Few-Body Physics @ HIγS

Werner Tornow

Duke University
&
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Outline

High-Intensity Gamma-ray Source (HIγS)

A=3

γ-^{3}He three-body breakup with double polarization

Outlook

γ-^{3}H three-body breakup

Gerasimov-Drell-Hearn Sum Rule of the deuteron

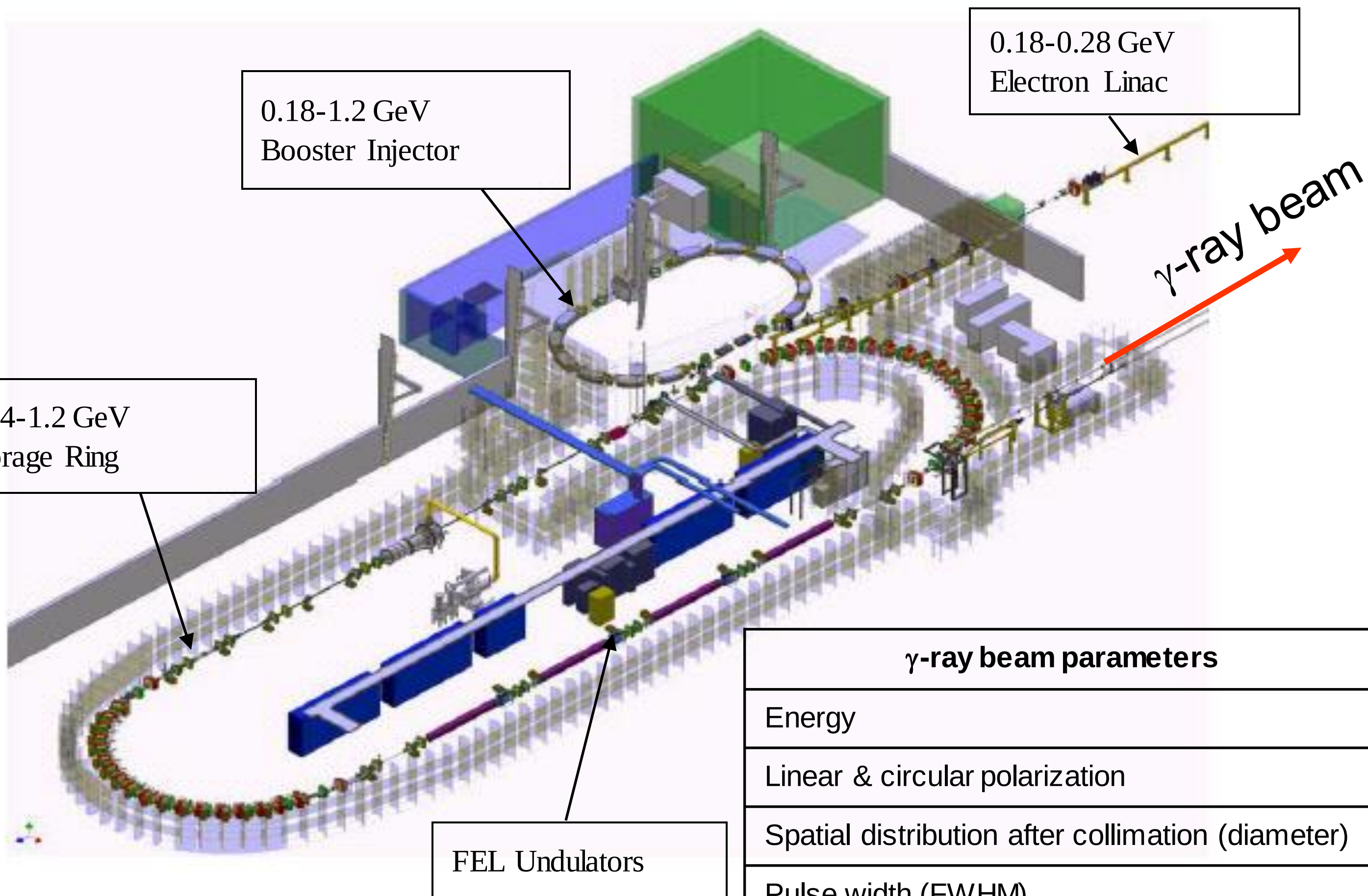
Compton scattering off the proton, deuteron and ^{3}He

Future Upgrade

(A=12 system)

^{12}C(γ,3α) and the 2$^+$ excitation of the Hoyle 0$^+$ state in ^{12}C

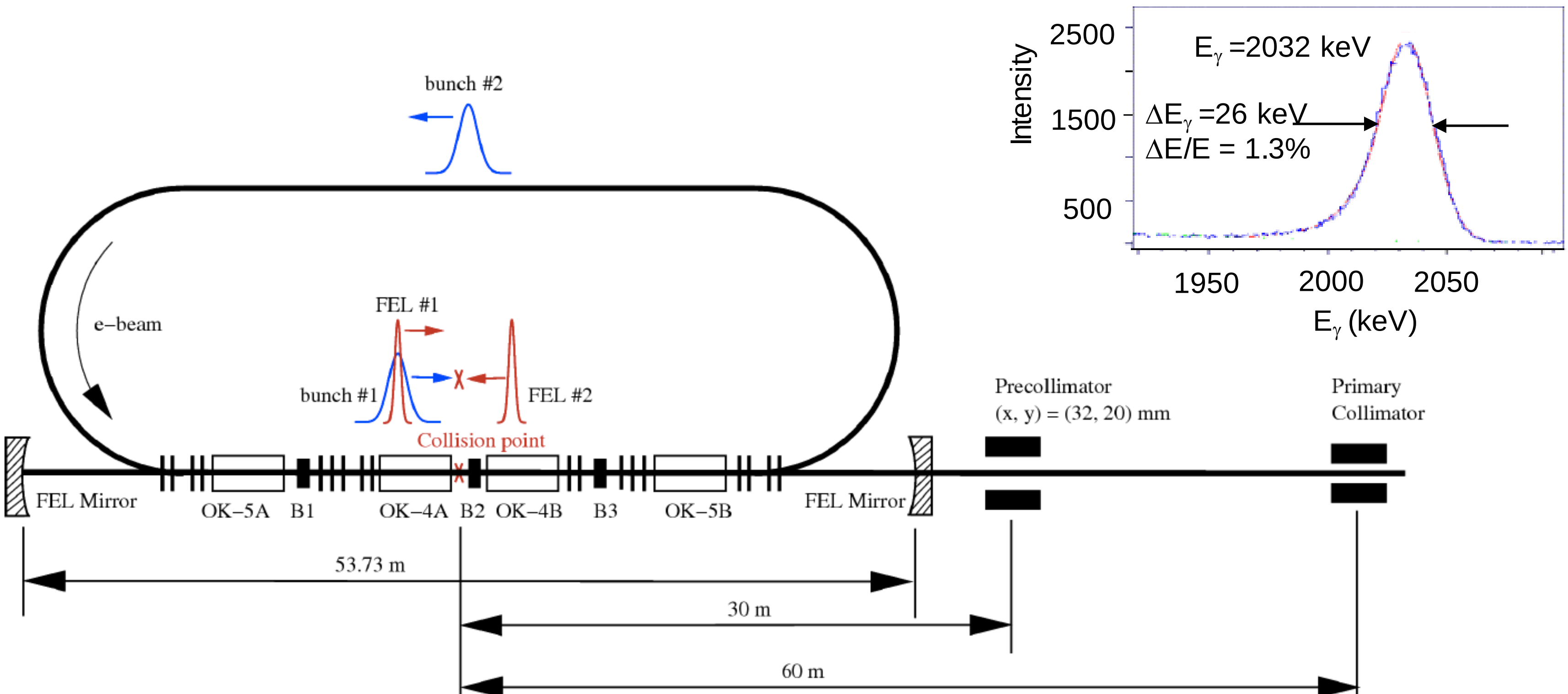
High-Intensity Gamma-ray Source (HIγS) @ TUNL



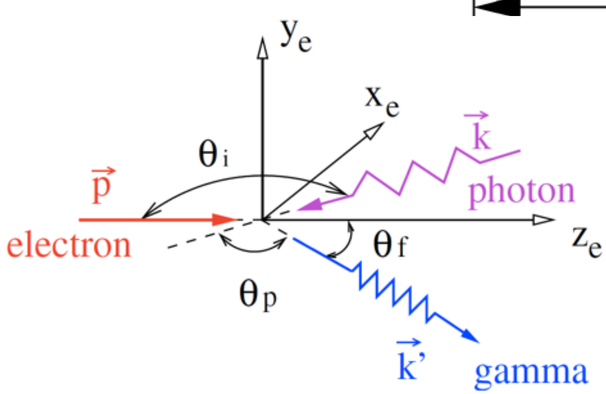
γ-ray beam parameters	Values
Energy	1 – 100 MeV
Linear & circular polarization	> 97%
Spatial distribution after collimation (diameter)	10 – 25 mm
Pulse width (FWHM)	0.5 – 0.8 ns
Pulse repetition rate	5.58 MHz
Flux with 2% $\Delta E_\gamma/E_\gamma$ (2 MeV < E_γ < 5 MeV)	> 3×10^6 γ/s
Flux with 5% $\Delta E_\gamma/E_\gamma$ (5 MeV < E_γ < 20 MeV)	> 7×10^7 γ/s
Flux on with 5% $\Delta E_\gamma/E_\gamma$ (20 MeV< E_γ < 100 MeV)	> 1×10^7 γ/s

World's most intense accelerator-driven γ-ray source
Intensity 10^3 γ/s/eV on target

HIγS: Intracavity Compton-Back Scattering



$$E_\gamma \equiv \hbar\omega' = \frac{\hbar\omega(1-\beta\cos\theta_i)}{1-\beta\cos\theta_f+\frac{\hbar\omega}{\mathcal{E}_e}(1-\cos\theta_{ph})}$$



Head-on collision: $E_\gamma \approx 4\gamma^2\hbar\omega$

Example: E_e = 500 MeV ➔ $\gamma = 978$

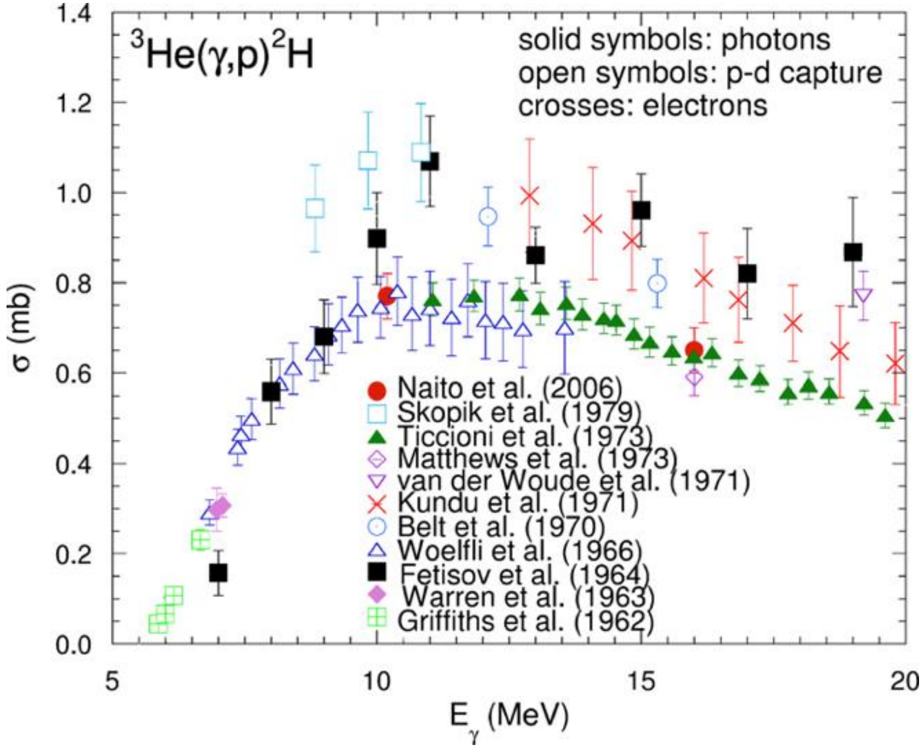
λ_{FEL} = 400 nm

$\hbar\omega$ = 3.11 eV

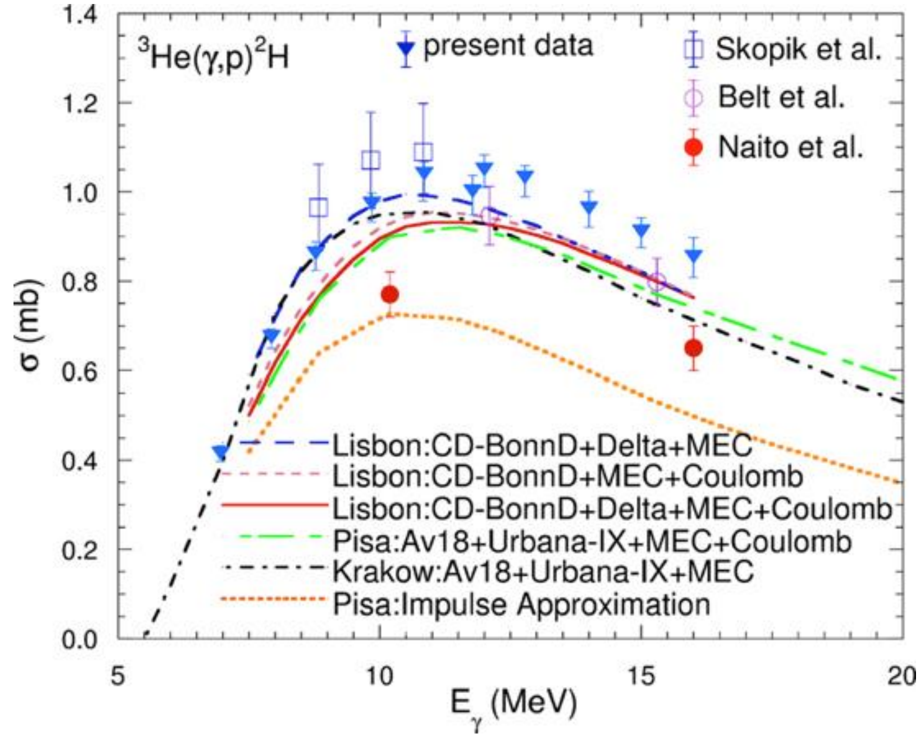
E_γ = 11.9 MeV

$A=3$

World Data



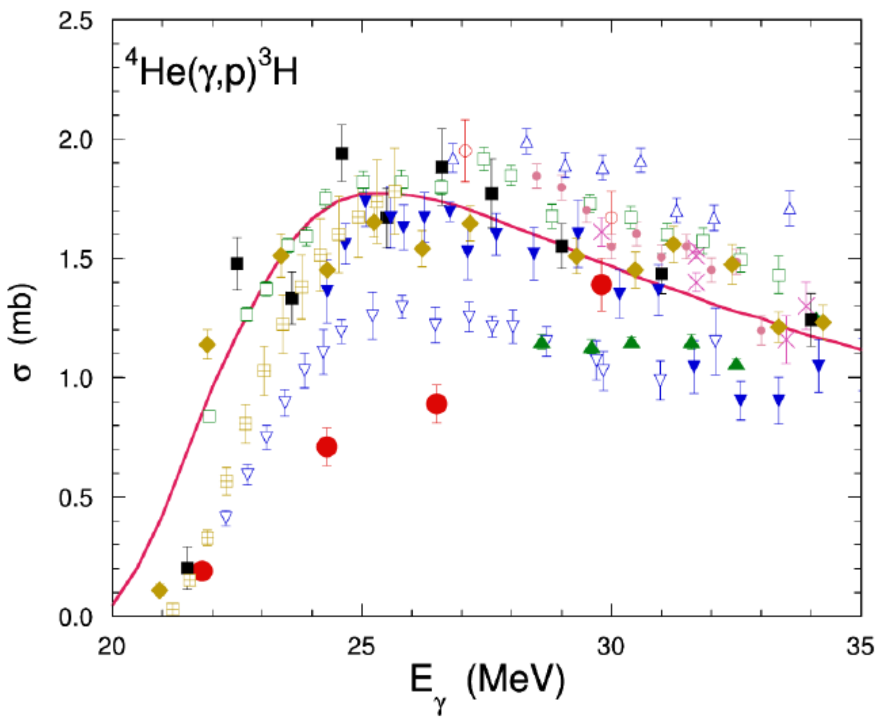
HIγS Data

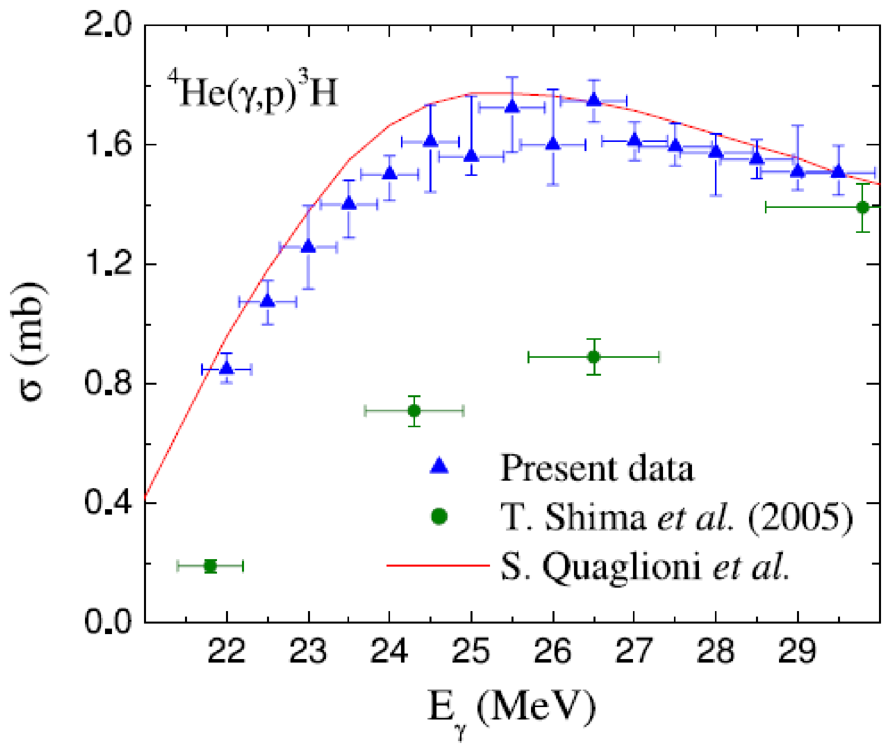


from W. Tornow *et al*., Phys. Lett. B **702**, 121 (2011)

World Data

HIγS Data





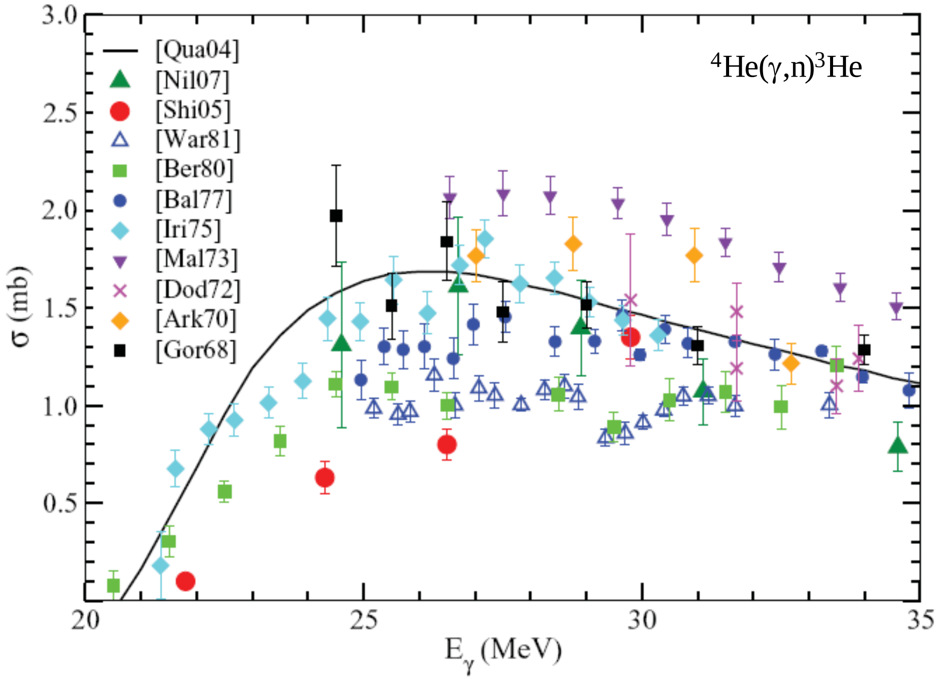
Lorentz Integral Transform
Trento Group

Giant Dipole Resonance

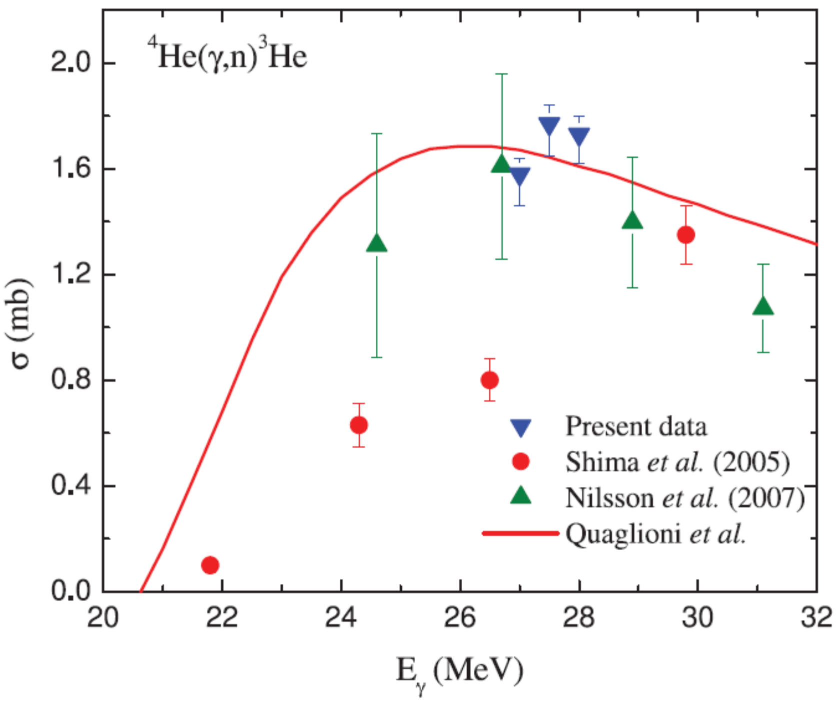
Wataru Horiuchi

from R. Raut, W. Tornow *et al.*, PRL, 108, 042502 (2012)

World Data



HIγS Data



from W. Tornow *et al.,* PR C85, 061001R (2012)

A=3

$$\vec{\gamma} + {}^{3}\vec{He} \rightarrow p + p + n$$

Three-body photodisintegration of ^{3}He with double polarizations at 12.8 and 14.7 MeV at HIGS/TUNL facility (Haiyan Gao's group)

$$\vec{\gamma} + \overrightarrow{^3He} \rightarrow p + p + n$$

We detect neutrons!

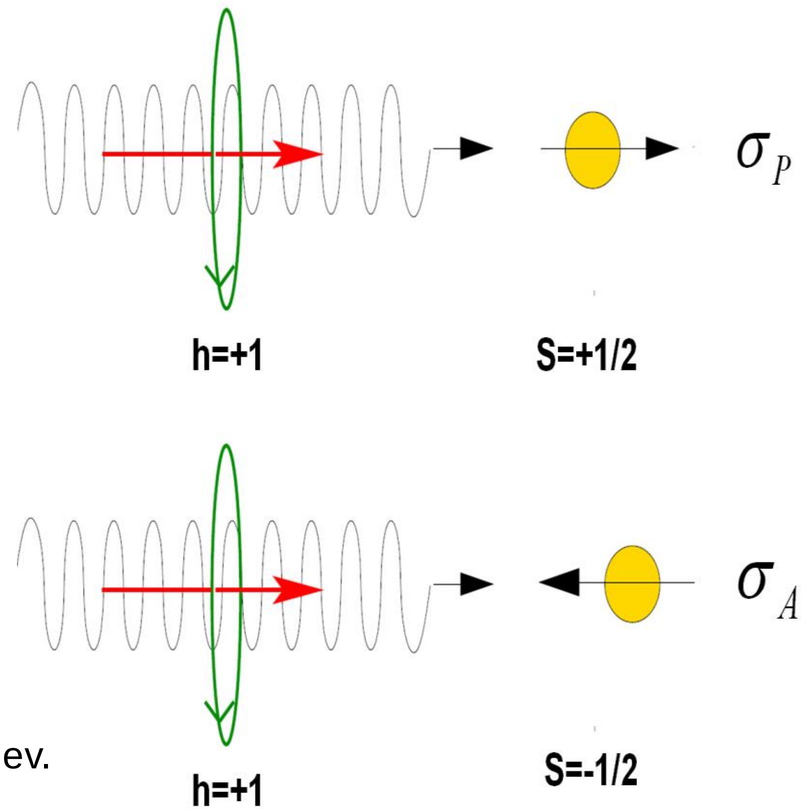
- <u>Two Primary Goals</u>:

- Test state-of-the-art three-body calculations made by Deltuva [1] and Skibiński [2], and future EFT calculations.

- Important step towards investigating the GDH sum rule for ^{3}He below the pion production threshold :

$$I^{GDH} = \int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu}\left[\sigma_N^P(\nu) - \sigma_N^A(\nu)\right] = \frac{4\pi^2\alpha}{M_N^2}\kappa_N^2 I$$

Lorentz & gauge invariance, crossing symmetry, causality and unitarity of the forward Compton scattering amplitude



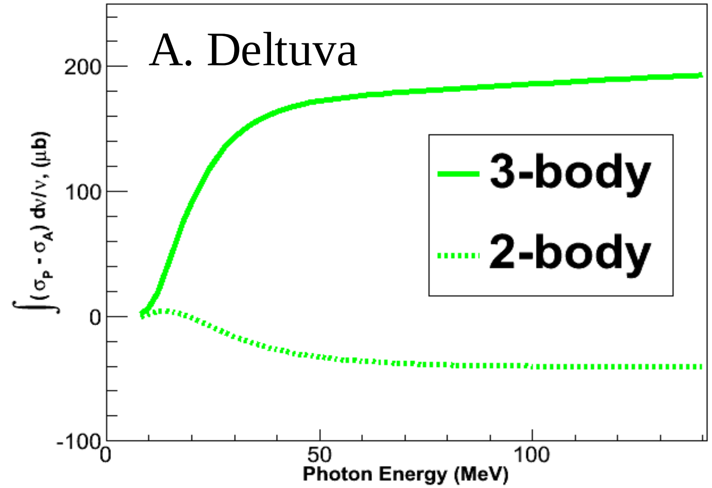
Gerasimov-Drell-Hearn

[1] A. Deltuva *et al.*, Phys. Rev. C 71, 054005 (2005); Phys. Rev. C 72, 054004 (2005) and Nucl. Phys. A 790, 344c (2007).

[2] R. Skibiński *et al*., Phys. Rev. C 67, 054001 (2003); R. Skibiński et al. Phys. Rev. C 72, 044002 (2005); R.Skibiński. Private communications.

Goal II: GDH Sum Rule on ^3He

$$\int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu}\left[\sigma_N^P(\nu)-\sigma_N^A(\nu)\right]=\frac{2\pi^2\alpha}{M_N^2}\kappa_N^2$$



$$\int_{\nu_{thr}}^{\infty} GDH_{^3He} \rightarrow 496\,\mu b$$

$$=$$

$$\int_{\nu_{thr}}^{\nu_\pi} GDH_{^3He} \rightarrow 217 \pm 39\,\mu b$$?? HIγS @ TUNL

$$+$$

$$\int_{\nu_\pi}^{2-3GeV} GDH_{^3He} \rightarrow \approx 247 \pm 38\,\mu b$$

Extrapolated from low Q^2 ^3He GDH (E94-010) measurement @ JLab, **(E97-110 much lower Q^2)**

Q^2 (GeV^2)	I_{GDH} (μb)	Statistical (μb)	Systematic (μb)
0.10	187.50	5.23	28.43
0.26	109.92	2.04	13.77
0.42	53.51	1.21	5.48
0.58	31.68	0.74	3.72
0.74	18.27	0.64	2.42
0.90	10.47	0.46	1.52

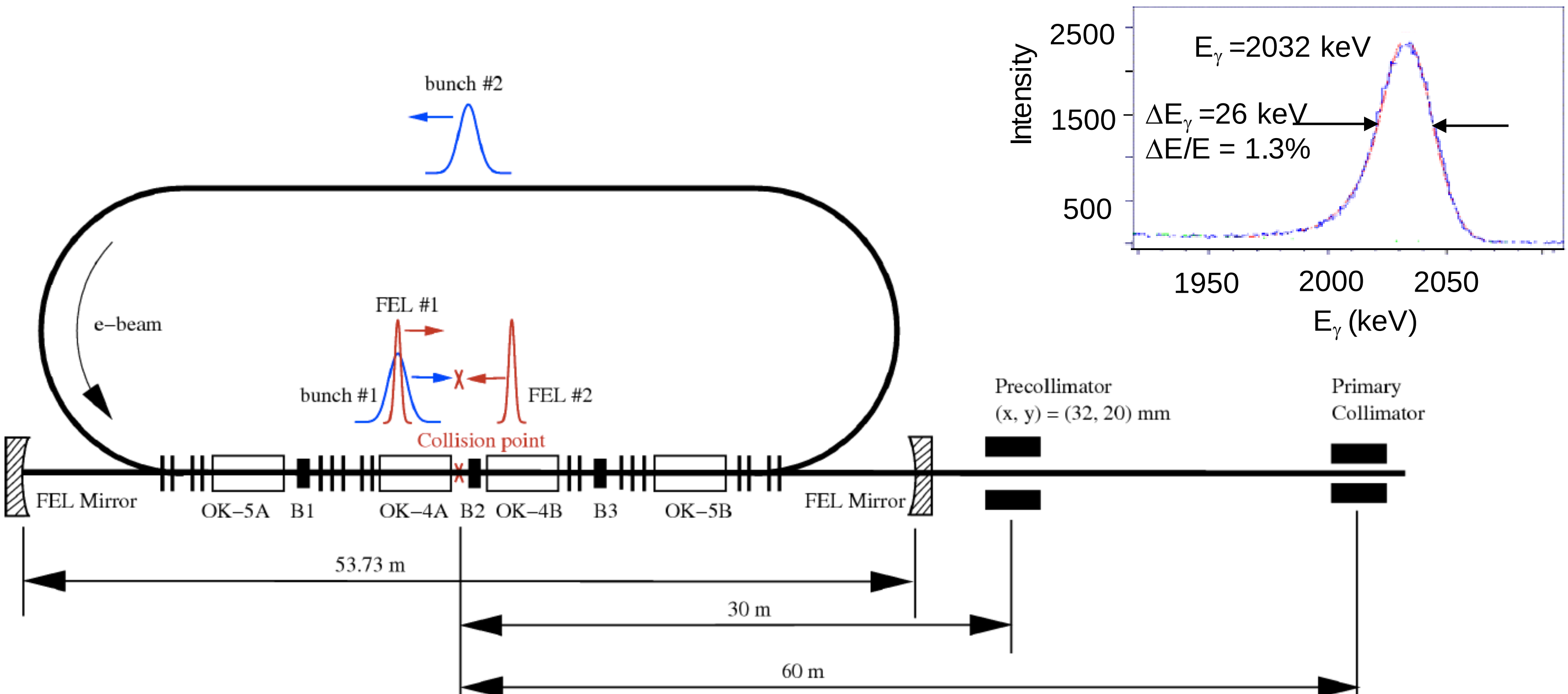
$$+$$

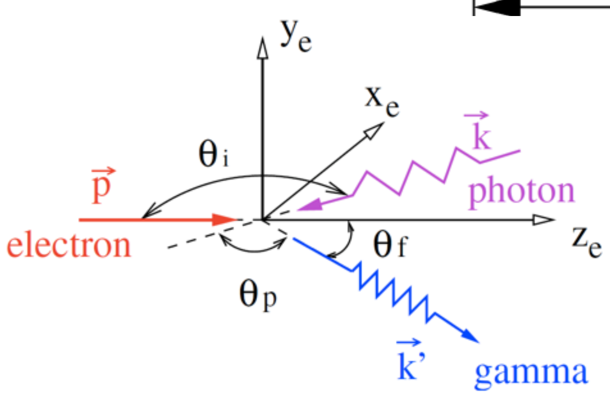
$$\int_{2-3GeV}^{\infty} GDH_{^3He} \rightarrow \approx 31.9 \pm 9.6\,\mu b$$

$$\int_{2-3GeV}^{\infty} GDH_{^3He} = P_n \times \int_{2-3GeV}^{\infty} GDH_n + 2\times P_p \times \int_{2-3GeV}^{\infty} GDH_p$$
$$= 0.87\times 35 + 2\times(-0.027)\times(-26)$$

M. Amarian, PRL 89, 242301(2002) J.L. Friar et al. PRC 42, 2310 (1990) N. Bianchi, et al. PLB 450, 439 (1999)

HIγS: Intracavity Compton-Back Scattering





$$E_\gamma \equiv \hbar\omega' = \frac{\hbar\omega(1-\beta\cos\theta_i)}{1-\beta\cos\theta_f + \frac{\hbar\omega}{\mathcal{E}_e}(1-\cos\theta_{ph})}$$

Head-on collision: $E_\gamma \approx 4\gamma^2\hbar\omega$

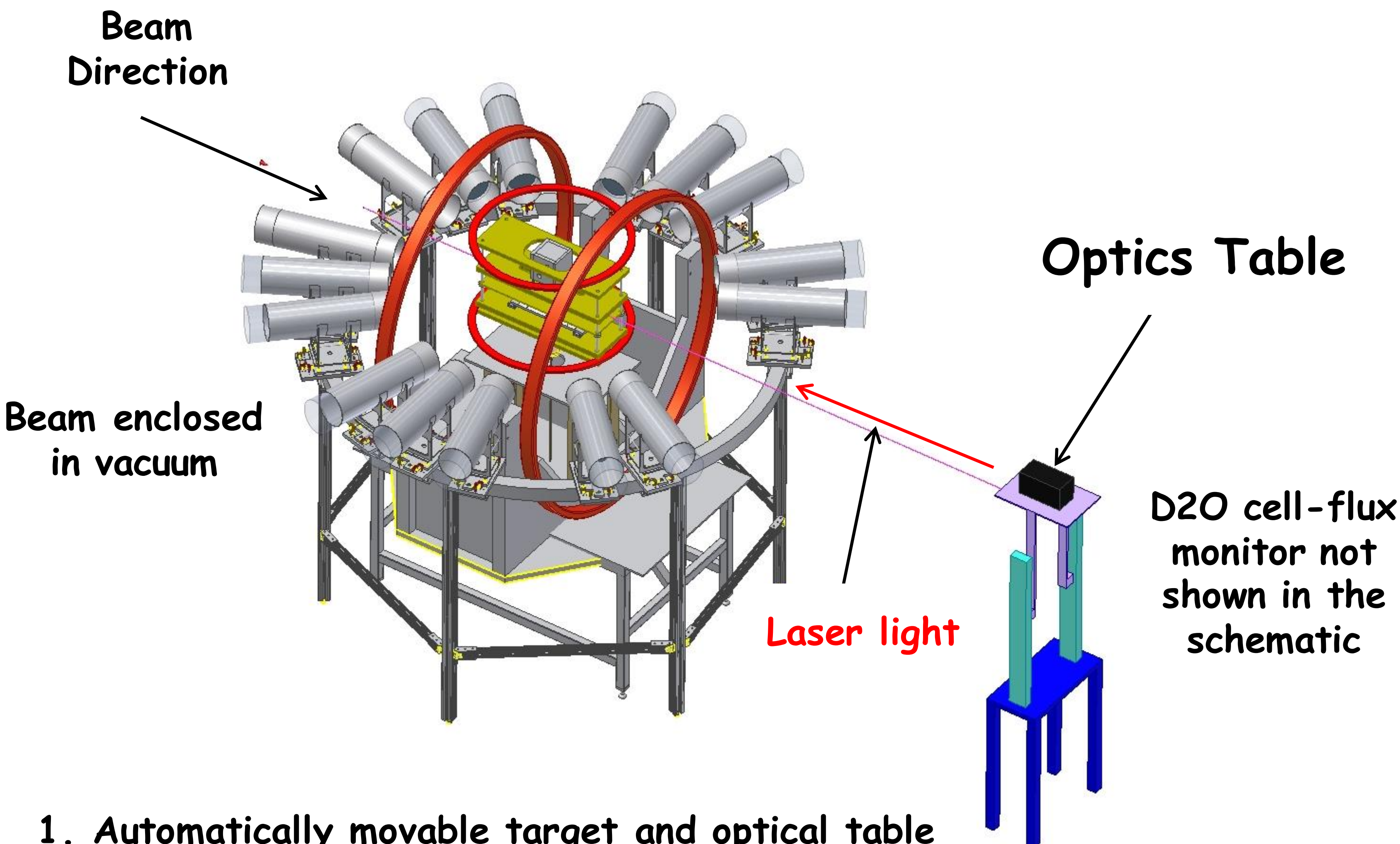
Example: E_e = 500 MeV ➔ $\gamma = 978$

λ_{FEL} = 400 nm

$\hbar\omega$ = 3.11 eV

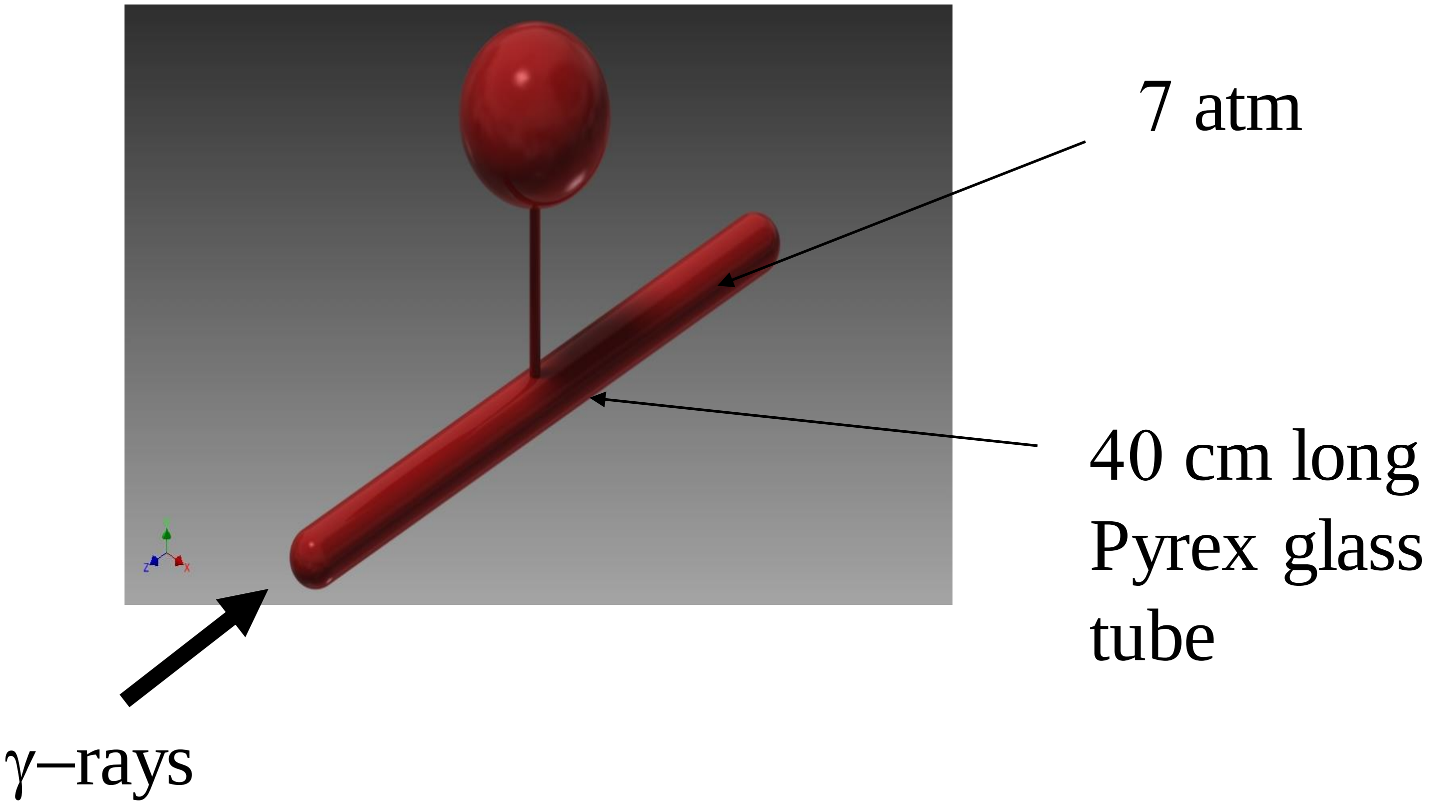
E_γ = 11.9 MeV

Apparatus of the Three-body Photodisintegration Experiment



1. Automatically movable target and optical table
2. Detectors in mu-metal shielding tubes

High-pressure hybrid ^{3}He target polarized longitudinally using spin-exchange optical pumping



First Measurements of Spin-Dependent Double-Differential Cross Sections and the Gerasimov-Drell-Hearn Integrand from $^3\vec{\mathrm{He}}(\vec{\gamma}, n)pp$ at Incident Photon Energies of 12.8 and 14.7 MeV

G. Laskaris,[1,2,*] Q. Ye,[1,2,†] B. Lalremruata,[1,2,‡] Q. J. Ye,[1,2] M. W. Ahmed,[1,2,3] T. Averett,[4] A. Deltuva,[5] D. Dutta,[6] A. C. Fonseca,[5] H. Gao,[1,2] J. Golak,[7] M. Huang,[1,2] H. J. Karwowski,[1,8] J. M. Mueller,[1,2] L. S. Myers,[1,2] C. Peng,[1,2] B. A. Perdue,[1,2,§] X. Qian,[1,2,‖] P. U. Sauer,[9] R. Skibiński,[7] S. Stave,[1,2,¶] J. R. Tompkins,[1,8,**] H. R. Weller,[1,2] H. Witała,[7] Y. K. Wu,[1,2] Y. Zhang,[1,2] and W. Zheng[1,2]

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[6]*Mississippi State University, Mississippi State, Mississippi 39762, USA*
[7]*M. Smoluchowski Institute of Physics, Jagiellonian University, PL-30059 Kraków, Poland*
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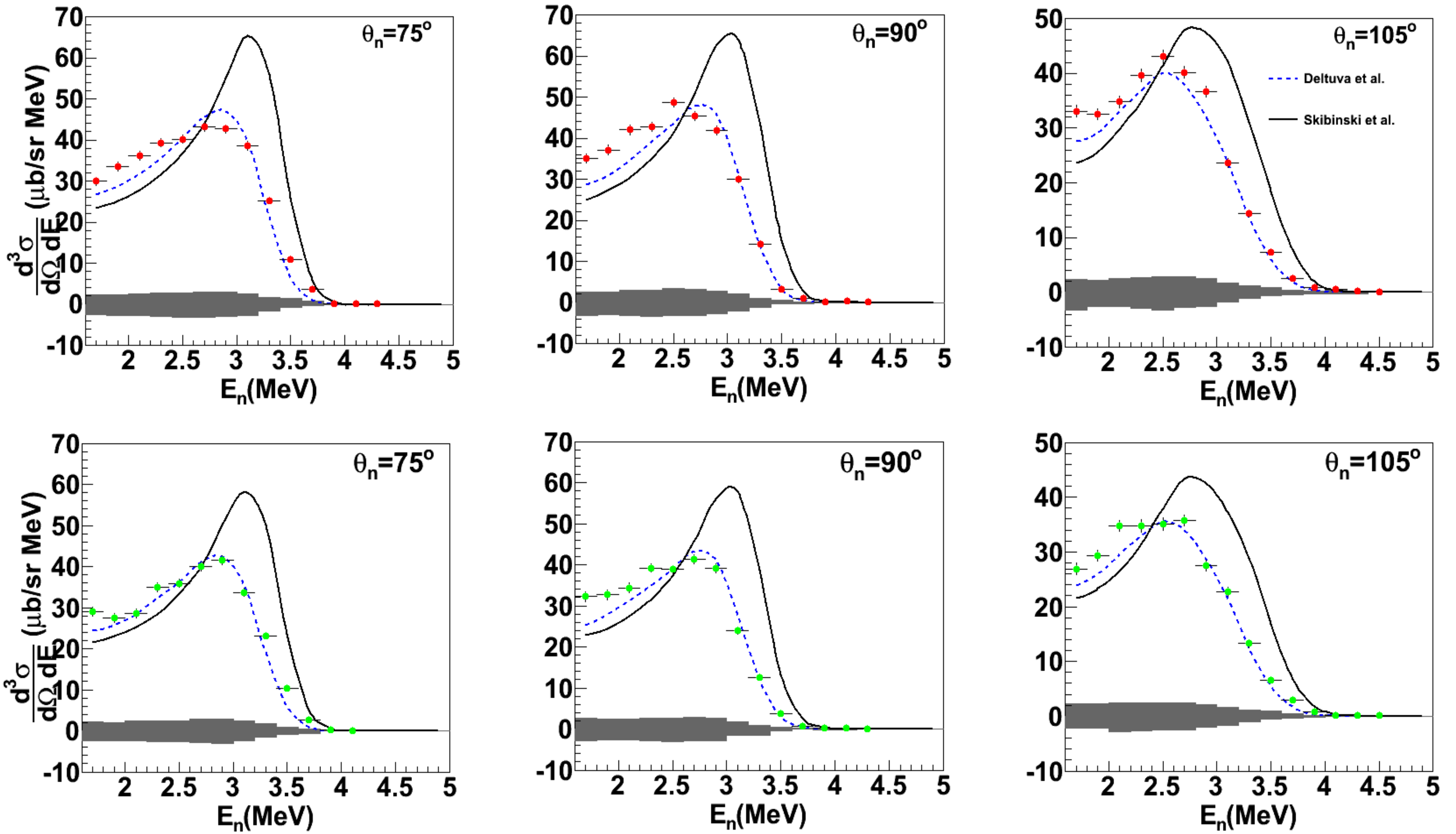
[9]*Institut für Theoretische Physik, Leibniz Universität Hannover, D-30167 Hannover, Germany*
(Received 5 March 2013; published 17 May 2013)

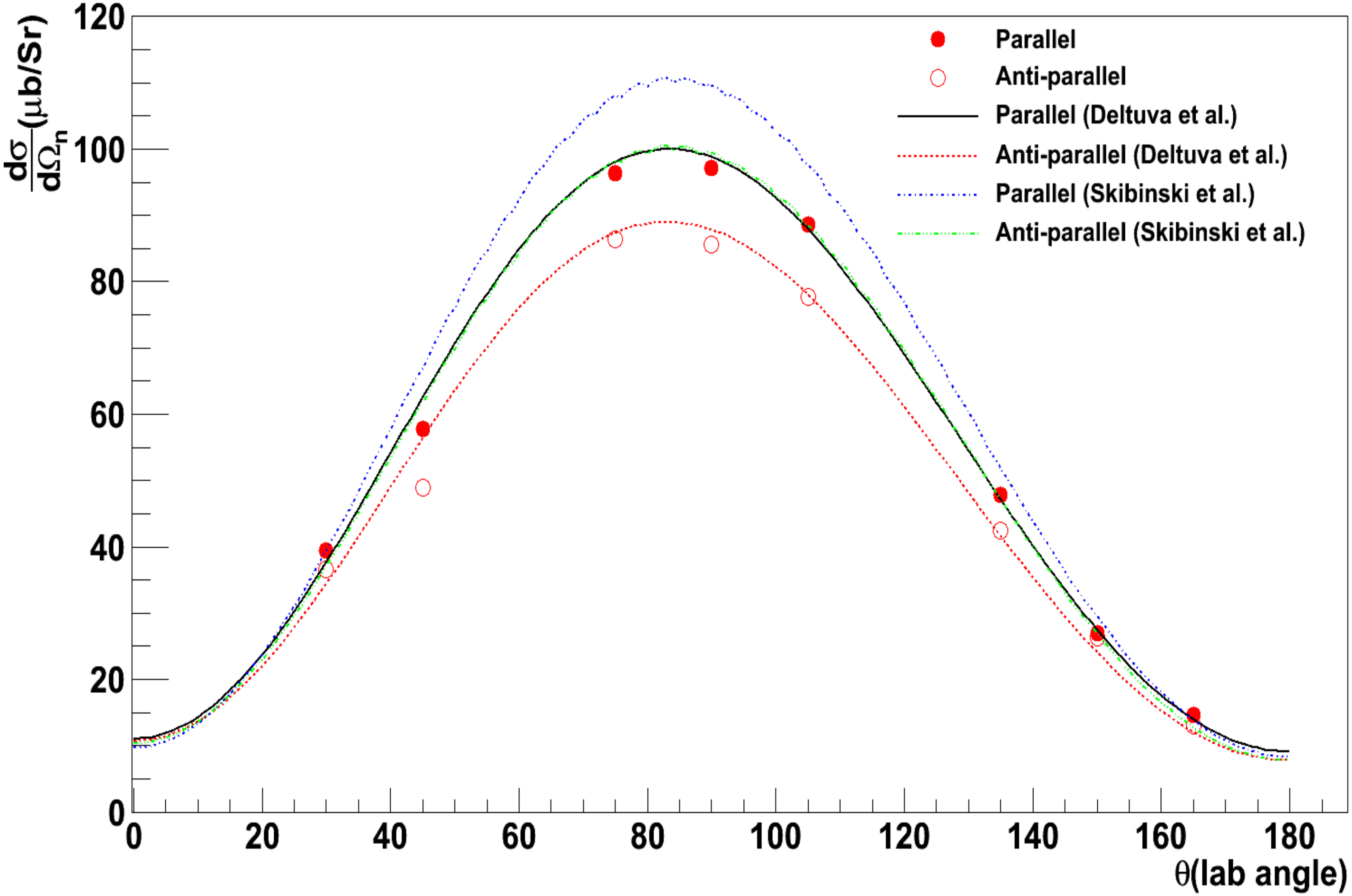
The first measurement of the three-body photodisintegration of longitudinally polarized ^{3}He with a circularly polarized γ-ray beam was carried out at the High Intensity γ-ray Source facility located at Triangle Universities Nuclear Laboratory. The spin-dependent double-differential cross sections and the contributions from the three-body photodisintegration to the ^{3}He Gerasimov-Drell-Hearn integrand are presented and compared with state-of-the-art three-body calculations at the incident photon energies of 12.8 and 14.7 MeV. The data reveal the importance of including the Coulomb interaction between protons in three-body calculations.

Spin-Dependent Double Differential Cross Sections at 12.8 MeV



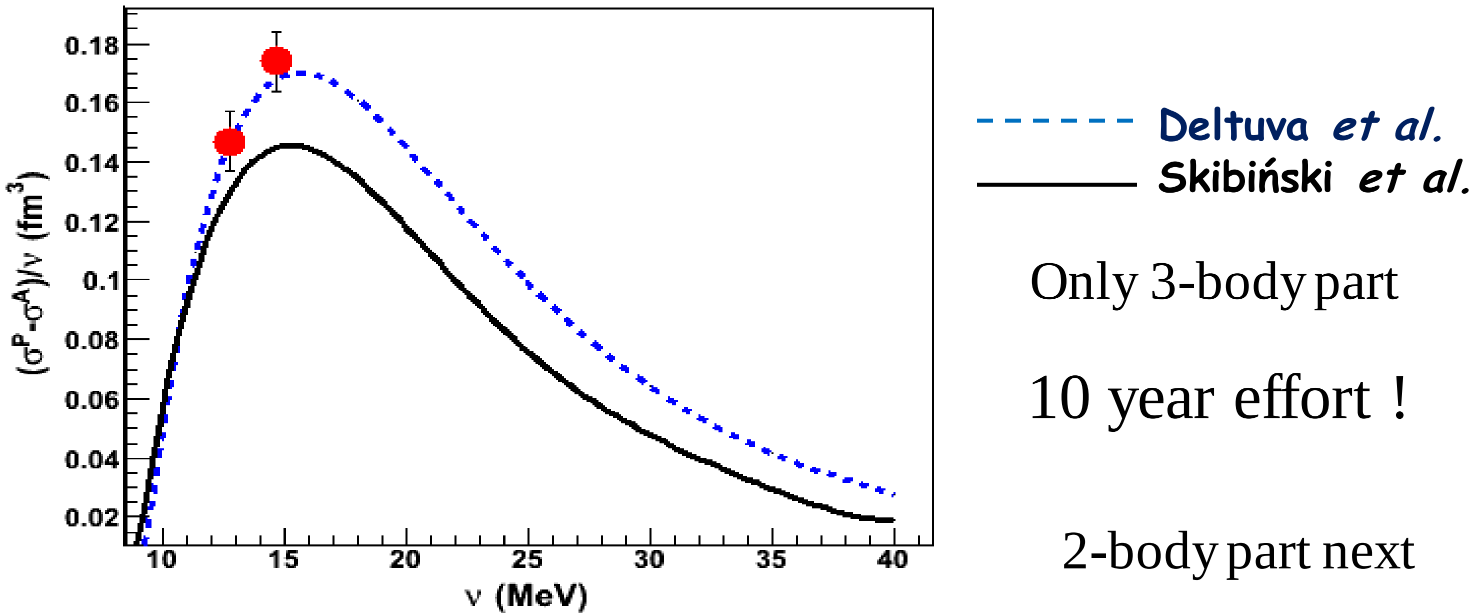
Solid curve: R. Skibiński *et al.* Dotted curve: A. Deltuva , A. Fonseça

Spin-Dependent Single Differential Cross Sections at 12.8 MeV



Spin-Dependent Total Cross Sections and the GDH Integrand

ν	$\sigma^P(\mu b)$	$\sigma^A(\mu b)$	$(\sigma^P - \sigma^A)/\nu\ (fm^3)$
This work 12.8	$861 \pm 5 \pm 81$	$765 \pm 5 \pm 71$	$0.147 \pm 0.010 \pm 0.018$
Deltuva *et al.*	872	777	0.146
Skibiński *et al.*	956	872	0.131
This work 14.7	$999 \pm 5 \pm 89$	$869 \pm 5 \pm 78$	$0.174 \pm 0.011 \pm 0.020$
Deltuva *et al.*	1026	900	0.168
Skibiński *et al.*	1079	970	0.146

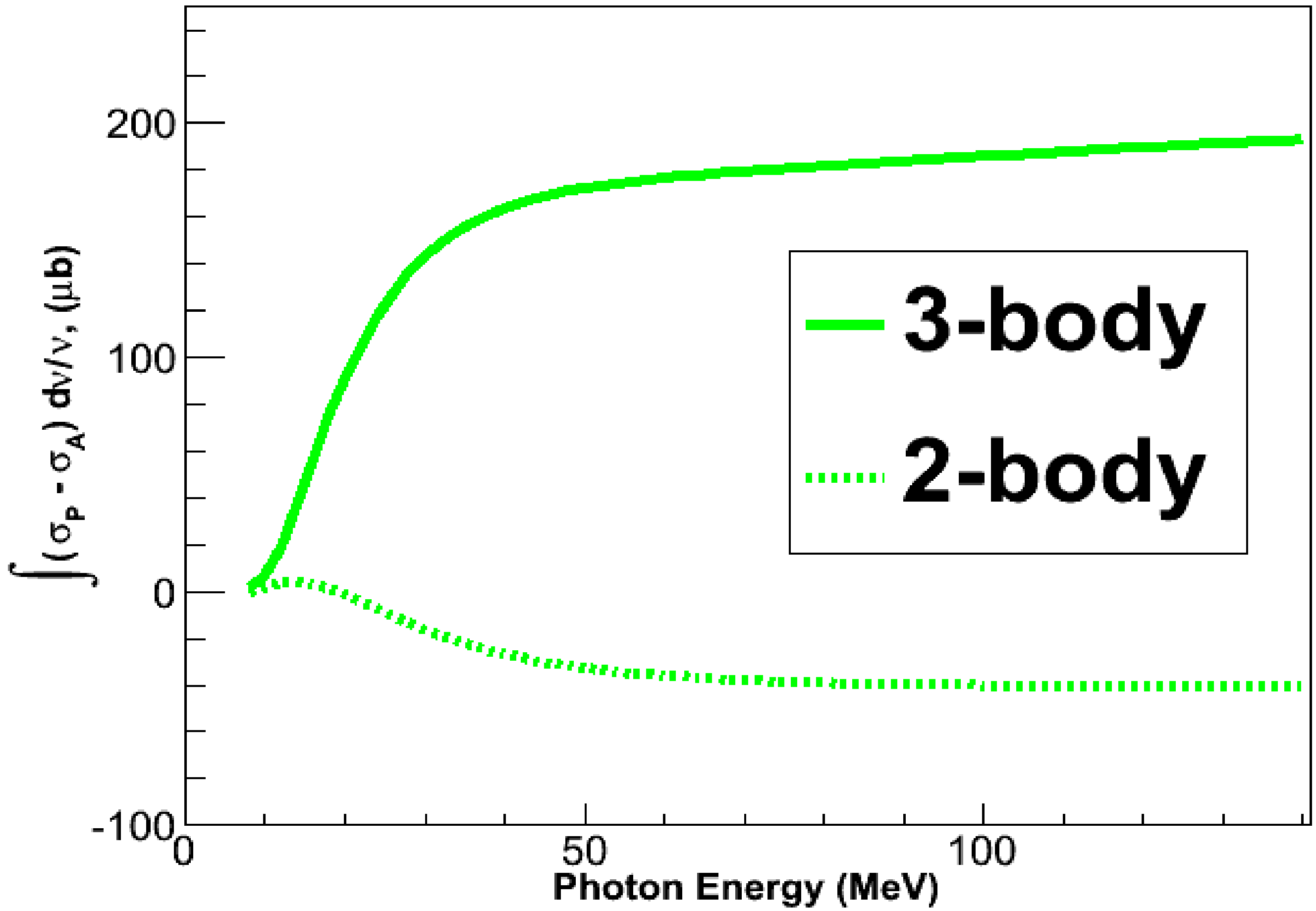


Only 3-body part

10 year effort !

2-body part next

G. Laskaris *et al.*, Phys. Rev. Lett. 110, 202501 (2013)



200
100
0
-100
0
50
100
Photon Energy (MeV)
$\int(\sigma_P - \sigma_A)\, d\nu/\nu$, (μb)
3-body
2-body

Deltuva

Outlook

What's next at HIγS ?

A=3

$\gamma + {}^3H$ three-body breakup

PHYSICAL REVIEW C **85**, 064003 (2012)

Di-neutron and the three-nucleon continuum observables

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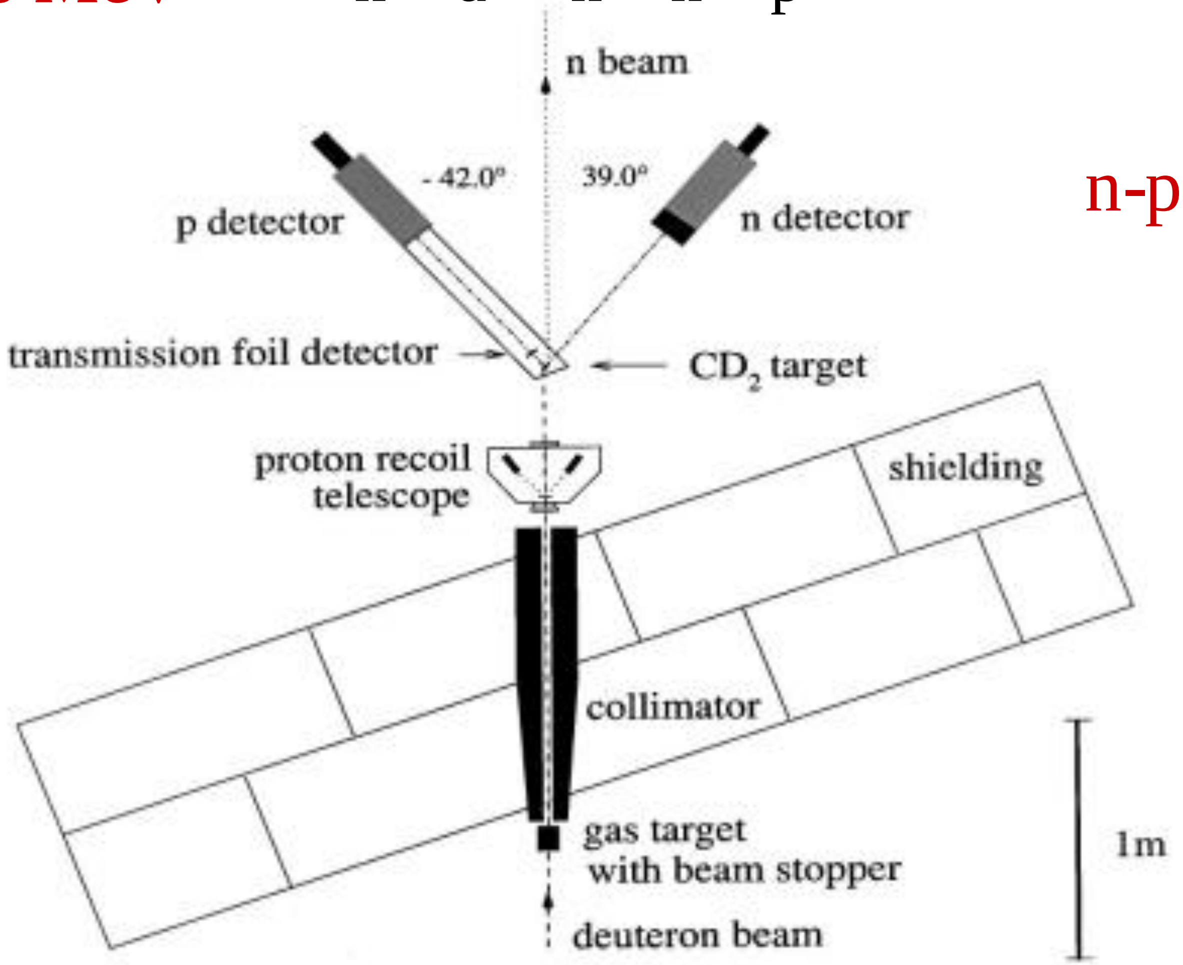
(Received 24 April 2012; published 25 June 2012)

We investigate how strongly a hypothetical $^1S_0$ bound state of two neutrons would affect observables in neutron-deuteron reactions. To that aim we extend our momentum-space scheme of solving the three-nucleon Faddeev equations and incorporate in addition to the deuteron also a $^1S_0$ di-neutron bound state. We discuss effects induced by a di-neutron on the angular distributions of the neutron-deuteron elastic scattering and deuteron breakup cross sections. A comparison to the available data for the neutron-deuteron total cross section and elastic scattering angular distributions cannot decisively exclude the possibility that two neutrons can form a $^1S_0$ bound state. However, strong modifications of the final-state-interaction peaks in the neutron-deuteron breakup reaction seem to disallow the existence of a di-neutron.

E_n=26 MeV

n + d > n + n + p



n-p QFS

$^2H(d,n)^3He$

For n-n QFS the proton detector is replaced by a neutron detector

W. von Witsch, A. Siepe *et al.*, 2002

W. von Witsch, A. Siepe *et al*. (Bonn)

E_n=26 MeV

^{2}H(n,np)n np QFS

^{2}H(n,nn)p nn-QFS

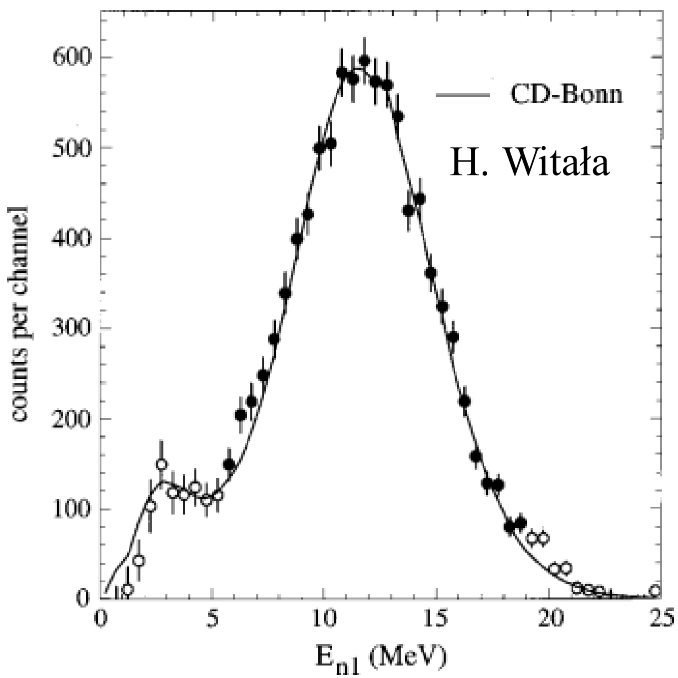


FIG. 2. Data for n-p QFS, projected onto the E_n axis. The solid line is the finite-geometry Monte Carlo prediction, using CD-Bonn for the N-N interaction.

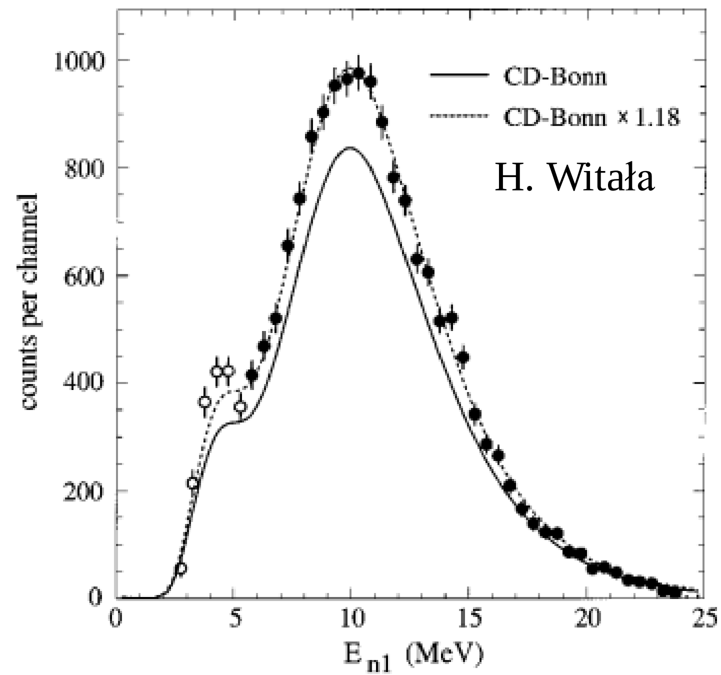


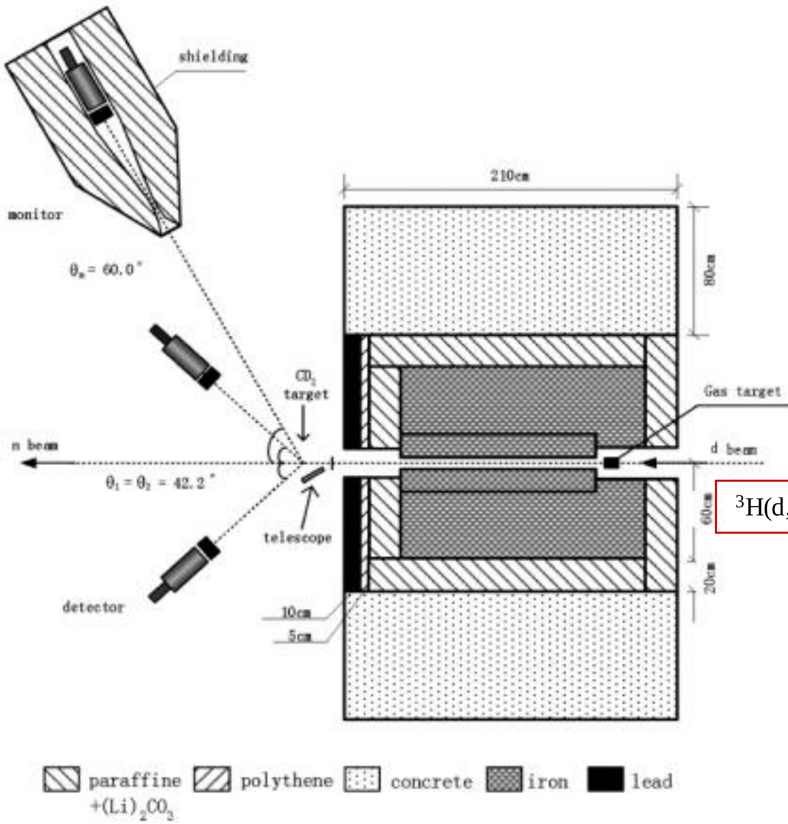
FIG. 4. HE data of Fig. 3, projected onto the E_{n1} axis. The solid curve represents the finite-geometry Monte Carlo prediction using CD-Bonn, the dotted line is the MC result normalized to the experiment by multiplication with a factor of 1.18. Only events with E_{n1} and E_{n2}>6 MeV have been included in the analysis.

E_n=25 MeV

X.C. Ruan (CIAE) & W. von Witsch (Bonn), 2007

China Institute of Atomic Energy

^{2}H(n,nn)p   nn-QFS



^{3}H(d,n)^{4}He

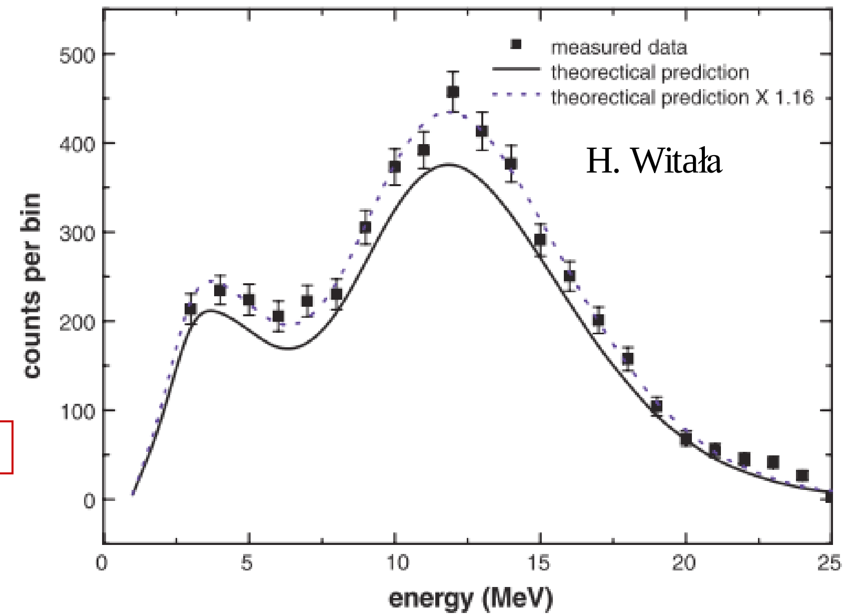


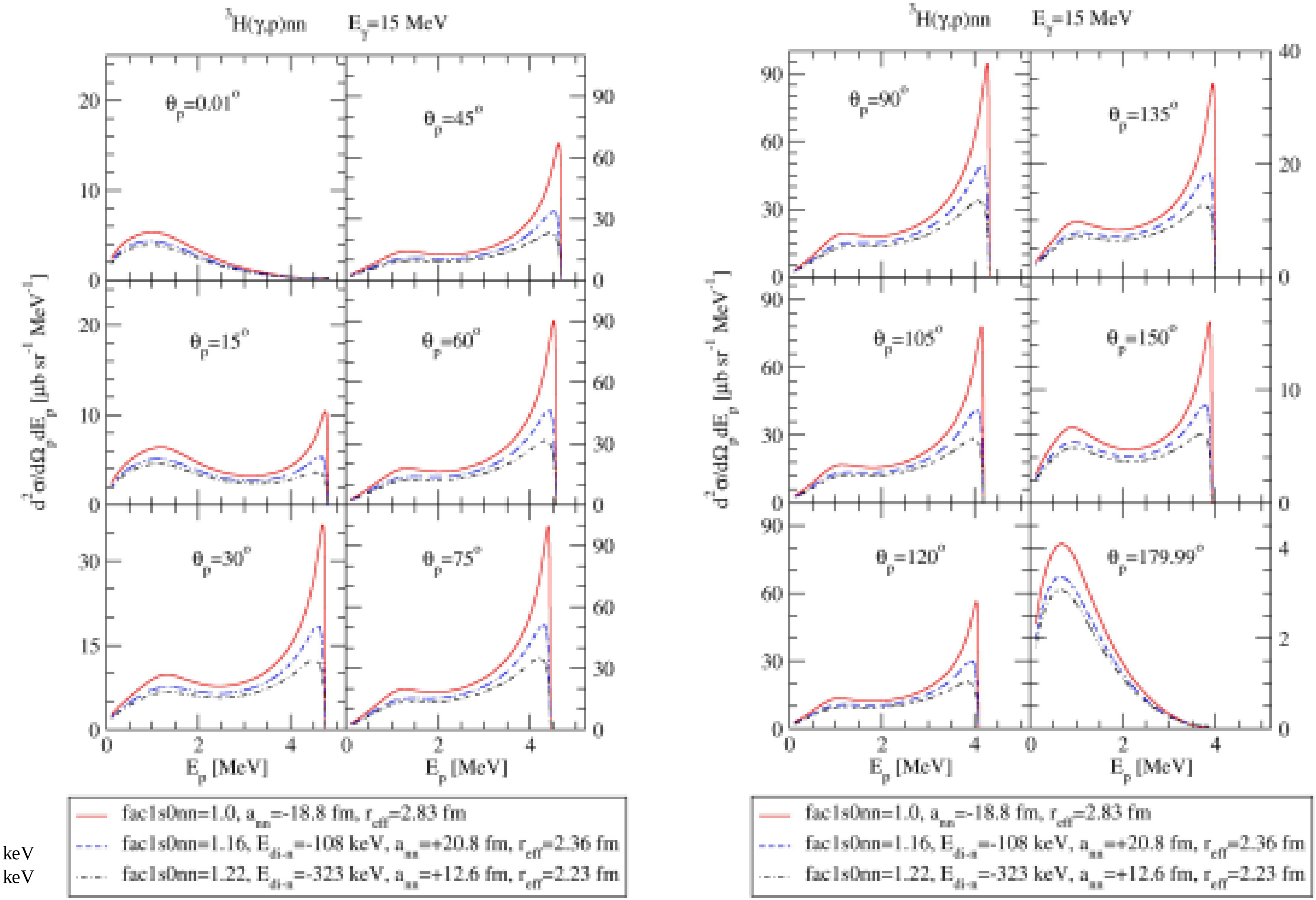
FIG. 5. (Color online) Measured neutron energy spectrum from QFS compared with the theoretical prediction by Monte Carlo simulation based on CD-Bonn. The solid squares show the measured data, and the solid curve is the theoretical prediction, whereas the dotted line gives the theoretical prediction multiplied by a factor of 1.16. The error bars denote the statistical uncertainty only.

$$n+d = n + n + p$$

versus

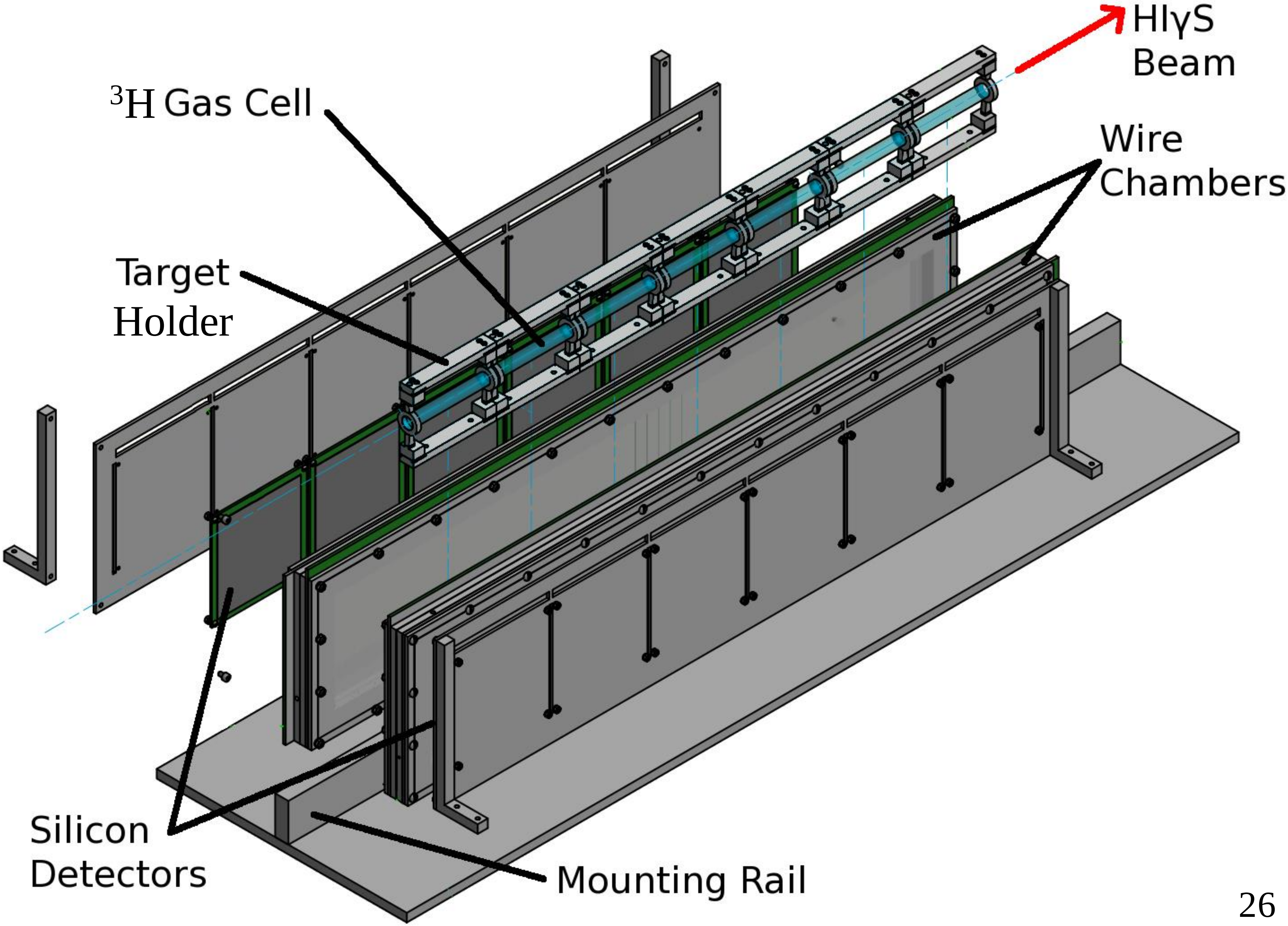
$$\gamma+{}^{3}H=n + n + p$$

Photon induced three-body breakup of ^3H > n +n +p



-108 keV
-323 keV

H. Witała



HIγS
Beam
^{3}H Gas Cell
Wire
Chambers
Target
Holder
Silicon
Detectors
Mounting Rail

A=2

$\gamma + {}^2H$ breakup

Gerasimov-Drell-Hearn Sum Rule on the Deuteron

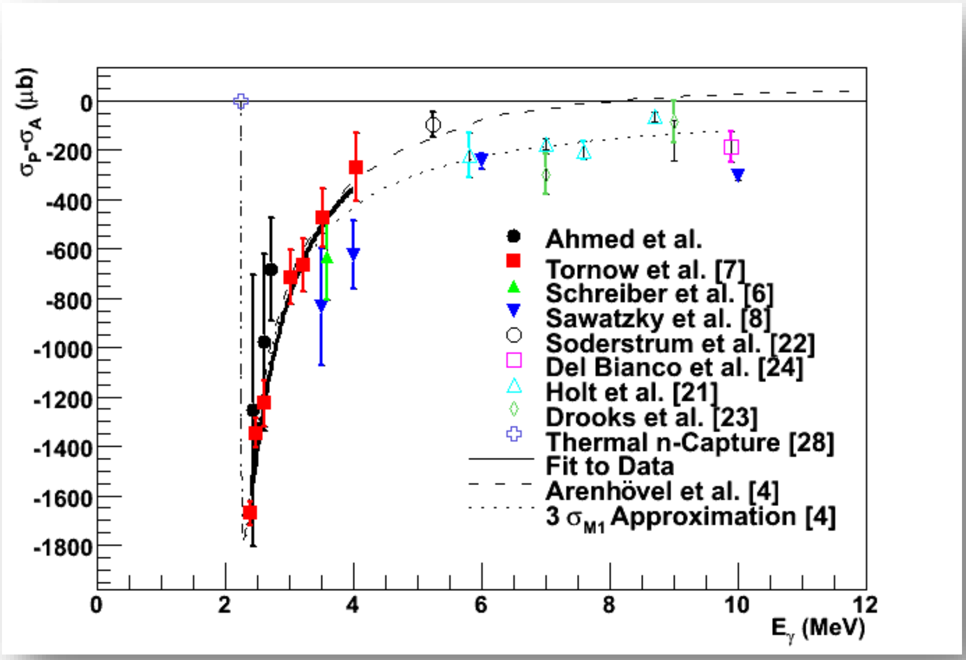
$$I^{GDH} = \int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu}\left[\sigma_N^P(\nu) - \sigma_N^A(\nu)\right] = \frac{4\pi^2\alpha}{M_N^2}\kappa_N^2 I$$

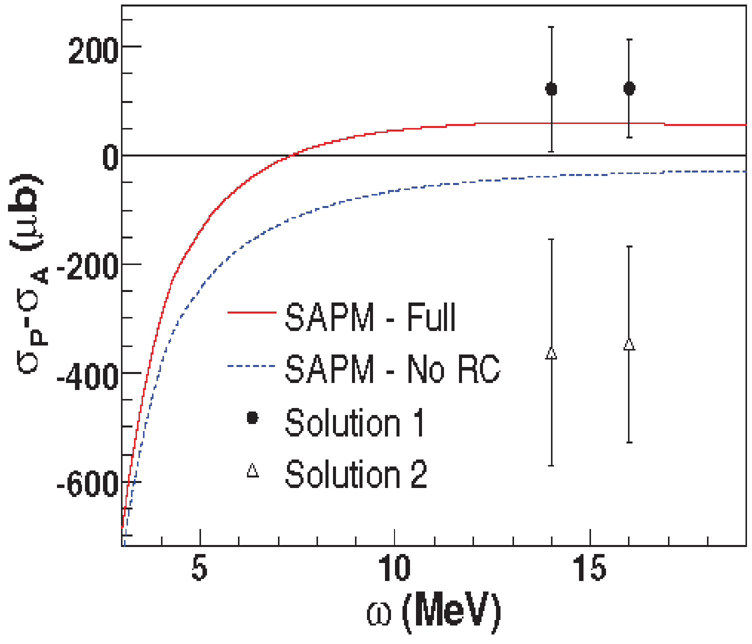
I_p=204.8 μb I_n=232.5 μb I_d=0.652 μb

Above pion production threshold: Large positive value

Below pion production threshold: Large negative value

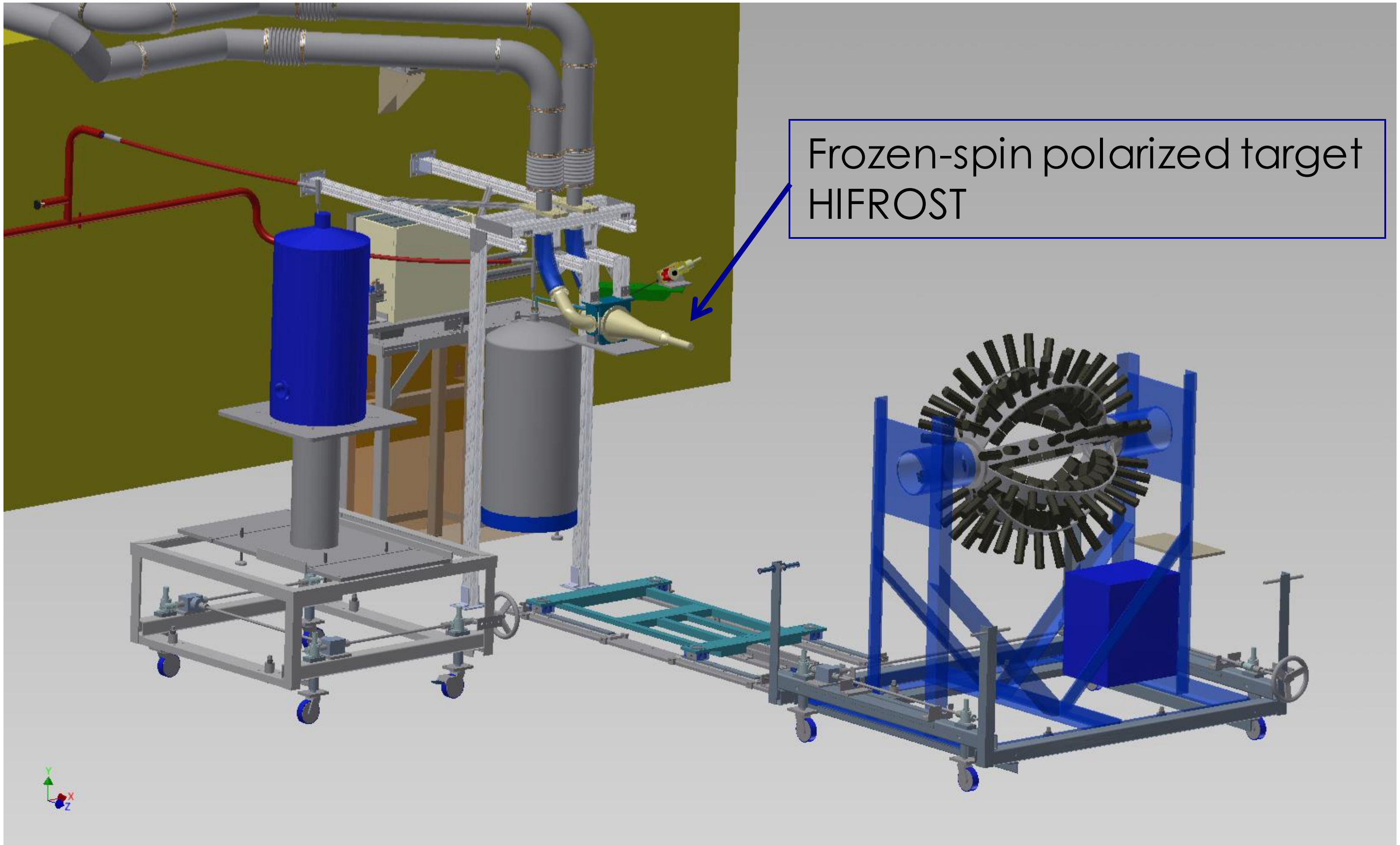
- HIGS is currently mounting the GDH experiment on the deuteron
- Installation of the HIGS Frozen Spin Target (HIFROST) is ongoing
- The majority of data taking will be completed by the end of 2014 between 4 and 16 MeV





Phys. Rev. C78, 034003 (2008)
Phys. Rev. C77, 044005 (2008)

Setup for GDH Measurement on Deuteron



Compton Scattering: A=1, A=2, A=3

Compton Scattering

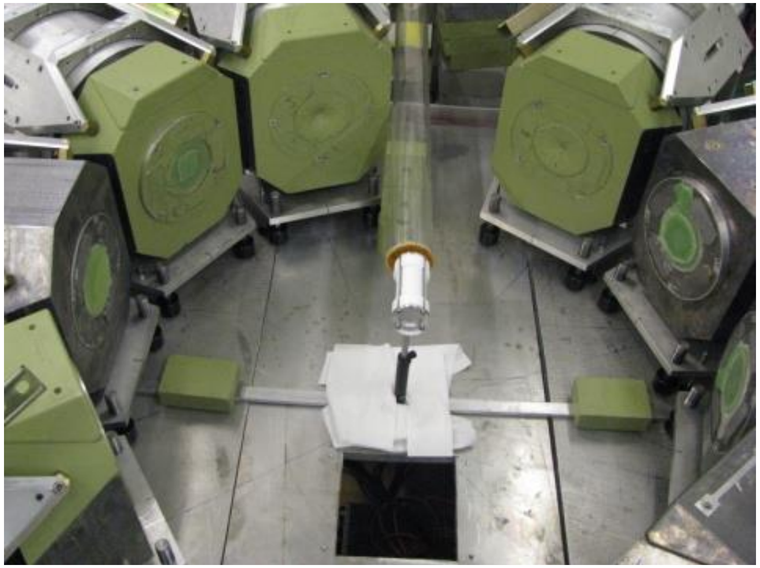
The T-matrix for the Compton scattering of incoming photon of energy ω with a spin (σ) ½ target is described by six structure functions

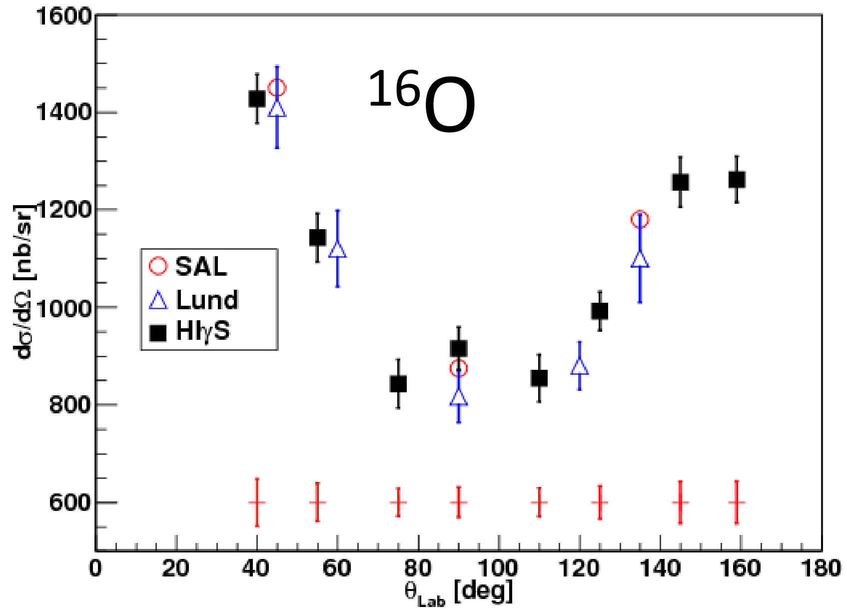
$$\begin{aligned}
T(\omega, z) = {} & A_1(\omega, z)(\vec{\epsilon}'^* \cdot \vec{\epsilon}) + A_2(\omega, z)(\vec{\epsilon}'^* \cdot \hat{\vec{k}})(\vec{\epsilon} \cdot \hat{\vec{k}}') \\
& + \mathrm{i}\, A_3(\omega, z)\, \vec{\sigma} \cdot (\vec{\epsilon}'^* \times \vec{\epsilon}) + \mathrm{i}\, A_4(\omega, z)\, \vec{\sigma} \cdot (\hat{\vec{k}}' \times \hat{\vec{k}})(\vec{\epsilon}'^* \cdot \vec{\epsilon}) \\
& + \mathrm{i}\, A_5(\omega, z)\, \vec{\sigma} \cdot [(\vec{\epsilon}'^* \times \hat{\vec{k}})\, (\vec{\epsilon} \cdot \hat{\vec{k}}') - (\vec{\epsilon} \times \hat{\vec{k}}')(\vec{\epsilon}'^* \cdot \hat{\vec{k}})] \\
& + \mathrm{i}\, A_6(\omega, z)\, \vec{\sigma} \cdot [(\vec{\epsilon}'^* \times \hat{\vec{k}}')(\vec{\epsilon} \cdot \hat{\vec{k}}') - (\vec{\epsilon} \times \hat{\vec{k}})(\vec{\epsilon}'^* \cdot \hat{\vec{k}})],
\end{aligned}$$

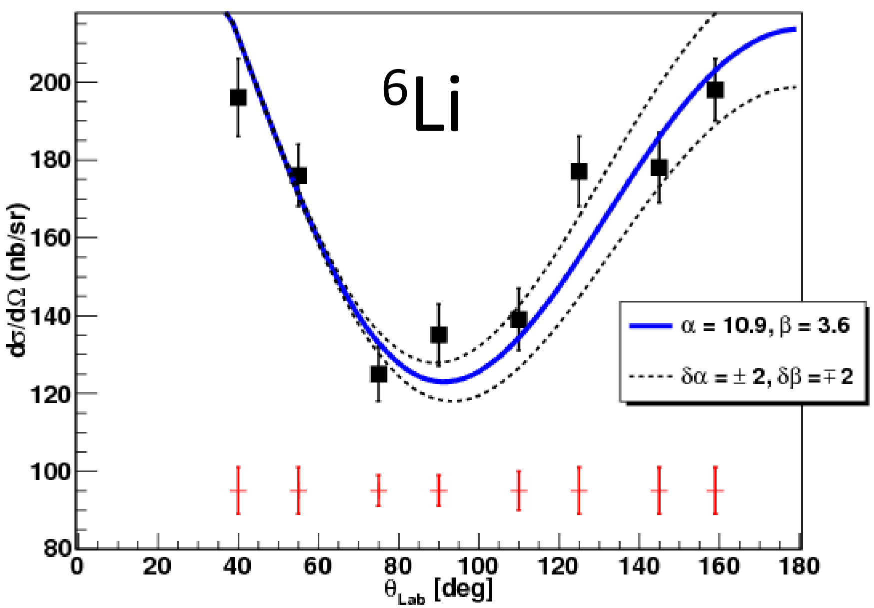
ε = photon polarization, *k* is the momentum

H.W. Grießhammer, et al., Progress in Particle and Nuclear Physics (2012), doi:10.1016/j.ppnp.2012.04.003

HIGS Results on ^{16}O and ^{6}Li Compton Scattering







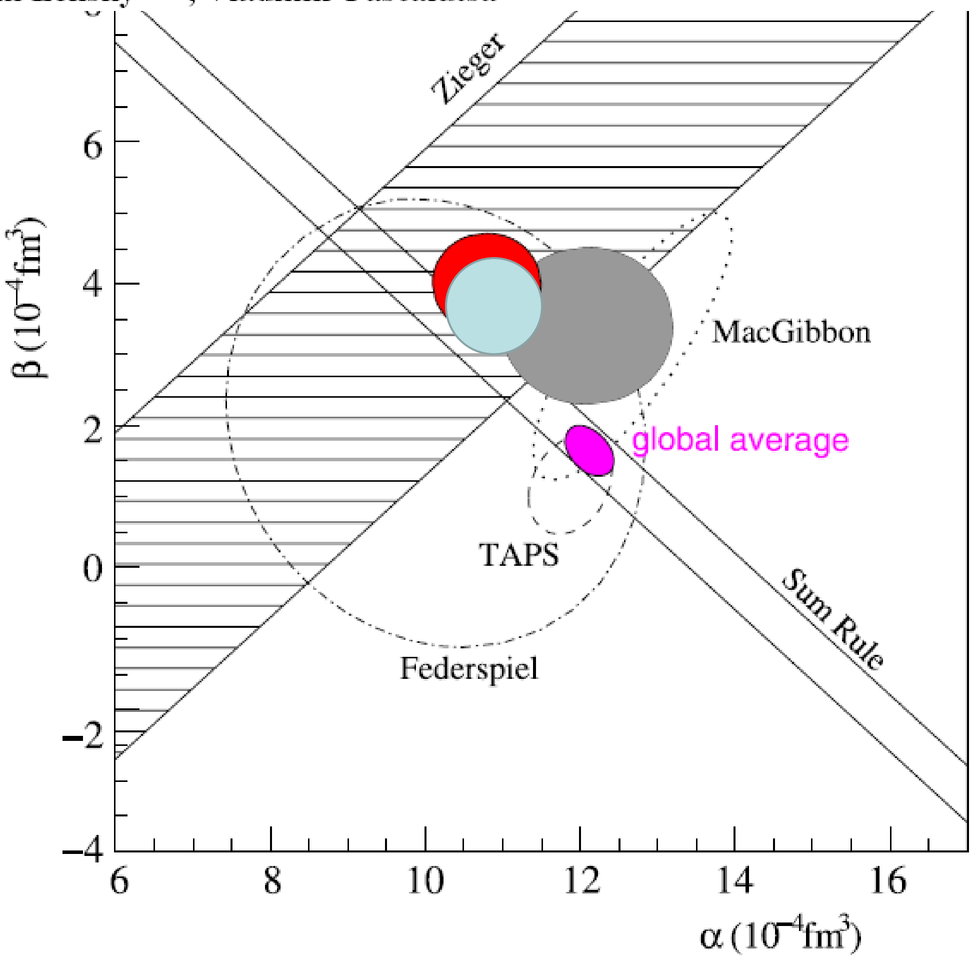
Phenomenological Model

- Giant Resonances
- Quasi-Deuteron
- Modified Thompson

Predictive powers of chiral perturbation theory in Compton scattering off protons

Eur. Phys. J. C (2010) 65: 195–209
DOI 10.1140/epjc/s10052-009-1183-z

Vadim Lensky[1,a,b], Vladimir Pascalutsa[1,2]



BχPT with Δ Prediction

$\alpha = 10.7 \pm 0.7$

$\beta = 4.0 \pm 0.7$

PDG Accepted Value

$\alpha = 12.7 \pm 0.6$

$\beta = 1.9 \pm 0.5$

Polarizabilities

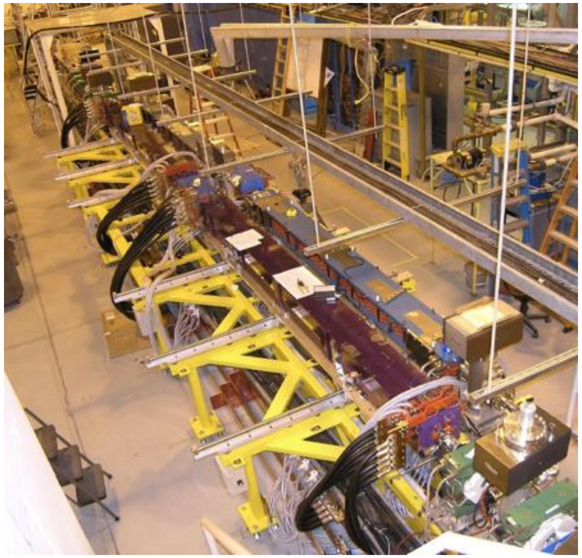
H.W. Grießhammer, et al., Progress in Particle and Nuclear Physics (2012), doi:10.1016/j.ppnp.2012.04.003

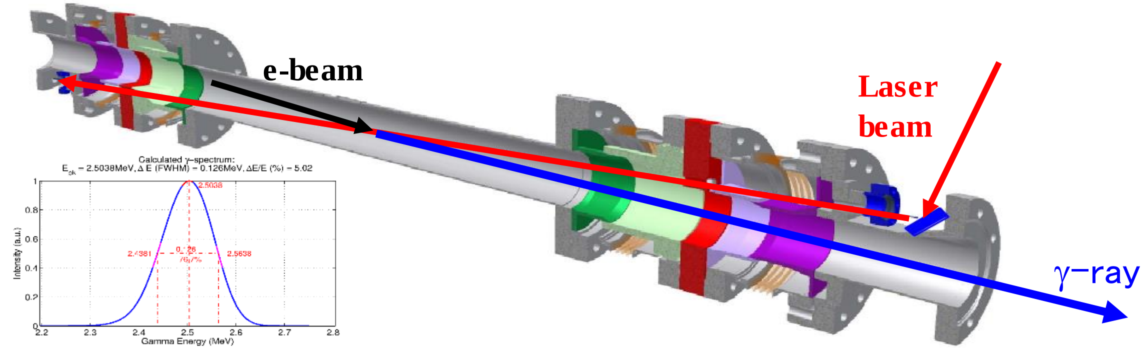
Using Effective Field Theory to analyse low-energy Compton scattering data from protons and light nuclei

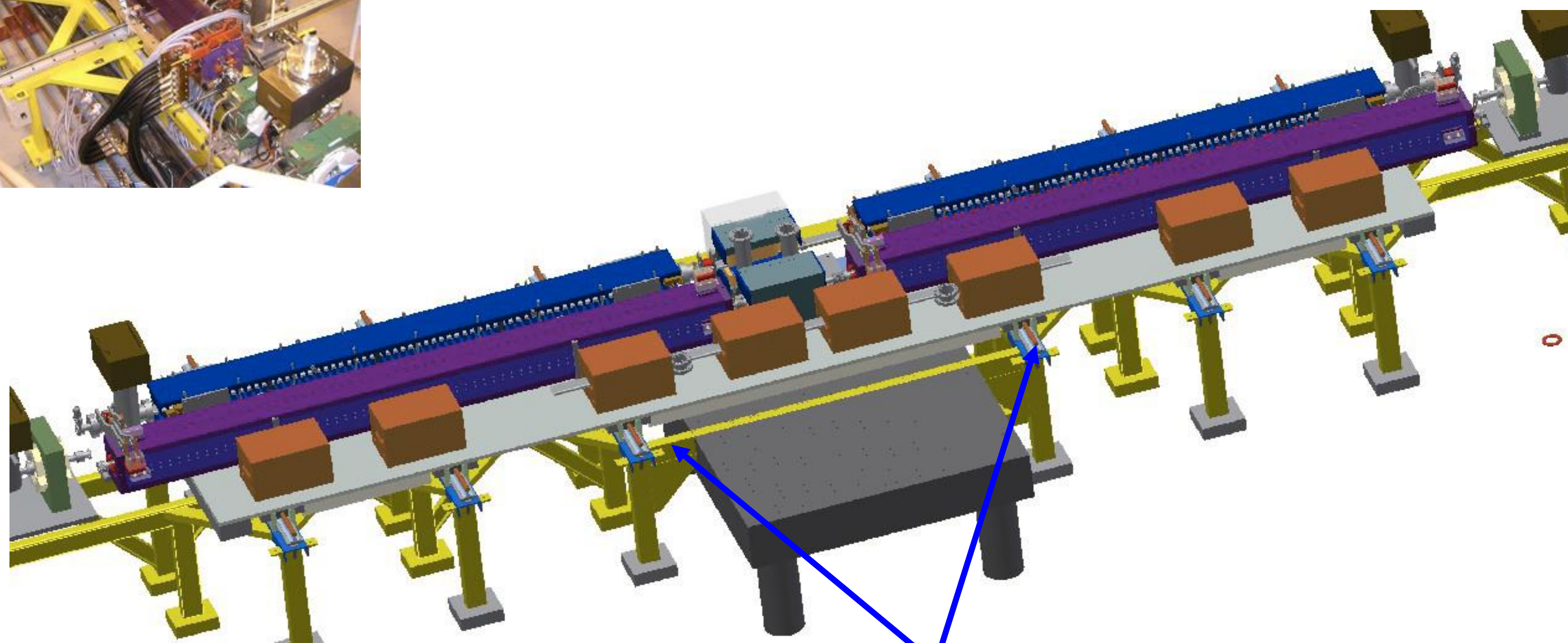
H.W. Grießhammer[a,*], J.A. McGovern[b], D.R. Phillips[c], G. Feldman[a]

Upgrade of HIγS: HIγS2

HIγS2 Layout







Mirrors of FP optical cavity
L_{cav} = 1.679 m
P_{FB} (avg) > 10 kW, 90 MHz

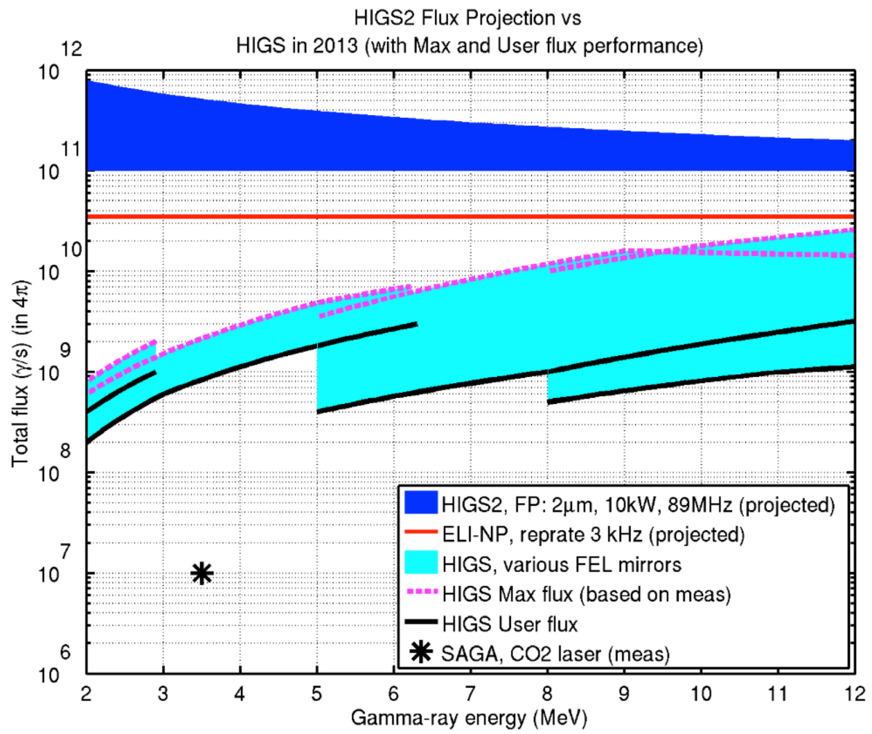
Collaborators: Jun Ye, JILA and U. of Colorado at Boulder

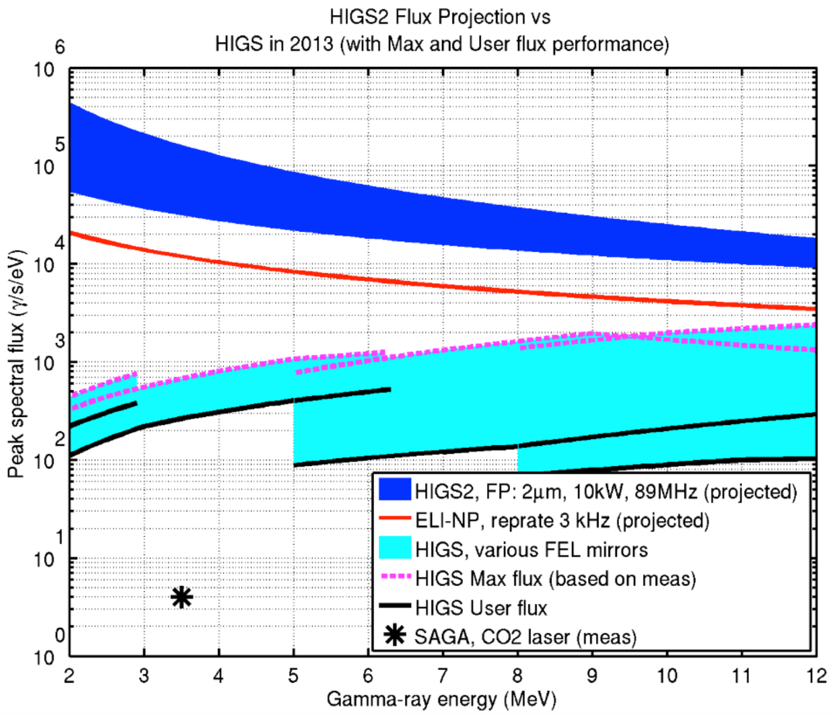
Major physics drivers

1. $\gamma + {}^{16}O = {}^{12}C + \alpha$
   (Holy Grail of Nuclear Astrophysics)

2. $\gamma + d = n + p$
   (Parity violation)

Comparison of HIγS2 to ELI





ELI: Extreme Light Infrastructure
Bucharest, Prague, Szeged

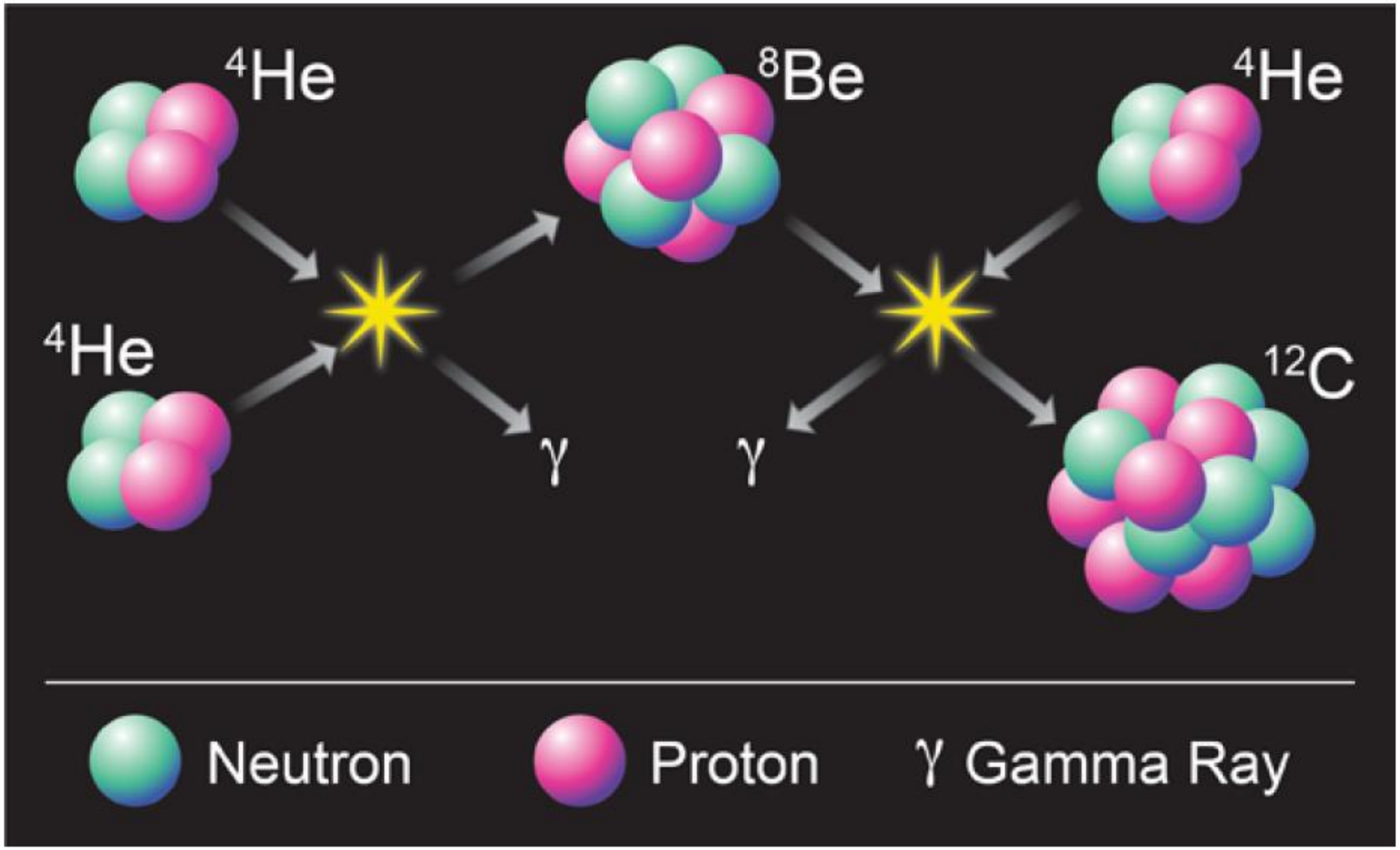
Backup slides

A=12

Nuclear Astrophysics

The 2^{nd} 2^+ state in ^{12}C

Triple-α Process:

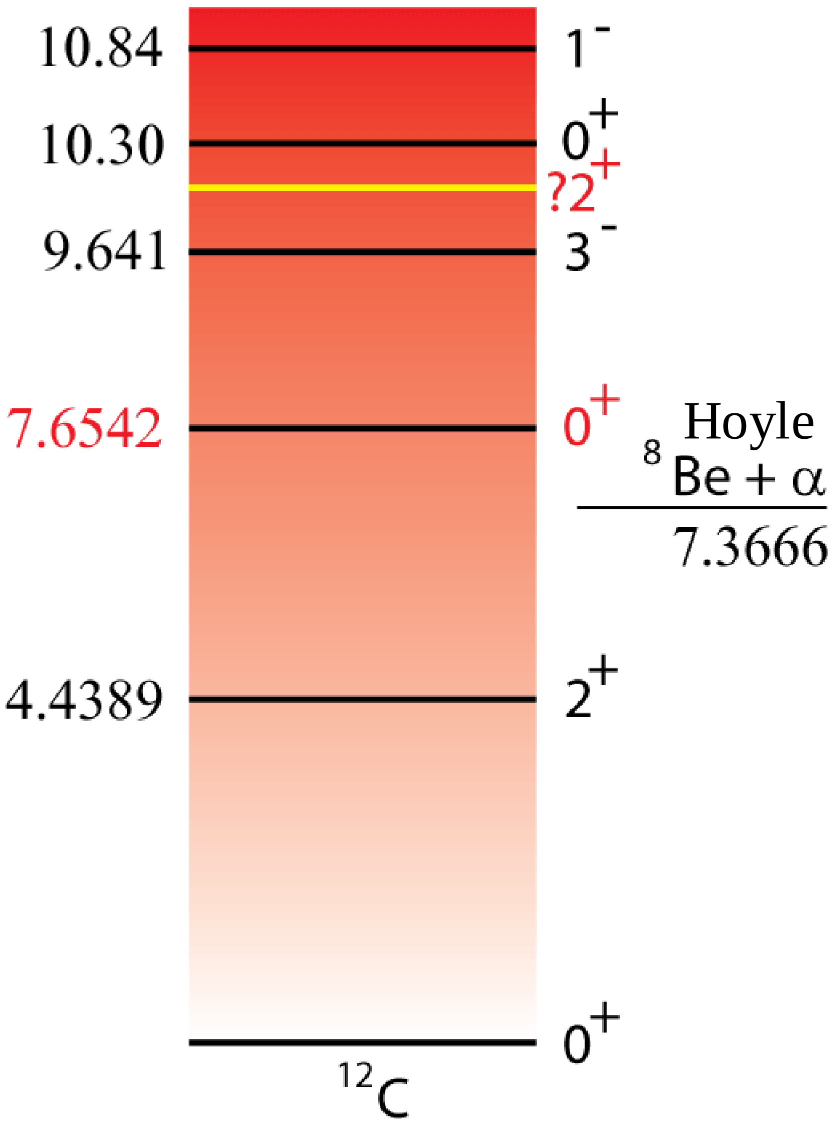


M. Hjorth-Jensen, Physics **4**, 38 (2011)

Red giant stars

Resonance enhancement is needed. Nature forms ^{8}Be (ground state is a resonance 92 keV above the ^{4}He-^{4}He threshold). Helps, but not sufficient. Hoyle (1954) proposed a resonance in ^{12}C just above the combined mass of ^{8}Be and α-particle. Observed in 1957.

Nuclear Astrophysics & EFT Lattice Calculations



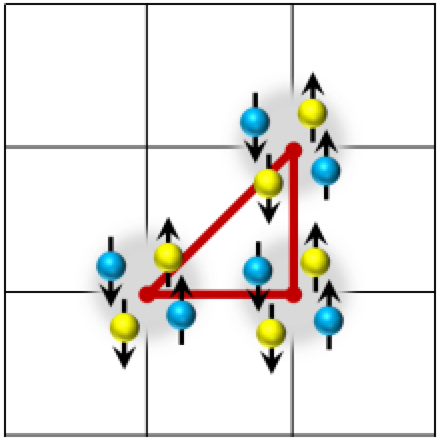
A 2_2^+ state in ^{12}C was predicted by Morinaga (Phys. Rev. 101, 1956) as the first rotational state of the "ground" state 7.654 MeV (Hoyle State)

Recently, Epelbaum, Krebs, Lee, Meißner (Phys. Rev. Lett. **106**, 192501, 2011) have performed *Ab Initio* Chiral Effective Field Theory Lattice calculations for the Hoyle State and its structure and rotations.

Epelbaum *et al*. Phys. Rev. Lett. 109 252501 (2012)

Structure of ground state and first 2+

Strong overlap with compact triangle configuration

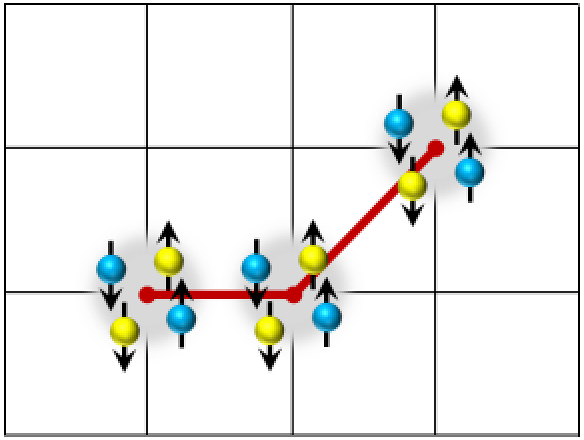


12 rotational orientations

$b = 1.97$ fm

Structure of Hoyle state and second 2+

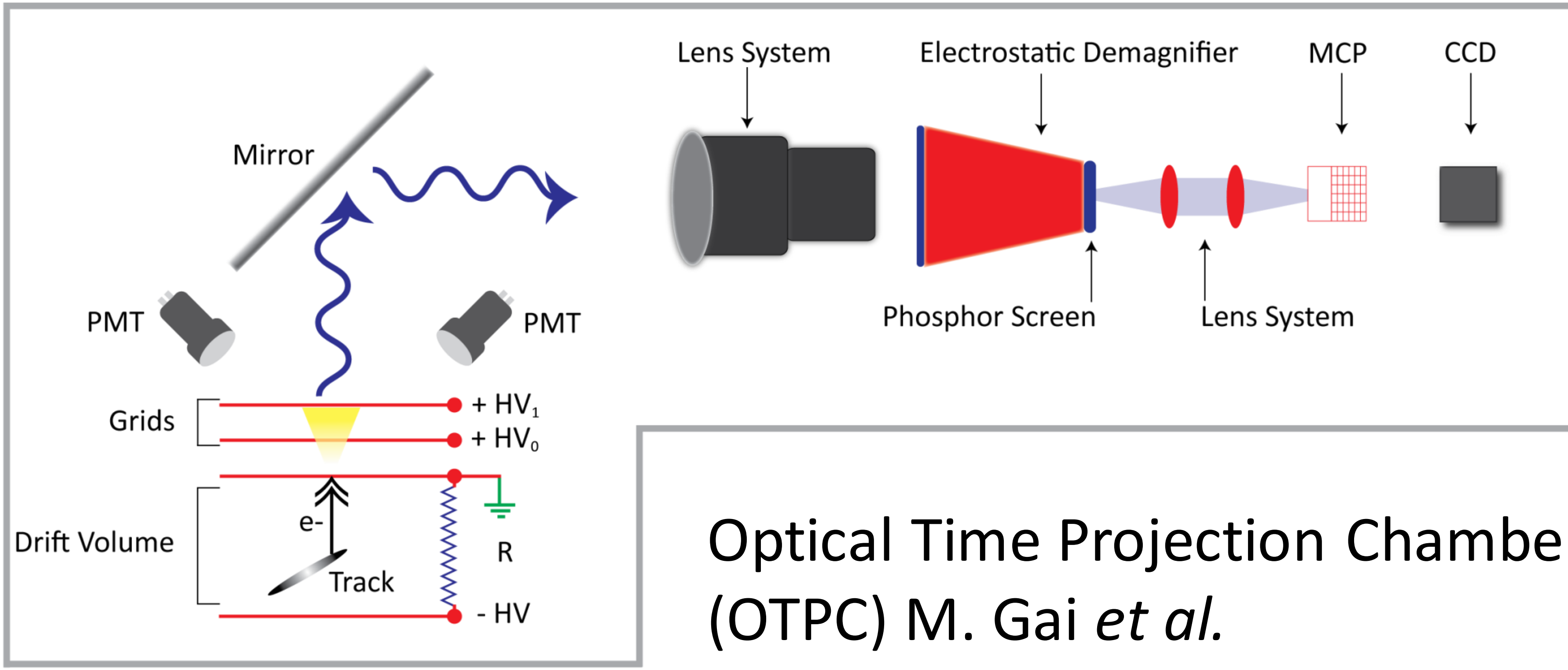
Strong overlap with bent arm configuration



24 rotational orientations

$b = 1.97$ fm

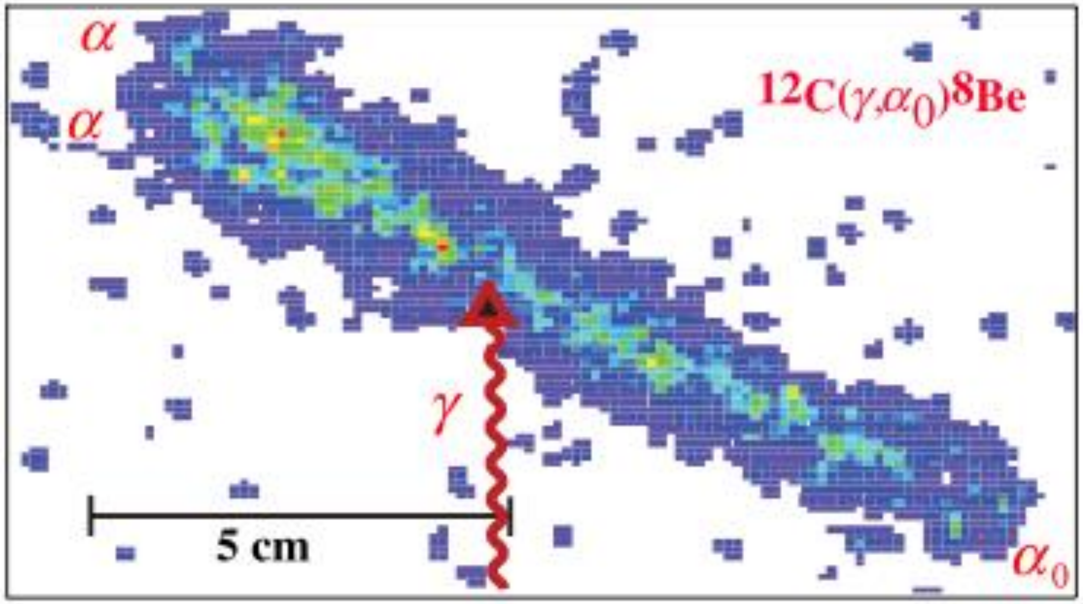
Evidence of 2^{nd} 2^+ state in ^{12}C



Optical Time Projection Chamber (OTPC) M. Gai *et al.*

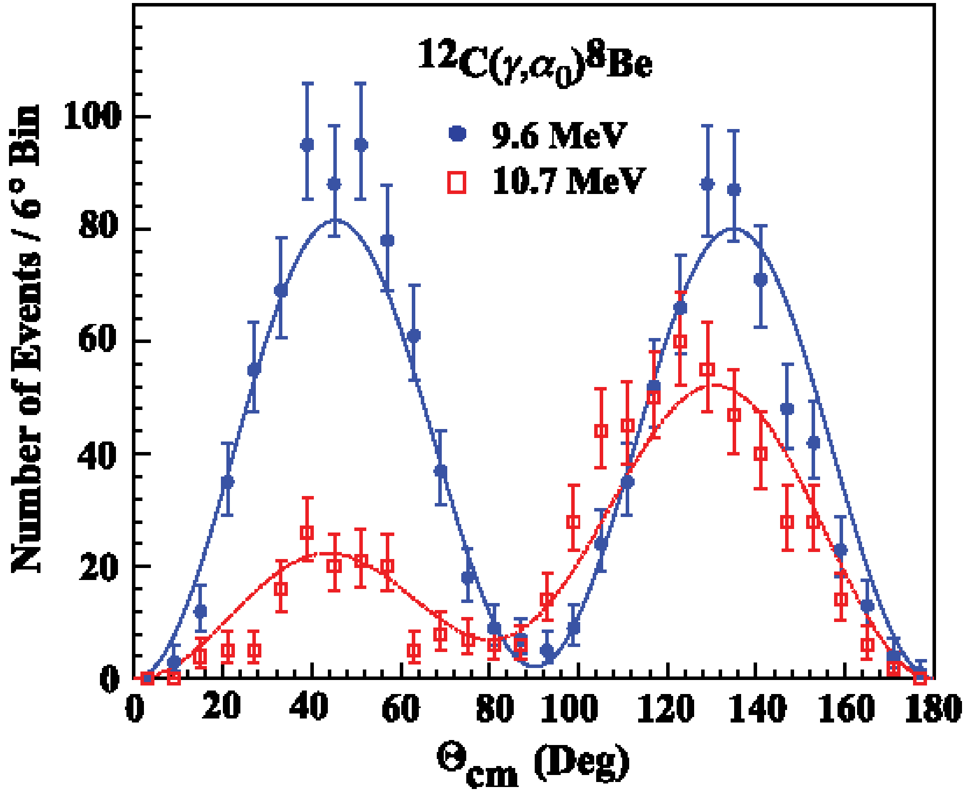
- ❑ Gas (Target/Detector) filled volume (CO_2+N_2)
- ❑ Grid provides the total energy ($\Delta E/E$ of 4 %)
- ❑ PMTs provide the Time-Projection (10 ns bins): out-of-plane angle of the track
- ❑ Optical Readout provides the track image: in-plane angle of the track

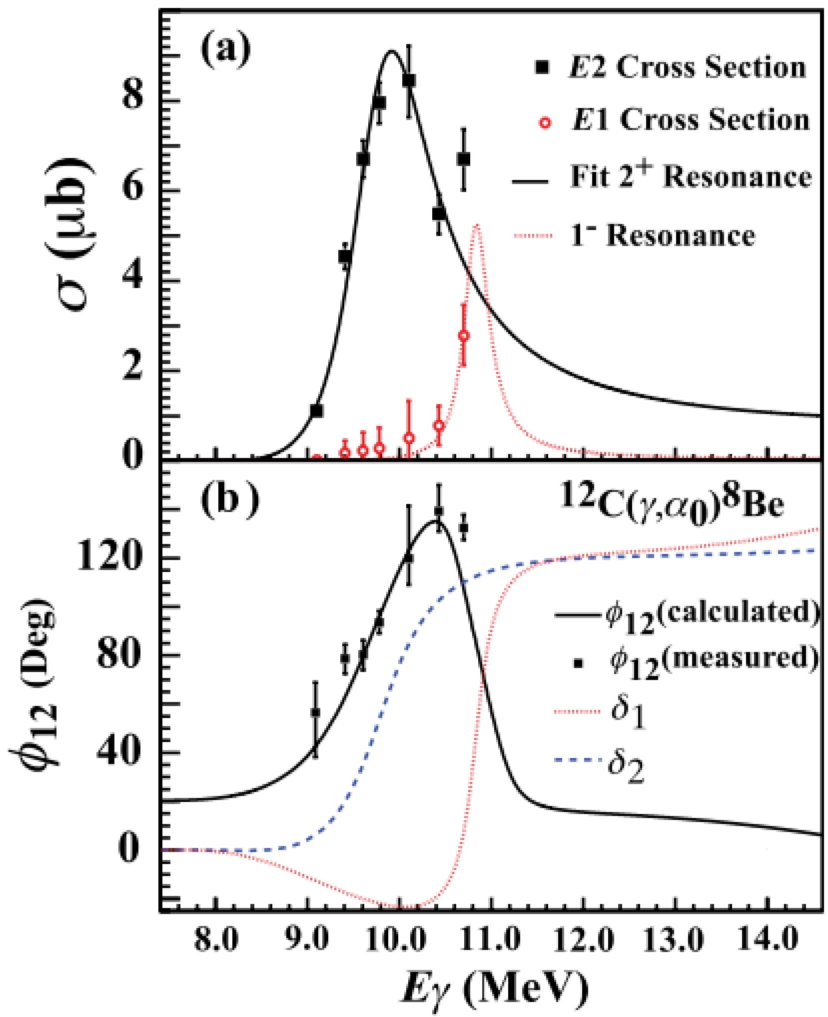
$$\gamma + {}^{12}C > 3\alpha$$


α
α
$^{12}C(\gamma,\alpha_0)^8Be$
γ
5 cm
α_0

Unambiguous Identification of the Second 2^+ State in ^{12}C and the Structure of the Hoyle State

W. R. Zimmerman,[1,2] M. W. Ahmed,[2,3] B. Bromberger,[4] S. C. Stave,[2] A. Breskin,[5] V. Dangendorf,[4] Th. Delbar,[6] M. Gai,[1,7] S. S. Henshaw,[2] J. M. Mueller,[2] C. Sun,[2] K. Tittelmeier,[4] H. R. Weller,[1,2] and Y. K. Wu[2]




(a)
E2 Cross Section
E1 Cross Section
Fit 2+ Resonance
1- Resonance
σ (μb)
8
6
4
2
0
(b)
12C(γ,α0)8Be
φ12(calculated)
φ12(measured)
δ1
δ2
φ12 (Deg)
120
80
40
0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
Eγ (MeV)

Evidence of a New 2_2^+ State in ^{12}C: Results

Experiment:

2_2^+			
E_{res} (MeV)	Γ_α(res) (keV)	$\Gamma_{\gamma 0}$(res) (meV)	$B(E2 : 2_2^+ \to 0_1^+)$ ($e^2 fm^4$)
10.03(11)	800(130)	60(10)	0.73(13)

Comparing the Experimental Results and the lattice EFT Calculation

	$E(2_2^+ - 0_2^+)$	$B(E2: E(2_2^+ \to 0_1^+)$
Experiment	2.37 ± 0.11	0.73 ± 0.13
Theory	2.0 ± 1 to 2	2 ± 1

Nuclear Astrophysics Impact of the 2_2^+ State

- Helium burning occurs at a temperature of 10^8–10^9K, and is completely governed by the Hoyle state;
- However, during type II supernovae, γ-ray bursts and other astrophysical phenomena, the temperature rises well above 10^9 K, and higher energy states in ^{12}C can have a significant effect on the triple-α reaction rate;
- Preliminary calculations suggest a dependence of high mass number (>140) abundances on the triple alpha reaction rate based on the parameters of the 2_2^+ state.