An introduction to mesic nuclei

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PACS 2010: 21.85.+d Mesic nuclei

Though the field had been around for more than 20 years earlier, in 2010 the APS finally recognised that there was a subject called “mesic nuclei”.

This is of interest for a variety of reasons:

1) It allows one to investigate the interaction of unstable particles with nucleons and nuclei.
2) If such states existed, they would represent exotic nuclear matter with several hundred MeV of excitation energy.
3) If one can produce a ${}^{3}_{\eta}\mathrm{He}$ through $dp \to {}^{3}_{\eta}\mathrm{He}$ this will contribute a small amount to $dp \to {}^{3}_{\eta}\mathrm{He} \to dp$, *i.e.*, deuteron-proton elastic scattering.
4) Theorists love to speculate and (some) experimentalists want to make their reputation by finding something really exotic, such as dibaryons or mesic nuclei. **But I am not accusing anybody in the room!**

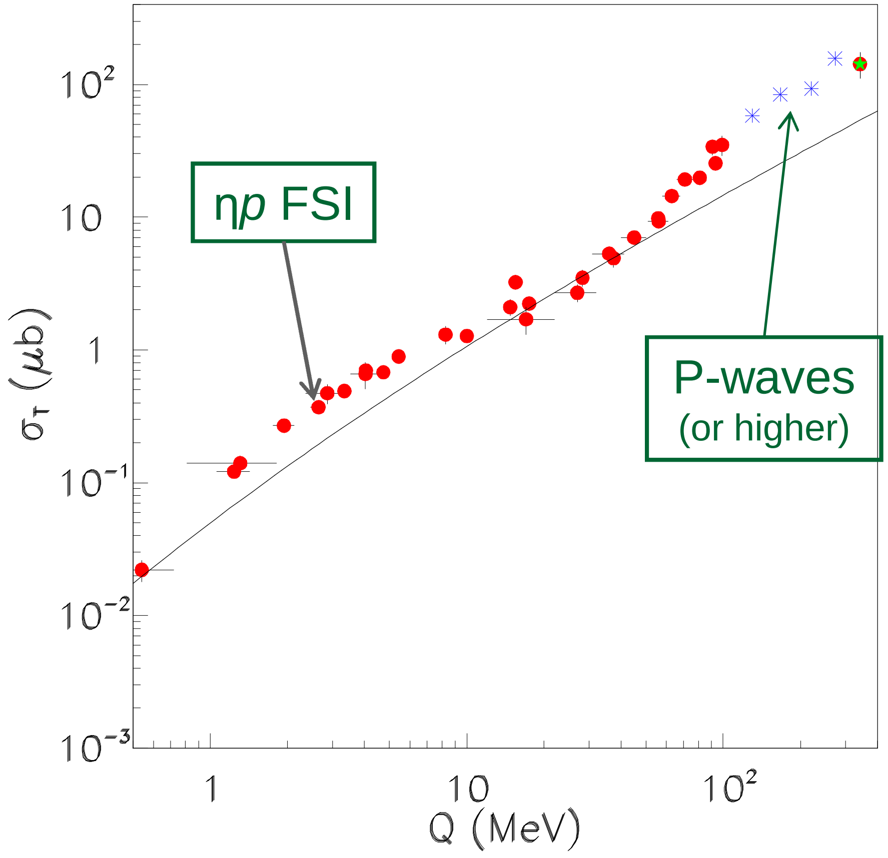
The meeting organisers asked me to give a broad introduction to the field. Volker Metag will give a summary at the end. Our views are rather complementary – but I claim to be the more cautious one!

Today's taster menu

The following points are the ones that I would like to discuss with you today.

- How can one put limits on the low energy interaction of mesons with nucleons through semi-exclusive and inclusive production reactions? In a sense, mesic nuclei are just a (fascinating) detail. Of greater importance is how the meson interacts with nucleons and the nucleus.
- The mesons to be considered are the π, η, ω, η', φ, and K^-.
- Production rates for the various mesons.
- Binding energy estimates.
- The case of ${}^{3}_{\eta}\mathrm{He}$.
- Deeply bound kaonic states – or K^- mesonic nuclei?

pp → *pp*η near threshold



Big deviations at low and high *Q.*

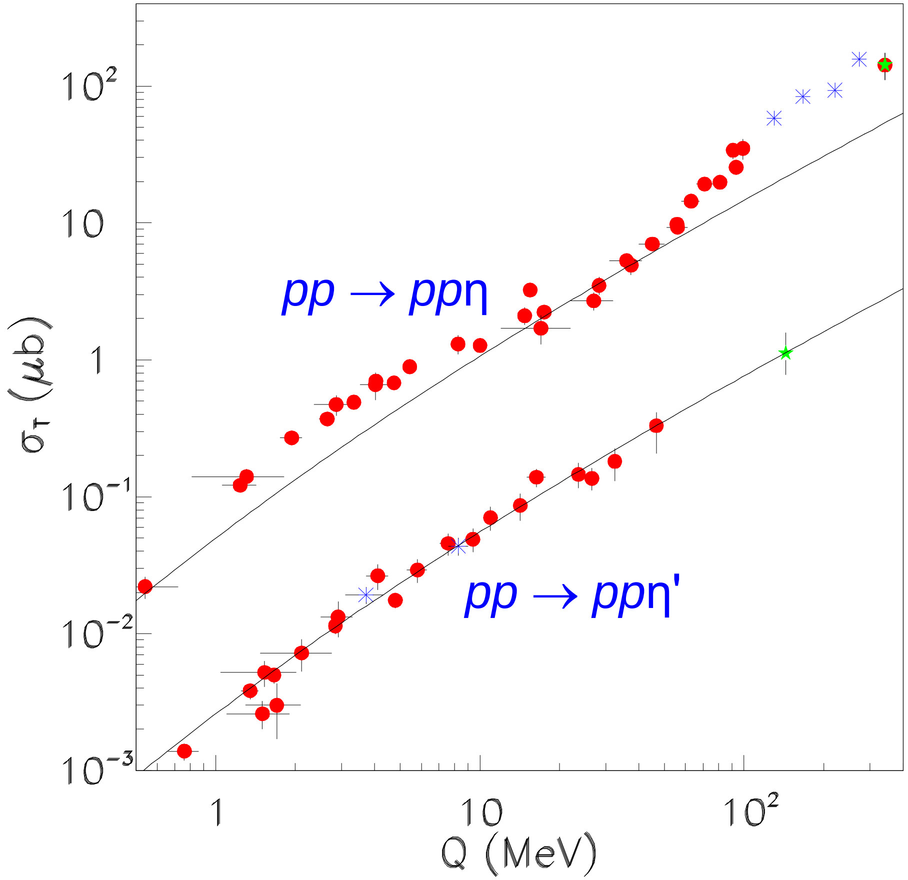
Curve assumes that
(1) Final *pp* system is purely S-wave,
(2) The η*p* interaction is neglected.
Simple final state interaction theory (FSI) then suggests that the energy dependence of the total cross section should be given by

$$\sigma_T(Q) = C\left(\frac{Q}{\varepsilon}\right)^2\left(1+\sqrt{1+Q/\varepsilon}\right)^{-2},$$

where ε ≈ 0.45 MeV gives the position of the "virtual" or "antibound" state in *pp* scattering.
C depends on the production mechanism – it is adjusted to fit the data.

Only really sensitive to large FSI

pp → *pp*η & *pp* → *pp*η' near threshold



For η' production there is no sign of any η'*p* final state interaction from the behaviour at low *Q*. There is no strong evidence for higher partial waves – but there is a lack of data at high *Q*.

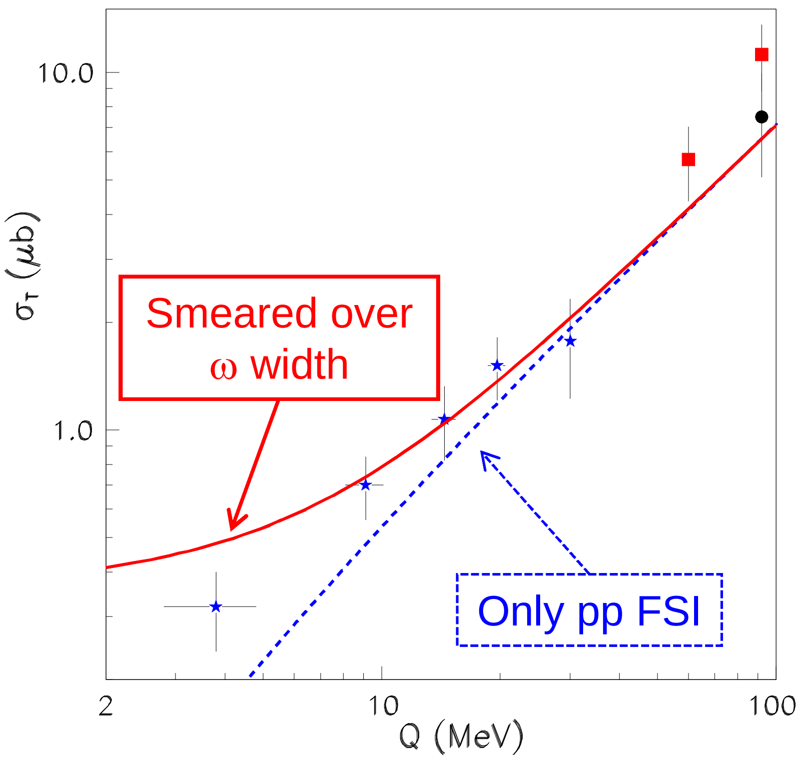
CONCLUSIONS:

(1) The η' production rate is about a factor of 20 below that of the η.

(2) The low energy η'*p* interaction must be much weaker than that in the η*p* system.

COSY-11 deduce limits on the strength of the η'*p* interaction but the uncertainties are large.

pp → ppω near threshold



with respect to the nominal ω mass

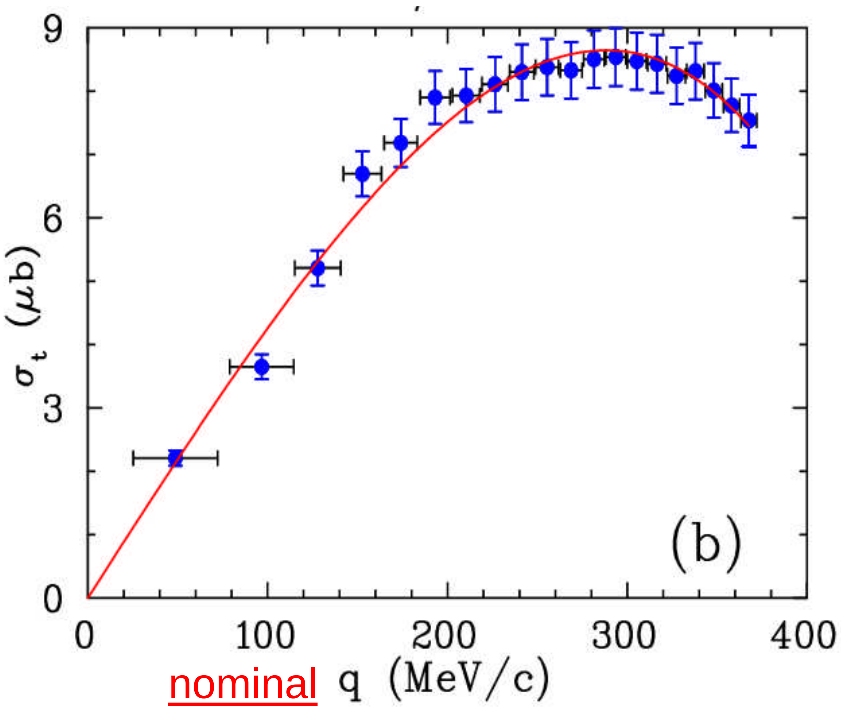
Situation much less certain for ω production.

The total cross section is similar to that for η production but, because of its natural width $\Gamma_\omega \approx 8.5$ MeV, the missing-mass peak is generally less narrow.

There are only the SPESIII (Saclay) points that have consistent relative normalisation. At low *Q* these lie above the trend of the *pp* FSI curve. This is (probably) not due to any attraction between the ω and *p* but rather an effect of the ω width.

Even when the nominal *Q* is negative, one can still produce the low mass tail of the ω.

An alternative approach for the ω



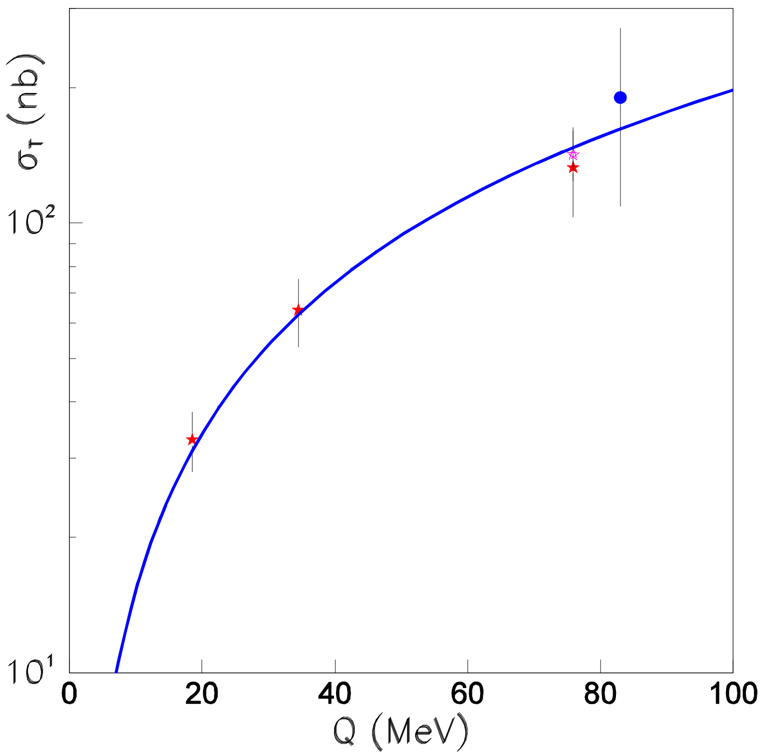
There are new data on $\gamma p \to \omega p$ near threshold *. Smearing over the decay width is less critical here and one finds for $q \approx 0$ that $\sigma/q \approx 0.044$ μb/(MeV/c). In the vector-dominance model, the photon reactions are related to ones driven by incident ρ, ω, and φ vector mesons, from which one can get an estimate of the ωp scattering length, $a_{\omega p} \approx (0.82 \pm 0.03)$ fm. However, one doesn't really know how much of this is due to the ρ-meson or the Born term.

Theoretical models give typically much smaller values of the scattering length, e.g., $a_{\omega p} = (-0.026 + i\ 0.28)$ fm from the coupled-channel analysis of ω production in γN and πN interactions.

[Volker Metag may have more to say on this.]

* I.I.Strakovsky *et al.*, Phys. Rev. C **91** (2015) 045207

$pp \rightarrow pp\varphi$ near threshold



Cross section is about a factor of 30 smaller than that of ω production.

Missing-mass experiments are not viable and data were obtained by looking at the K^+K^- decay of the φ.

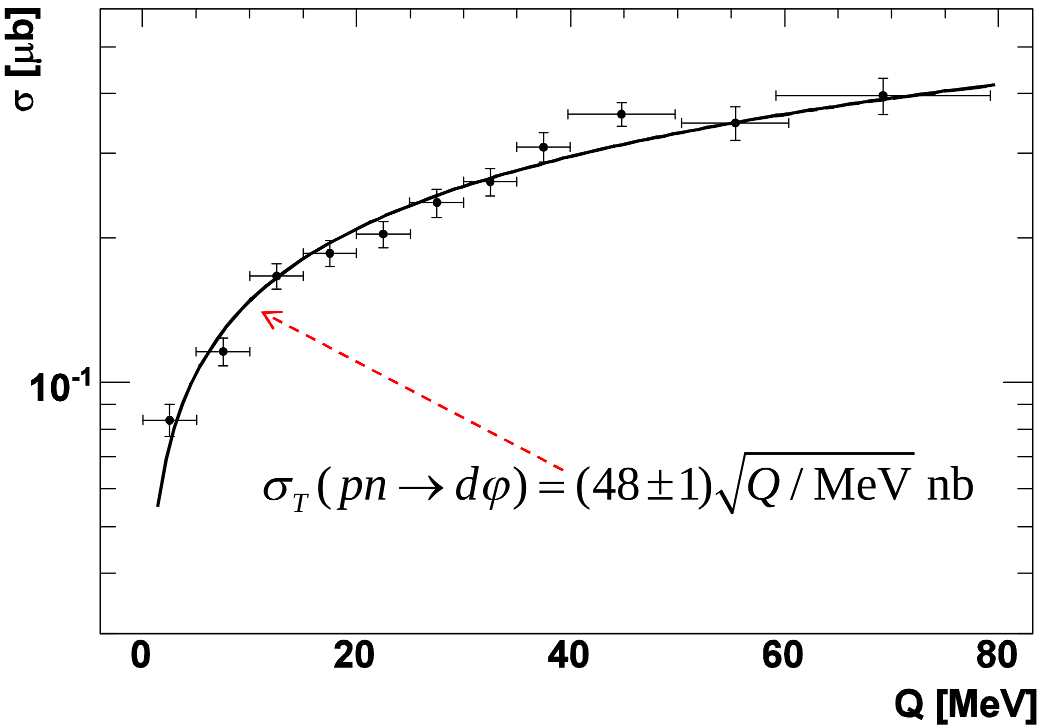
The simple pp FSI curve

$$\sigma_T(Q) = C\left(\frac{Q}{\varepsilon}\right)^2 \left(1+\sqrt{1+Q/\varepsilon}\right)^{-2},$$

may be fortuitous because many partial waves could enter.

Lack of data at low Q. Cannot tell if φ*p* interaction is attractive.

$pn \to d\varphi$ near threshold

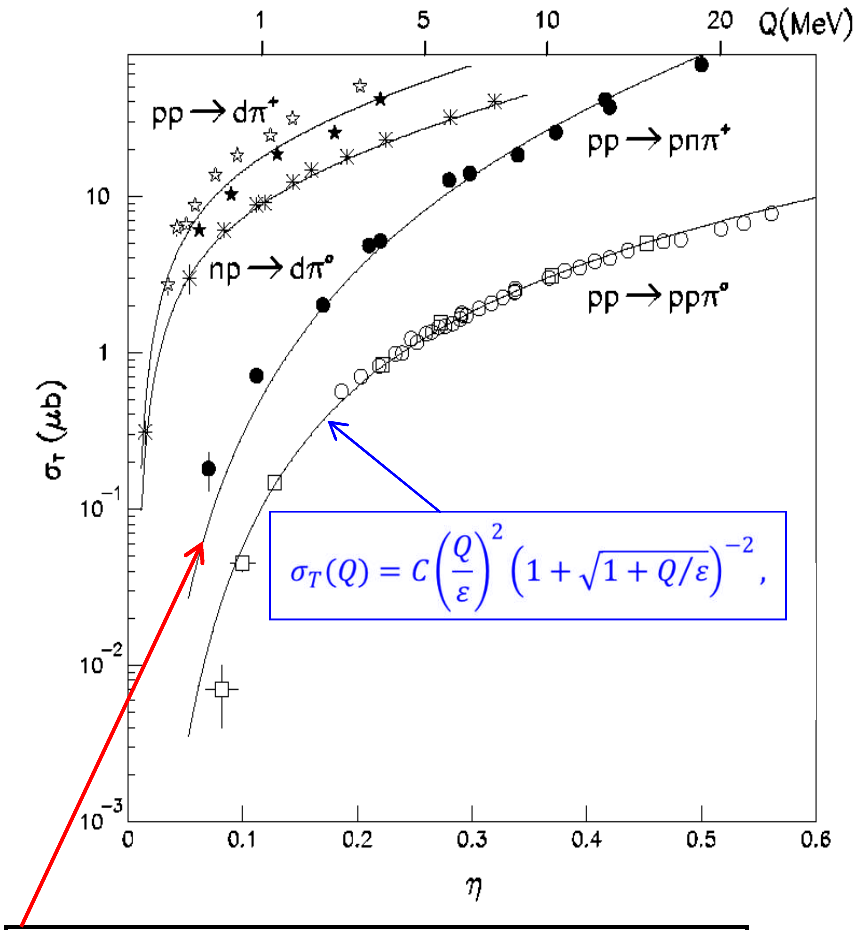


Surprisingly, the energy dependence of φ production is better measured in quasi-free $pn \to d\varphi$ than in pp collisions.

The message is, however, similar in that the total cross section behaves like $\sqrt{Q}$, i.e., like phase space with no sign of any φ attraction to the deuteron at low energy.

CAVEAT: The φ decay distribution shows higher partial waves above ≈ 40 MeV.

Pion production near threshold



Prediction based upon the $pp \to d\pi^+$ and $pp \to pp\pi^0$ data shown

S-wave pion production is VERY weak indeed. In terms of the reduced pion momentum, $\eta \approx \sqrt{2Q/m_\pi}$, the total $pp \to d\pi^+$ cross section behaves like $\sigma = A_s\eta + A_p\eta^3$, where the relative *s*-wave strength, $A_s/A_p \approx 1/4$.

pp → *pp*π^0 is dominantly s-wave but data show no evidence for π^0 attraction; the curve includes only the effects of the *pp* FSI.

Hence, the low energy π^0*pp* interaction seems to be very weak.

The interaction of antikaons with nucleons

Due to strangeness conservation, we cannot produce the K^-pp or the K^0pp system in isolation in pp collisions. The best that we can do is look at kaon pair production, $pp \rightarrow K^+K^-pp$, and compare the K^+pp and K^-pp distributions.

The K^+ is believed to be weakly interacting with nucleons and the force may even be slightly repulsive!

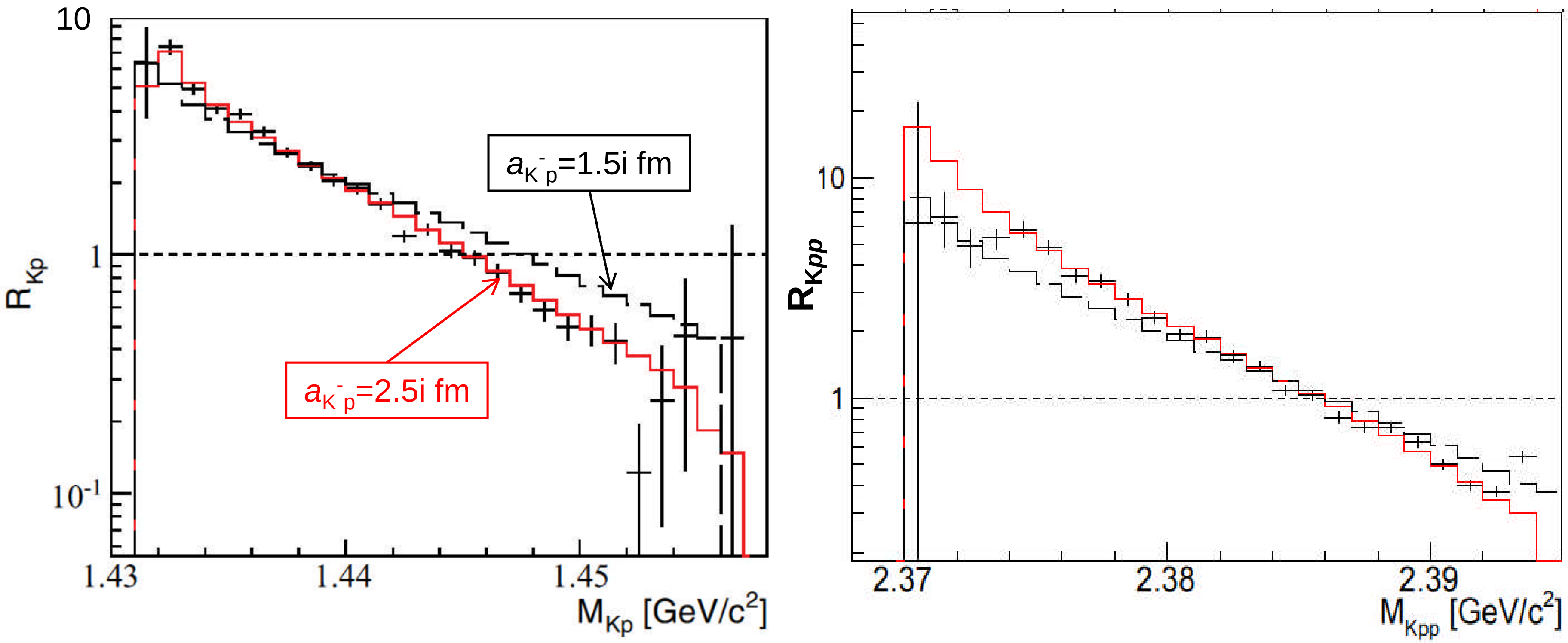
The results might be much cleaner in experiments with kaon beams!

Define cross section ratios $R_{Kp} = \frac{d\sigma/dM_{K^-p}}{d\sigma/dM_{K^+p}}, \quad R_{Kpp} = \frac{d\sigma/dM_{K^-pp}}{d\sigma/dM_{K^+pp}}.$

The K^- likes to form low invariant masses with one or both protons. The preference is up to an order of magnitude!

These $pp \to K^+K^-pp$ data were taken just below the φ threshold, where the effect seems even bigger than just above threshold.

The K^- is strongly attracted to protons!



Summary of information from semi-inclusive measurements

Both the η and the K^- seem to be strongly attracted to protons at low energy. This is not a surprise because there are *s*-wave resonances sitting at (and overlapping with) the ηp and $K^- p$ thresholds. There are thus strong couplings $N^*(1535)$:ηp and $\Lambda(1405)$:$K^- p$.

Since the η is isoscalar, this means that the meson is also attracted to neutrons. Data on $pn \to dK^+K^-$ can be interpreted as suggesting that the K^- attraction to neutrons is weaker than to protons – no hyperon resonance here.

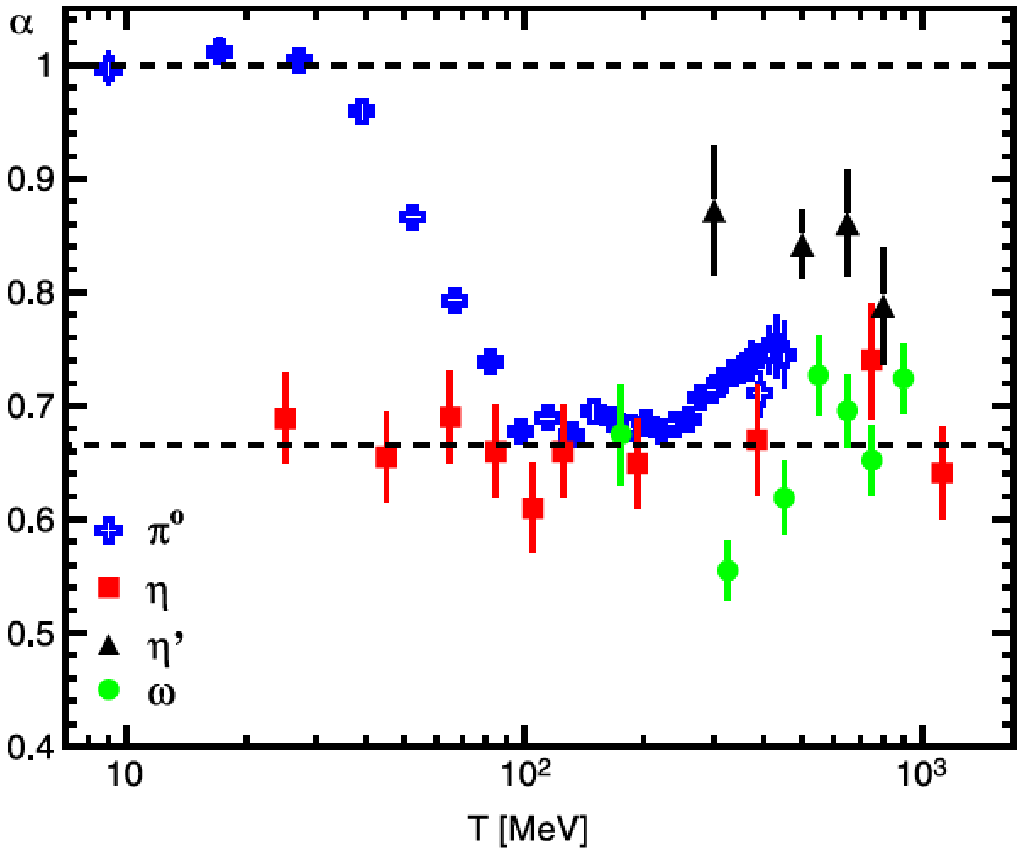
The *s*-wave pion interaction is weak (though the p-wave is <u>very</u> strong).

No hard evidence for strong η', ω, or φ attraction to nucleons at low energies but the ω case is made complicated by the decay width $\Gamma_\omega \approx 8.5$ MeV.

Are there alternative ways of extracting useful information for these mesons?

Information from inclusive photoproduction

Cross sections for inclusive photoproduction of meson from a nucleus with mass number *A* are often fitted with $\sigma \sim A^{\alpha}$. If α is close to unity, the whole nucleus is participating and the meson interaction is weak. If α approaches 2/3 only the back surface is contributing and the interaction is very strong. Data show that the nucleus is fairly transparent to low energy pions, but the picture changes when the $\Delta(1232)$ is reached. The η is strongly absorbed at all the energies shown.



The η' is an intermediate case but ω also looks to be strongly absorbed.

BUT: only in the π or possibly the η case are we in the near-threshold s-wave domain.

There are also complications from two-step processes, *e.g.*, $\gamma N \rightarrow \pi N$ followed by $\pi N \rightarrow \omega N$. (These may be kinematically favoured because they share the momentum transfer.)

Nuclear transparency measurements

The A^{α} parameterisation is very close to that of the nuclear transparency approach, where one compares the production on a nucleus to that on a reference nucleus, which is invariably carbon, to form the ratio

$$R = \left(\frac{12}{A}\right)\frac{\sigma_A}{\sigma_C}$$

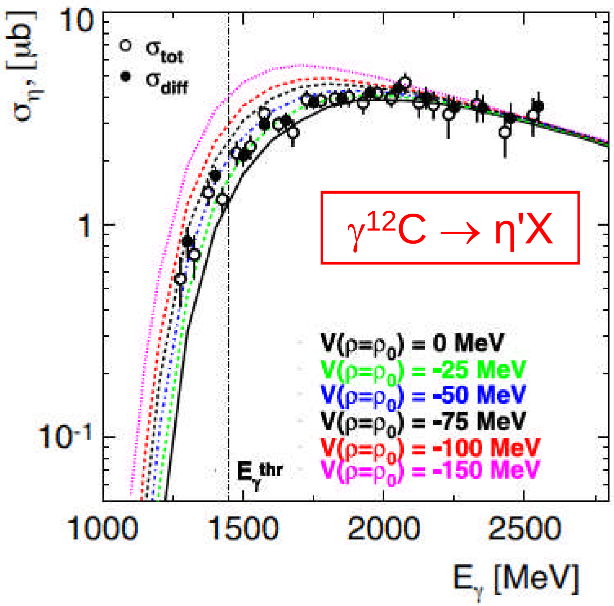
There are measurements of *R* also in proton-nucleus collisions, e.g., in the production of the φ meson. However, these are all for $T_{\varphi} > 160$ MeV and have little relevance to the mesic nucleus question.

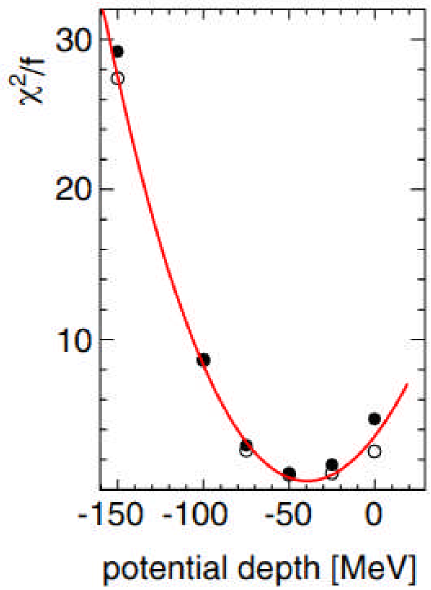
All the models used to analyse such data have large contributions from two-step processes involving, perhaps, intermediate π or ω mesons. Hence the interpretation depends on the models used and it is difficult to be sure from this how absorptive the s-wave φp interaction really is.

Nevertheless, this is one way of getting some information regarding the imaginary part of the potential between the meson and the nucleus.

Energy dependence of photoproduction

It has been suggested that the energy dependence of, say, $\gamma A \rightarrow \eta'$ in and below the free nucleon threshold should be sensitive to the $\eta' A^*$ potential.
There will always be production below this threshold due, *e.g.*, Fermi motion. But, if the η' is attracted to the nucleons, that effectively reduces the total mass of a cluster and so this might be produced at lower photon energies.
A lot of corrections are included in the modelling. The distinction between the production on nucleon clusters and two-step processes is not always clear and two-step effects depend critically upon the particular meson produced.





<u>Within the models used</u>,
an η'A potential of about
– (10±3) – i(37±14) MeV
at normal nuclear density was extracted.

The model dependence is hard to quantify.

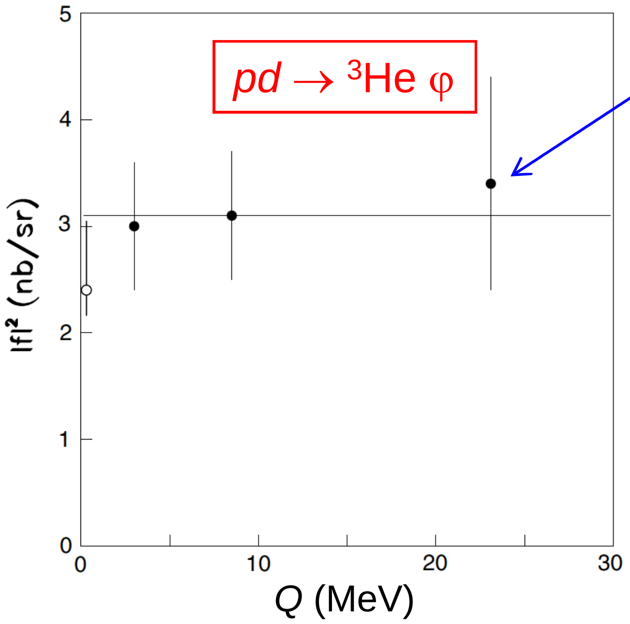
Production rates

Some information on relative production rates was contained in the $pp \to ppX$ data but $pd \to {}^3\text{He}\,X$ may be more informative.

$$\text{Define amplitude by } |f(pd \to {}^3\text{He}X)|^2 = \frac{p_d}{p_X}\frac{d\sigma}{d\Omega}(pd \to {}^3\text{He}X).$$

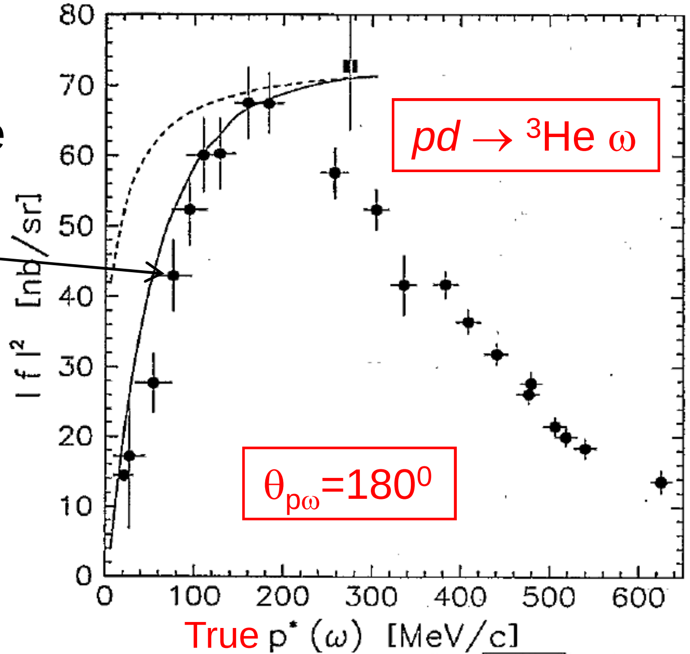
Close to the thresholds, $|f(pd \to {}^3\text{He}\,\eta)|^2 \approx 2500$ nb/sr, $|f(pd \to {}^3\text{He}\,\omega)|^2 \approx 30$ nb/sr, $|f(pd \to {}^3\text{He}\,\eta')|^2 \approx 0.9$ nb/sr, and $|f(pd \to {}^3\text{He}\,\varphi)|^2 \approx 2.3$ nb/sr

η' production seems to be more than three orders of magnitude less than η, compared to a factor of twenty in *pp* collisions.



φ rate is confirmed.

ω production is strange because $|f|^2$ dips towards threshold. Unlike $pp \to pp\omega$, p^* is the true (not nominal) c.m. momentum. Perhaps 70 nb/sr is a more realistic value.

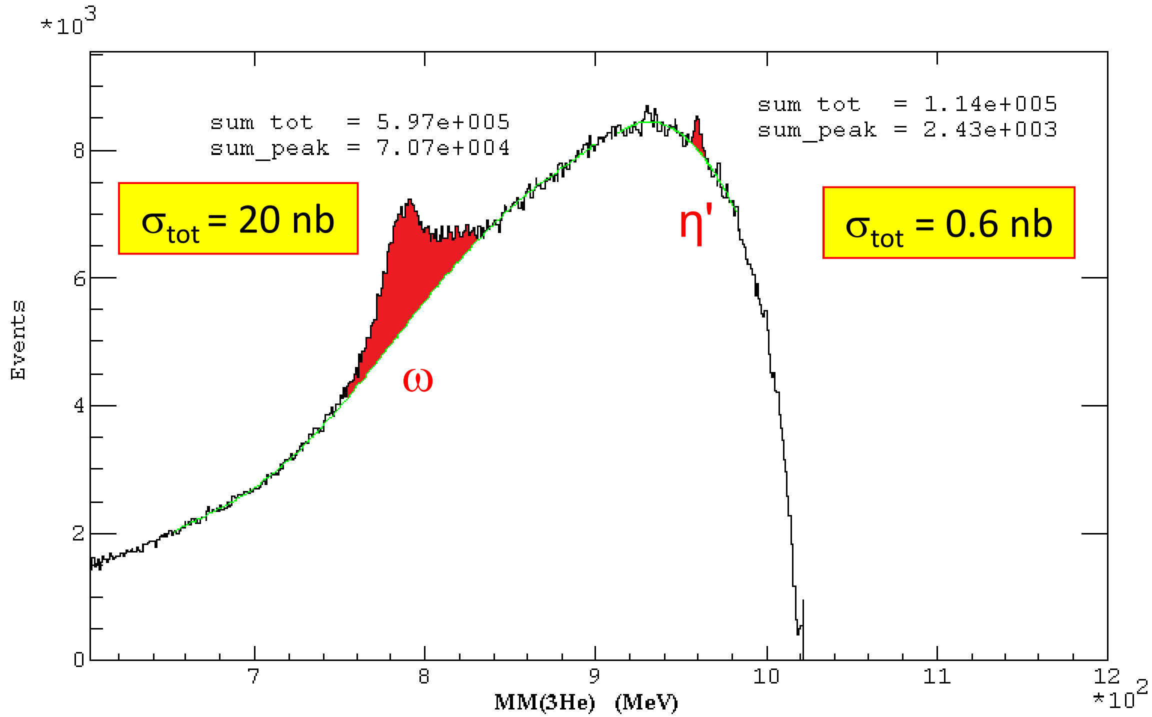


Very preliminary and very unpublished WASA data on $pd \to {}^3\mathrm{He}\,X$. Assuming that the WASA acceptance is given by phase space,

$|f(pd \to {}^3\mathrm{He}\,\omega)|^2 \approx 11$ nb/sr at $Q = 240$ MeV, $p_\omega^* = 612$ MeV/c.

$|f(pd \to {}^3\mathrm{He}\,\eta')|^2 \approx 0.6$ nb/sr at $Q = 64$ MeV, $p_{\eta'}^* = 305$ MeV/c.

In tolerable agreement with the near-threshold measurements.



Wolke & Złomanczuk, private communication.

How does one estimate binding energies?

Liu & Haider started the whole bound η-mesic business through their estimates of binding within single-channel potential models, where $V_{\eta A} \propto f_{\eta N}\,\rho(r)$, with $\rho(r)$ being the nuclear density and $f_{\eta N}$ the η-nucleon elastic scattering amplitude.

<u>PROBLEMS</u>

1. One doesn't know what to assume for $f_{\eta N}$.
2. Due to the *N**(1535) resonance, the potential is likely to have a strong energy dependence. How can this be taken into account? Which energy?
3. It seems as though there may be nearby poles in the η^3He and η^4He systems. Who would trust the predictions of a one-particle optical potential for such light nuclei?
4. Use of such potentials suggest that the binding energy of a meson to the ground state of a nucleus is likely to be similar in magnitude to that of one of its excited states, so that:

$$M\left({}^{12}_{\eta}C(2^+)\right) - M\left({}^{12}_{\eta}C(0^+)\right) \approx 4.4\text{MeV}$$

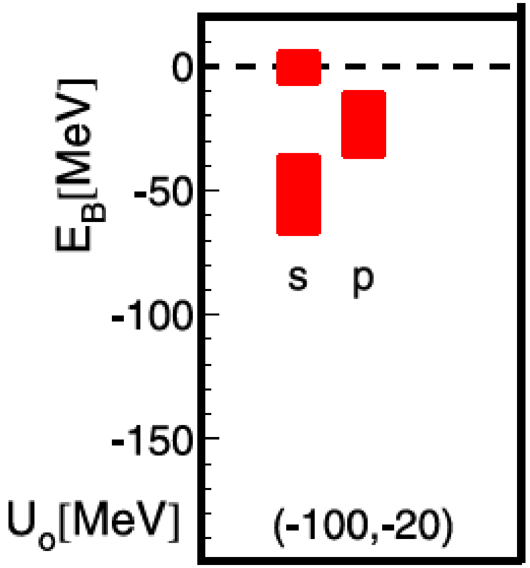
This means that one would need very favourable kinematic conditions if the mesic nuclear widths were as large as the nuclear level spacing.

Jido et al. made estimates of the binding of an η' to ^{12}C in an optical potential approach for a variety of potential strengths. The one shown is for -100 – 20i MeV (at normal nuclear density).

The real part is much stronger than the estimate of -10 MeV and the imaginary part smaller than the -37 MeV, but these estimates have large uncertainties.

Nevertheless, the widths (shown by shading) are large compared to the nuclear level spacing.

This nuclear excited states problem is likely to hinder most mesic nuclei searches.

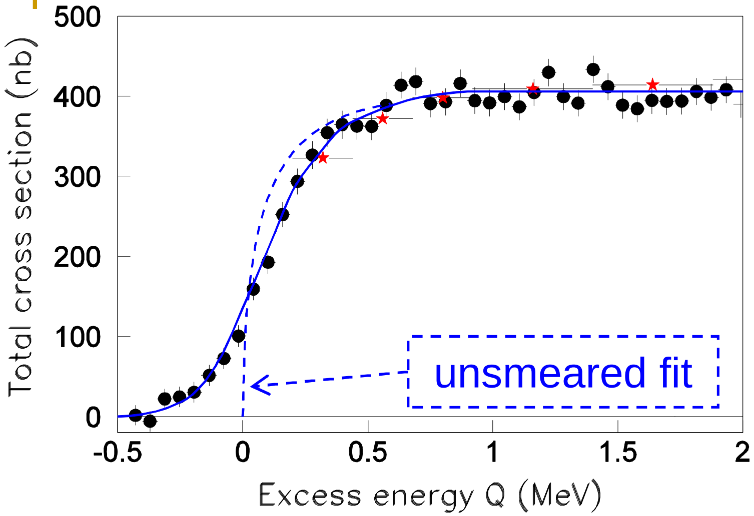


Mesic nucleus experiments

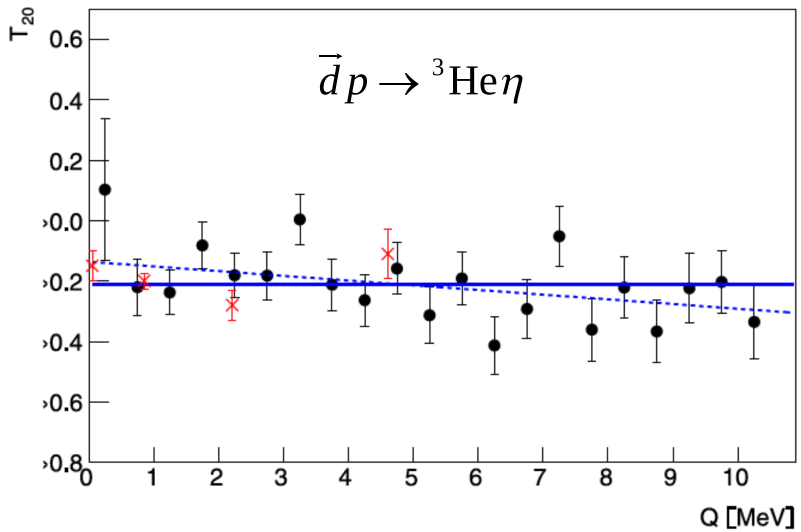
There are two very different methods to search for mesic nuclei:

1. Measure meson production at a few energies just above threshold and attempt to extrapolate to below threshold, where a quasi-bound nucleus may reside. This approach does overcome the very serious background problem but it could only work if the mesic nucleus were lightly bound. Even more troublesome is the fact that above-threshold experiments can never distinguish between bound and virtual (antibound) states. This is just like asking if one can deduce that the $^3S_1$ *np* has a bound state (deuteron) but the $^1S_0$ has none if one only looks above the *np* threshold.
   A typical (*i.e.*, best) example is $dp \to {}^3\text{He}\,\eta$.
2. Look directly in the bound state region. By definition the meson cannot emerge and the background could be overwhelming unless one can identify the quasi-free decay of the meson. But is the only way to be 100% sure that one has a quasi-bound state. One tries to suppress the background by choosing "favourable" kinematics.
   A typical example of this in the η case is $\gamma^3\text{He} \to \pi^0 p X$, where the π^0 and *p* come out back-to-back in the overall c.m. frame.

The *dp* → ^{3}He η near threshold



The total cross section jumps to its plateau value within say 0.5 MeV of threshold. The jump is even sharper if one takes the beam momentum distribution into account. Pole is at $p_\eta = (-5\pm7) \pm i(19\pm3)$ MeV/*c*, *i.e.*,
Q = (-0.30±0.15) ± i(0.21±0.06) MeV.
Why is the imaginary part so small?



If the pole is due to the η^{3}He FSI, it should be present for all entrance channels. A big near-threshold jump is seen in γ^{3}He → η^{3}He but the resolution is not as good.

Best proof is the deuteron tensor analysing power T_{20}, which is sensitive to the spin-3/2/spin-1/2 ratio in the initial *dp* state. This is constant, despite the cross section jumping around.

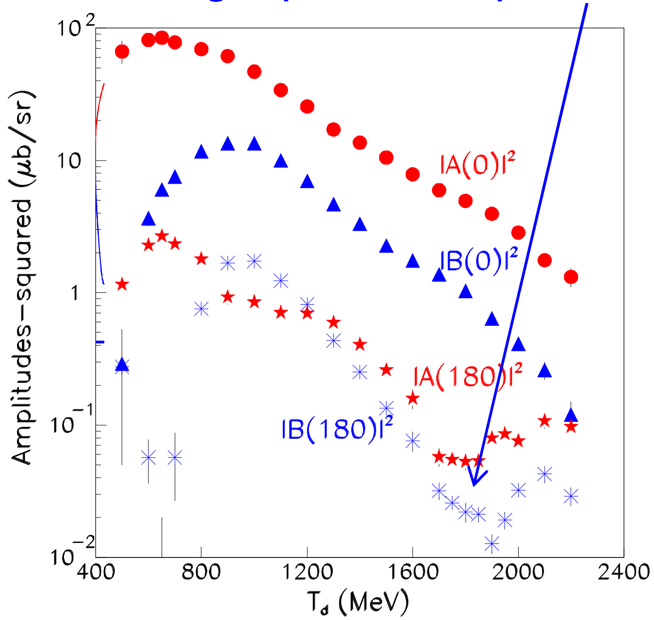
Data on np → dη currently under analysis.

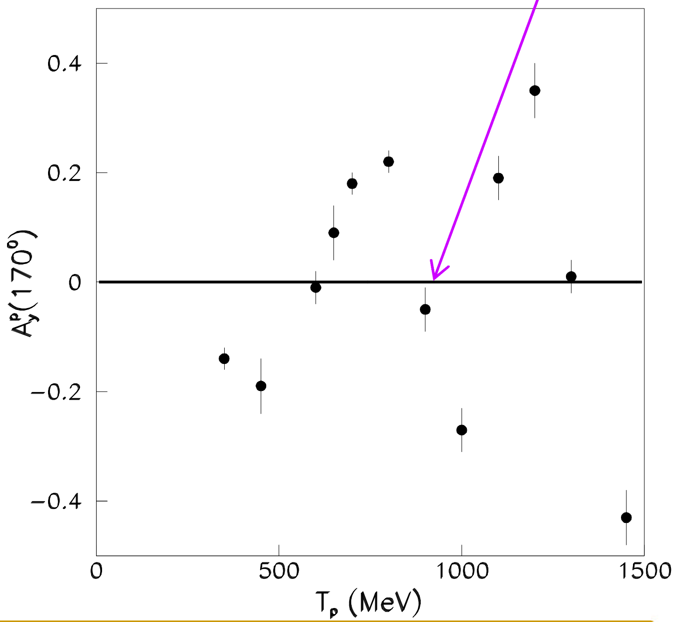
Two intriguing "coincidences"

Near the backward direction the cross section for *pd* → ^{3}He π^0 becomes very small away from threshold and might therefore be perturbed by small effects.

Magnitudes of the two backward amplitudes have been evaluated by measuring the cross section and tensor analysing power with a polarised deuteron beam. Both show big dips at the η threshold.

The proton analysing power vanishes at 180^0 but near there it fluctuates violently with energy in the vicinity of the η threshold.





One must always be suspicious of "coincidences"!

Suppose the two effects are connected with the opening of the η^3He threshold. This would require an extra, mainly s-wave amplitude arising from $dp \to {}^3\mathrm{He}\,\eta$ followed by $\eta^3\mathrm{He} \to \pi^0\,{}^3\mathrm{He}$.

If one tries to extrapolate the existing $\eta^3\mathrm{He} \to \pi^0\,{}^3\mathrm{He}$ differential cross section data smoothly to threshold, the contribution from the two-step (coupled-channel) process seems to be an order of magnitude too low to be significant. Can only be important if there is a strong η^3He enhancement.

Another way of looking at the problem is to evaluate the ratio of the amplitudes for producing a (<u>backwards</u>) π^0 or an η, at the η threshold:

$$\frac{|\,f(dp \to {}^3\mathrm{He}\,\pi^0)\,|^2}{|\,f(dp \to {}^3\mathrm{He}\,\eta)\,|^2} \approx 1\%.$$

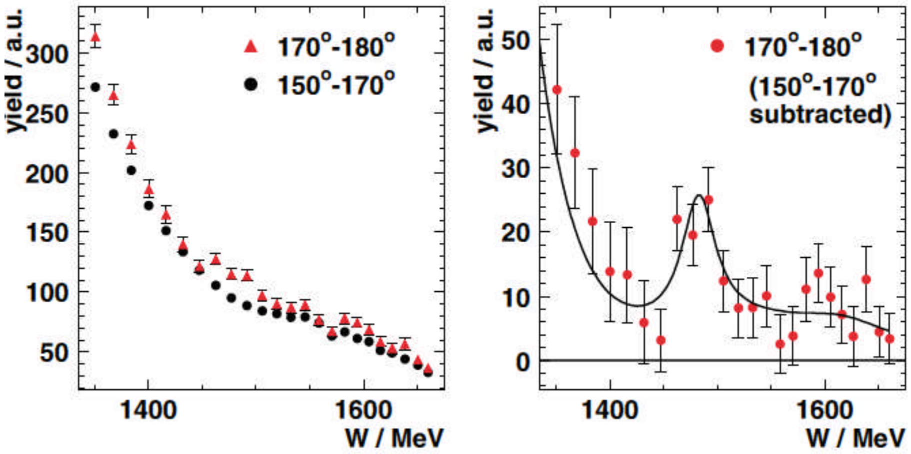
To be relevant, one would need a significant decay rate ${}^3_\eta\mathrm{He} \to {}^3\mathrm{He}\,\pi^0$.

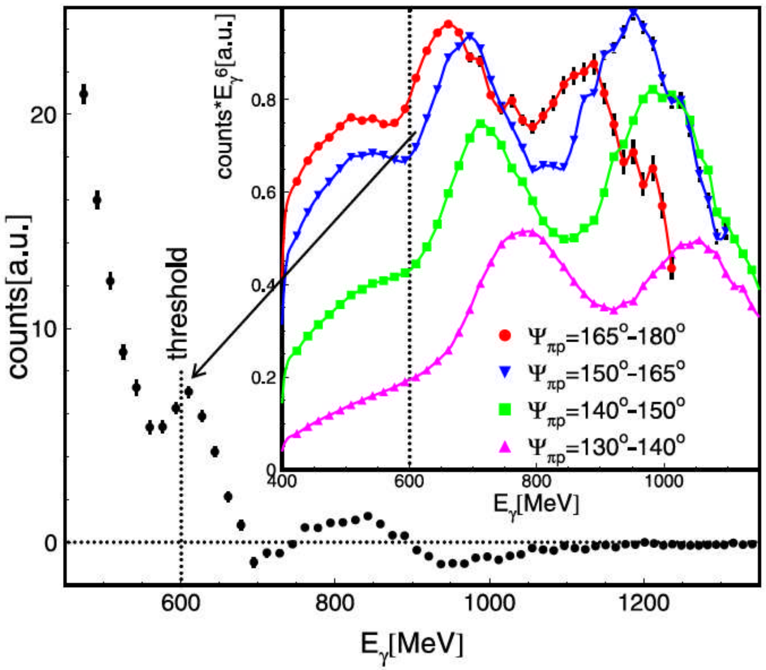
But perhaps these really are just coincidences!

Sub-threshold searches

Most sub-threshold (i.e., direct) searches have given disappointing results.

MAMI $\gamma^3He \rightarrow \pi^0 pX$.
In the ${}^3_\eta He$ rest frame the π^0 and p should emerge back-to back.
Subtract one data set from another and generate a peak!





Later MAMI data confirmed the peak but showed that the interpretation was <u>very</u> "suspect". The energy dependence showed lots of structure but this seemed to evolve smoothly with opening angle.
No sign of any mesic nucleus decay.

Quasi-bound K^-pp systems

The K^+/K^- distortions in the COSY $pp \to K^+K^-pp$ data seem to be driven mainly by $pp \to K^+p\Lambda^*(1405)$ and the decay of the tail of $\Lambda^*(1405) \to K^-p$. This might be an indication for a lightly bound K^-pp, or $\Lambda^*(1405)p$, system, which could correspond to an S = -1, B=2 mesic nucleus.

The mesic nucleus could decay via $\Sigma^0\pi^0p$, but counting rates for $pp \to K^+\Sigma^0\pi^0p$ are not very high and the acceptance of the available spectrometers for multiparticle final states are rather low!

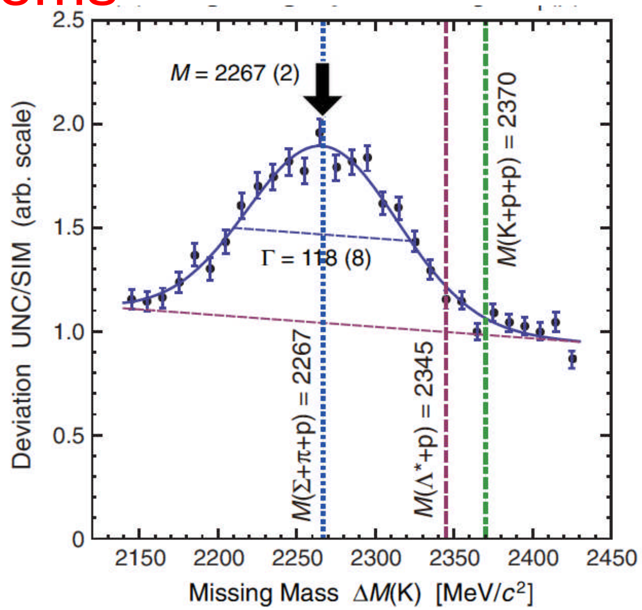
There is a severe lack of experimental data for other nuclei. COSY studied $pd \to {}^3He\,K^+K^-$, but there was no magnetic field for the kaon detection so that they could only produce average $K\,{}^3He$ distributions, which are little sensitive to the $K^-\,{}^3He$ interaction.

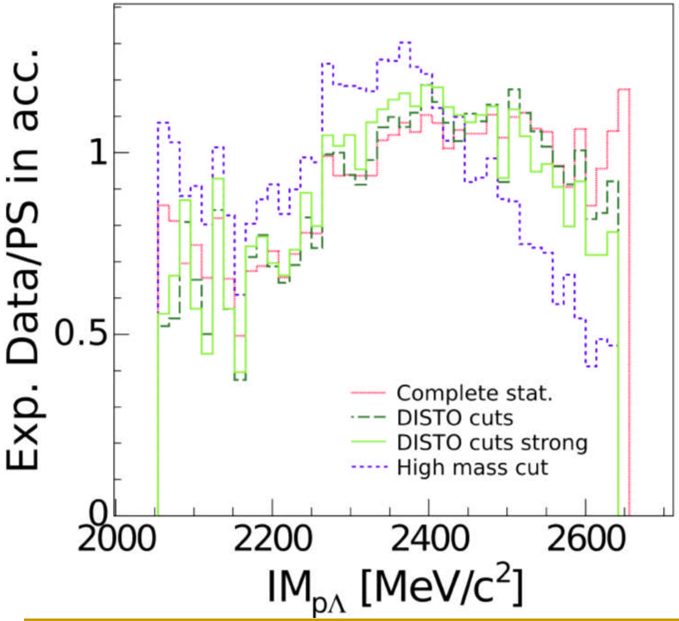
But are there systems that are bound so deeply that they can only decay via hyperon production, $pp \to K^+p\Lambda$?

The subject is VERY controversial!

Deeply bound K$^-$*pp* systems

Yamazaki took 2.85 GeV DISTO $pp \rightarrow K^+ p\Lambda$ data divided by a phase-space distribution that was passed through the DISTO analysis program. He generated a $p\Lambda$ invariant mass peak with M ≈ 2267 MeV/c^2 and $\Gamma \approx$ 118 MeV/c^2. Could be interpreted as $\Lambda^*(1405)p$ bound state. No sign of the "beast" in 2.5 GeV DISTO data.





Epple & Fabbietti analysed the 3.5 GeV HADES data and found that the generated shape depended on the cuts imposed. The data just do not look like phase space.

They also questioned Yamazaki's estimate of the energy dependence of $pp \rightarrow p\Lambda^*(1405)$, which was supposed to be the doorway to his *X*(2267) state.

Concentrate on strange mesic nuclei with K$^-$ beams at, e.g., DAΦNE.

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Having presented some aspects of the mesic nucleus hopes and fears, I now leave it to the specialists to show that my fears are not well founded!

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Thanks and Goodbye!

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Theorists love to speculate.

Some experimentalists want to make their reputation by finding something really exotic, such as dibaryons or mesic nuclei.

Be cautious!