# Search for Bound η- Nucleus States

**GEM Collaboration**

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# Outline

- Introduction – physics motivation
- $\alpha({}^{4}He\eta)$ from $\vec{d} + d \rightarrow {}^{4}He + \eta$
- Results from $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$
- Summary

# Introduction - Physics motivation

## Theoretical predictions of η – nucleus bound states

- ***Haider & Liu, PLB 172 (1986)*** η-nucleus bound states, existence detemined by the scattering length, can be formed for *A > 10*
- ***Bhalerao & Liu, PRL 54 (1985)*** η-nucleon interaction attractive

  s-wave η-N scattering length $a_{\eta N}$= (0.28 + 0.19i) fm and $a_{\eta N}$= (0.27 + 0.22i) fm

  π-N phase shift analysis – Arndt and CERN

Other groups found similar results:

- ***Hayano, Hirenzaki & Gilitzer, Eur. Phys. J. A6 (1999)***
- ***Tsushima, Nucl. Phys. A 670 (2000)***
- ***Garcia-Recio, Inoue, Nieves & Oset, Phys. Lett. B 550 (2002)***

# Introduction - Physics motivation

- relation between the s-wave scattering amplitude and the scattering length for a strong FSI

$$f_s = \frac{f_B}{1 - ip_\eta \alpha}$$

Watson-Migdal (PR 88(1952), JTEP 1(1955) )

Where $\alpha = \alpha_r + \alpha_i$ is the complex s-wave η-N scattering length,

$f_B$ is the production amplitude – usually taken as a constant,

$p_\eta$ is eta meson momentum.

- cross section and the scattering amplitude

$$|f|^2 = \frac{p_d}{p_\eta}\left(\frac{d\sigma}{d\Omega}\right)$$

$$|f_S|^2 = \frac{{f_B}^2}{1 + {p_\eta}^2 |\alpha|^2 + 2 p_\eta \operatorname{Im} \alpha_i}$$

# Introduction - Physics motivation

- in the case of binding the following relations have to be fulfilled: (Haider & Liu, PR C 66 (2002) )

$\alpha_r < 0$ and $\alpha_i > 0$ from unitarity and

$$R = {|\alpha_i|}/{|\alpha_r|} < 1$$

to have a pole in the complex $p_n$ plane.

# Introduction - Physics motivation

- ***Ueda PRL 66 (1991)*** hints that η can form bound states with $^{3,4}He$ and deuteron

- ***Wilkin PRC 47 (1993)*** large near threshold production amplitude and is rapid decrease with energy of the $p + d \rightarrow \eta + {}^{3}He$ reaction as evidence for strong FSI, the scattering length (-2.31 + 2.57i) fm, indirect evidence for η-mesic nucleus

- ***Willis et al. PRL B406 (1997)*** predictions for near threshold η-He quasi-bound state, scattering lengths $\alpha(^{3}He\eta)$ = (-2.3 + 3.2i) and $\alpha(^{4}He\eta)$ = (-2.2 + 1.1i) fm,

- ***Green & Wycech PRC 55 (1998)*** bound state only for $A \geq 4$

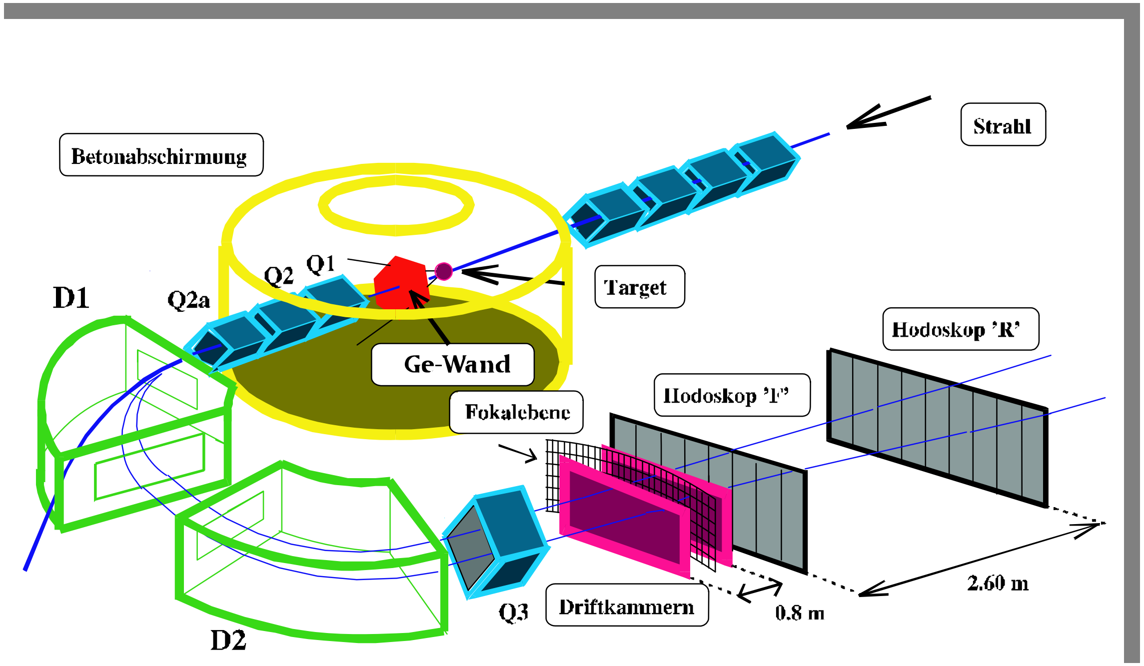
- ***Rakitansky et al. PRC 53 (1996)*** $\alpha(\eta N)$ uncertanties can support bound states with d, $^{3}H$, $^{3}He$,$^{4}He$

- ***Fix & Arenhövel PRC 66 (2002)*** previous results not approved

# $\alpha\left({}^4He\,\eta\right)$ from $\vec{d} + d \to {}^4He + \eta$

- To test these criteria $\vec{d} + d \to {}^4He + \eta$ studied near the threshold
- Vector and tensor polarized deuteron beam allows to measure cross sections, analyzing powers and to deduce partial wave amplitudes.
- $\alpha$ particles detected with BIG KARL

# GEM Detector




*Magnetic*
Spectrograph
Big Karl

## $\alpha\left({}^{4}He\eta\right)$ from $\vec{d} + d \rightarrow {}^{4}He + \eta$

Experimental conditions

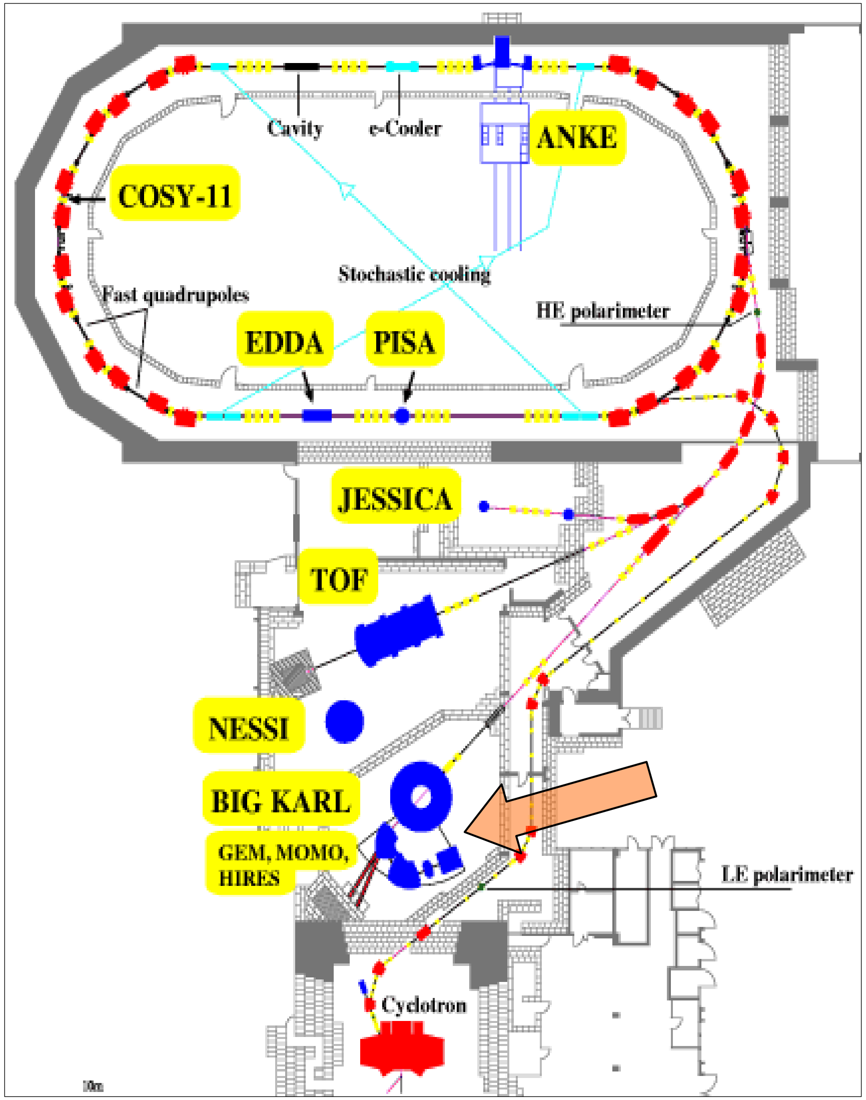
- liquid hydrogen and liquid deuterium targets, 4mm thick
- deuteron beam momentum: 2385.5 MeV/c, Q=16 MeV
- selected vector and tensor polarisations of the beam:
  1) $p_z = 0$ $p_{zz} = 0$
  2) $p_z = -1/3$ $p_{zz} = +1$
  3) $p_z = -1/3$ $p_{zz} = -1$

$\alpha\left({}^4He\,\eta\right)$ from $\vec{d} + d \rightarrow {}^4He + \eta$

Experimental conditions

- tensor polarization measured in $\vec{d}p \rightarrow pd$
- vector polarization measured with low energy polarimeter in the beam line between the cyclotron and COSY

# COSY




- up to 3.6 GeV/c
- e and stochastic cooling,
- stochastic extraction (10 s - min)
- luminosity achieved:
  $L = 10^{32}$ cm$^{-2}$s$^{-1}$
- p and d beams
- (cooled) beam quality:
  $\varepsilon = 0.4\,\pi$ mm mrad ($\varnothing = 0.5$ mm)
  ~0.1% halo at $\varnothing = 2.5$ mm
  $\Delta p/p = 5\times10^{-5}$
- close to target tracking
- p vector polarised
- d vector and tensor polarised

$\alpha\left({}^4He\,\eta\right)$ from $\vec{d} + d \rightarrow {}^4He + \eta$

Results of vector and tensor polarization measurements

| $p_z$ | | $p_{zz}$ | |
|---|---|---|---|
| Nominal | measured | Nominal | measured |
| -1/3 | -0.33± 0.02 | -1 | -0.87±0.11±0.01 |
| -1/3 | -0.32± 0.02 | +1 | +0.91±0.14±0.01 |

## $\alpha\left({}^{4}He\eta\right)$ from $\vec{d} + d \rightarrow {}^{4}He + \eta$

### Observables

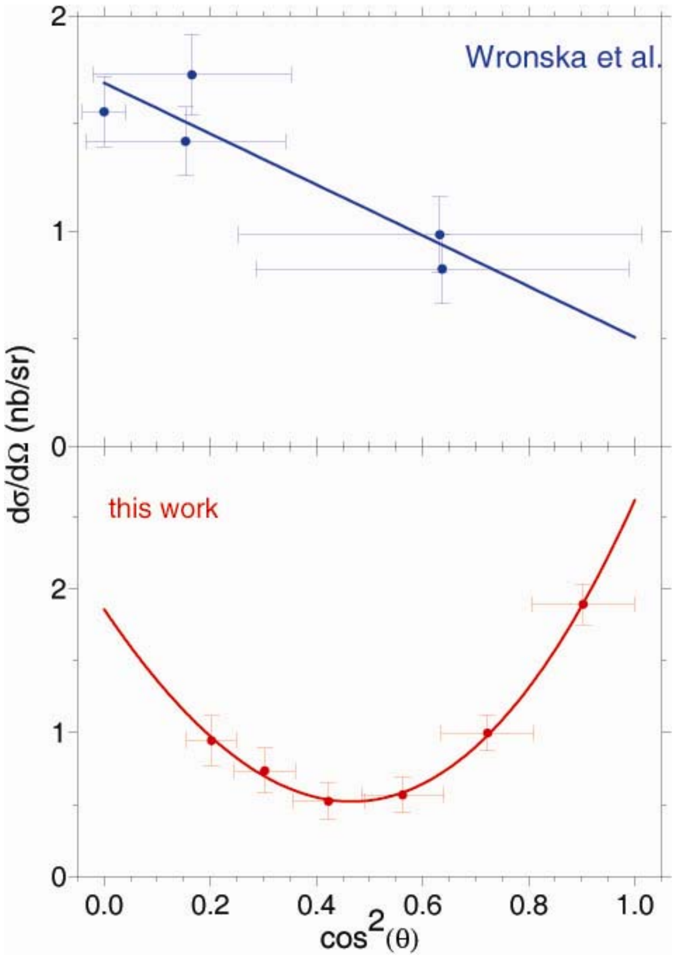
- differential cross sections $\frac{d\sigma}{d\Omega}$

- analyzing powers $A_{xx}(\Theta)$

- fit $$\frac{d\sigma}{d\Omega} = \sum_{l=0,\Delta l=2}^{l_{max}} a_l P_l(\cos\Theta)$$

- $l_{max}$= 4 found ➔ s-, p-, d- waves contribute

# $\alpha\left({}^4He\eta\right)$ from $\vec{d} + d \to {}^4He + \eta$




- Wronska et al. EPJ A26 (2005) - ANKE

$l_{max}$= 2, ~$\cos^2\theta$ – origin unclear:

p- wave

s-d – wave interference

- s wave has to be extracted

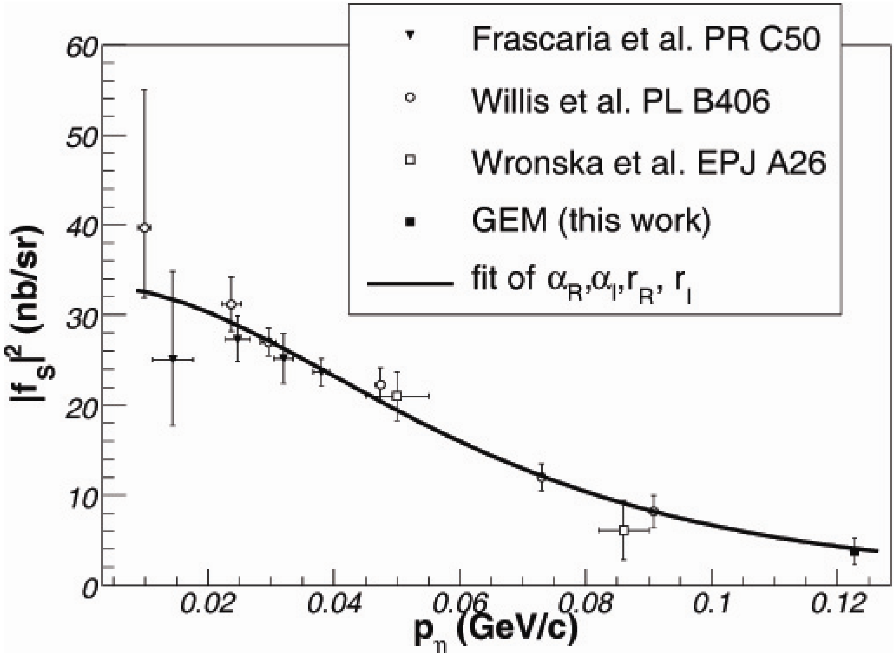
Lower panel unpolarized cross section

- this work s-, p-, d-waves fitted, s-wave amplitude was made real. Strong correlation among the parameters ➔ only s-wave fraction could be extracted

- then the spin averaged amplitude

$$\frac{d\sigma}{d\Omega} = \frac{p_\eta}{p_d}\left|f_s\right|^2 \propto \frac{p_\eta}{p_d}\left|a_s\right|^2$$

$\alpha\left({}^{4}He\eta\right)$ from $\vec{d} + d \rightarrow {}^{4}He + \eta$




Spin averaged s-wave amplitude as a function of the excess energy

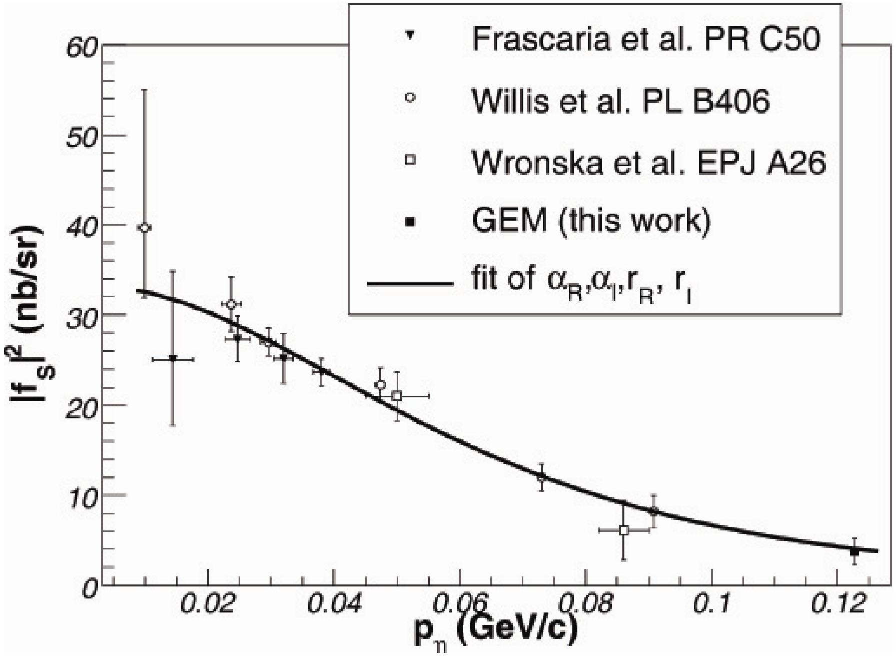
Optical model fit to all near threshold (Willis et al. PLB 406) pd→$^3$Heη and dd→$^4$Heη data

- assuming only *s-wave* resulted in α=(-2.2 + 1.1i) fm, where Re(α) was fixed by $^3$Heη data,
- for *s*+p assumption α=(-2.2 + 2.3i) fm.

Keeping Re(α) = -2.2 and repeating the fit we get bad $\chi^2$ .

$\alpha\left({}^{4}He\eta\right)$ from $\vec{d} + d \rightarrow {}^{4}He + \eta$

Introducing the effective range $r = r_R + ir_I$




$$f_s = \frac{f_B}{1 - ip_\eta\,\alpha + \frac{1}{2}\alpha r p_\eta^2}$$

and fitting all 4 parameters, result solid curve.

The ratio R = 0.19 ± 0.66 fulfills the condition for bound η, however the sign of real part Re(α) has to be extracted in order to be decisive

# Results from $p+{}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$

- First experiments at BNL *Chrien et al. PRL 60 (1988)* and LAMPF *Lieb,Proc.Int. Conf. Nucl. Phys., Sao Paulo(1988) searching for $\eta$-mesic nuclei used missing mass technique in ($\pi^+$,p) came to negative results.*
- *Turned out peaks are not necessarily narrow*
- *The BNL experiment was far from recoilfree, what significantly reduces the cross section.*

- *More recently Pfeiffer et al. PRL 92(2004)* reports η-mesic $^3$He found in $\gamma\, {}^3He \rightarrow \pi^0 pX$ reaction at photon energy just above the $^3He\eta$ threshold if $\pi^0 p$ is emitted back-to-back. Hanhart PRL 94 (2005): the data do not permit unambigous determination of $^3He\eta$ bound state. Theoretical studies: $^3He\eta$ is not bound Haider & Liu, PR C 66 (2002) and Sofianos & Rakytyansky arXive nucl-th 07004.

Recoil free kinematics:

$$p + \begin{pmatrix} d \\ A-2 \end{pmatrix} \rightarrow \begin{pmatrix} \eta \\ A-2 \end{pmatrix} + {}^{3}He$$

Big Karl

$$\eta + N \rightarrow N^{*}(1535) \leftrightarrow \begin{cases} \boxed{\pi^{-} + p} \\ \pi^{0} + n \\ \pi^{0} + p \\ \pi^{+} + n \end{cases}$$

# Results from $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$

The transfer reaction chosen at recoil free kinematic:

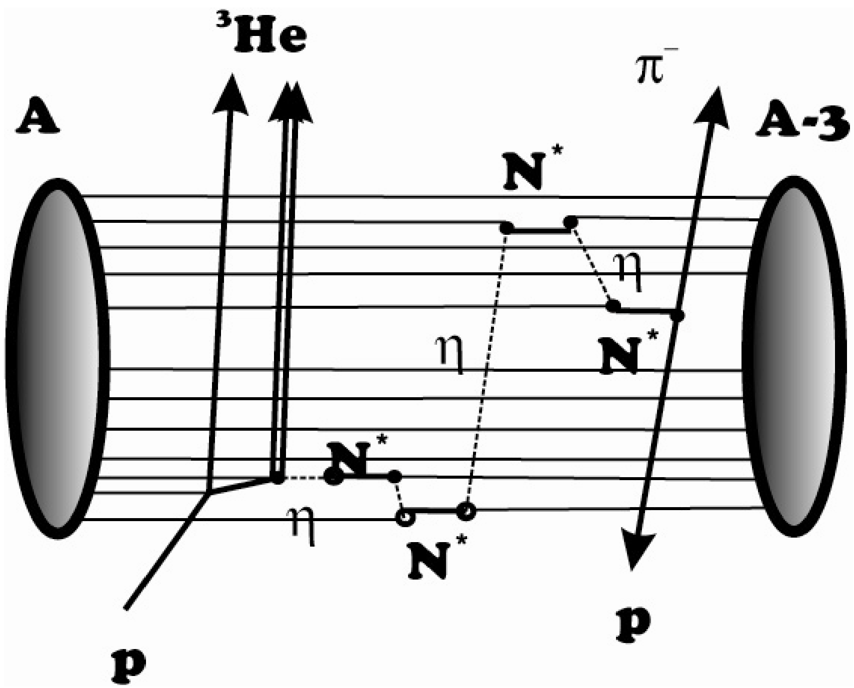
$$p + {}^{27}\mathrm{Al} \rightarrow {}^{3}\mathrm{He} + {}^{25}\mathrm{Mg} \times \eta$$

$^{3}$He ion carries almost all beam momentum, the residual system is @ rest and the $\eta$ WF has large overlap with the nuclear WF and a second step

$$\eta + \mathrm{N} \rightarrow \mathrm{N}^{*}$$

can take place with high probability, $\mathrm{N}^{*}(1535)$ mass extends down to the $\eta$-N threshold.

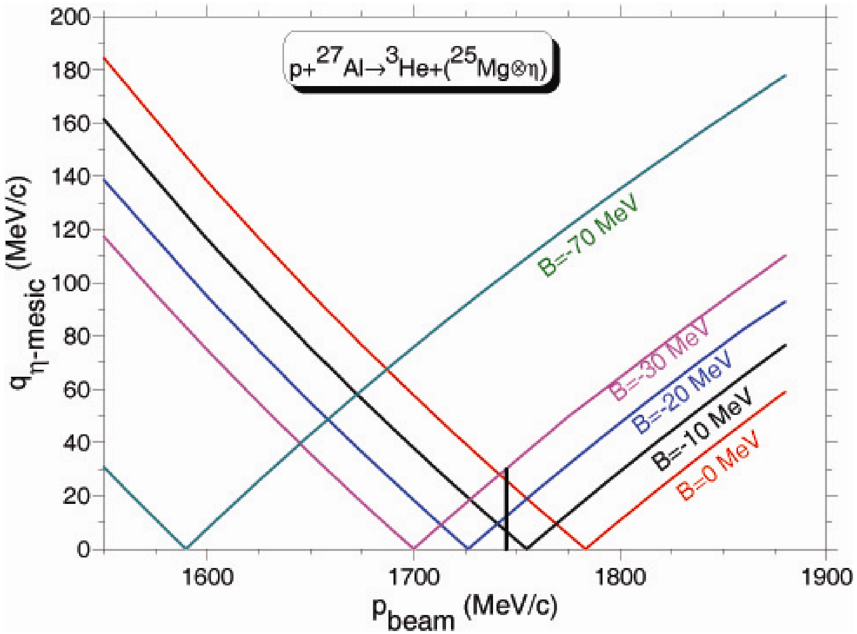
# Results from $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$




When η is bound the associated $N^{*}(1535)$ has its mass below η-N threshold and cannot decay into visible η-N, but successive interactions with N in nuclei, what is usually called bound η. The only probable decay is πN.

The system is @ rest, so, the π and N are emitted almost back-to-back.

# Results from $p+{}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$

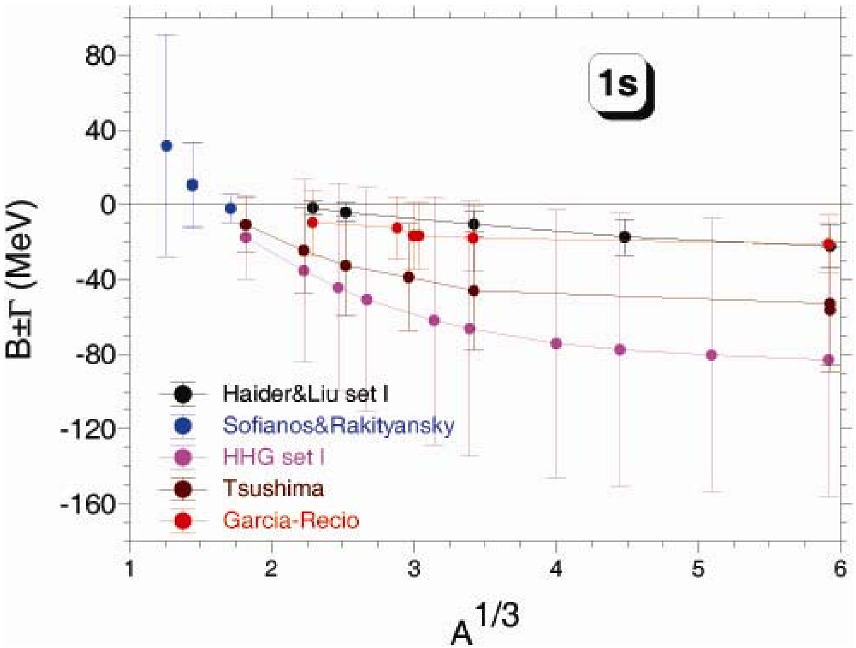



Momentum transfer vs beam momentum for different binding energies B in the mesic nucleus. Vertical line indicates The beam momentum chosen.

For $0 > B > -30$ MeV the transfer is less than 30 MeV/c.

Where the bound system is expected to occur ….

# Results from $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$




Predictions for binding energies and widths of η-mesic nuclei (with η and the nucleus in their ground state) as a function of the mass number.

General trend: binding energy becomes stronger with increasing mass number as does the width.

For A=27 predicted B≈ -10 MeV except for HHG.

# Results from $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$

- Background – heavy nuclei not favoured
- Light nuclei – the effect may be small
- Choice medium to light nuclei
- To avoid nuclear excitations – odd-odd target –d $\rightarrow$ even-even
- No solid odd-odd available ➔ $^{27}$Al
- $d + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$

# Results from $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$

- $\eta N$ or $N^{*}$ almost @ rest, conservation laws➔

  p & $\pi^{-}$ emitted back-to-back with energies $\approx 348$ MeV and $\approx 100$ MeV

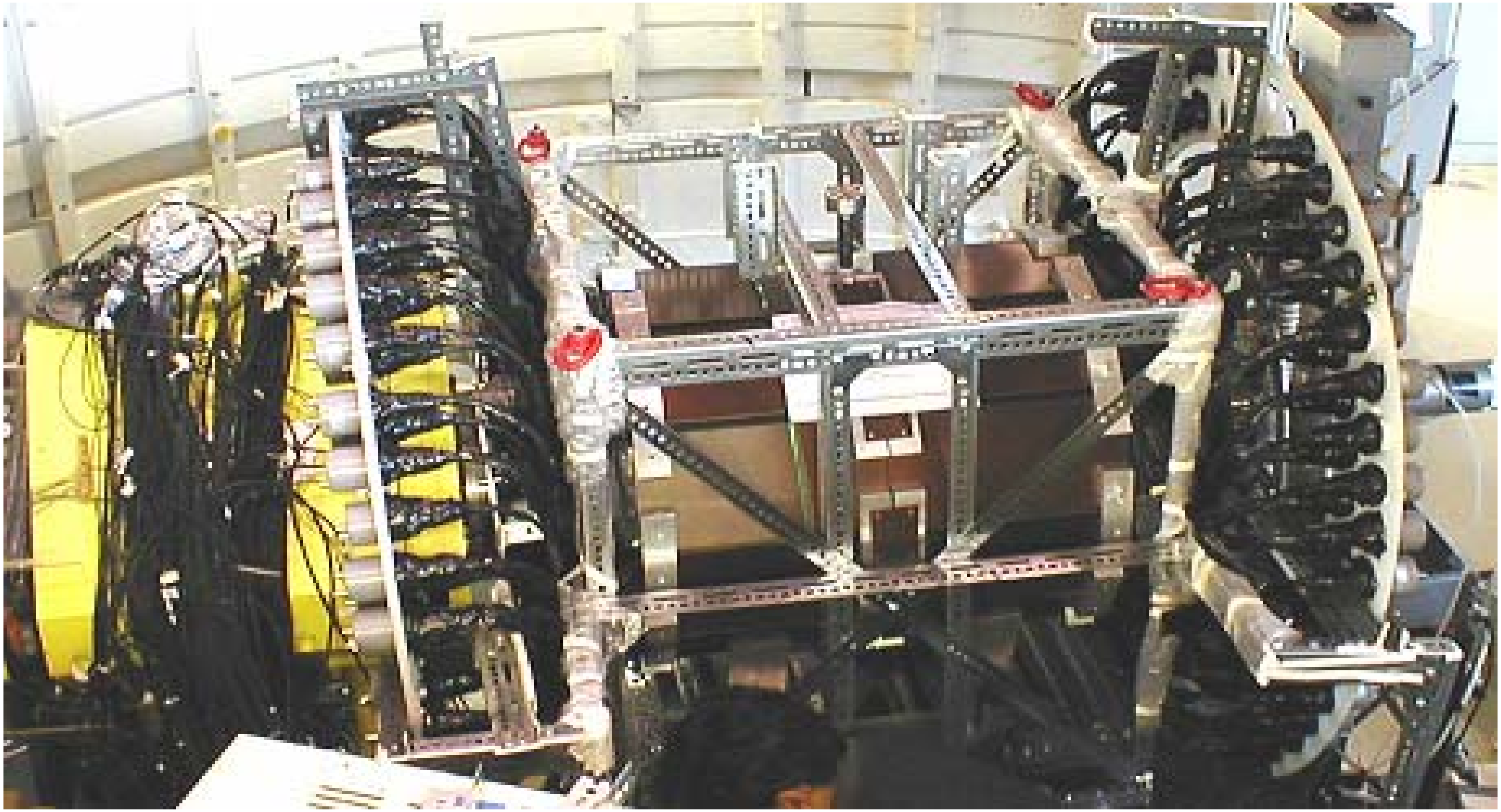
- Fermi motion smears the relative angle distribution peaks at $\approx 150^{o}$ with a width $\approx 40^{o}$

# Results from $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$

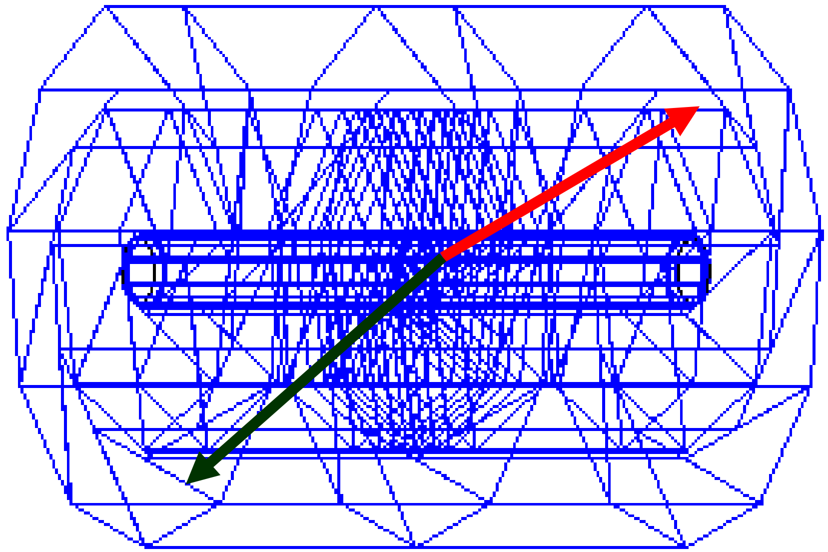
Dedicated detector ENSTAR was built

photo and schematic wievs on the next slides

# ENSTAR Detector

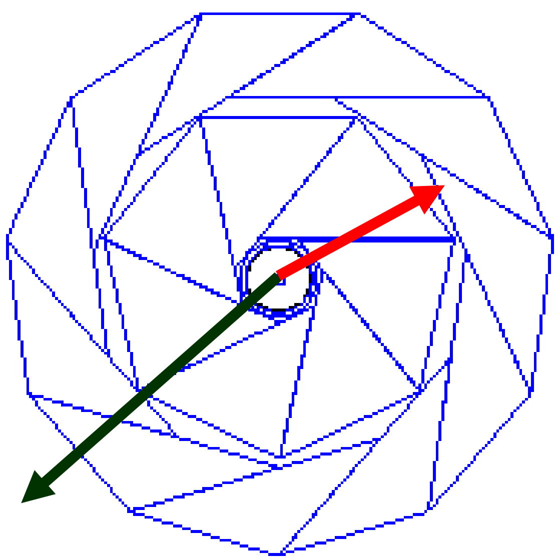


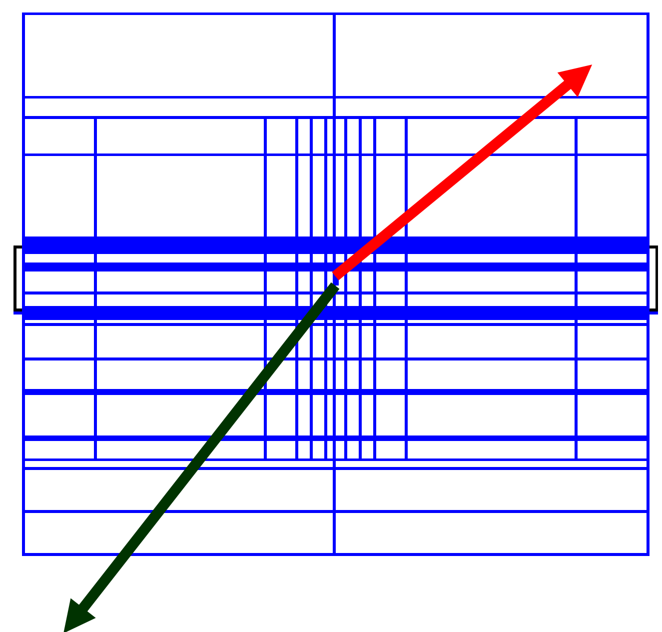
ENSTAR detector



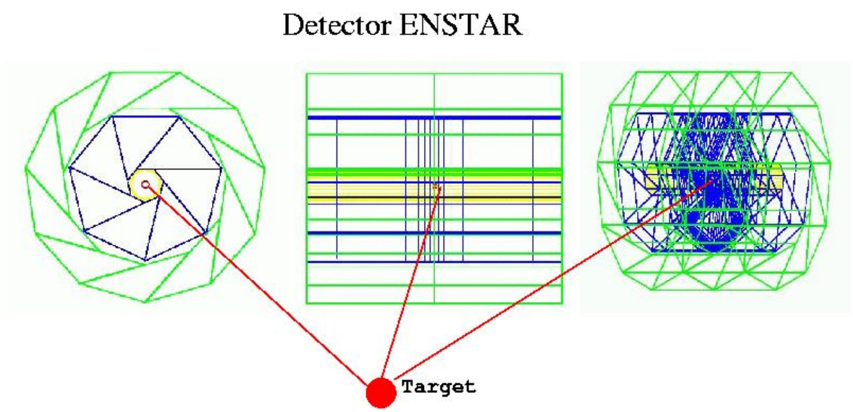
$$N^* \rightarrow \pi^- + p$$

3 layers





# ENSTAR

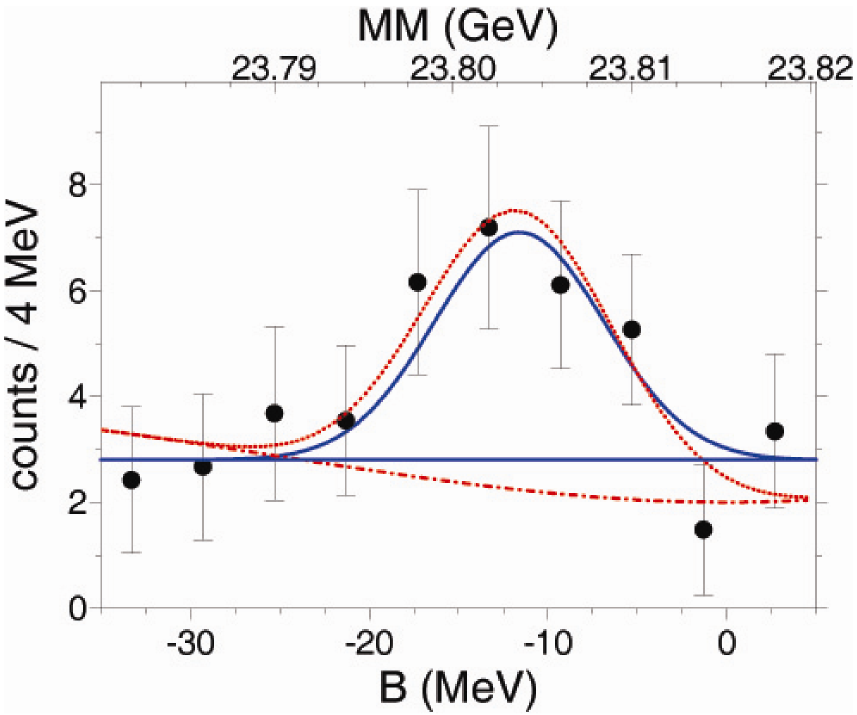



- 3 cylindrical layers
- Layers divided into bars to measure azimuthal angle
- Bars divided along length to measure polar angle - middle
- Protons stop in middle
- Pions only ΔE inform.

# Results from $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$

- ${}^{3}He$ detected with magnetic spectrograph BIG KARL
- $N^{*}$ decay products detected with ENSTAR
- Proton beam momentum of 1745 MeV/c
- Target thickness 1 mm, resolution 2 MeV
- Two settings of BK 0-20 MeV binding energy
- Integrated luminosity for each run $0.50 \pm 0.05$ $pb^{-1}$
- Calibration $pp \rightarrow pp$, $pd \rightarrow d\,\pi^{+}$

# Results from $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$




- Peak in both BK settings 859, 879 MeV/c close to threshold
- Luminosity weighted & added data
- ← Result is shown
- MM missing mass
- $B = m(\eta) + m({}^{25}Mg) - MM$
- Gauss + constant –solid line
- Gauss + polynomial – dashed
- Stat. signif. 4σ
- Est. cross section upper limit ≈ 0.5 nb

# Results from $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$

The enhancement may not be purely due to the binding in the ground state but also to an excited ${}^{25}\mathrm{Mg}$ state.

This requires pick-up more deeply lying nucleons which is less probable than pick-up of least bound ones.

Spectra without strong $\mathrm{N}^{*}$ condition do not show enhancement.

# SUMMARY

- Vector & tensor polarized deuteron beams
- Beam polarization determined

For the reaction : $\vec{d} + d \rightarrow {}^4He + \eta$

- Cross section, analyzing power & s-wave amplitude extracted
- $\boldsymbol{\alpha}$($^4$He$\eta$) scattering length & effective range determined
- $\boldsymbol{\alpha}$($^4$He$\eta$) fulfills bound state condition, but the sign of real part must be extrcated to be decisive

# SUMMARY

The reaction $p + {}^{27}Al \rightarrow {}^{3}He + p + \pi^{-} + X$

- Studied in recoil free kinematics
- For p, $\pi^-$ back-to-back emission @ both BK setting enhancement was found for negative binding energies
- The upper limit for the cross section was found to be $\approx 0.5$ nb.

*Thank  you for*

*the attention*

# Back-up slides

# Introduction - Physics motivation

Experimental indications

***Chrien et al. PRL 60 (1988)*** inconclusive results in case of lithium, carbon, oxygen
***Berger et al. PRL 61 (1988), Willis et al. PLB 406 (1997)*** data interpreted as suggesting $\eta$-$^3$He and $\eta$-$^4$He bound systems

There is no clear experimental evidence

# Theoretical predictions for η-bound states

- Bhalerao and Liu (1985) - First predictions $a_{\eta N} = (0.27 + i0.22)\,fm$
- Liu and Haider *A > 10*
- Ueda (1992) predicted *ηNN* quasi-bound state *I=0, J=1*
- Wilkin (1993) interpreted spectra
- Rakityansky et al. (1996) $^{4}He_{\eta}$
- Garcia-Recio et al. (2002) binding energy and Γ for heavy nuclei

L.C. Liu calculations

Recoil free kinematics:

$$p + \begin{pmatrix} d \\ A-2 \end{pmatrix} \rightarrow \begin{pmatrix} \eta \\ A-2 \end{pmatrix} + {}^{3}He$$

Big Karl

$$\eta + N \rightarrow N^{*}(1535) \leftrightarrow \begin{cases} \pi^{-} + p \\ \pi^{0} + n \\ \pi^{0} + p \\ \pi^{+} + n \end{cases}$$