_\gamma\ell}{\sqrt{3}}\right), \tag{6}$$

where k_γ is the photon momentum and k that of the η. Here, an η-meson is produced on the first nucleon by the amplitude $f_{\gamma N\to\eta N}$ and it is this meson that rescatters on the target nucleons. However, it does <u>not</u> allow for the possibility of a pion being produced on the first nucleon and this being transformed into an η-meson on a subsequent nucleon. Such effects may be as important as direct η-meson rescattering but there is no reason to assume that the πN scatterings are dominated by the s-waves.

The results are slightly disappointing in that, with an input of $a_{\eta N} = 0.7$ fm, the angle-integrated cross section is 6.2 times the impulse approximation at 2.5 MeV and only 2.2 at 9.5 MeV, so that the effects of the pole are quite clear. As is seen in Fig. 1, this fall-off is much steeper than in the MAMI data. On the other hand, with $a_{\eta N} = (0.476 + 0.279i)$ fm and a reasonable value for the effective range [23], the deviations from impulse approximation shown in the figure seem to be very *modest* and both multiple scattering calculations give very similar results for $Q > 15$ MeV.

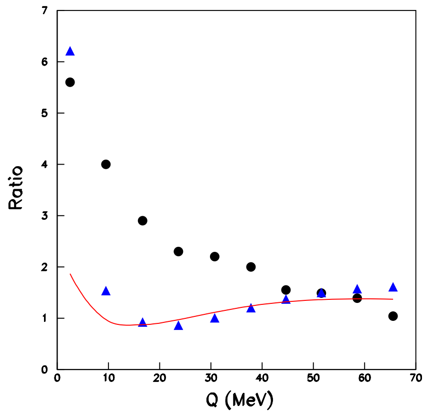

Fig. 1. Ratio of the angle-integrated γ^3He $\to \eta^3$He cross section to impulse approximation [3] (black circles) as a function of the excess energy Q. The multiple scattering predictions with $a_{\eta N} = 0.7$ fm are shown as blue triangles; the corresponding results with $a_{\eta N} = (0.476 + 0.279i)$ fm are shown by the solid/red curve.

One gets far more information from the angular distributions, two of which are illustrated in Fig. 2. In the lowest energy bin ($Q \approx 2.5$ MeV), the shape of the angular distribution is reproduced by the multiple scattering scheme using either the moderate or strong input. In contrast to the impulse approximation, both of these give more cross section in the backward hemisphere. It should be noted that the $a_{\eta N} = 0.7$ fm input was chosen to reproduce the normalisation.

Though the multiple scatterings did not seem to change significantly for $Q > 15$ MeV the integrated cross sections shown in Fig. 1, the shapes of the angular distributions are utterly altered, with a backward peak being generated at all energies, even at 65.5 MeV shown in Fig. 2.

However, the rescatterings are just too important because the very strong forward peaking seen in the experimental data is only reproduced at the highest energy and even then the predicted cross section in the backward hemisphere is far too big. Even with the $a_{\eta N} = (0.476 + 0.279i)$ fm input, it is still only for Q above about 25 MeV that there is more cross section predicted in the forward than in the backward hemisphere.

The lesson that we can draw from this crudest of models is that multiple scatterings of the η-meson can lead to a suppression of the forward peaking seen in the impulse approximation. However, if the interaction is so strong that the virtual state pole is close by then the rescatterings remain too important even well away from threshold. This may be due to neglecting terms where one first produces a pion which produces an η-meson in a second interaction. The challenge is to produce a better reaction model that couples the π and η in the dynamics.

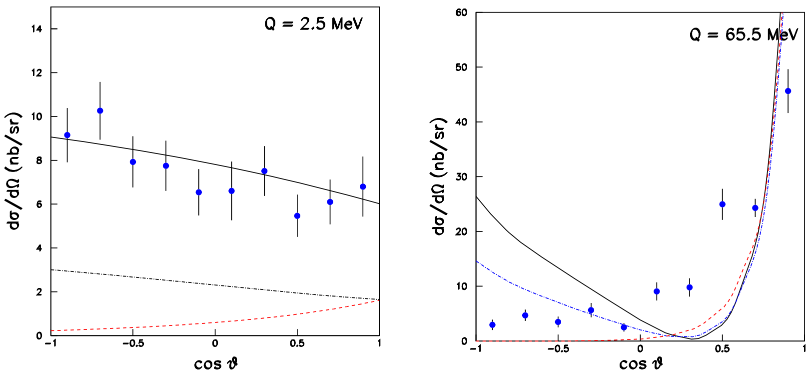

Fig. 2. Angular distributions of the γ^3He $\rightarrow \eta^3$He reaction at mean excess energies of 2.5 MeV and 65.5 MeV. The MAMI experimental data (circles/blue) [3] are compared to the shapes expected in impulse approximation (dashed/red curves). The multiple scattering predictions with $a_{\eta N} = 0.7$ fm and $a_{\eta N} = (0.476 + 0.279i)$ fm are shown by the solid black and dot-dashed curves, respectively. To illustrate the shape variation, the curves for the higher energy data have been scaled to coincide near the forward direction.

4. η-mesic nuclear widths and decay rates

Though the searches for bound η-nucleus states through their semi-inclusive decays involving pions and nucleons or missing-mass experiments have generally proved fruitless, one has to ask if there is any relation between the above-threshold experiments involving real η production and those where the binding does not allow the meson to emerge intact.

The first point to make is that the contribution of the η-mesic nuclear pole to the production of say $\pi^- pX$ final states will generally be a small fraction of the non-η events. Hence, if such a pole were at all significant, its first manifestation might be through its interference with the background and this would not look like a Breit–Wigner shape. The effect here is rather analogous to the momentum dependence of the angular slope parameter in the $dp \rightarrow {}^3\text{He}\,\eta$ reaction where the s-wave pole with its rapidly changing phase interferes with the smoother p-wave amplitude [18].

To illustrate the possibility of relating the bound and scattering region data, suppose that ${}^3_\eta$He is bound but that its width overlaps the threshold. Suppose further that the interference effect is washed out by the resolution in the experiment. An s-wave Breit–Wigner representation of the $dp \rightarrow {}^3\text{He}\,\eta$ total cross section takes the form

$$\sigma\left(dp \rightarrow {}^3\text{He}\,\eta\right) = \frac{2\pi}{p_d^2}\frac{\mathit{\Gamma}_{pd}\mathit{\Gamma}_{\eta\tau}/4}{[(Q - Q_R)^2 + \mathit{\Gamma}^2/4]} = \frac{2\pi p_\eta}{p_d^2}\frac{\mathit{\Gamma}_{pd}\gamma_{\eta\tau}/4}{[(Q - Q_R)^2 + \mathit{\Gamma}^2/4]}\,, \quad (7)$$

where $\mathit{\Gamma}_{\eta\tau} = p_\eta \gamma_{\eta\tau}$.

The energy dependence of the cross section allows one to deduce a value of $Q_0 = Q_R \pm i\Gamma/2$, where Γ is the total width of the state. The values of the real and imaginary parts are strongly coupled in the fits to the data and the sign of Γ, *i.e.* whether the state is bound or anti-bound, can never be established from above-threshold data. The product of the partial widths $\Gamma_{pd}\gamma_{\eta\tau}$ can then be extracted from the magnitude of the $dp \to {}^3\mathrm{He}\,\eta$ cross section. At $Q = 0$, this gives [18]

$$\frac{p_d}{p_\eta}\sigma\left(dp \to {}^3\mathrm{He}\,\eta\right) = 4\pi \times 2.5\ \mu\mathrm{b}\,, \tag{8}$$

which leads to

$$\Gamma_{pd}\gamma_{\eta\tau} = p_d|Q_0|^2 \times (20\ \mu\mathrm{b})\,. \tag{9}$$

Taking now $|Q_0| \approx 1$ MeV and $p_d = 878$ MeV/c, this gives

$$\Gamma_{pd}\gamma_{\eta\tau} = 4.5 \times 10^{-5}\ \mathrm{MeV}\,. \tag{10}$$

However, this is not sufficient to allow one to put a useful limit on the cross section for $dp \to \pi^- pX$. For that, one needs the values of Γ_{pd} and/or $\gamma_{\eta\tau}$ separately, and this must involve more assumptions.

The contribution of the pole to the total cross section for elastic η^3He scattering is

$$\sigma\left(\eta^3\mathrm{He} \to \eta^3\mathrm{He}\right) = 2\pi\frac{[\gamma_{\eta\tau}]^2/4}{[(Q-Q_R)^2 + \Gamma^2/4]}\,. \tag{11}$$

One can estimate this in a multiple scattering or potential model but let us for simplicity assume that the FSI enhances the single scattering approximation by say a factor of ten so that at threshold $\sigma(\eta^3\mathrm{He} \to \eta^3\mathrm{He}) \approx 600\ \mathrm{fm}^2$, from which it follows that $\gamma_{\eta\tau} = 0.1$ and $\Gamma_{pd} = 4.5 \times 10^{-4}$ MeV. This leads to a total dp cross section passing through the η-mesic pole of about 0.4 μb. Of these perhaps about 20% emit a $\pi^- p$ pair.

Since the passage via the ${}^3_\eta$He pole should be independent of the entrance channel, similar considerations will also apply to photoproduction data [2, 3], though there we do have a zeroth order dynamical model of the $\gamma^3\mathrm{He} \to \eta^3\mathrm{He}$ reaction as an extra check.

If one tries to play the same game for the $dd \to {}^4\mathrm{He}\,\eta$ reaction, one finds that the total dd cross section passing through the ${}^4_\eta$He pole should be a bit less, perhaps of the order of 100 nb, depending upon the assumptions made. The $\pi^- pX$ final state should account for about one third of this. The recent measurement from the WASA-at-COSY Collaboration led to an upper limit of about 20 nb for producing the $\pi^- p\,{}^3$He final state [25]. However, this must be lower than the semi-inclusive estimate of $\approx 100/3$ nb by a sticking factor corresponding to finding a ^{3}He nucleus in the final state.

Although these numbers could be different in other approaches, the crucial idea is that data where, say, a $\pi^- p$ pair is observed cannot be completely independent from those where the η emerges in a reaction. This point was also stressed by Wycech [26], though the assumptions that he made were somewhat different.

5. The production of $^{7}_{\eta}$Li and $^{7}_{\eta}$Be

Krusche has shown results for the $\gamma^7\text{Li} \to \eta^7\text{Li}$ reaction near threshold [17] and these complement earlier data taken on the $p^6\text{Li} \to \eta^7\text{Be}$ reaction [15, 16]. It is important to note here that the structure of these $A = 7$ nuclei consists of a ground state doublet with orbital angular momentum $L = 1$ and another doublet with $L = 3$. These are then split by a small spin-orbit term which, in the ^{7}Li case, gives levels with $J^{\text{P}} = 3/2^-$, $1/2^-(0.48$ MeV$)$, $7/2^-(4.65$ MeV$)$, and $5/2^-(6.60$ MeV$)$. None of the three experiments had sufficient energy resolution to be sensitive to the splitting between the $J^{\text{P}} = 3/2^-$ and $1/2^-$ levels, though one of the $p^6\text{Li} \to \eta^7\text{Be}$ experiments [16] only measured particle-stable levels where $E_X < 2.47$ MeV, *i.e.* the $L = 1$ doublet, and the shape of the missing-mass distribution in the photoproduction data allowed a degree of separation between the $L = 1$ and $L = 3$ excitations [17]. In no case was there compelling evidence for a strong final state enhancement of the type that was so obvious for η^3He.

The $p^6\text{Li} \to \eta^7\text{Be}$ data were analysed in an αd and $\alpha\tau$ cluster-model approach, using the $dp \to {}^3\text{He}\,\eta$ data as input [27]. The good description of the two data sets [15, 16] suggests that, if the energy allows it, the excitation of the $L = 3$ doublet will be stronger than that of the $L = 1$ doublet. Have we any idea what the situation is likely to be in the photoproduction case?

It has been shown that the $\gamma^7\text{Li} \to \eta^7\text{Li}$ data can be plausibly described in an undistorted impulse approximation model, where the production cross section on an unpaired proton is modified by ^{7}Li elastic form factor [17]. The momentum transfers in this experiment are typically $q = 2$–3 fm^{-1} and in this region the square of the transverse form factor for exciting the $7/2^-$ level is very similar to that for elastic scattering whereas that for exciting the $1/2^-$ level is about a factor of three lower [28]. There is far less information available for the $5/2^-$ level but one might expect it to be lower than that for the $7/2^-$ by a statistical factor of $\frac{3}{4}$. Hence the population of the $L = 3$ final states should be comparable or perhaps even a bit bigger than those for the $L = 1$ doublet. Are the MAMI data [17] compatible with this? As one can see from Fig. 3, the answer is a resounding *perhaps*! However, we really have to ask to what extent the ground state data themselves are reproduced in impulse approximation, and here we turn again to a cluster-model description.

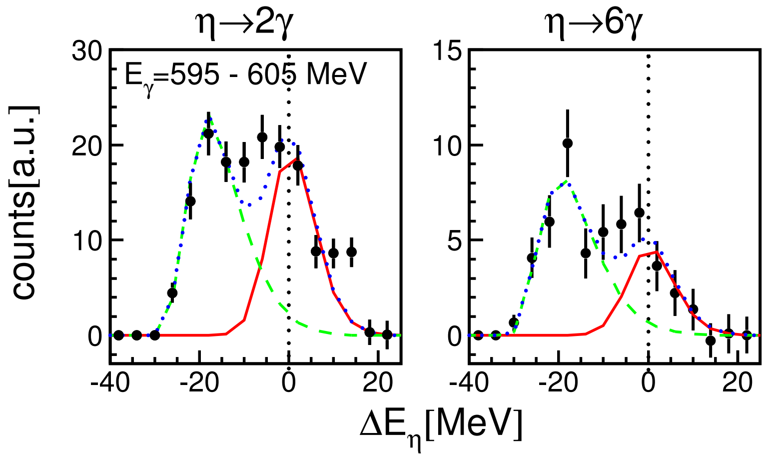

Fig. 3. Missing-energy spectrum for the γ^7Li $\to \eta X$ reaction for $595 < E_\gamma <$ 605 MeV where the meson was detected through its 2γ or 6γ decay [17]. The vertical dotted lines correspond to the central position of the ^{7}Li ground state. The solid/red curve is a Gaussian fit to the production of the ground-state doublet whereas the dashed/green one corresponds to the assumed background from higher states. The dotted/blue curve represents the sum of these two contributions.

In a ^{4}He–^{3}H model for ^{7}Li, the charge form factor at momentum transfer q is of the form

$$F_7(q) = [2F_4(q)\,G(3q/7) + F_3(q)\,G(4q/7)]\,/3\,, \qquad (12)$$

where $F_4(q)$ and $F_3(q)$ are the form factors for ^{4}He and ^{3}H, respectively, and $G(q)$ reflects the relative motion of the two clusters. All spin details have been neglected here and the filling-in of minima through quadrupole transitions is brushed under the carpet by using an empirical form for $G(q)$. This is constructed from electron scattering data where the excitation of the 0.48 MeV is not separated from the ^{7}Li ground state [30].

If we take an analogous form to that used already to describe the ^{7}Li data [17], the squares of the amplitudes for the photoproduction of the η meson on ^{3}He and ^{7}Li targets are related by

$$\frac{k_\gamma^{(7)}}{k_\eta^{(7)}}\frac{d\sigma}{d\Omega}\left(\gamma^7\mathrm{Li}\to\eta^7\mathrm{Li}\right) = \frac{k_\gamma^{(3)}}{k_\eta^{(3)}}\frac{d\sigma}{d\Omega}\left(\gamma^3\mathrm{He}\to\eta^3\mathrm{He}\right)\times[G(4q/7)]^2\,. \qquad (13)$$

Even if we accept this simple *ansatz*, we still have to prescribe how the energies or momenta of the production on the two targets are related. This is ambiguous but the rule that I shall adopt is that the η momentum in the inverse reaction is the same in the laboratory frame. The values of the right-hand side of Eq. (13), which are proportional to the absolute square of the production amplitude, have been obtained using as input a parametrisation of the MAMI γ^3He $\to \eta^3$He data [3]. Both the data and the predictions include contributions from the 0.48 MeV level. One learns relatively little from the angular distribution because the data and the model are both peaked so strongly towards the forward direction, but the integration over all angles leads to the results shown in Fig. 4. The rapid rise at low η momentum is a reflection of the FSI in the η^3He case, which is hard to discern for η^7Li. One would therefore need far more data close to threshold in order to extract definitively any FSI effect.

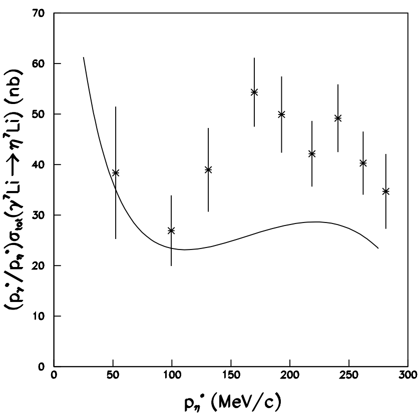

Fig. 4. The total cross section for γ^7Li $\to \eta^7$Li to the ground state and first excited level of ^{7}Li modified by the ratio of the c.m. momenta of the photon and η meson. The experimental data [17] are compared to the curve of the impulse-approximation predictions based on Eq. (13) using the MAMI γ^3He $\to \eta^3$He data [3] as input.

The predictions in such a simple model are very encouraging and suggest that it would be worthwhile to explore the problem in a more microscopic cluster model, where the spin degrees of freedom are more adequately treated. This would also allow one to make more robust estimates of the excitation of the $L = 3$ doublet, which would then have to be taken into account in untangling the experimental ^{7}Li energy spectrum.

6. Two-body absorption

Gal *et al.* [19, 29] raised the question of the possible contribution to the η-nucleus widths from the absorption of the meson on two nucleons inside a nucleus. Although one might expect this to be small, a more quantitative estimate is clearly desirable.

From fits to low energy $\pi^- p \to \eta n$ cross section data, it is seen that [4]

$$\frac{p_\eta^{\rm lab}}{m_\eta}\sigma_{\rm tot}(\eta N \to \pi N) \approx 22 \text{ mb}\,, \tag{14}$$

where $p_\eta^{\rm lab}$ is the η momentum in the frame where the initial nucleon is at rest.

Now it is well known that near threshold the production of η mesons is much stronger in neutron–proton collisions than in proton–proton and the first evidence of this was found in the inclusive production of the meson by protons on hydrogen and deuterium targets [31]. The $np \to d\eta$ cross section has been measured near threshold [5], and this shows that

$$\frac{p_\eta^{\rm lab}}{m_\eta}\sigma_{\rm tot}(\eta d \to pn) \approx 1.7 \text{ mb}\,. \tag{15}$$

Although one might quibble about the values quoted here, and there will be some variation when extrapolating below threshold (especially in the deuteron case), since there are two nucleons in the deuteron it is clear that the single body absorption on the deuteron is about twenty five times stronger than that of the two-body. But how does this change in a nucleus?

Detailed Monte Carlo variational calculations of light nuclei [32] provide estimates of the numbers R_{Ad} of deuteron-like pairs at short np separations. It is claimed that the expectation value of any short-ranged two-body operator that is large only in the $(T,S) = (0,1)$ state should scale as R_{Ad}, estimates of which are presented in Table I.

TABLE I

Estimates for the numbers of *quasi-deuterons* in various light nuclei [32].

A	^{3}He	^{4}He	^{6}Li	^{7}Li	^{16}O
R_{Ad}	2.0	4.7	6.3	7.2	18.8

To a first approximation, one sees from Table I that R_{Ad} varies roughly like the number of nucleons A, as does the single-particle absorption. This means that the two-nucleon absorption is at most 5% of the total for a light nucleus and this is much smaller than the uncertainty in the imaginary part in the optical potential[1]. It is therefore reasonable to neglect it when trying to estimate widths of η-mesic nuclei [19].

[1] Wycech pointed out in the discussion that the non-mesonic decays for K^- captured on light nuclei scaled much more strongly with A than suggested by Table I.

The search for η-mesic states through their decay into back-to-back $\pi^- p$ pairs has given rather disappointing results due to the large background that is not associated with virtual η production [3]. Despite the 5% factor, one has to wonder whether the background conditions might be better if one looked instead at back-to-back np pairs, the other nucleons in the ${}_{\eta}A$ state being *spectators* in the decay [33]. To avoid detecting the neutron, it might be easier to study a *spectator*, and this could be simplest in the $dp \to {}^{3}_{\eta}\text{He} \to p_{\text{sp}}np$ reaction. The central value of the proton *spectator* p_{sp} momentum would be around 440 MeV/c, which should not be confused with a proton coming from the deuteron break-up, where the momenta are centred around 1570 MeV/c. [In the deuteron rest frame this would correspond to a momentum ≈ 440 MeV/c, which is enormous compared to typical Fermi momenta.] Kinematically the approach looks promising but one really has no idea what the signal/noise ratio would turn out to be.

A slightly different consideration is whether it is possible to detect the decay of the η meson while it is orbiting around a nucleus. The total width of the η is about 1.3 keV and we know that the width of ${}^{3}_{\eta}\text{He}$ is less than about 500 keV. Taking into account the 2γ branching ratio of 39%, one sees that about one ${}^{3}_{\eta}\text{He}$ in a thousand should decay with 2γ emission. The 6γ branch should be only slightly less. Though these are small numbers, they do offer the tantalising possibility of beating the background.

Although I do not believe that there is much chance that an η' would actually bind to a nucleus, if it did there is the much more significant natural width of ≈ 226 keV [34] to play with. Depending upon the width of the mesonic nucleus, there is likely to be a larger fraction of η' that decay within the nucleus. However, of these only $\approx 2\%$ would go via the 2γ mode.

7. Conclusions

There is very good experimental evidence that the strong final state interaction seen in the $\vec{d}p \to {}^{3}\text{He}\,\eta$ and $\gamma^{3}\text{He} \to \eta^{3}\text{He}$ reactions near threshold must be associated with a pole in the excess energy Q plane for $|Q| < 1$ MeV. In contrast, any FSI leading to an ηpp, ηd, $\eta^{4}\text{He}$, or $\eta^{7}\text{Li(Be)}$ system is less obvious. The radically different behaviour seen in the $\eta^{3}\text{He}$ and $\eta^{4}\text{He}$ cases can be "explained" within a single-channel optical potential approach but only if this potential is almost real, and this is very hard to justify.

Although the magnitude and shape of the $\gamma^{3}\text{He} \to \eta^{3}\text{He}$ differential cross section away from threshold seem to be described by the single-scattering approximation, the enhancement at low Q certainly involves significant multiple scattering. The crudest of multiple scattering models presented here suggests that, if the parameters are chosen to give the threshold enhancement, the effects do not vanish in the higher Q data and the forward peaking presented in the data (and the impulse approximation) is wiped out.

The application of the impulse approximation to the $\gamma^7\text{Li} \to \eta^7\text{Li}$ data indicates that the production of the $L = 3$ doublet should be as large as that of the $L = 1$ ground state doublet and this may influence the apparent threshold behaviour because the η should *bind* to an excited nuclear state in much the same way that it does to the ground state. The $\gamma^3\text{He} \to \eta^3\text{He}$ data could be compared directly with those for $\gamma^7\text{Li} \to \eta^7\text{Li}_{\text{gs}}$ in a $^4\text{He}-^3\text{H}$ cluster model and this gives a reasonable description, though with more uncertainty in the FSI region.

Searches for states such as $^3_\eta\text{He}$ through their decay into say $\pi^0 pX$ have been unsuccessful. In this case, this might be due to $^3_\eta\text{He}$ being an antibound state but, in general, the narrow width limits the coupling strength and perhaps one could look instead at two-nucleon or even two-photon decay.

Nothing has been said here about η production in nucleon–nucleon collisions. The effects of the FSI in a three-body final state are hard to identify experimentally and no data have been published recently on the $np \to d\eta$ reaction. This should change soon when results are available from the new quasi-free measurements of the differential and total cross section that were made at COSY earlier this year [35].

Numerous discussions with Göran Fäldt and Bernd Krusche have been very influential in the preparation of this manuscript. The support of the workshop Organisers, especially Paweł Moskal, is gratefully acknowledged.

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