Are there bound eta mesons?

UNIVERSITÄT DUISBURG ESSEN

Offen im Denken

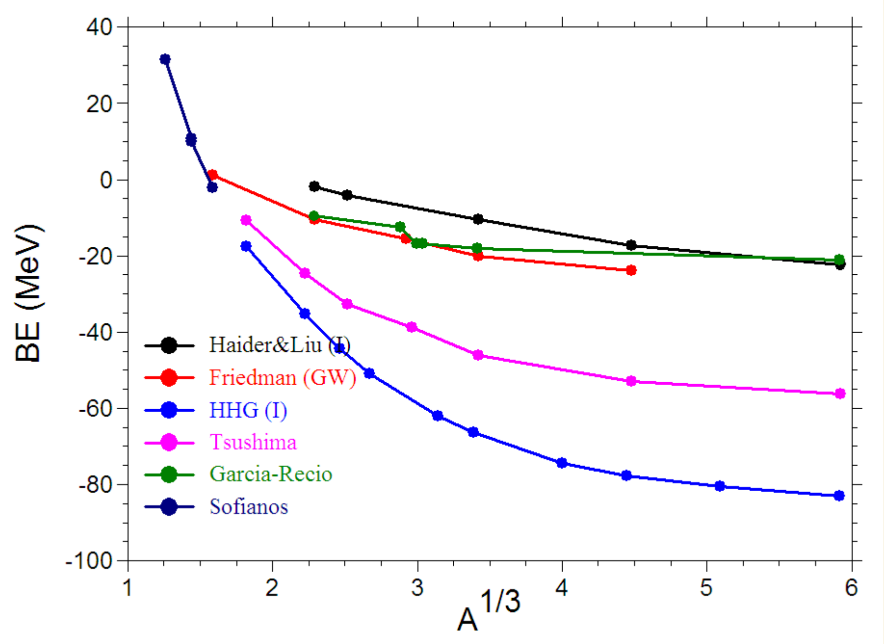
Hartmut Machner

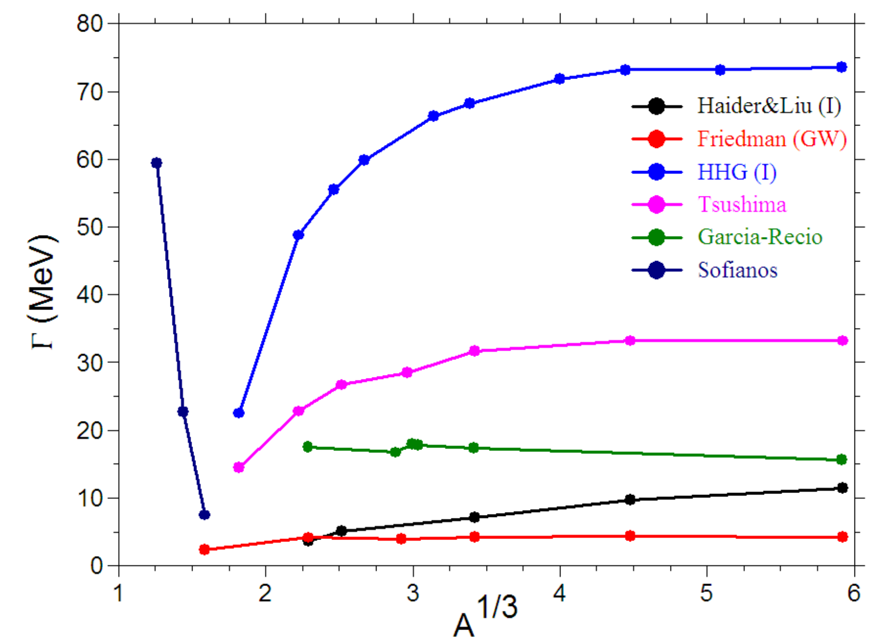
Fakultät für Physik, Universität Duisburg-Essen

- A rather large s-wave η-nucleon scattering length lead to the idea of bound η-nucleus systems.
- This would be a strong bound system, contrary to pionic atoms (Coulomb bound).
- How to measure?

1. Direct Production
   - The η meson has to be produced at rest
   - Best: transfer reactions, one ejectile carries the beam momentum (recoilles kinematics) FF=exp[-(ħq)^2/BE]
   - But (d,^{3}He) bad because break up protons and ^{3}He have the same magnetic rigidity
2. FSI
   - Best: two particle final state
   - Limited to light nuclei where the existance of bound states is improbable

What to expect?



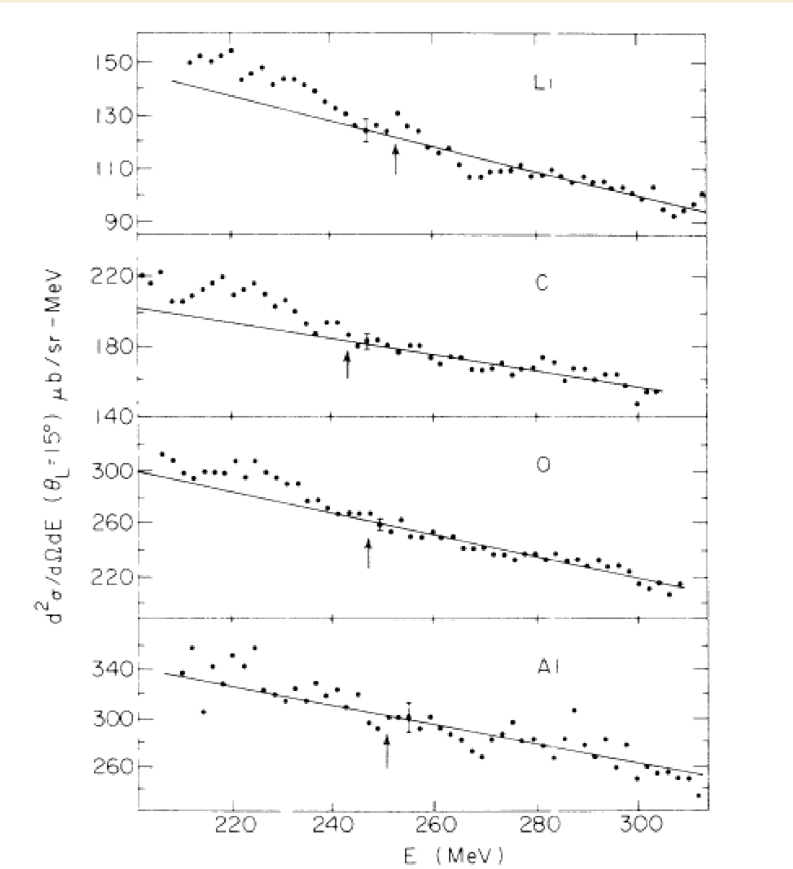


Authors	a_R (fm)	a_I (fm)
Haider & Liu (set I)	0.28	0.19
Friedman, Gal & Mares (GW)	0.22	0.24
Hayano, Hirenzaki&Gillitzer	0.718	0.269
Garcia-Recio et al.	0.264	0.245
Sofianos et al.	< 0.47	0.3

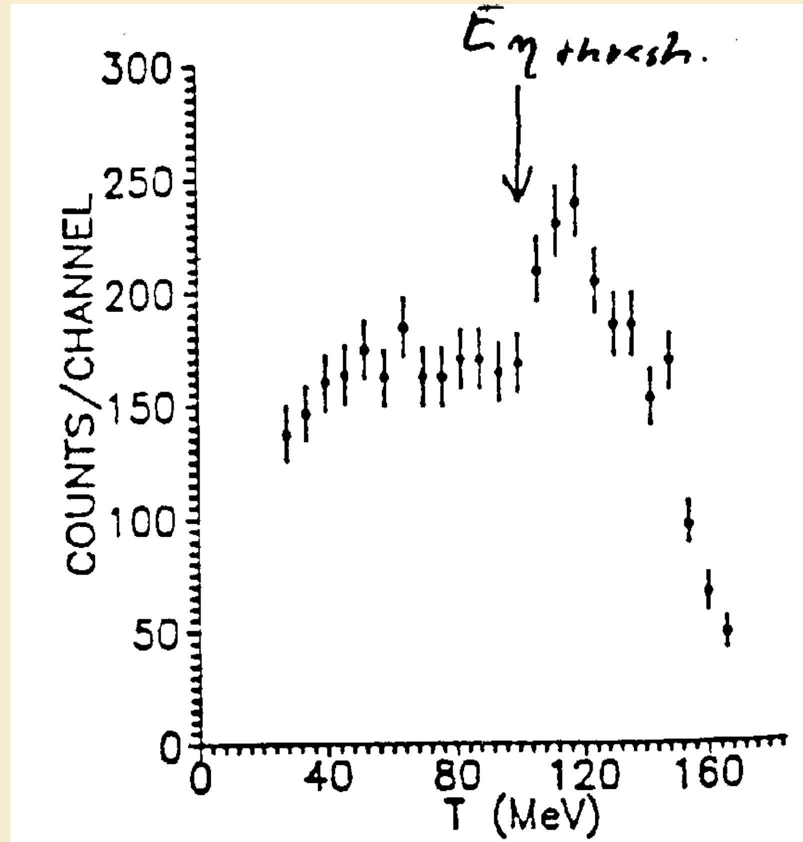
$\pi^+ + A \rightarrow p + (A\text{-}1)_\eta$

UNIVERSITÄT DUISBURG ESSEN

Offen im Denken



Chrien et al. PRL 60(88)2595
- q=200 MeV/c
- inclusive



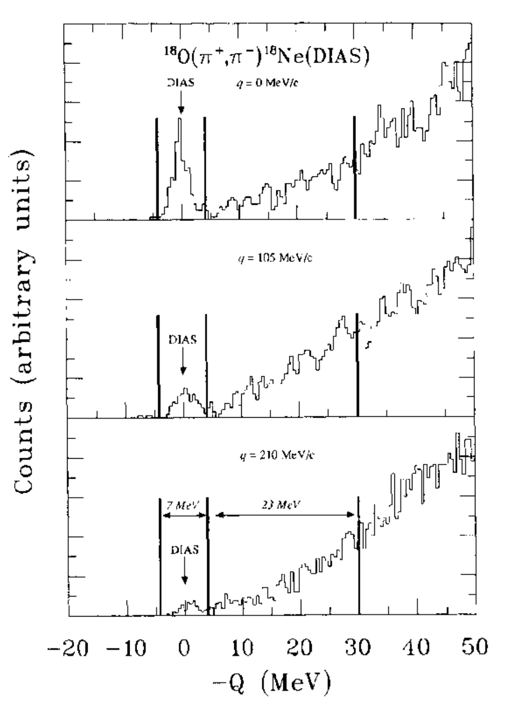
Lieb et al. (unpublished)

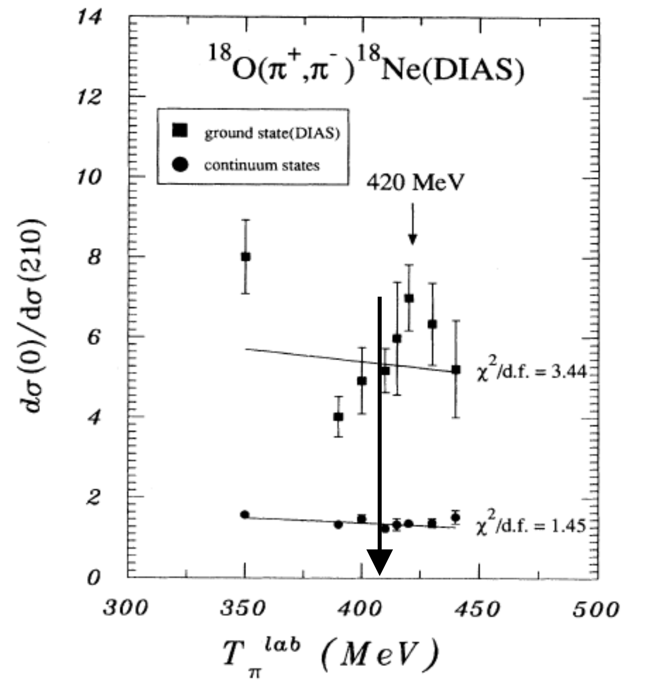
Peak due to detector acceptance?

DCX : Johnson et al., PRC 47(93)2521

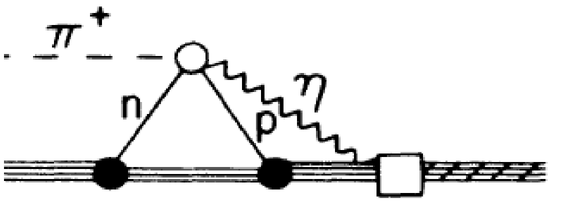
UNIVERSITÄT DUISBURG ESSEN

Offen im Denken





BE≈20 MeV
Γ≈18 MeV



$$\pi^+ + \begin{pmatrix} ^{17}O \\ n \end{pmatrix} \rightarrow \begin{pmatrix} ^{17}O \\ \eta + p \end{pmatrix} \rightarrow \begin{pmatrix} ^{18}F \\ \eta \end{pmatrix} \rightarrow \begin{pmatrix} ^{17}F \\ \eta + n \end{pmatrix} \rightarrow \pi^- + {}^{18}Ne$$

$$\pi^+ + \begin{pmatrix} ^{17}O \\ n \end{pmatrix} \rightarrow \begin{pmatrix} ^{17}O \\ \pi^0 + p \end{pmatrix} \rightarrow \begin{pmatrix} ^{17}F \\ \pi^0 + n \end{pmatrix} \rightarrow \pi^- + {}^{18}Ne$$

η kinetic energy only a few MeV.

γ+A→π+p+X

UNIVERSITÄT DUISBURG ESSEN
Offen im Denken

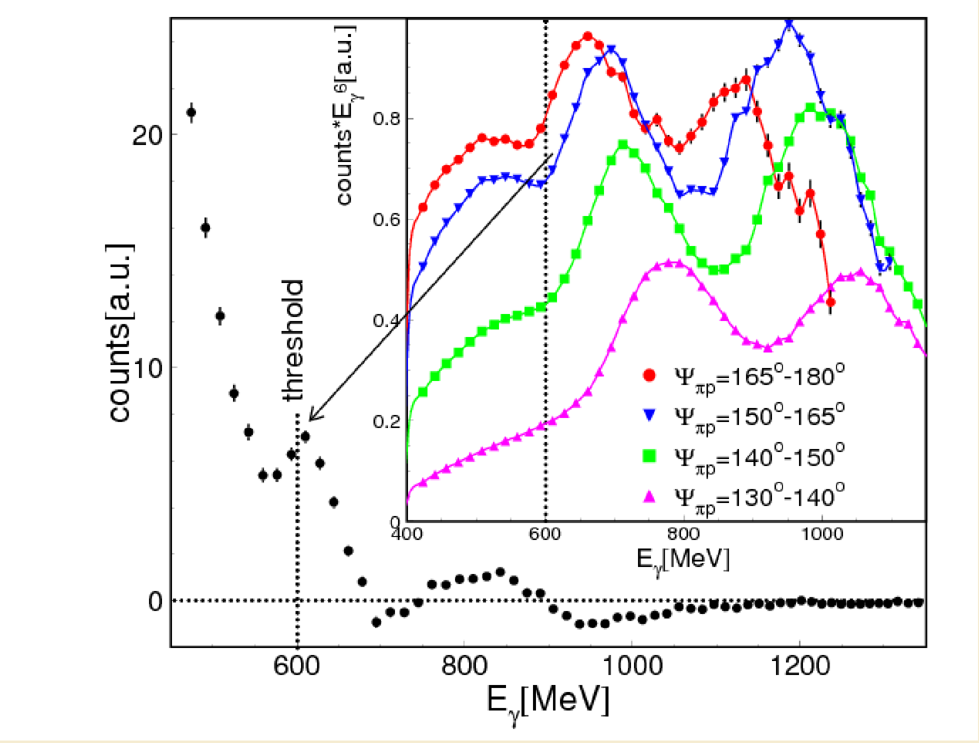
Sokol et al.: $\gamma + {}^{12}C \rightarrow N + (\pi^+ + n) + X$

Both ejectiles are anti-correlated;

$\langle E_\pi \rangle = 300$ MeV, $\langle E_n \rangle = 100$ MeV

But beam momentum nucleon not measured!

$\sigma(\pi n) = (12.2 \pm 1.3)\ (\mu b)$



Pheron (CB+TAPS)

$\gamma + {}^3He \rightarrow (\pi^0 + p) + X$

Difference of excitations functions of $\pi^0 - p$ back-to-back pairs with opening angles between 165° - 180° and 150° - 165°. Insert excitations functions for different ranges of the opening angle $\Psi_{\pi p}$ after removal of the overall energy dependence $\propto E_\gamma^{-6}$. Vertical dotted lines: coherent η-production threshold.

Experiments not discussed here

UNIVERSITÄT DUISBURG ESSEN

Offen im Denken

Unpublished searches:

$$d + {}^{12}C \rightarrow {}^{3}He + X \text{ @ GSI fragment separator}$$

difficult to distinguish break up protons from ^{3}He;

scan around η threshold, the bound , the bound A_{η}-system carries the full beam momentum:

$$p + d \rightarrow \eta + {}^{3}\mathrm{He} \rightarrow p + p + p + \pi^{-} \text{ @ COSY TOF (unpublished)}$$

$$d + d \rightarrow \eta + {}^{4}\mathrm{He} \rightarrow \pi^{-} + p + {}^{3}\mathrm{He} \text{ @ WASA (PRC 87 (2013) 035204)}$$

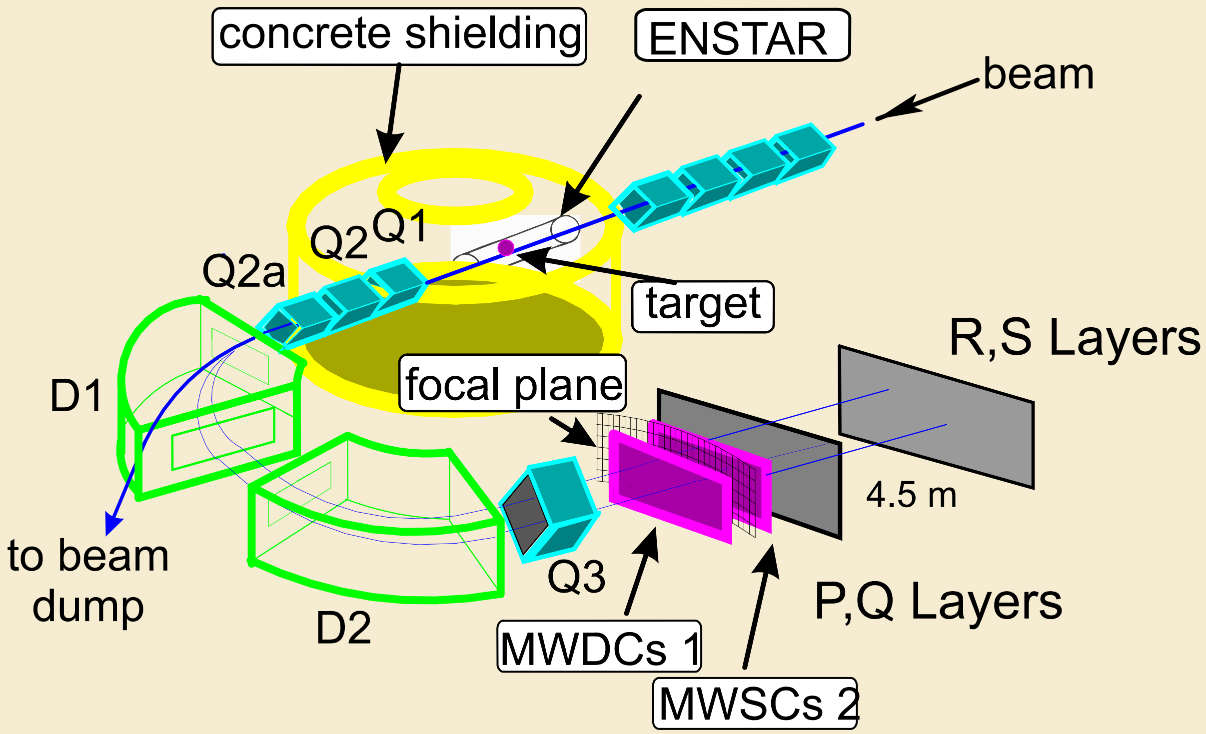
Coherent photproduction

$$\gamma + {}^{7}\mathrm{Li} \rightarrow \eta + 7\mathrm{Li} \rightarrow 2\gamma(6\gamma) + X \text{ (Eur. Phys. J. A (2013) 49: 38)}$$

GEM @ COSY (transfer reaction)

$$p + {}^{27}Al \rightarrow {}^{3}He + {}^{25}Mg_{\eta}$$

$$\hookrightarrow {}^{24}Mg + \pi^{-} + p$$



Best target: odd-odd leads to even-even, low level density. Not existent as solid material.
Compromise: even odd

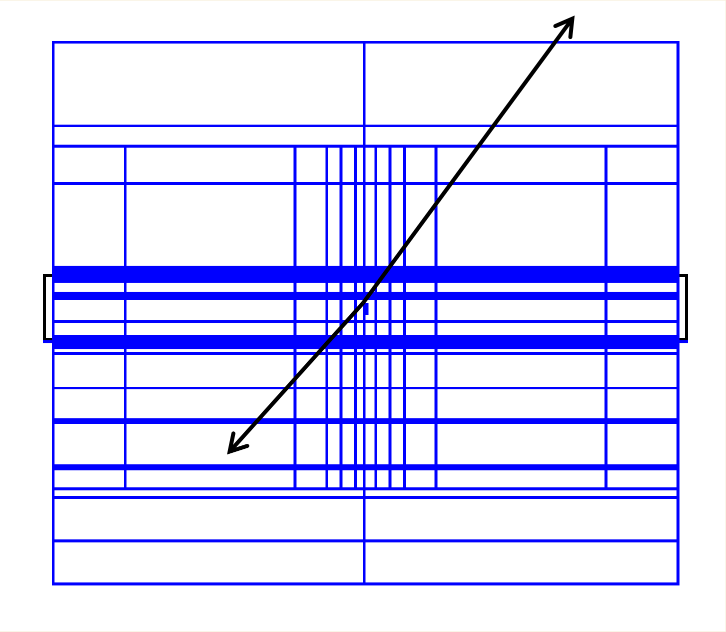
^{3}He in BIG KARL, carries the full beam momentum

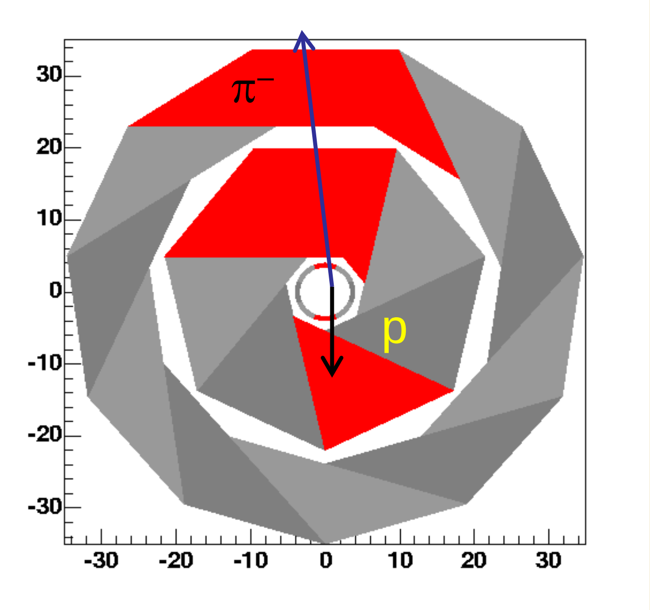
π-p almost back to back in ENSTAR

3-particle coincidence + 3 more constraints!

Beam pipe from carbon fibre

Particle identification with BK focal plane detectors



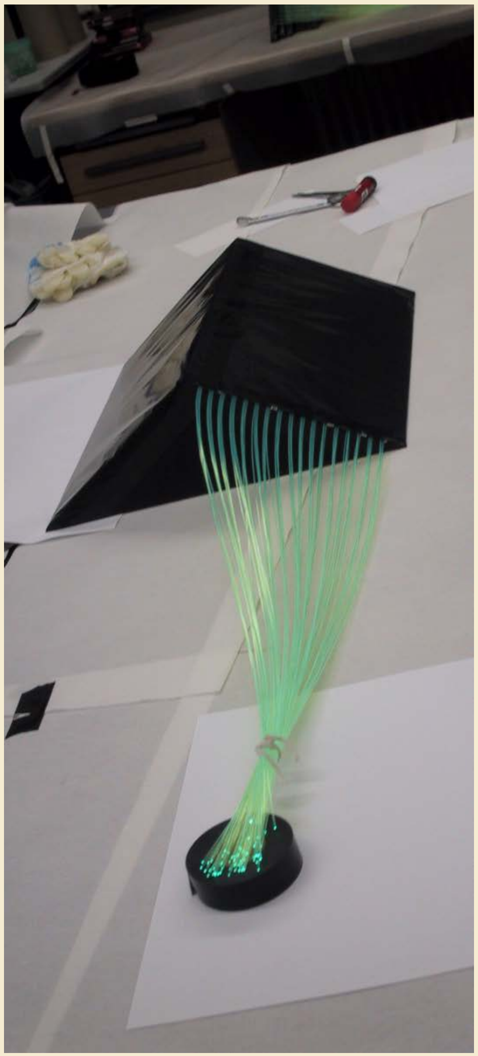


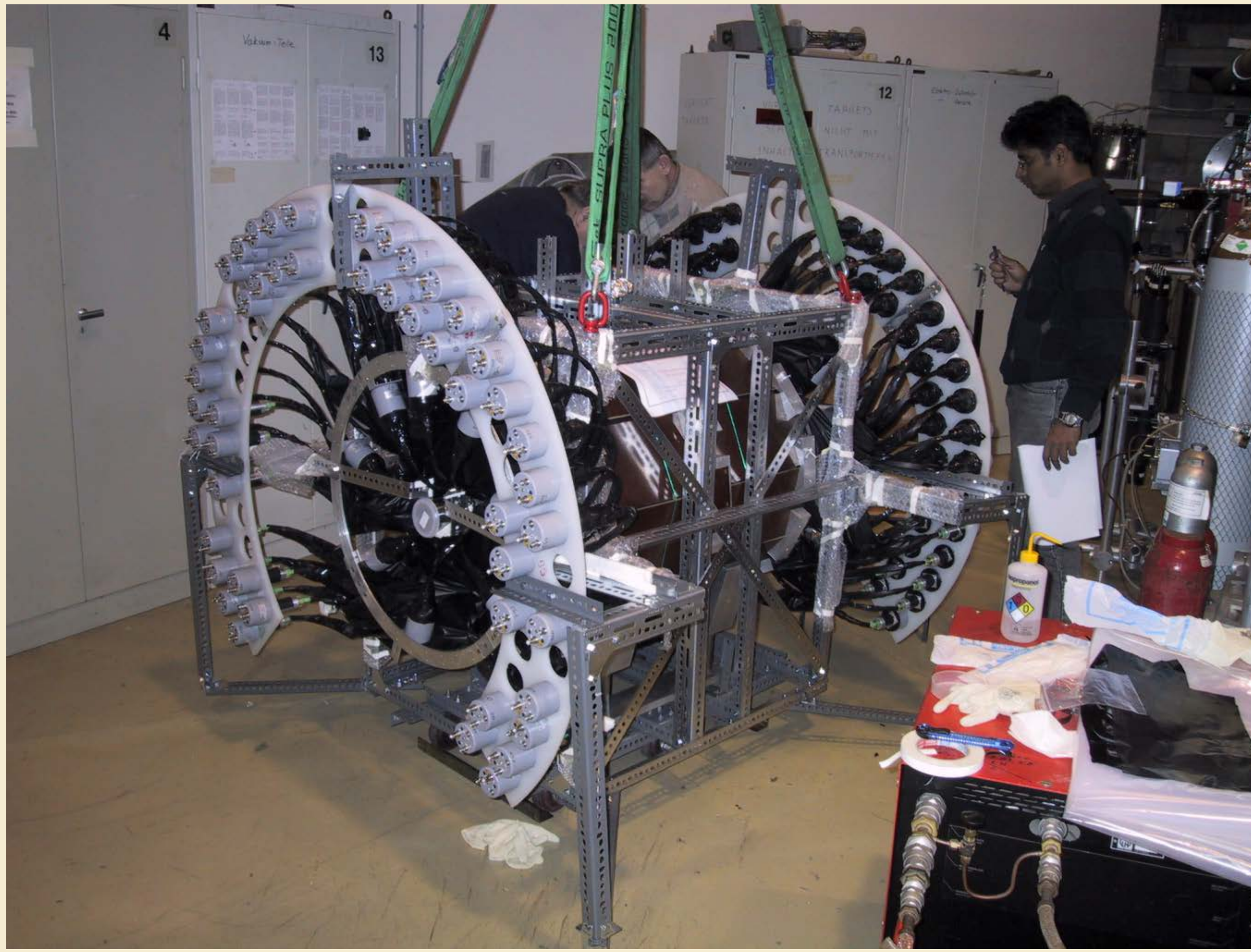
Event of interest:

- Two correlated particles: 5+4=9 fold coincidence
- Pion leaves the detector: outer layer fires
- Proton stopped in the middle layer

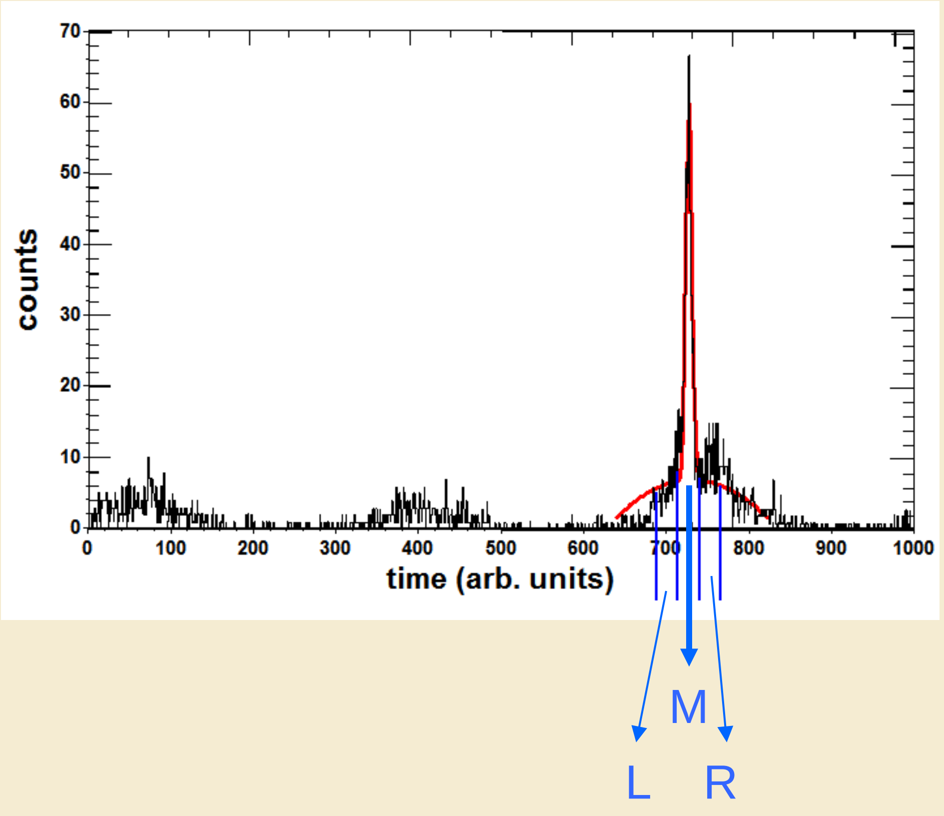
NIM A 596 (08) 31

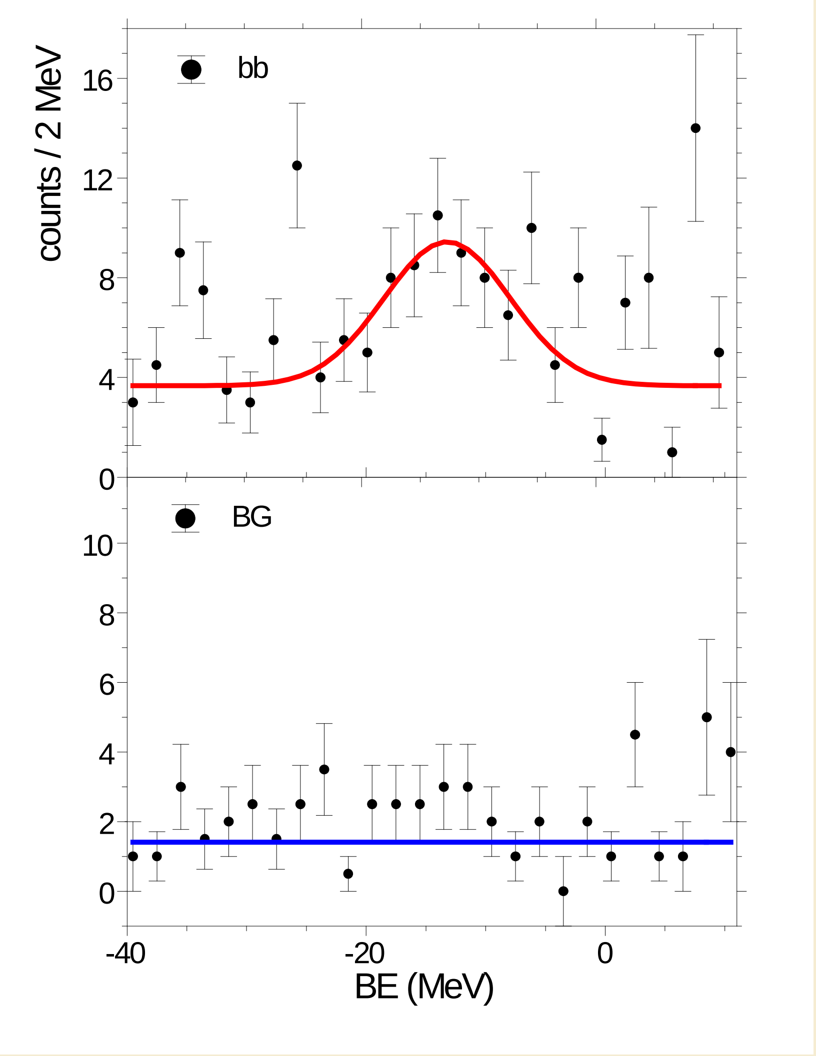
ENSTAR





Coincidences ^{3}He + ENSTAR bb

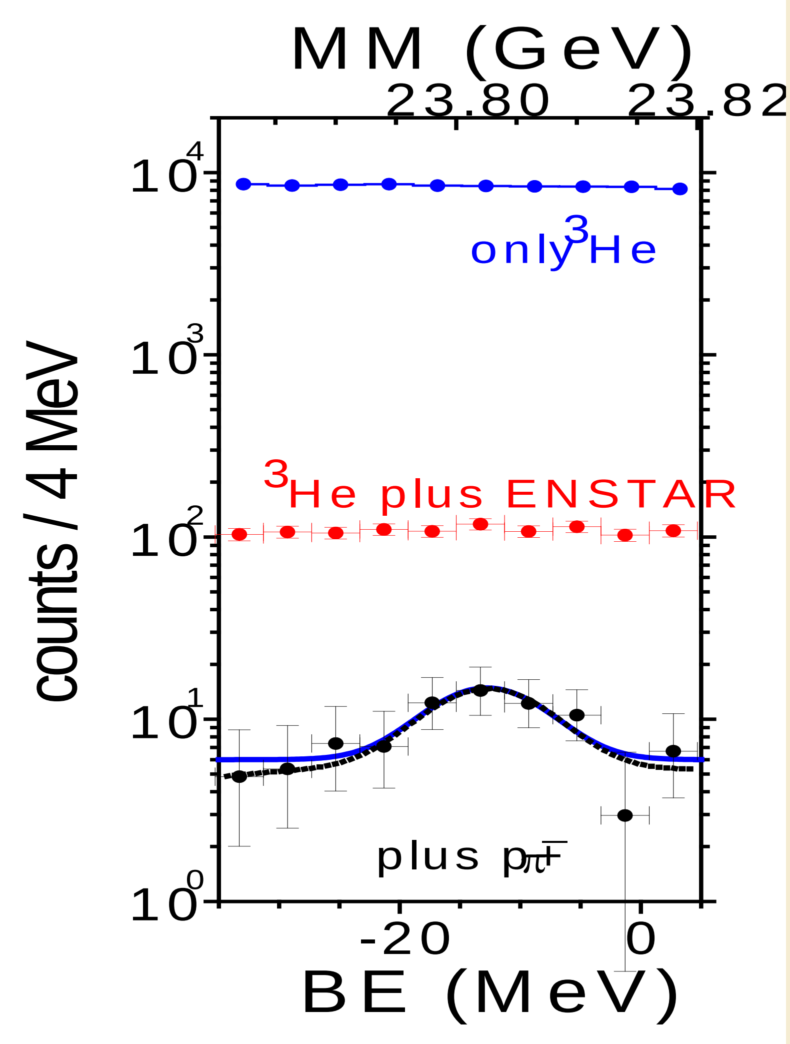




Time- and ^{3}He spectra

UNIVERSITÄT DUISBURG ESSEN

Offen im Denken



$BE_0 = 12.0 \pm 2.2$ MeV

FWHM = 11.04±4.0 MeV

Gaussian errors:

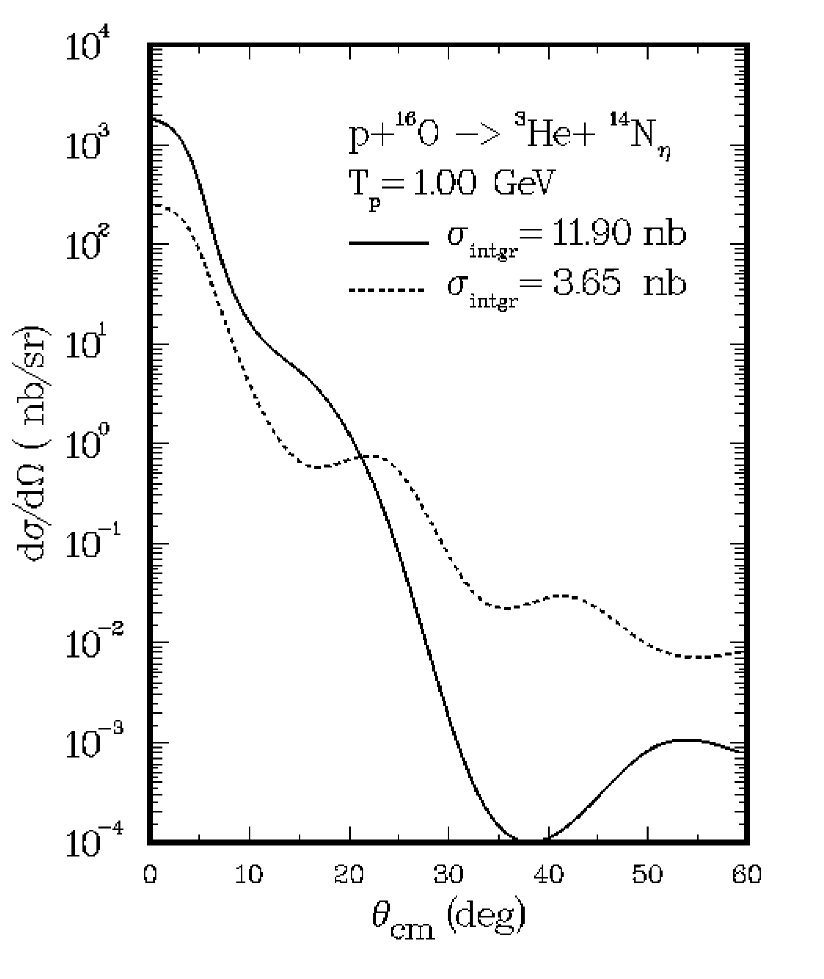
$(N - BG)/\sqrt{(BG + \sigma_{BG})} = 5.3\sigma$

Poisson errors:

$(N - BG)/\sqrt{(BG + \sigma_{BG})} = 4.9\sigma$

Likelihood $\sqrt{-2\Delta lnL} = 6.2\sigma$

Cross section



L.-C. Liu (priv. comm.)

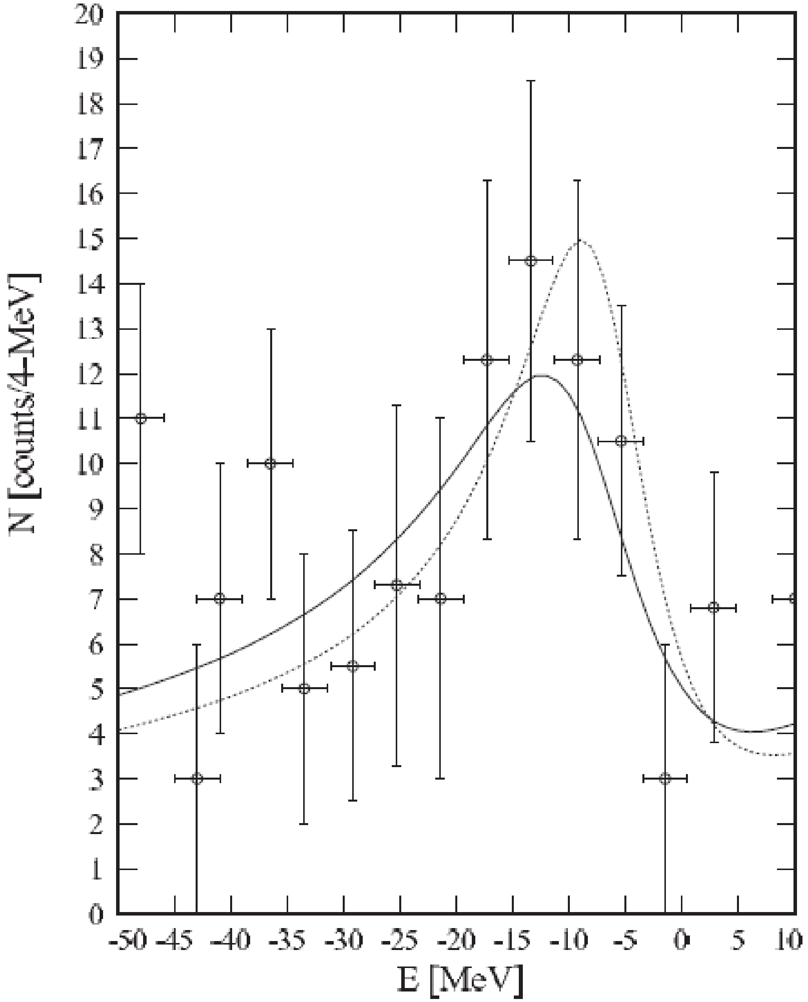
Expected(for the present system):

σ=5-22 nb

acceptance, isospin yields

$$\sigma_{exp.} = 0.46 \pm 0.16(\text{stat.}) \pm 0.06(\text{syst.})\ \text{nb}$$

$$\sigma(\text{pd} \rightarrow \eta\, ^3He,\ BK\ \ accept) = 39\,\mu b$$



Haider&Liu, J. Phys G 37(10)125104

$$\sigma \propto | f_{bound} |^2 \qquad \text{dashed}$$

$$\sigma \propto | f_s + f_{bound} |^2$$

$$f_{bound} = BW$$

Friedman et al: $\Re(a_{\eta N}) \approx 1 \text{ fm}$

Two body final state interaction

Tacid assumption:

s-wave, and then $d\sigma/d\Omega=\sigma/4\pi$

$$\frac{p_i}{p_f}\left(\frac{d\sigma}{d\Omega}\right)=|f|^2=|f_B\cdot FSI|^2=|f_B|^2\cdot|FSI|^2$$

$$FSI=\frac{1}{1-i\cdot a\cdot p_f+\frac{1}{2}a\cdot r_0\cdot p_f^2}$$

Quasi-bound requires:

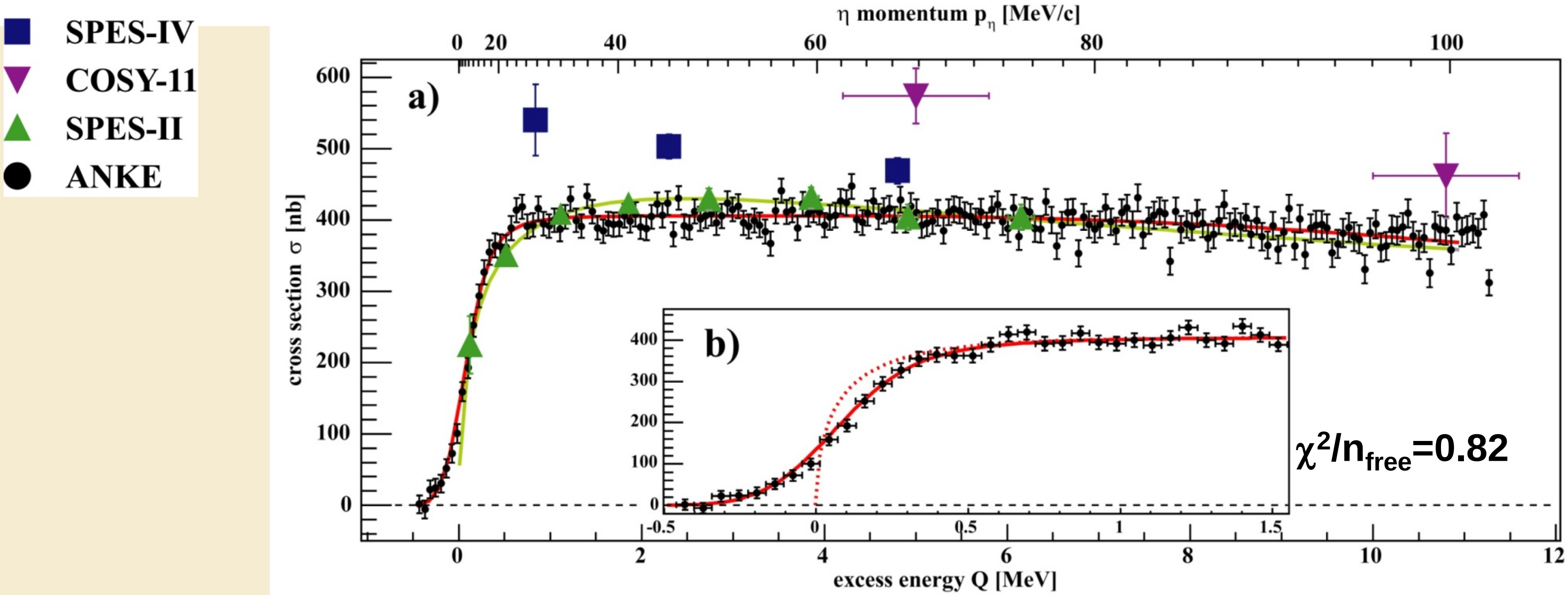
- $\mathrm{Im}(a_{\eta A})>0$ from unitarity
- $|\mathrm{Im}(a_{\eta A})|<|\mathrm{Re}(a_{\eta A})|$ to have a pole in the negative energy half plane
- $\mathrm{Re}(a_{\eta A})<0$ to have a bound state, but

$|FSI|^2 \propto 1/\mathrm{Re}(a_{\eta A})^2$ thus experiments give no sign

$|Q_0(\eta^3He)|<|Q_0(\eta^4He)|\ )|<|Q_0(\eta^7Be)|$

Otherwise: virtual (unphysical) state

Excitation function: $dp \to {}^3He\eta$



T. Mersmann et al., PRL 98 (07) 242301

$$a_{^3He\eta} = \left[\pm\left(10.7 \pm 0.8^{+0.1}_{-0.5}\right) + i\cdot\left(1.5 \pm 2.6^{+1.0}_{-0.9}\right)\right]\mathrm{fm}$$

$$r_0 = \left[\left(1.9 \pm 0.1\right) + i\cdot\left(2.1 \pm 0.2^{+0.2}_{-0.0}\right)\right]\mathrm{fm}$$

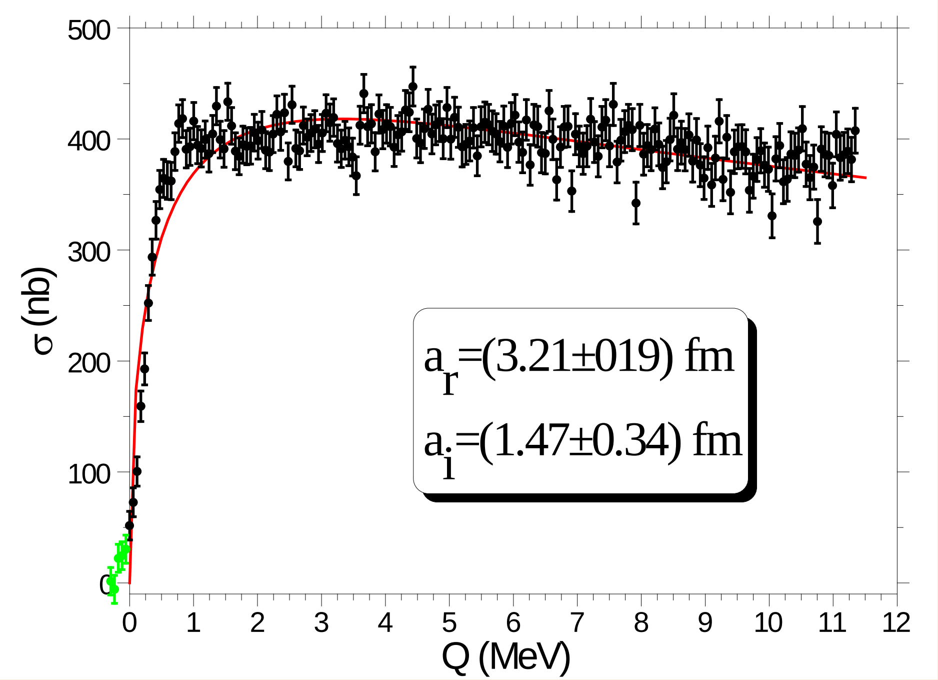
$$|Q_0| \approx 0.30\ \mathrm{MeV}$$

Smyrski et al.

a = ±(2.9 ± 2.7)+i(3.2 ± 1.8) fm

r_0 = 0 fm

Scattering length of the ANKE data

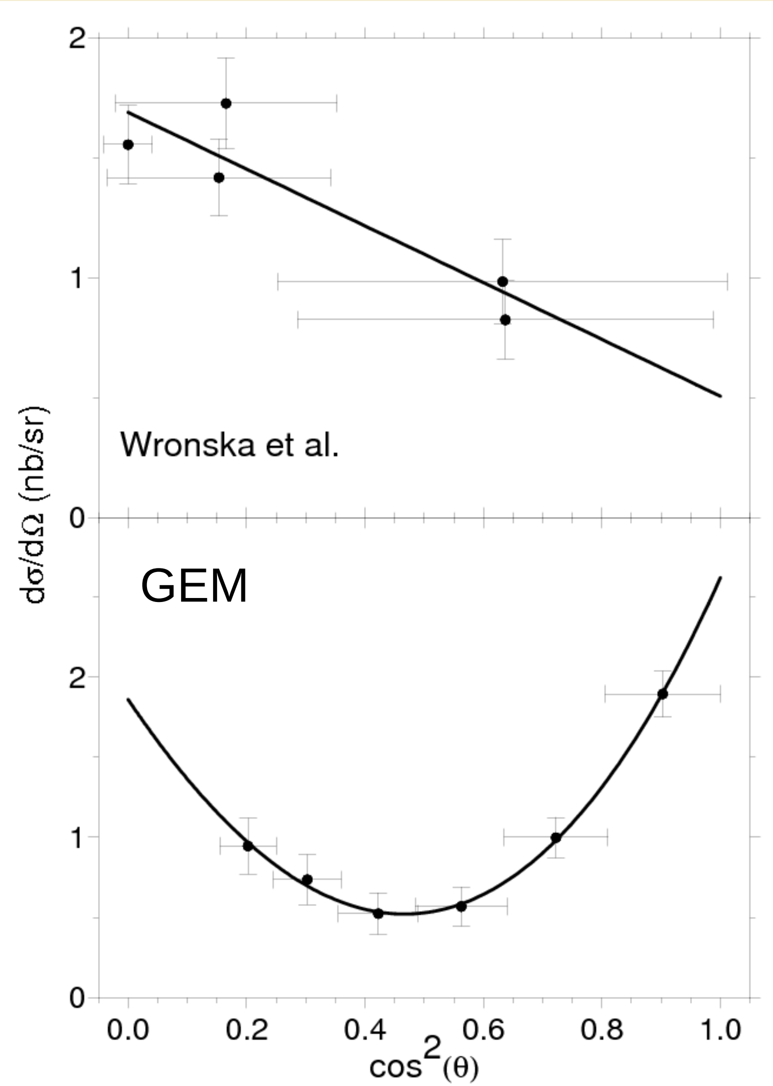


$$f = \frac{f_B}{1 - iap}$$

Condition to have a pole:
$|a_i|<|a_r|$

$$|Q_0| = (3.41 \pm 0.42)\,\mathrm{MeV}$$

d+d→η+α



Legendre polynomials

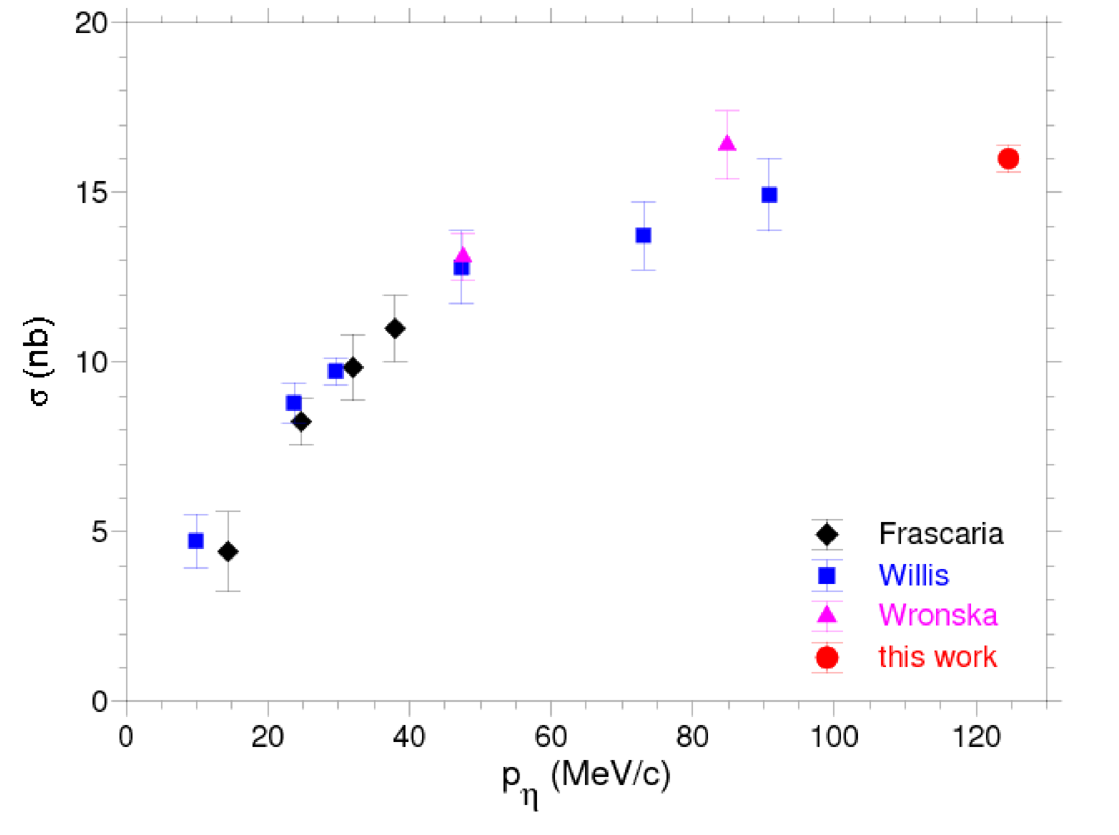
Exp.	a_0	a_2	a_4
ANKE	1.30 ±0.18	-0.79 ±0.19	
GEM	1.27 ±0.03	-0.29 ±0.06	1.65 ±0.07

s, p and d-waves!

Excitation Function

UNIVERSITÄT DUISBURG ESSEN

Offen im Denken



Same momentum range as in p+d, but less data points. Cross section less than 5%!

How to extract s-wave?

Tensor polarized d-beam

$$\mathcal{M} = A(\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \hat{p}_d + B(\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot [\hat{p}_d \times (\hat{p}_\eta \times \hat{p}_d)] (\hat{p}_\eta \cdot \hat{p}_d)$$
$$+C [(\vec{\epsilon}_1 \cdot \hat{p}_d) \vec{\epsilon}_2 \cdot (\hat{p}_\eta \times \hat{p}_d) + (\vec{\epsilon}_2 \cdot \hat{p}_d) \vec{\epsilon}_1 \cdot (\hat{p}_\eta \times \hat{p}_d)],$$

$$A(\theta) = A_0 + A_2 P_2(\cos\theta)$$

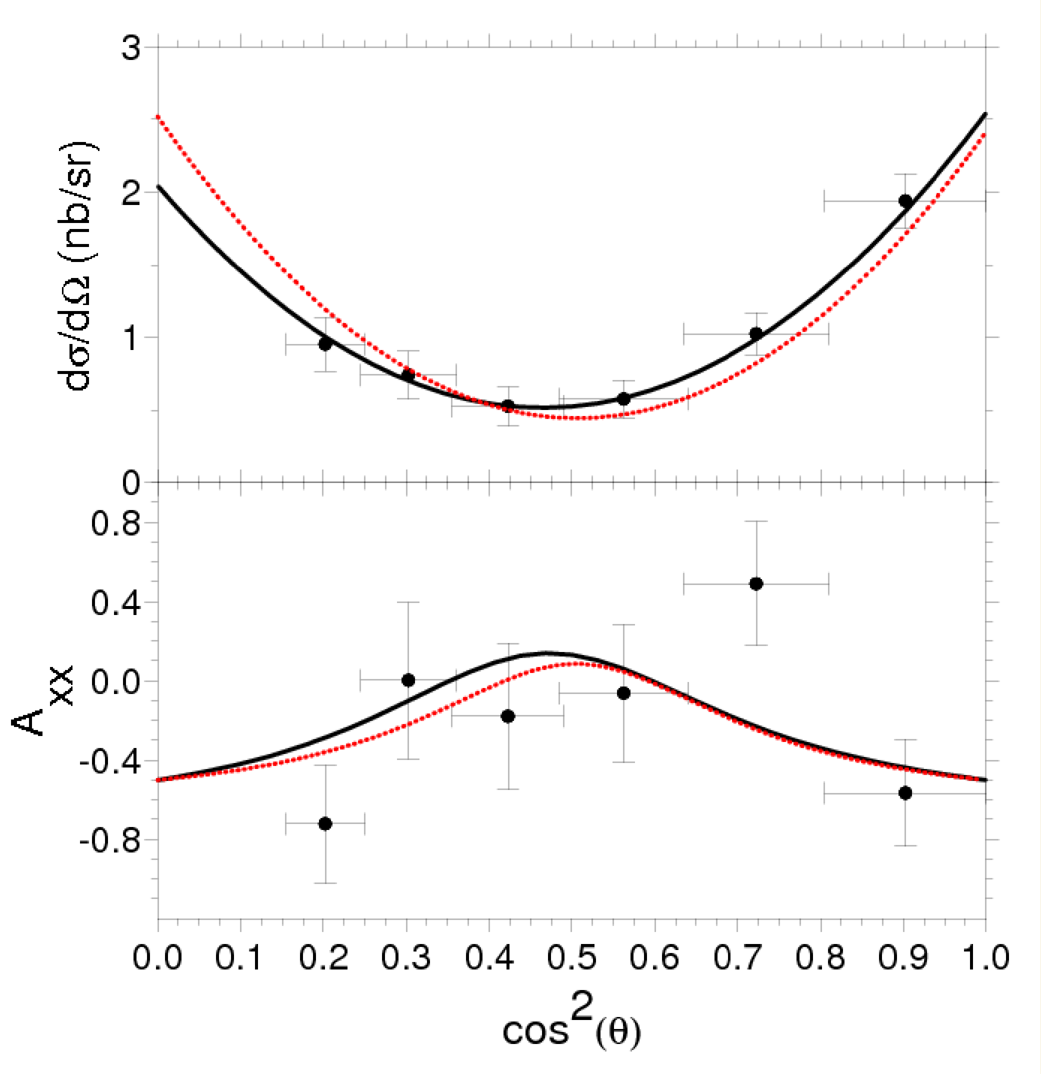
fit parameter	value
$\|A_0\|^2$	6.6 ± 1.7
$2Re(A_0^* A_2)$	-25.0 ± 9.5
$\|A_2\|^2$	48.4 ± 14.5
$\|B\|^2$	9.3 ± 5.1
$\|C\|^2$	0

Better fit than partial wave amplitudes (s, p, 2d waves), because less parameters (4 instead of 7)

Angular dependence due to s-d interference

Final result

PWA	———
spin ampl.	- - - - - -

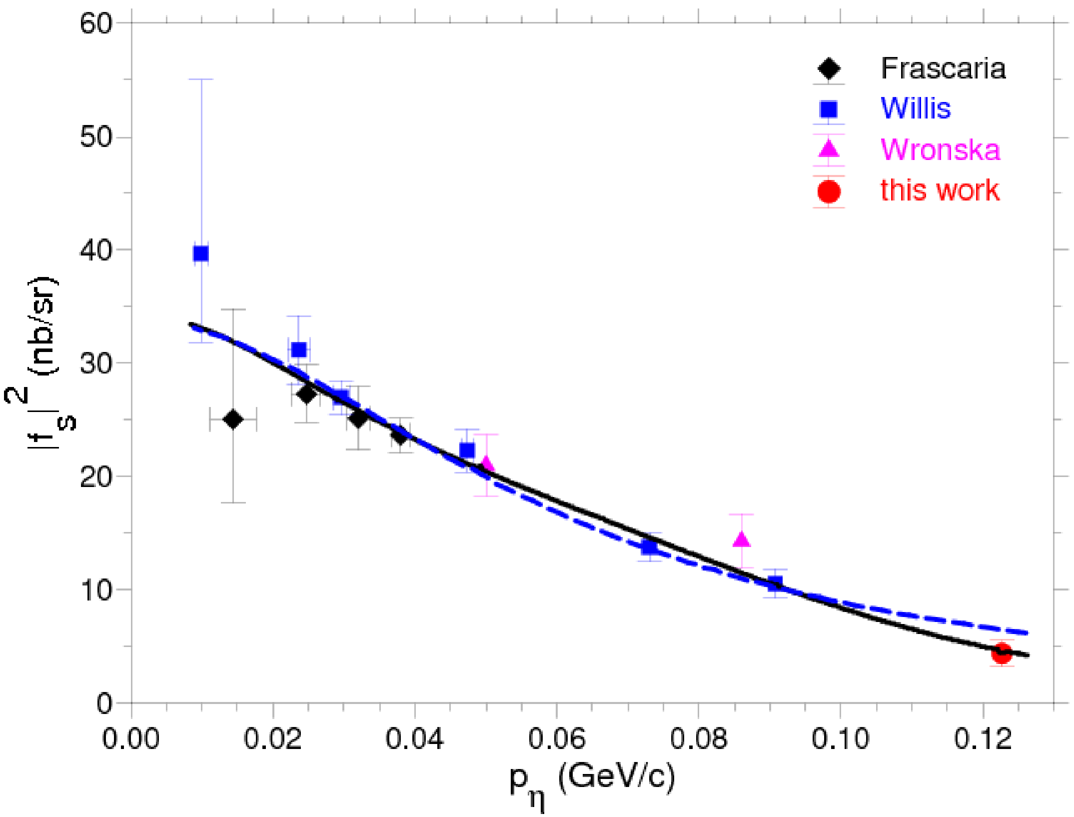


NP A 821 (2009) 193

Final result

$$\frac{d\sigma_s}{d\Omega} = \frac{p_\eta}{p_d}|f_s|^2 = \frac{2p_\eta}{3p_d}|A_0|^2 = \frac{1}{27}\frac{1}{4\pi}|a_0|^2$$

$$|f_s|^2 = 4.4 \pm 1.1 \text{ nb/sr}$$



scatt. length

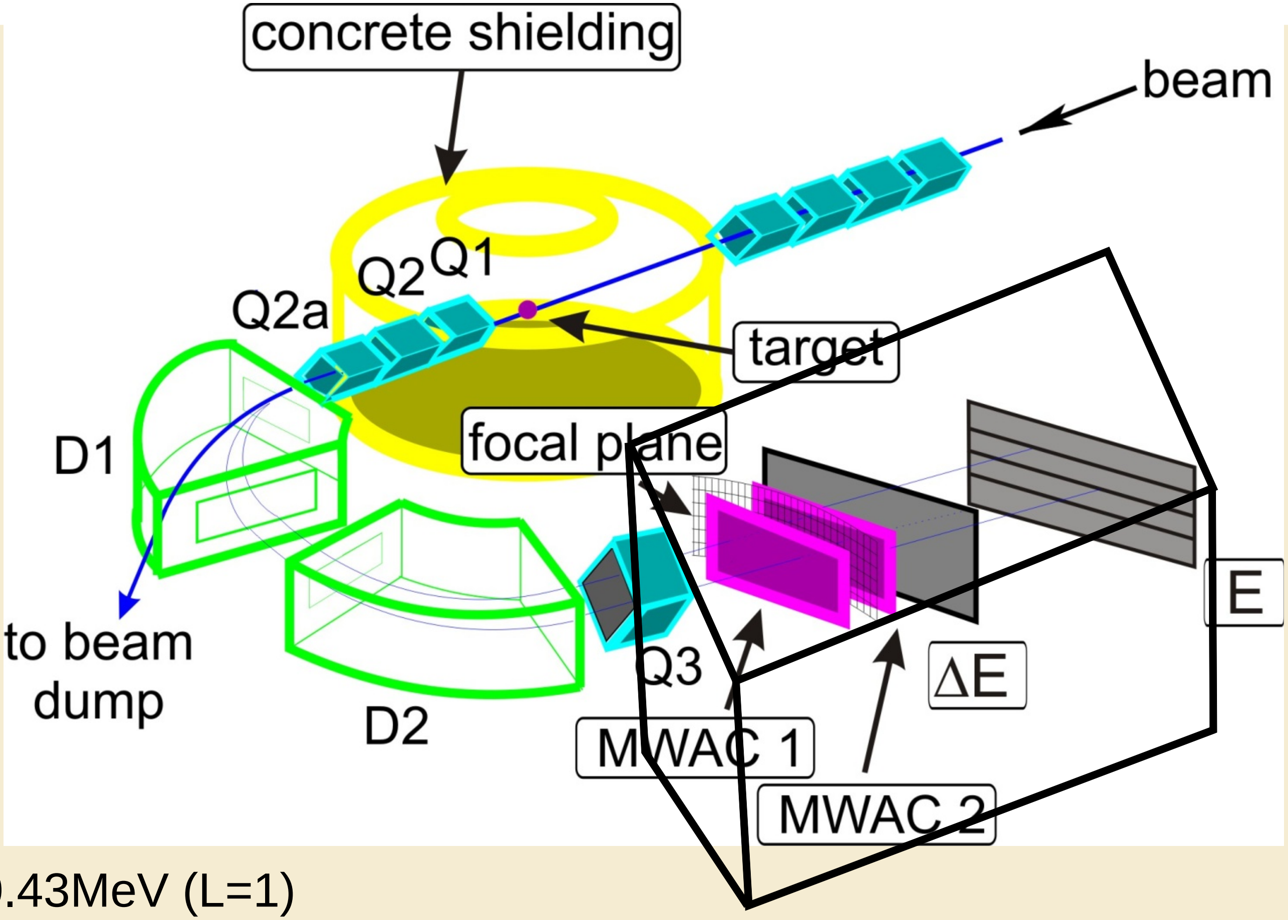
effective range

$$|a_r| = 3.1 \pm 0.5 \text{ fm}$$

$$a_i = 0.0 \pm 0.5 \text{ fm}$$

$$|Q_0| \approx 4.4\text{MeV} > |Q_0(\eta\,^3\text{He})|$$

p+^{6}Li →η+^{7}Be 11 MeV above threshold

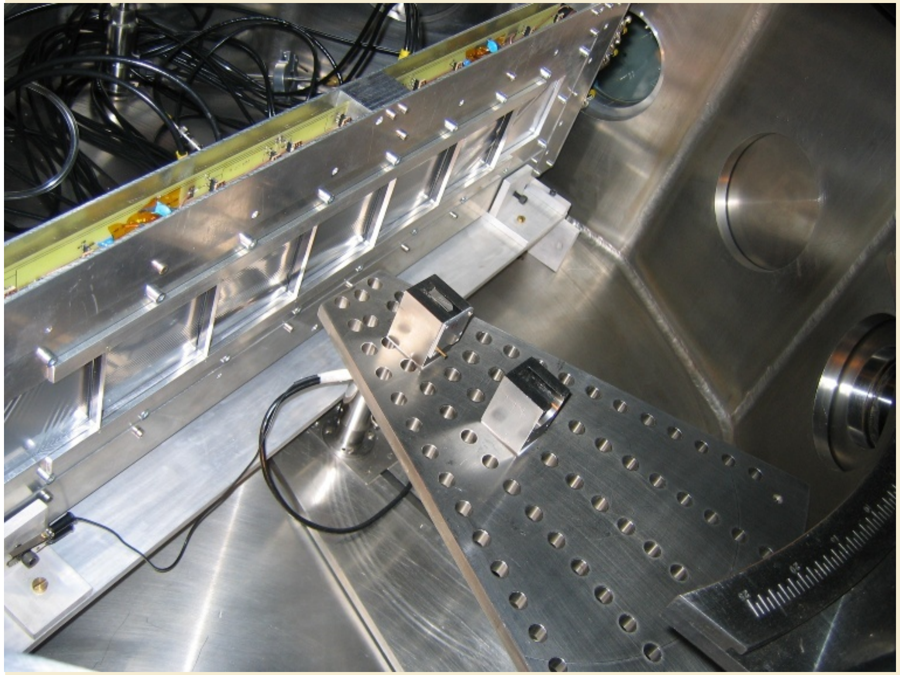


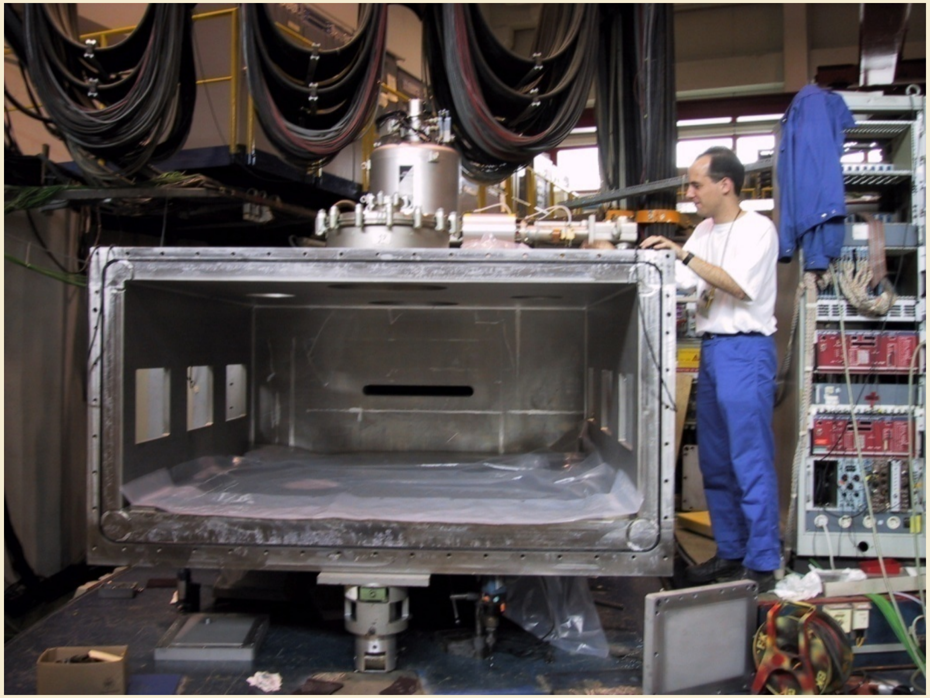
g.s.+0.43MeV (L=1)

previous exp. 4 states (L=1+L=3)

p+^{6}Li→γγ+X

Set up

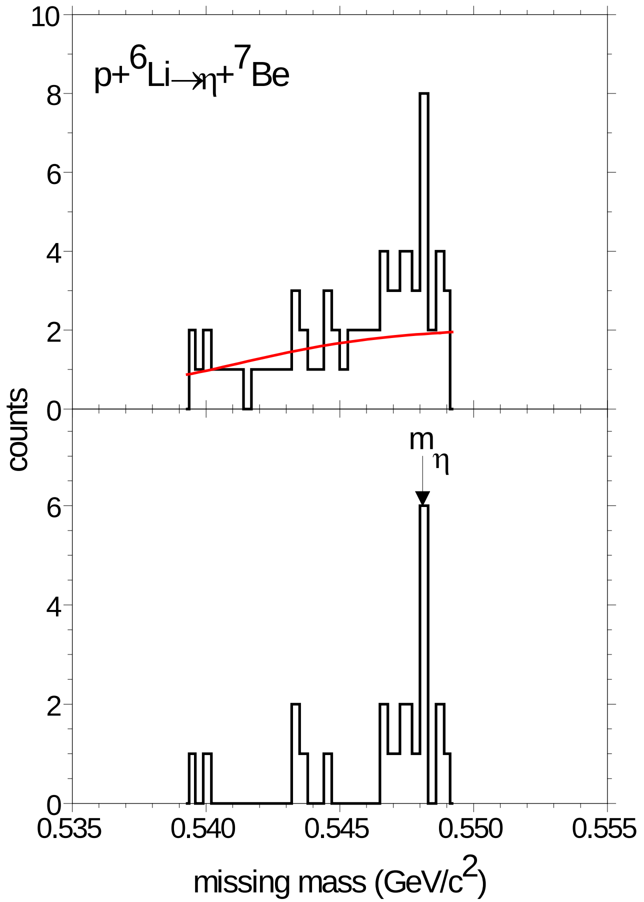


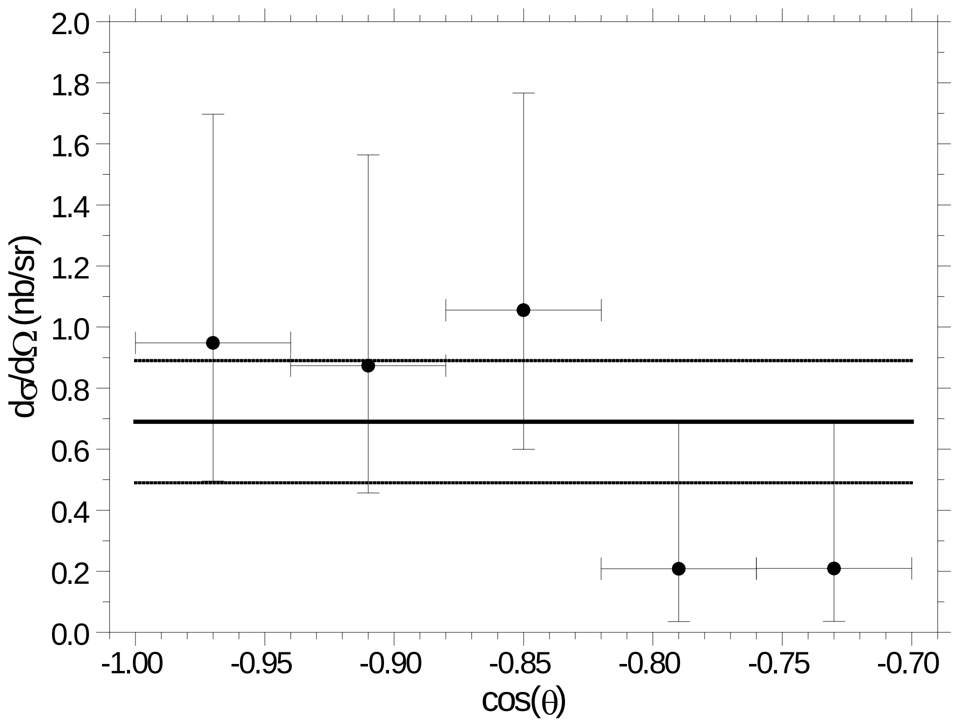


Tests of MWAC with TIFR Pelletron beams of
- ^{7}Li at 48 MeV,
- ^{12}C at 60 MeV,
- ^{16}O at 50 MeV.

All focal plane detectors in big vacuum box

Results





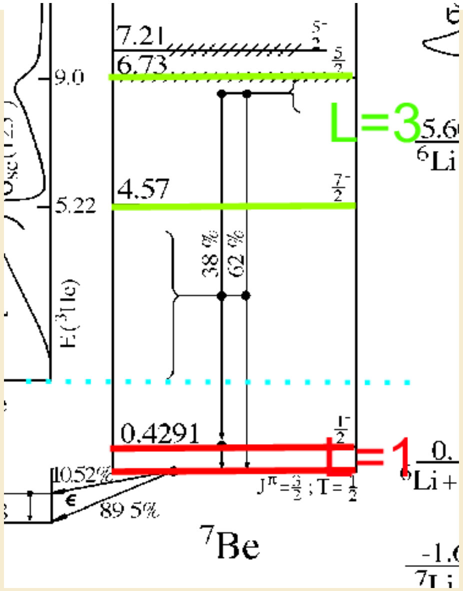
$$\frac{d\sigma}{d\Omega} = (0.69 \pm 0.20(\text{ stat.}) \pm 0.20(\text{ syst.}))\ \text{nb/sr.}$$

Subtraction of L=3 yield

UNIVERSITÄT DUISBURG ESSEN
Offen im Denken

Al-Khalili et al.:

$$\frac{d\sigma(p^6\mathrm{Li}\rightarrow\eta^7\mathrm{Be})}{d\Omega} = \mathrm{C}\frac{p_\eta^*}{p_p^*}\,|\,f(pd\rightarrow\eta^3\mathrm{He})|^2\sum_j\frac{2j+1}{2}\mathrm{F}_j^{\,2}$$

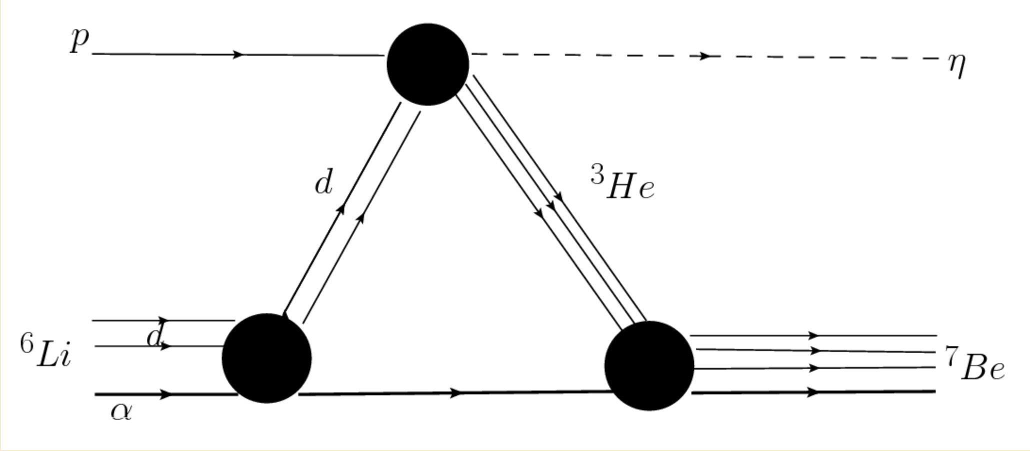


C overlapp cluster wavefunctions

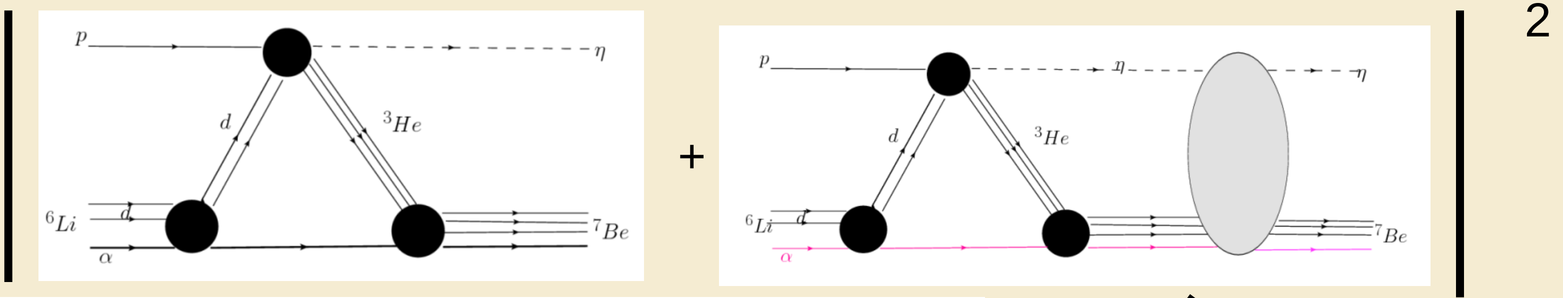
$f(pd\rightarrow\eta^3\mathrm{He})$ spin averaged amplitude

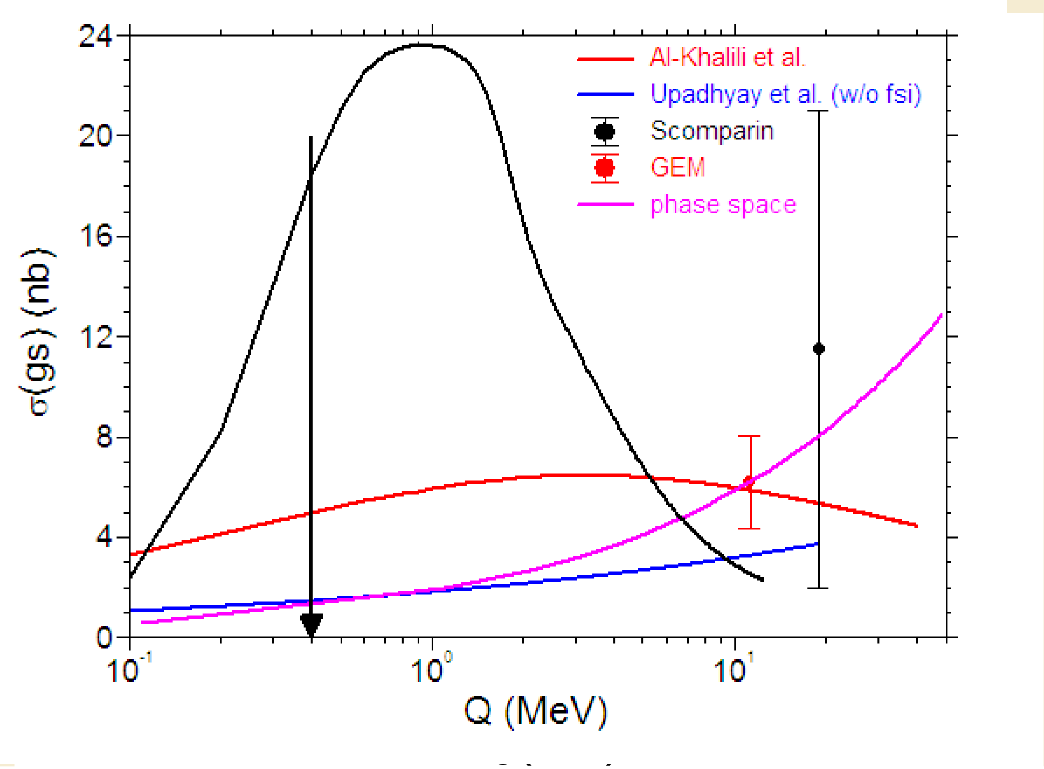
F_j form factor

$$\frac{d\sigma(L=1)}{d\Omega} \approx \frac{d\sigma(exp.)}{d\Omega}\,\frac{\sum\limits_{j=3/2,1/2}\frac{2j+1}{2}\mathrm{F}_j^{\,2}}{\sum\limits_{j=3/2,1/2,7/2,5/2}\frac{2j+1}{2}\mathrm{F}_j^{\,2}}$$



Mumbai Group





=FSI: from

$a_{\eta N}$ =(0.88+i0.41) fm

$a_{\eta Be}$ = (-9.18+i8.53) fm

Proposal for WASA:

$$p + {}^7\mathrm{Li} \rightarrow \eta + {}^7\mathrm{Be}$$

$$\eta \rightarrow \gamma + \gamma$$

at Tp=659 MeV

Q=0.33 MeV

Influence effective range

Final state	$\|a_r\|$	a_i	E_B	comment
$^3He\eta$	2.9 ±2.7	3.2 ± 1.8	2.3	Smyrski no e.r.
$^3He\eta$	3.21±0.19	1.47±0.34	4.1±0.4	data Mersmann no e.r.
$^3He\eta$	10.7 ±0.9	1.5 ±2.8	0.3	data Meersmann e.r.
$^4He\eta$	3.1±0.5	0.0±0.5	4	GEM no e.r.
$^4He\eta$	6.2 ± 1.9	0.001±6.5	10±3	GEM e.r.
$^7Be\eta$	9.18	8.83	0.33	calculation

Data contradict expectations