Experimental Study of Photodisintegration Cross Sections on ^{3}He and ^{4}He at Low Energies

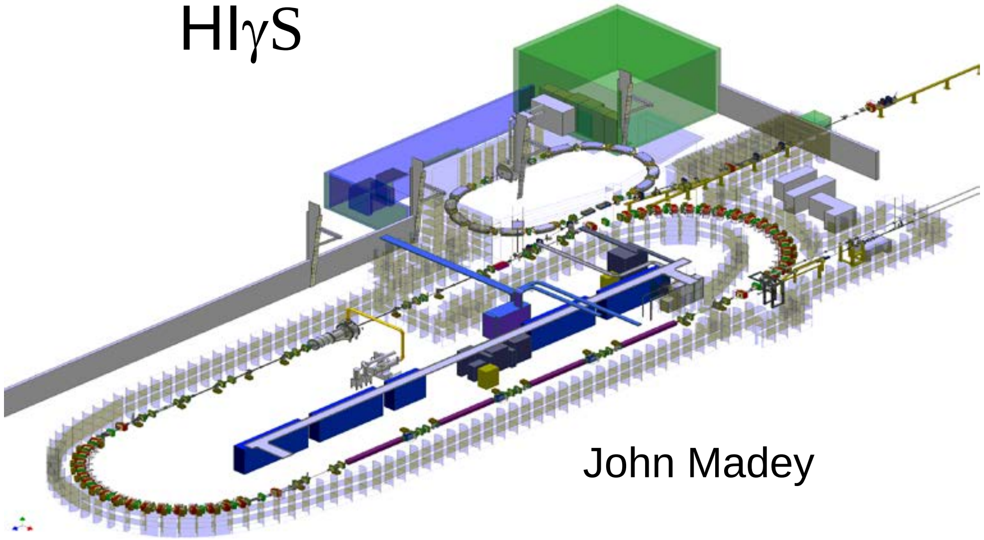
Werner Tornow

Duke University & Triangle Universities Nuclear Laboratory

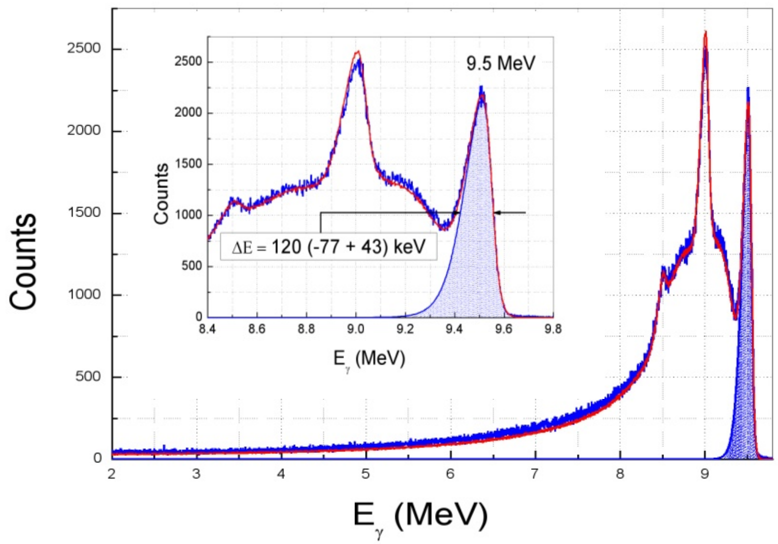
Outline

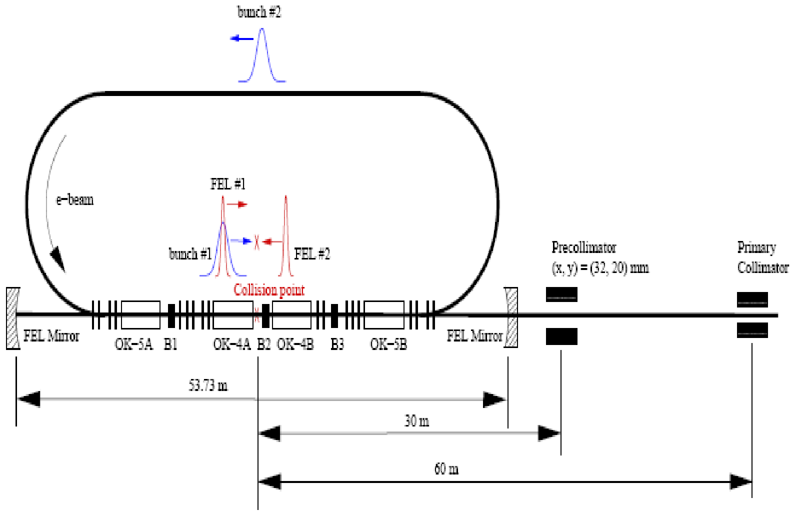
- $^3He(\gamma,pd)$ σ_{tot} between E_γ=7 and 16 MeV
- $^4He(\gamma,pt)$ σ_{tot} between E_γ=22 and 29.5 MeV
- $^4He(\gamma,{}^3He)n$ σ_{tot} between E_γ=27 – 28 MeV
- $^3He(n,n)^3He$ $A_y(\theta)$ between E_n=1.6 and 5.4 MeV

HIγS



John Madey



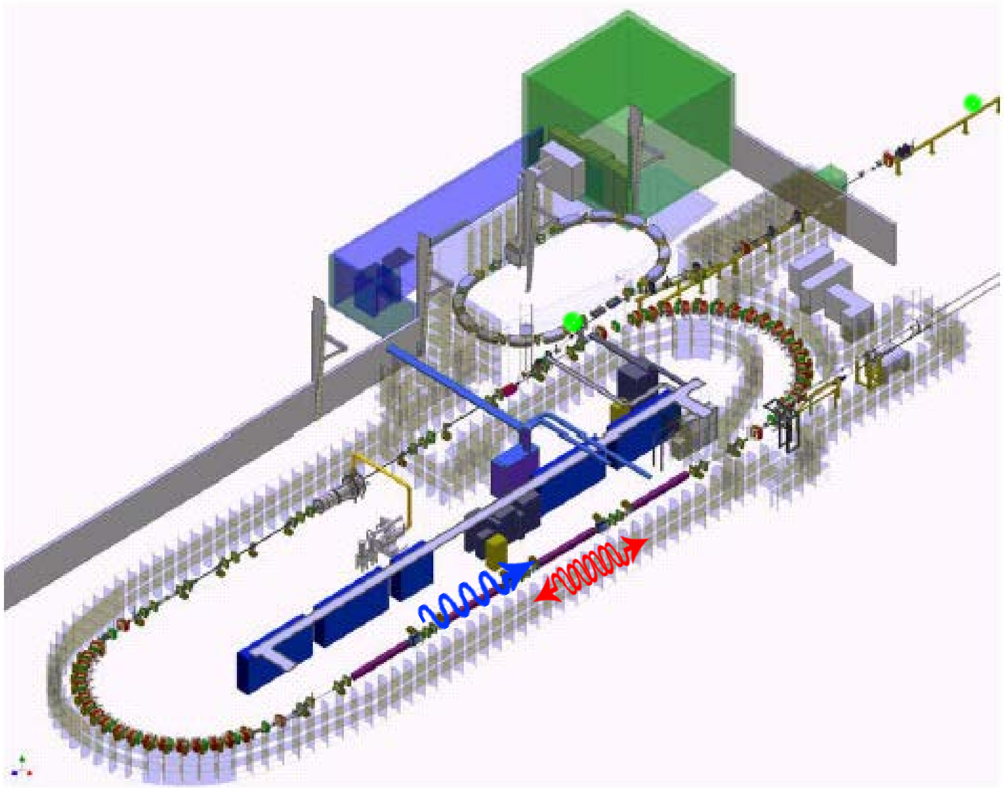


Vladimir Litvinenko (1992)

Quasi monoenergetic
γ-ray flux on target: >$10^8 s^{-1}$

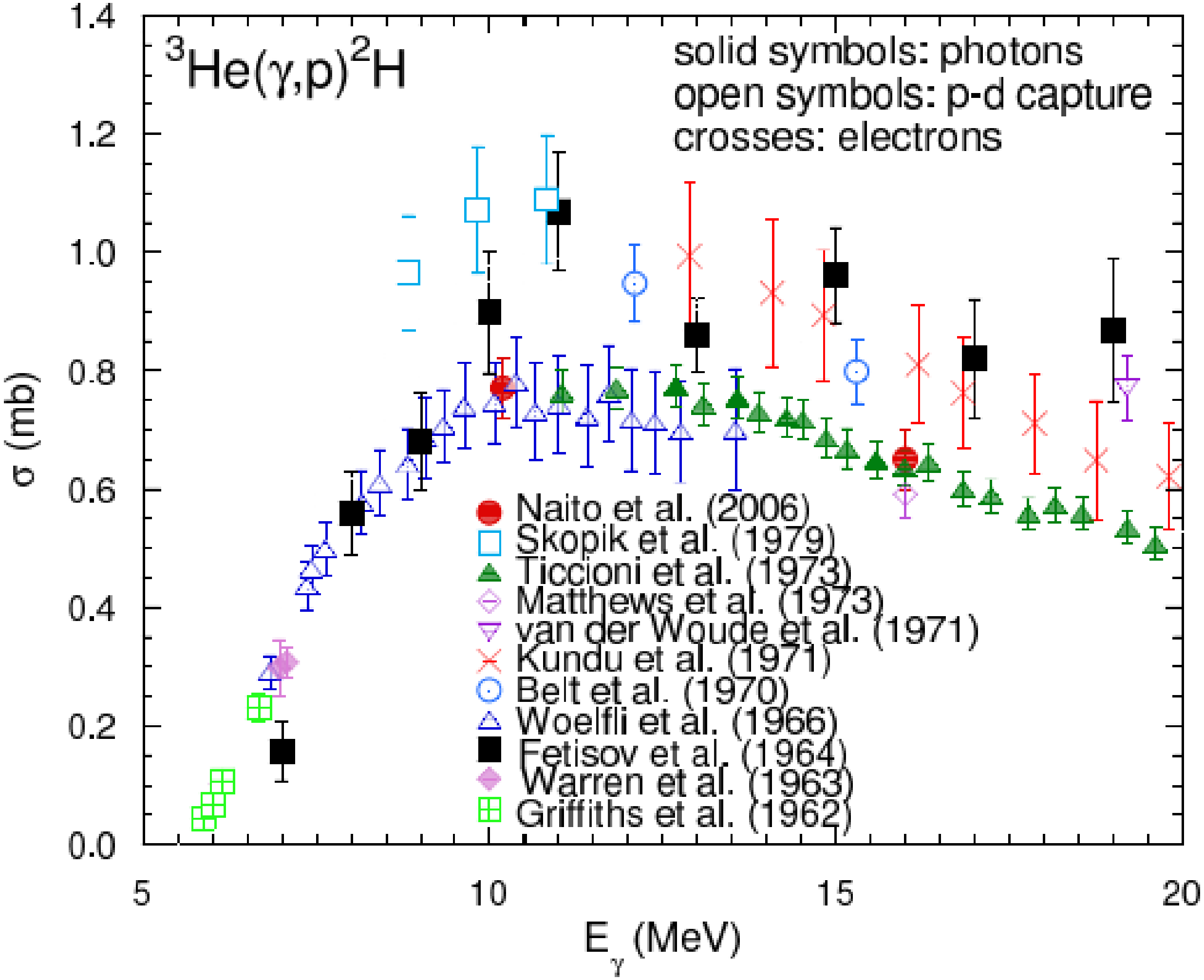
Tunable from 1 to 97 MeV
100% linear or circular polarization
Energy resolution determined by
Collimation; no need for tagging

HIγS Facility at TUNL



$^{3}He(\gamma,pd)$

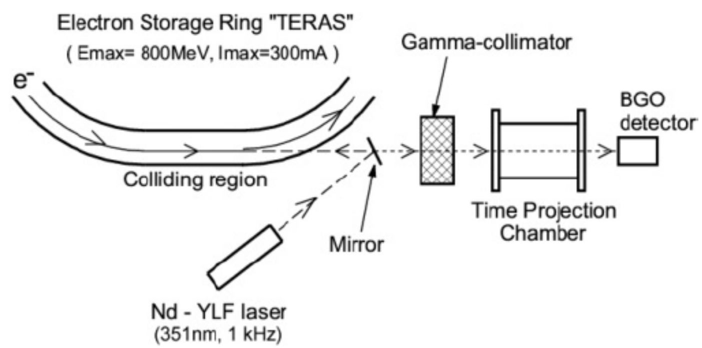
Q=-5.49 MeV



$^3He(\gamma,p)^2H$
solid symbols: photons
open symbols: p-d capture
crosses: electrons
Naito et al. (2006)
Skopik et al. (1979)
Ticcioni et al. (1973)
Matthews et al. (1973)
van der Woude et al. (1971)
Kundu et al. (1971)
Belt et al. (1970)
Woelfli et al. (1966)
Fetisov et al. (1964)
Warren et al. (1963)
Griffiths et al. (1962)
σ (mb)
E_γ (MeV)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
5
10
15
20

National Institute of Advanced Industrial Science and Technology (AIST)

Tsukuba, Japan



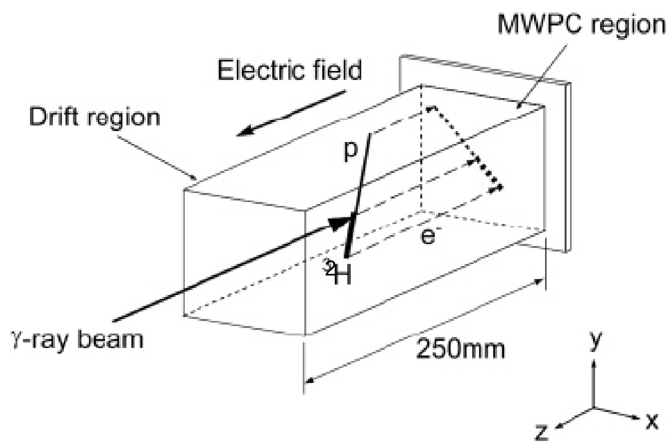
~1.7 MeV γ-ray energy width

10^4 γ rays per second

Shima *et al*., 2005

Time projection chamber

as target as detector



We don’t have a time-projection chamber

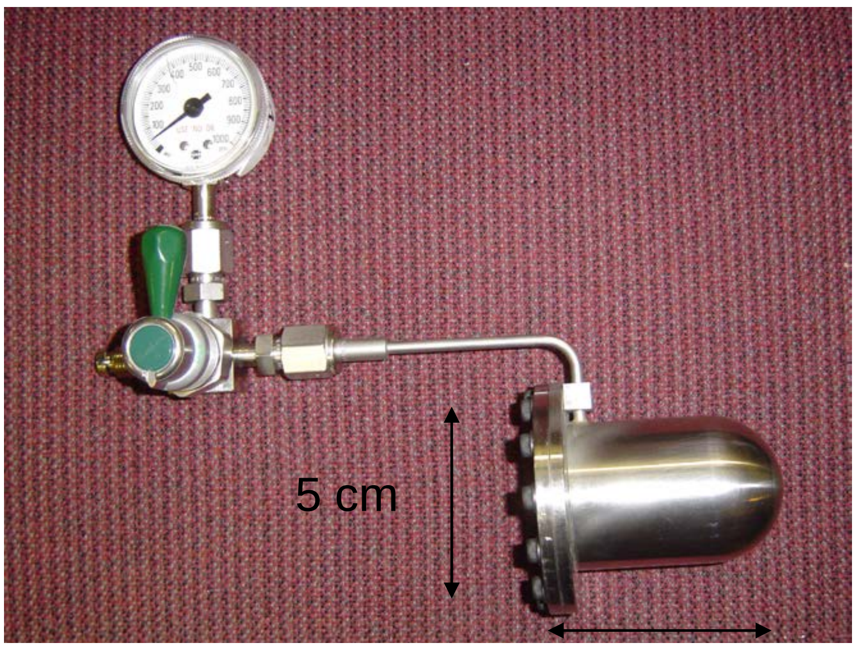
We used ^{3}He-Xe high-pressure gas scintillators instead

Xe admixture (~5 – 10%) is needed :

a) to increase light output, *i.e.,* energy resolution
b) provide stopping power for the protons within scintillator volume (proton energies vary from 1.1 MeV at E_γ=7 MeV to 7.6 MeV at E_γ=16 MeV)

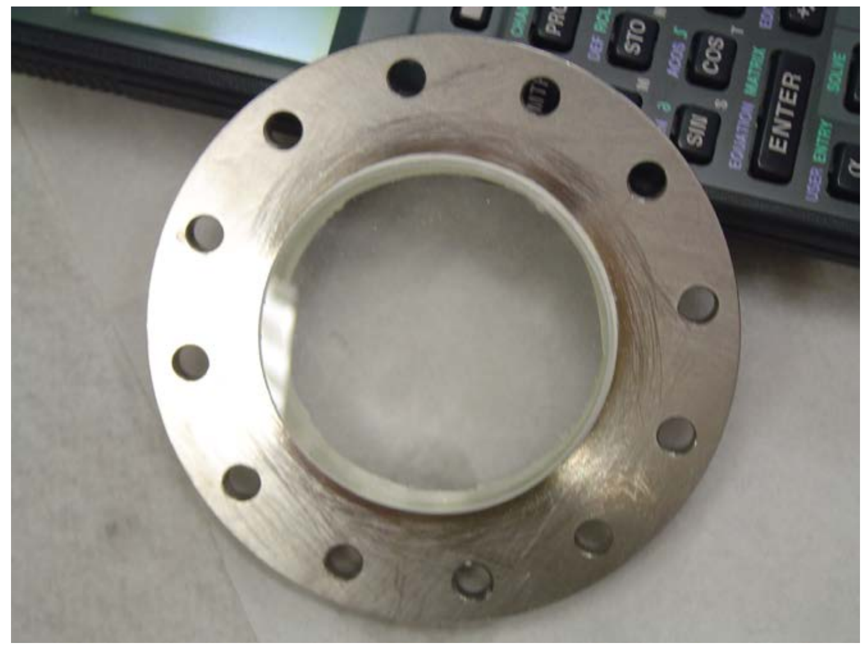
Construction

1 mm thick stainless steel



10 cm

1 cm thick glass window

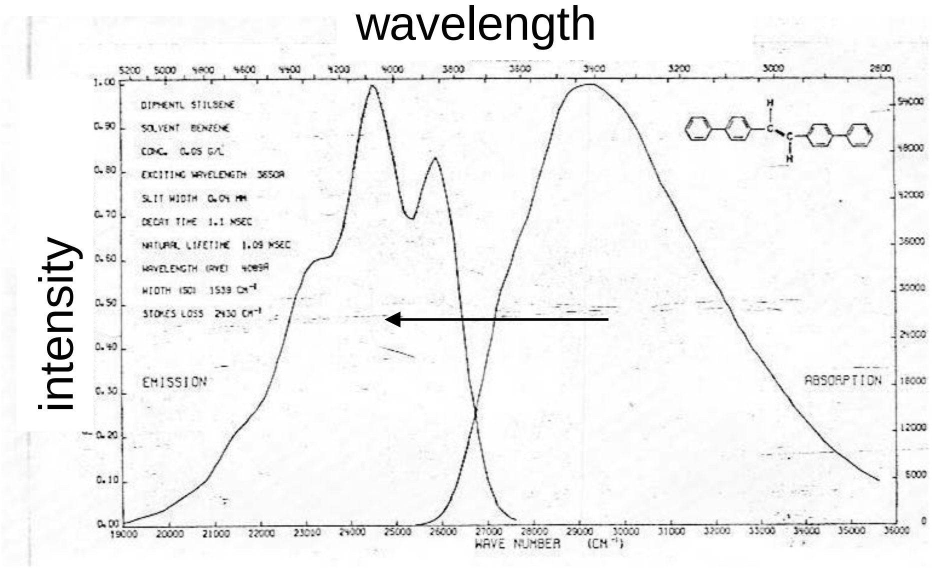


Glue Maxos glass window into cap
Araldit + Hardener

- MgO creates white film on gas cell walls

- Evaporate Diphenylstilbene (DPS) onto glass window and inside of gas cell
- DPS shifts the wavelength from

  340 nm to 410 nm

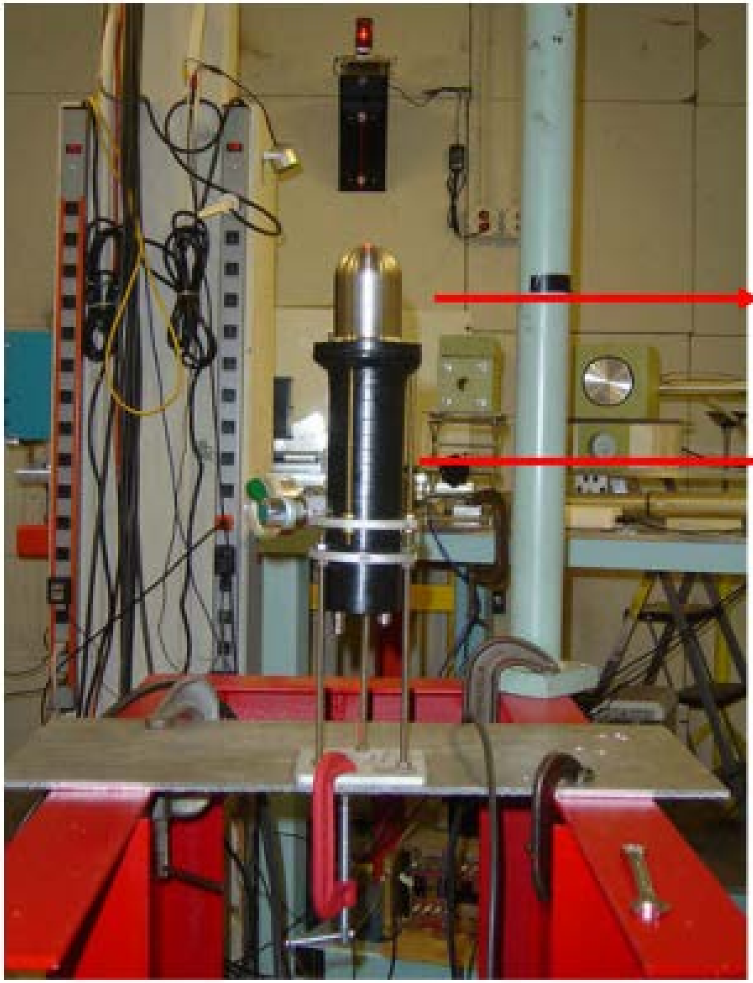


- Fill cell with ^{3}He (95%) and Xenon (5%)
  - (Xenon is also a wavelength shifter)
- Attach PMT to gas cell

- Pressure test cell bringing pressure to 1000 psi

- Response function is linear
- Light output is independent of particle type
- Energy resolution is energy dependent
- ^{3}He-Xe gas scintillators have very good energy resolution (2-10%)

Experimental Setup

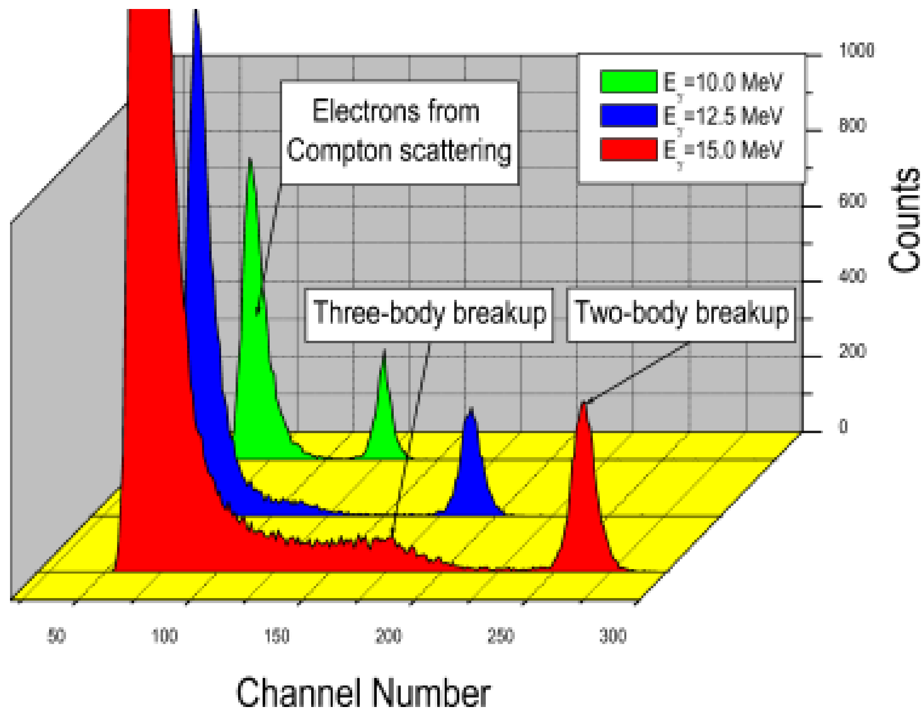


Gas Cell

PMT

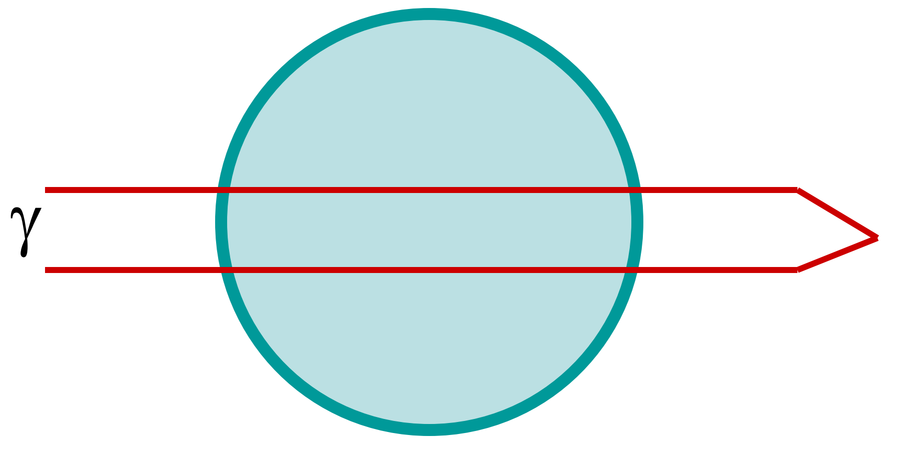
^{3}He and Xe pressures used for ^{3}He(γ,pd) experiment

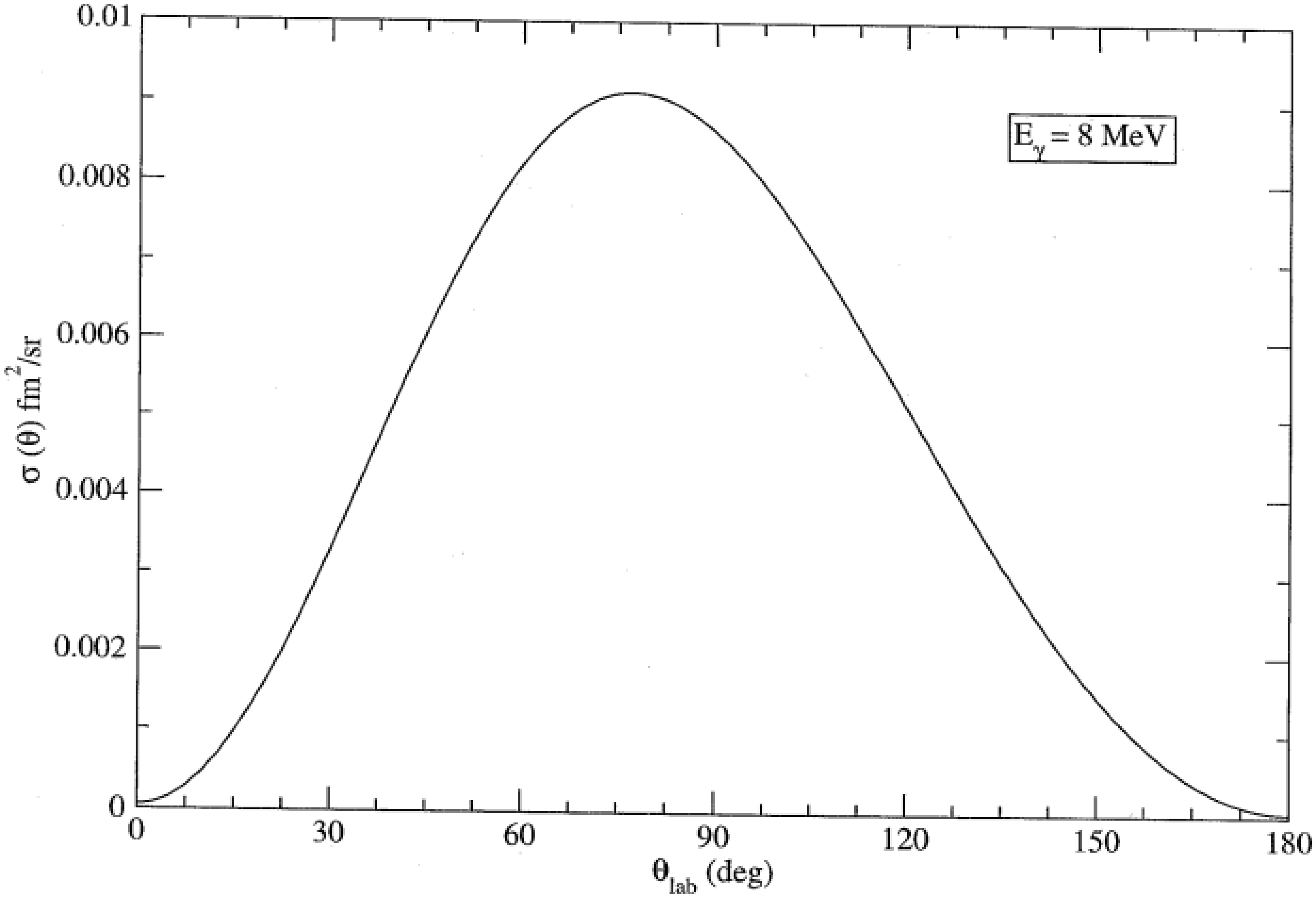
42 psi Xe & 458 psi ^{3}He at 6.96 and 7.93 MeV
148 psi Xe & 602 psi ^{3}He at 8.78, 9.85, 10.85 12.78 MeV
132 psi Xe & 528 psi 3He at 12 MeV
300 psi Xe & 450 psi ^{3}He at 12.78 MeV
294 psi Xe & 442 psi ^{3}He at 14, 15, 16 MeV



Electrons from
Compton scattering
Three-body breakup
Two-body breakup
Eγ=10.0 MeV
Eγ=12.5 MeV
Eγ=15.0 MeV
1000
800
600
400
200
0
Counts
50
100
150
200
250
300
Channel Number

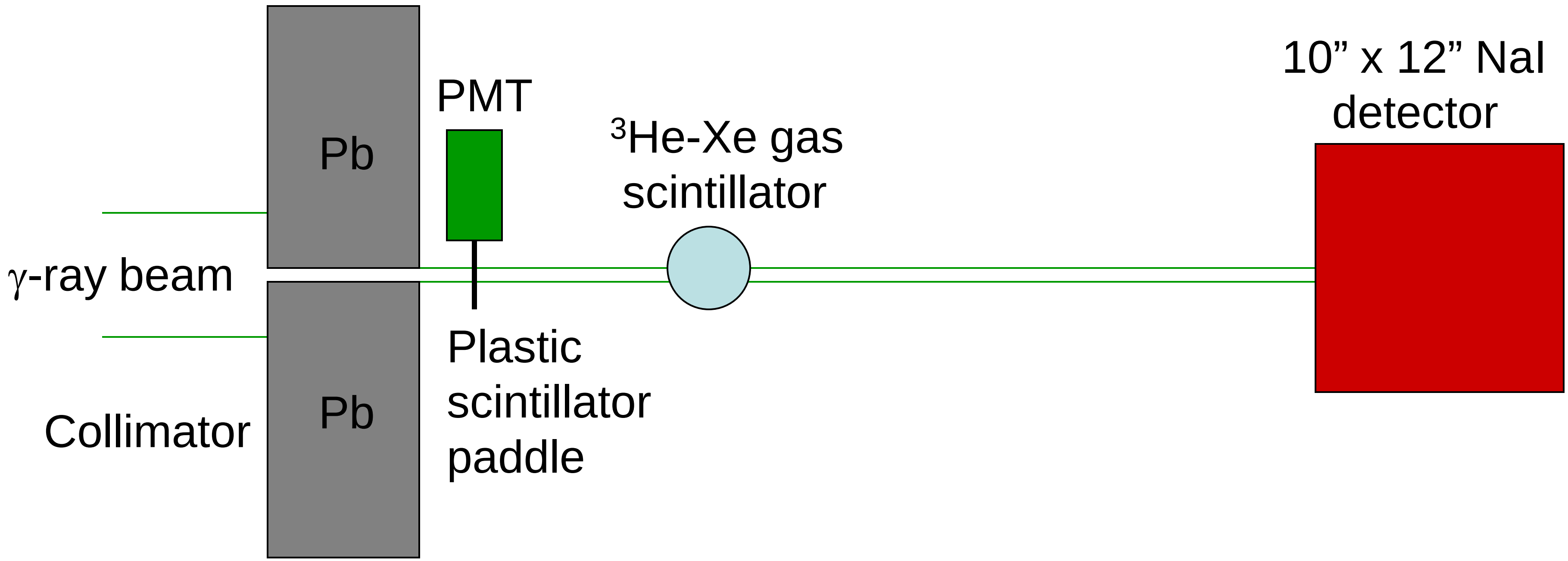
Edge Effects: Range of protons <1 cm





0.01
0.008
0.006
0.004
0.002
0
σ (θ) fm²/sr
0
30
60
90
120
150
180
θ_lab (deg)
E_γ = 8 MeV

Photon Flux Determination

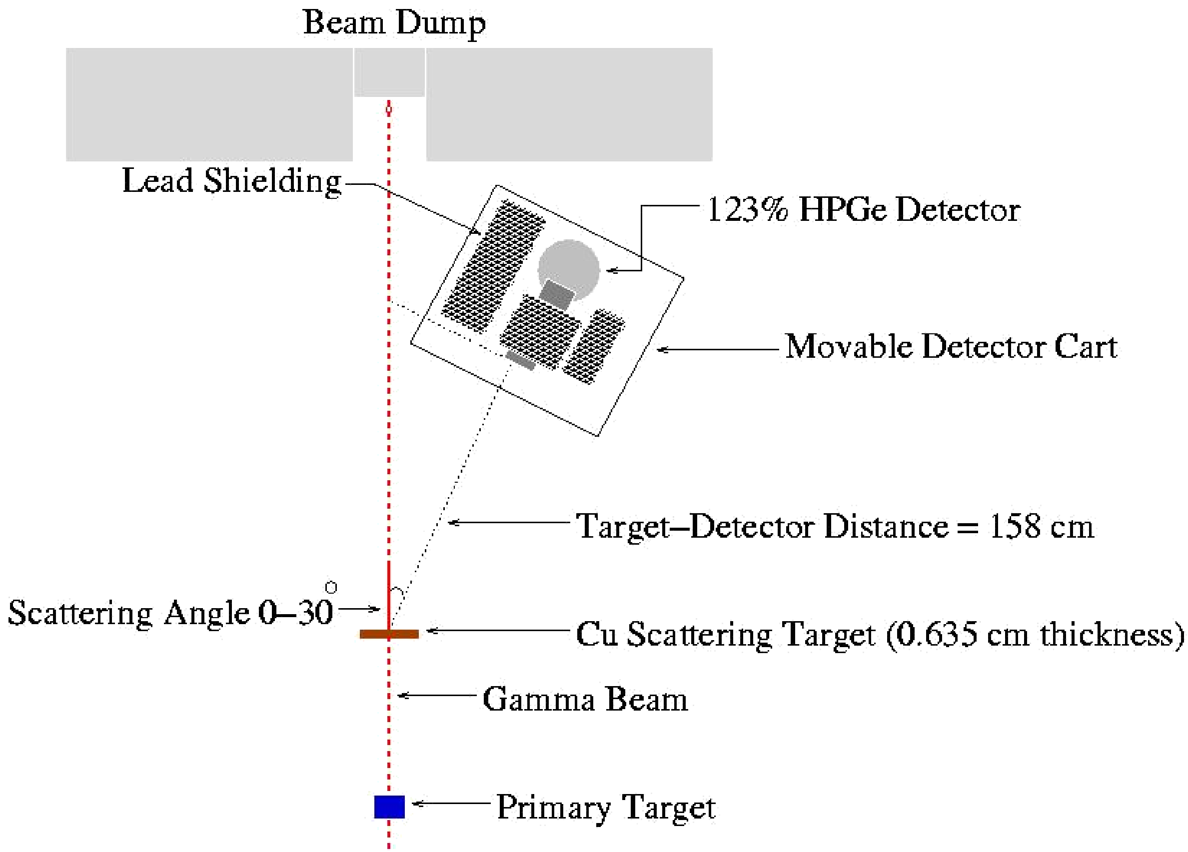


1) Move ^{3}He - Xe gas scintillator out of the photon beam
2) Reduce γ-ray flux to a few kHz rate
3) Move NaI scintillator of known efficiency into photon beam
4) Take data to determine ratio of Plastic Scintillator Paddle and NaI detector counts
5) Move NaI detector out of the photon beam
6) Move ^{3}He - Xe gas scintillator into the photon beam
7) Increase γ-ray flux to about 1 MHz
8) Take ^{3}He(γ,pd) data
9) Use Plastic Scintillator Paddle yield and 4) to determine γ-rays used in 8)

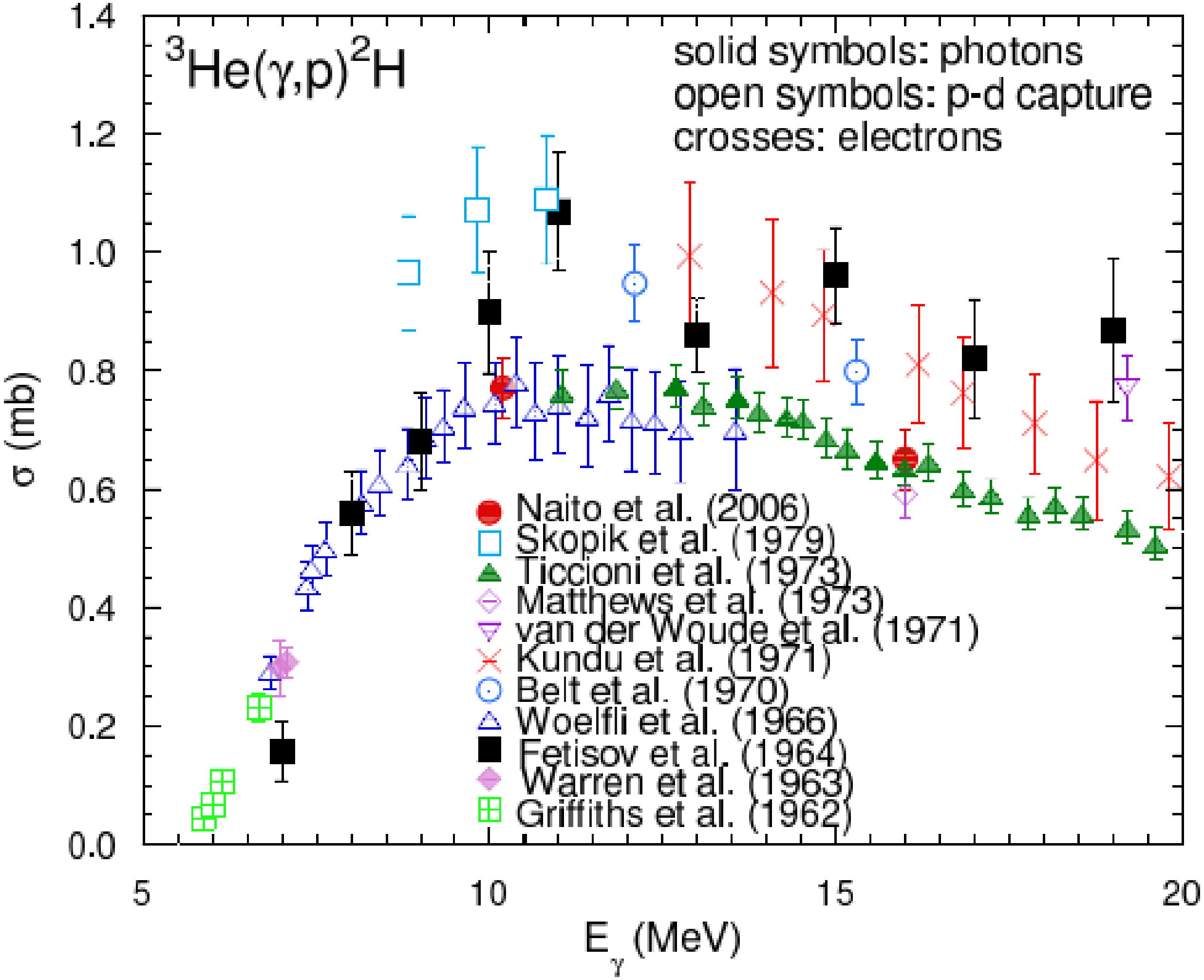
Statistical Uncertainty: <1%

Systematic Uncertainty: 4% (NaI detector efficiency)

Check on γ-ray flux via Compton scattering from a Cu plate into an off-axis HPGe detector at energies below 10 MeV



Check on γ-ray flux determination via activation: $^{197}Au(\gamma,n)^{196}Au$ between 12 and 16 MeV



$^3He(\gamma,p)^2H$
solid symbols: photons
open symbols: p-d capture
crosses: electrons
Naito et al. (2006)
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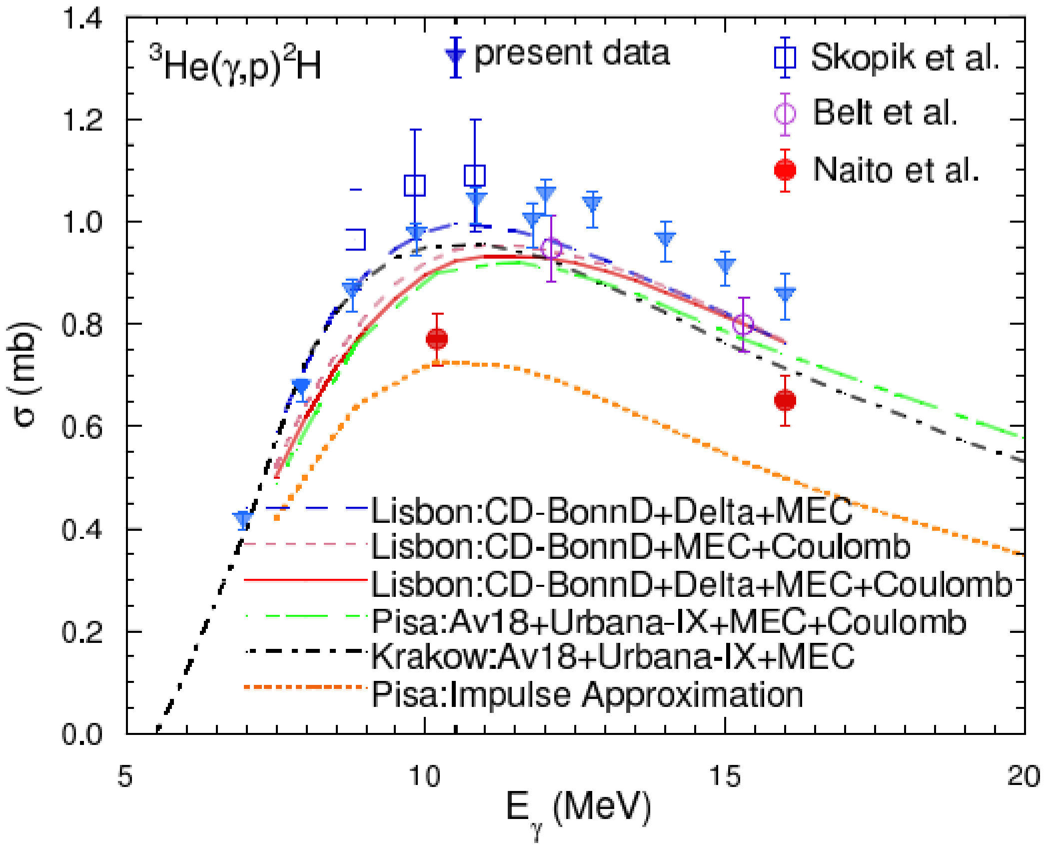
Woelfli et al. (1966)
Fetisov et al. (1964)
Warren et al. (1963)
Griffiths et al. (1962)
σ (mb)
E_γ (MeV)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
5
10
15
20

$^3He(\gamma,p)^2H$



ıkup

Electromagnetic interactions of 4N systems

$$\gamma + {}^{4}\mathrm{He} = {}^{3}\mathrm{H} + p \qquad Q = -19.81\ \mathrm{MeV}$$

$$\gamma + {}^{4}\mathrm{He} = {}^{3}\mathrm{He} + n \qquad Q = -20.58\ \mathrm{MeV}$$

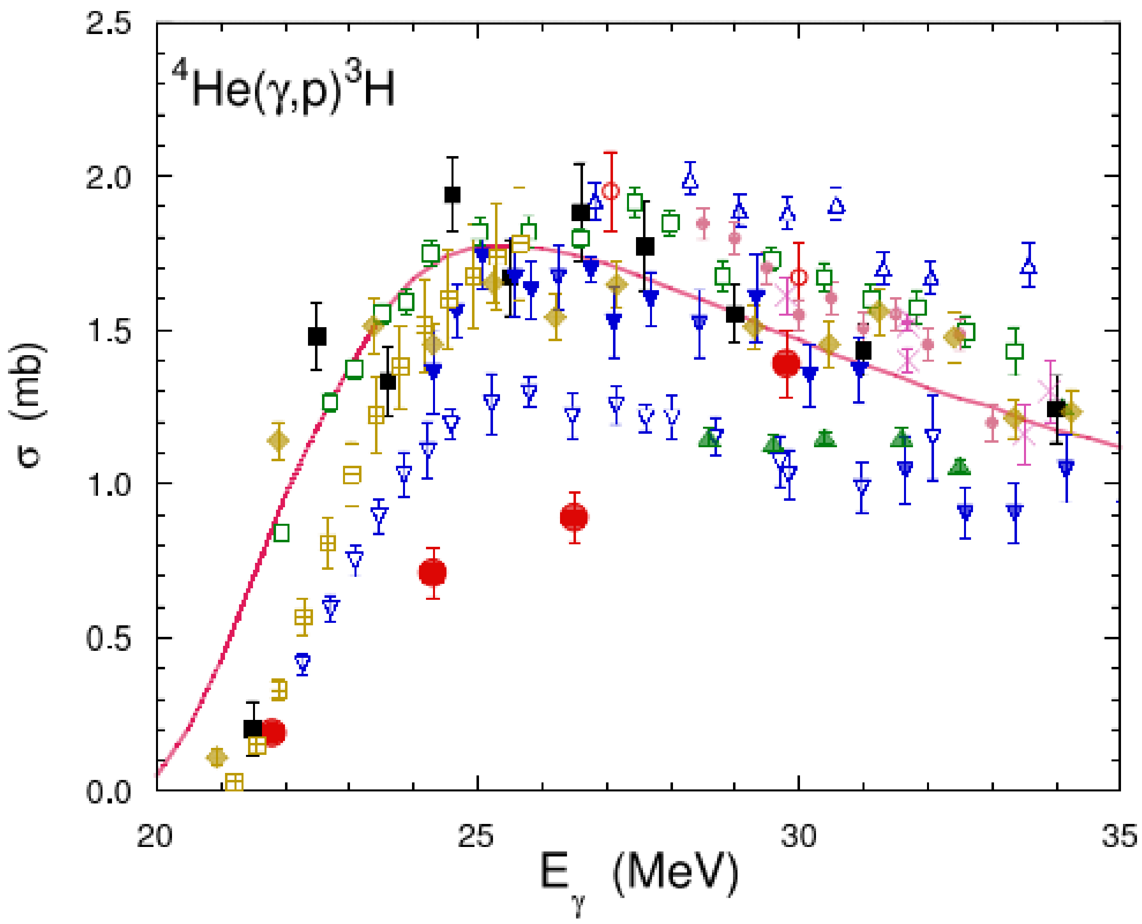
$$\gamma + {}^{4}\mathrm{He} = d + d \qquad Q = -23.85\ \mathrm{MeV}\ \text{(isospin forbidden)}$$

$$\gamma + {}^{4}\mathrm{He} = d + n + p \qquad Q = -26.07\ \mathrm{MeV}$$

$$\gamma + {}^{4}\mathrm{He} = n + p + n + p \qquad Q = -28.30\ \mathrm{MeV}$$

$^4He(\gamma,pt)$

Trento Group: G. Orlandini, W. Leidemann, S. Quaglioni, N. Barnea, V.D. Efros,
Lorentz integral transform method, final-state interaction and Coulomb included, MTI-III



"New constraints on radiative decay of long lived particles in big bang nucleosynthesis with new 4He photodisintegration data" by M. Kusakabe et al., Phys. Rev. D 79, 123513 (2009)

Now using ^{4}He-Xe gas scintillators

Photon Energy (MeV)	Xe (psi)	^{4}He (psi)	Proton Energies (MeV)
22.0	50	700	1.3 - 1.9
22.5	50	700	
23.0	150	605	1.9 – 2.8
23.5	150	605	
24.0	150	605	2.6 – 3.6
24.5	200	400	
25.0	200	400	3.3 – 4.4
25.5	200	400	
26.0	250	500	3.9 – 5.2
26.5	250	500	
27.0	250	500	4.6 – 6.1
27.5	250	500	
28.0	350	400	5.3 – 6.9
28.5	350	400	
29.0	350	400	6.0 – 7.7
29.5	350	400	

Photon-induced reaction thresholds (in MeV) on xenon isotopes

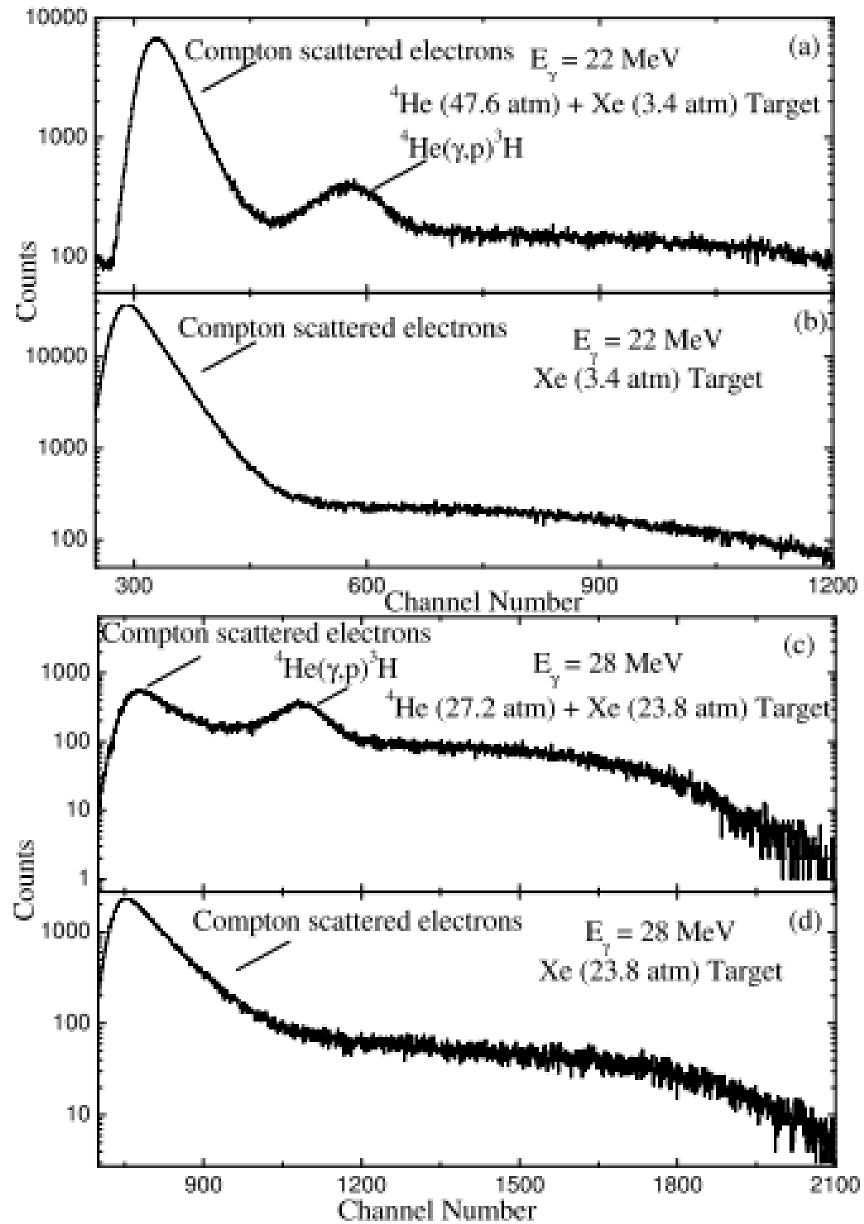
Isotope	Nat. Abundance (%)	(γ,p)	(γ,α)	(γ,n)	$(\gamma,2n)$	$(\gamma,n\alpha)$
128	1.92	8.17	1.77	9.61	16.84	11.19
129	26.44	8.25	2.09	6.91	16.52	8.68
130	4.08	8.67	2.24	9.26	16.16	11.35
131	21.18	8.82	2.55	6.61	15.87	8.85
132	26.89	9.12	2.71	8.93	15.54	11.48
134	10.44	9.55	3.20	8.54	14.99	11.62
136	8.87	9.93	3.66	7.99	14.44	11.73

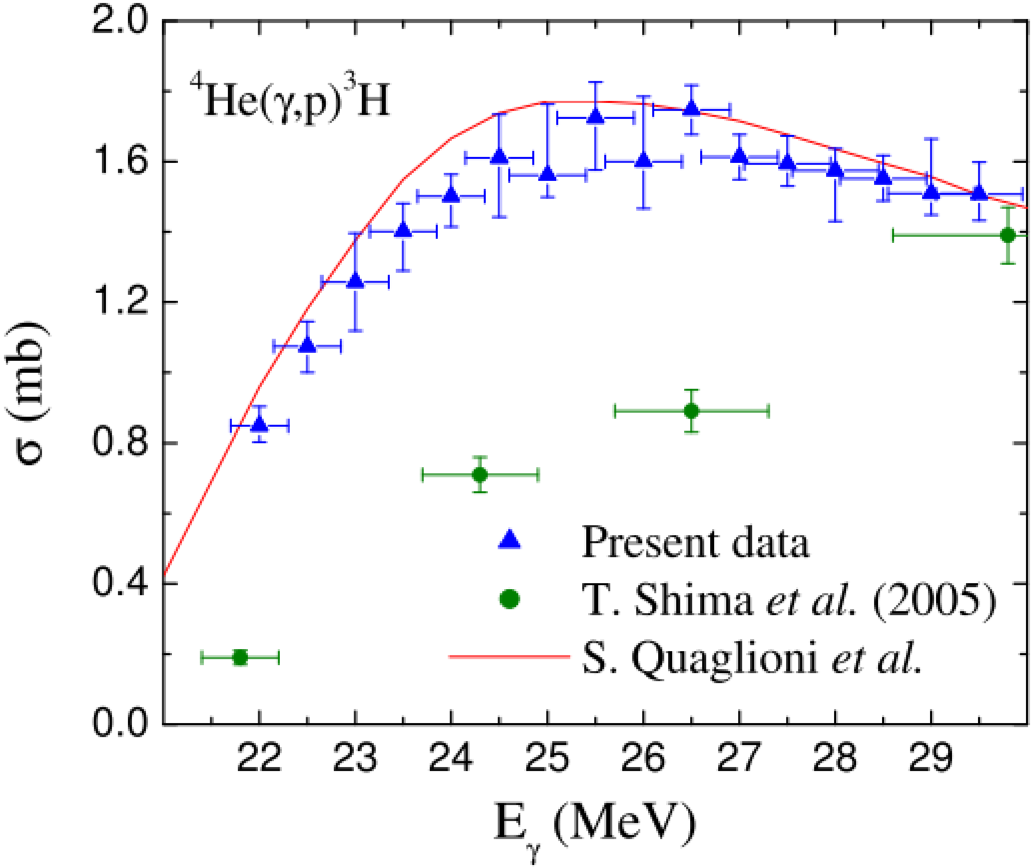
Photon-induced reaction thresholds (in MeV) on magnesium isotopes

Isotope	Nat. Abundance (%)	(γ,p)	(γ,α)	(γ,n)	$(\gamma,2n)$	$(\gamma,n\alpha)$
24	78.99	11.69	9.31	16.53		
25	10.00	12.06	9.89	7.33		
26	11.01	14.15	10.61	11.09		

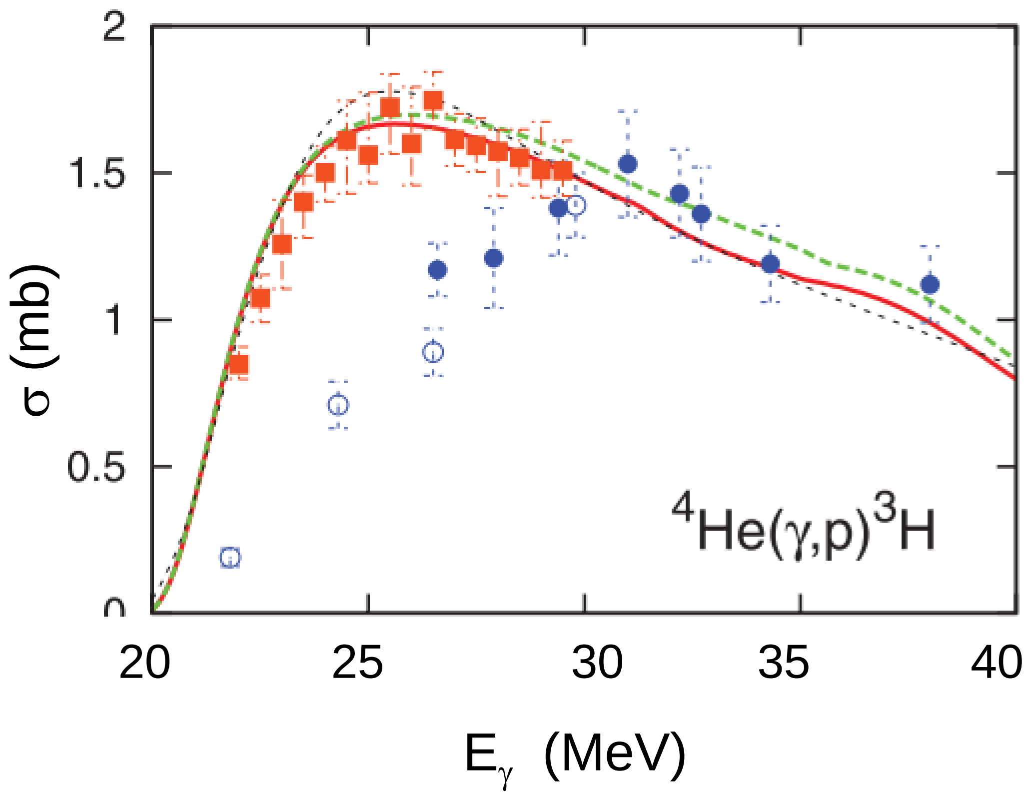
Photon-induced reaction thresholds (in MeV) on oxygen isotopes

Isotope	Nat. Abundance (%)	(γ,p)	(γ,α)	(γ,n)	(γ,2n)	(γ,nα)
16	99.762	12.13	7.16	15.67		
17	0.038	13.78	6.36	4.14		
18	0.200	15.94	6.23	8.05		


Compton scattered electrons
E_γ = 22 MeV
(a)
^{4}He (47.6 atm) + Xe (3.4 atm) Target
^{4}He(γ,p)^{3}H
Counts
Compton scattered electrons
E_γ = 22 MeV
(b)
Xe (3.4 atm) Target
Channel Number
Compton scattered electrons
^{4}He(γ,p)^{3}H
E_γ = 28 MeV
(c)
^{4}He (27.2 atm) + Xe (23.8 atm) Target
Counts
Compton scattered electrons
E_γ = 28 MeV
(d)
Xe (23.8 atm) Target
Channel Number



$^4He(\gamma,p)^3H$
2.0
1.6
1.2
0.8
0.4
0.0
σ (mb)
22
23
24
25
26
27
28
29
E_γ (MeV)
Present data
T. Shima *et al.* (2005)
S. Quaglioni *et al.*



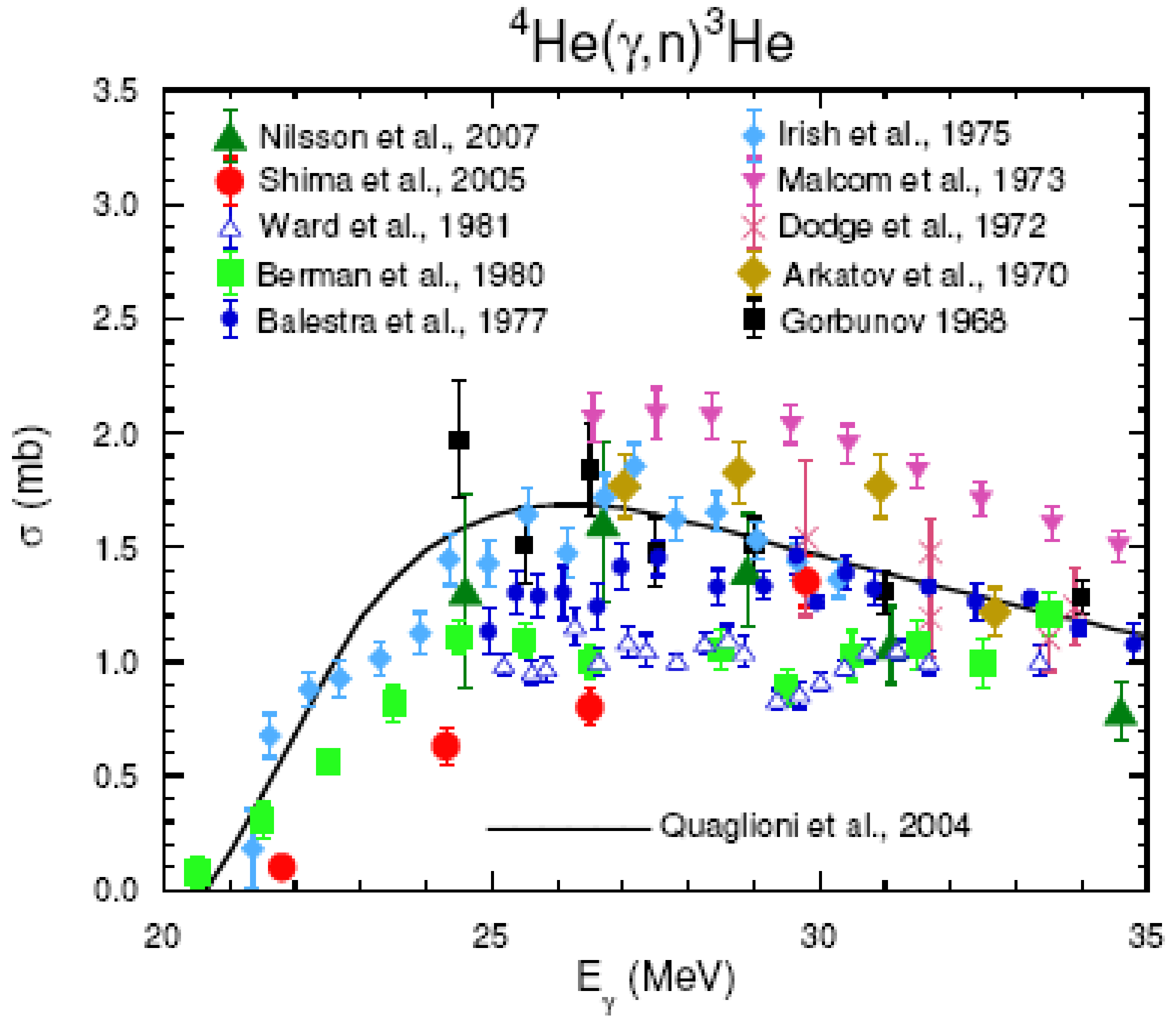
Circles: old data of Shima et al.
Dots: new data of Shima et al.

W. Horiuchi
Y. Suzuki
K. Arai

Solid: AV8'
Dashed: G3RS + 3NF (Tamagaki)
Dotted: LIT with Malfliet Tjon

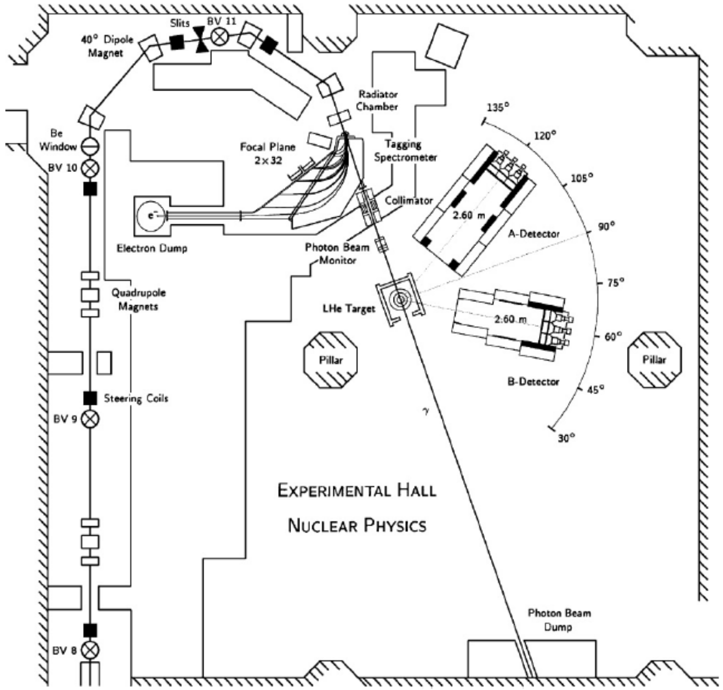
$^{4}He(\gamma,{}^{3}He)n$

Trento Group: G. Orlandini, W. Leidemann, S. Quaglioni, N. Barnea, V.D. Efros,
Lorentz integral transform method, final-state interaction and Coulomb included, MTI-III



MAX – lab at Lund, Sweden

Bremsstrahlung tagging technique

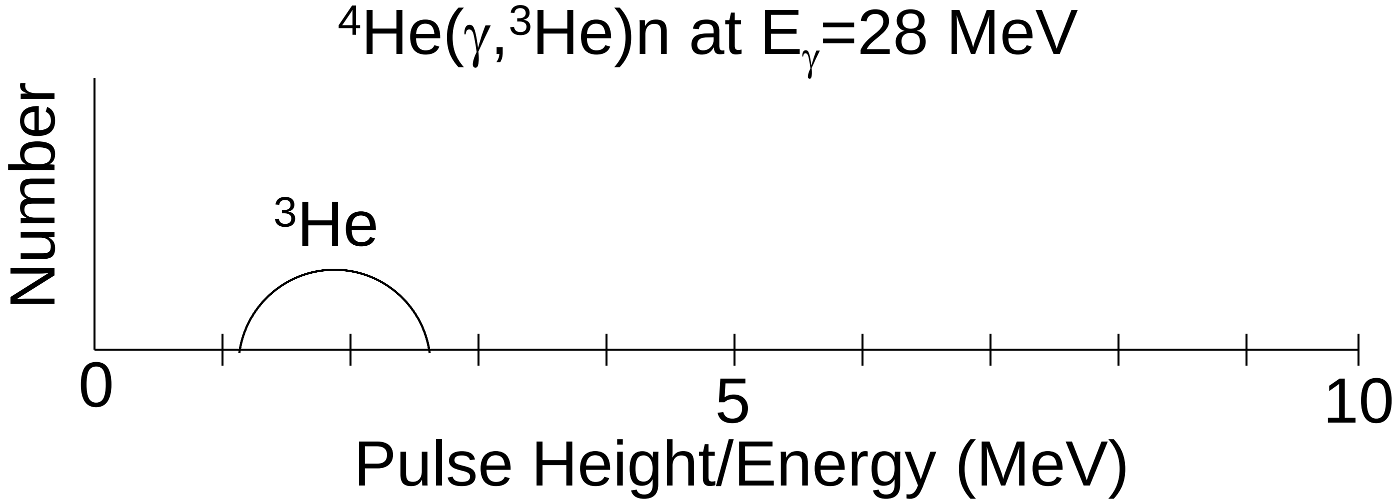


$^4He(\gamma,n)^3He$

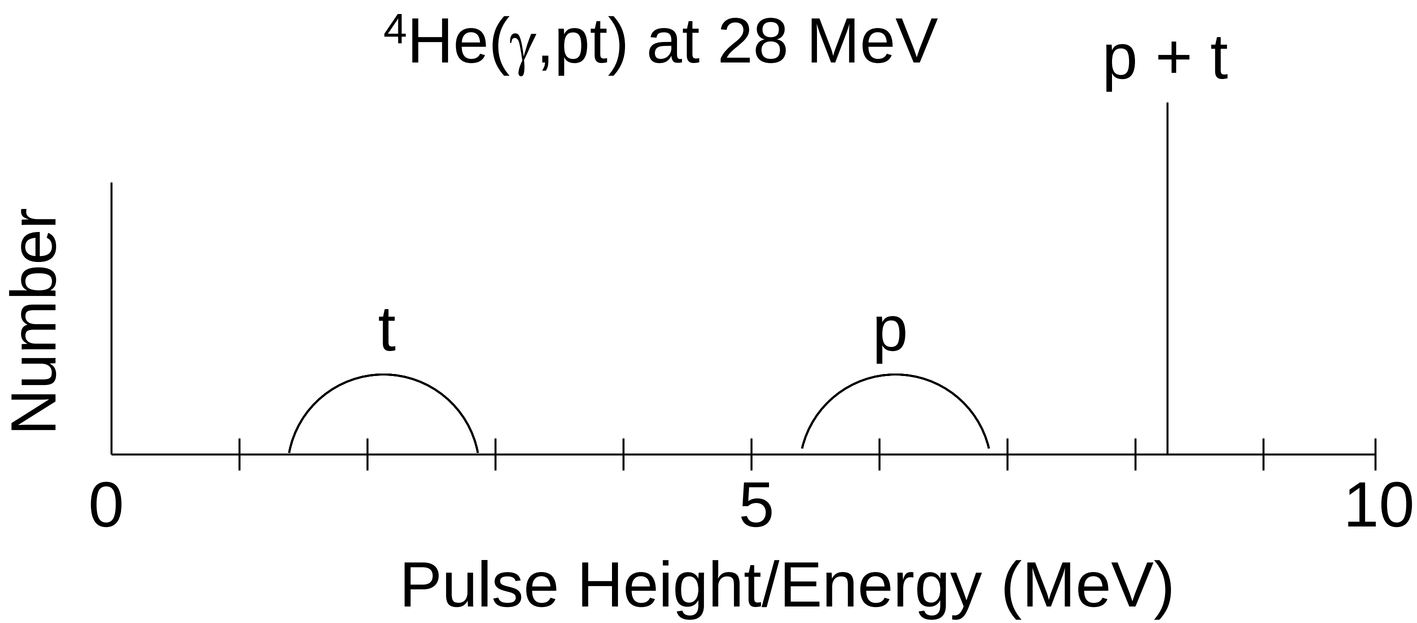
Neutron detectors

~300 keV γ-ray energy width

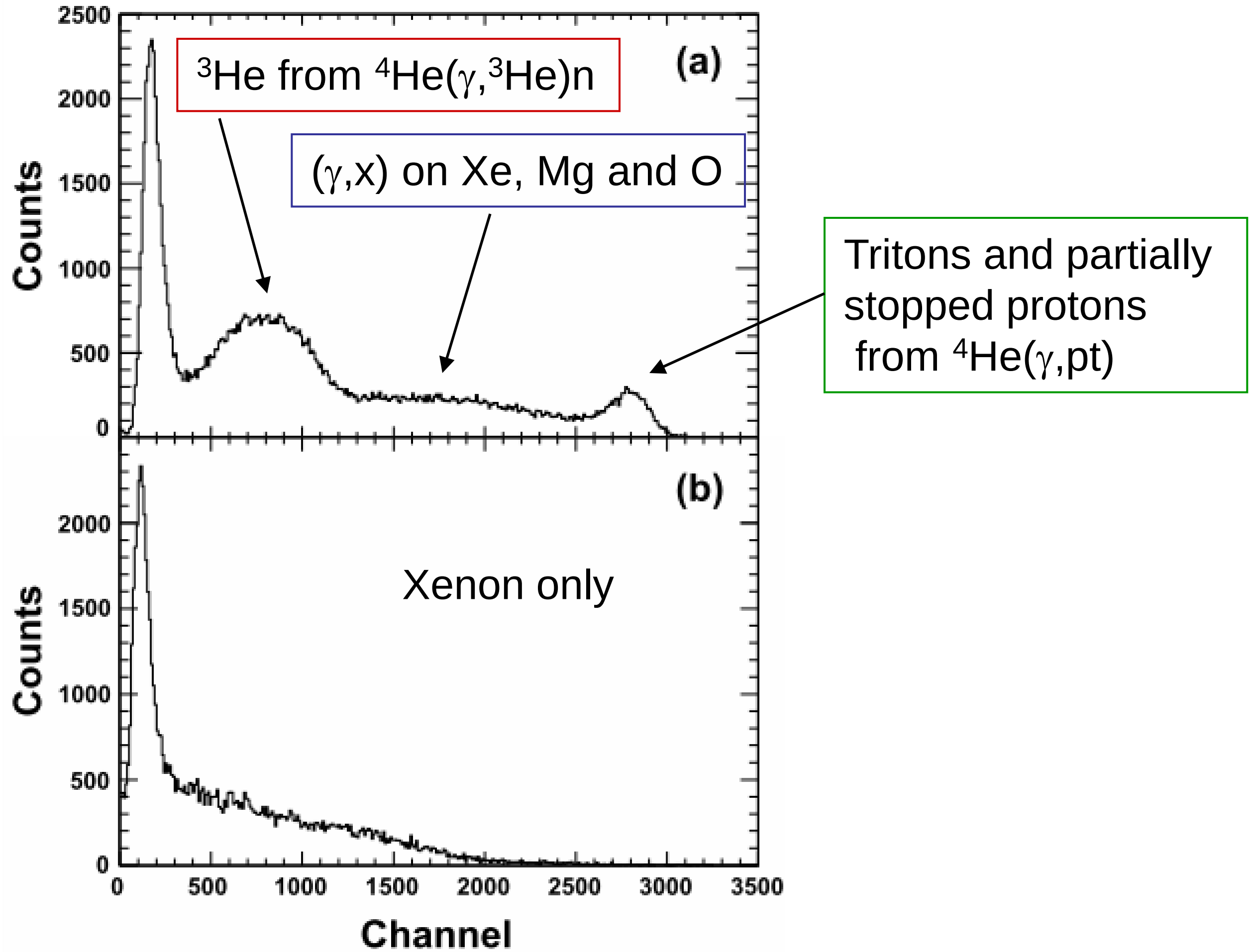
10^5 γ rays per second



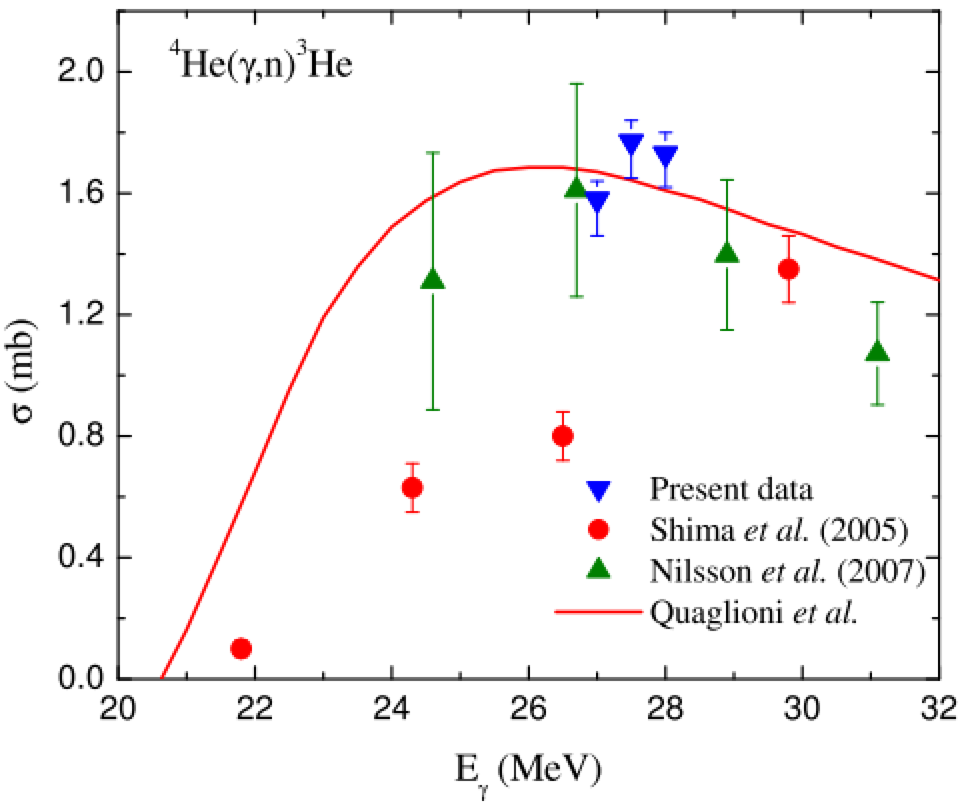
$^4He(\gamma,^3He)n$ at E_γ=28 MeV
Number
^3He
0
5
10
Pulse Height/Energy (MeV)



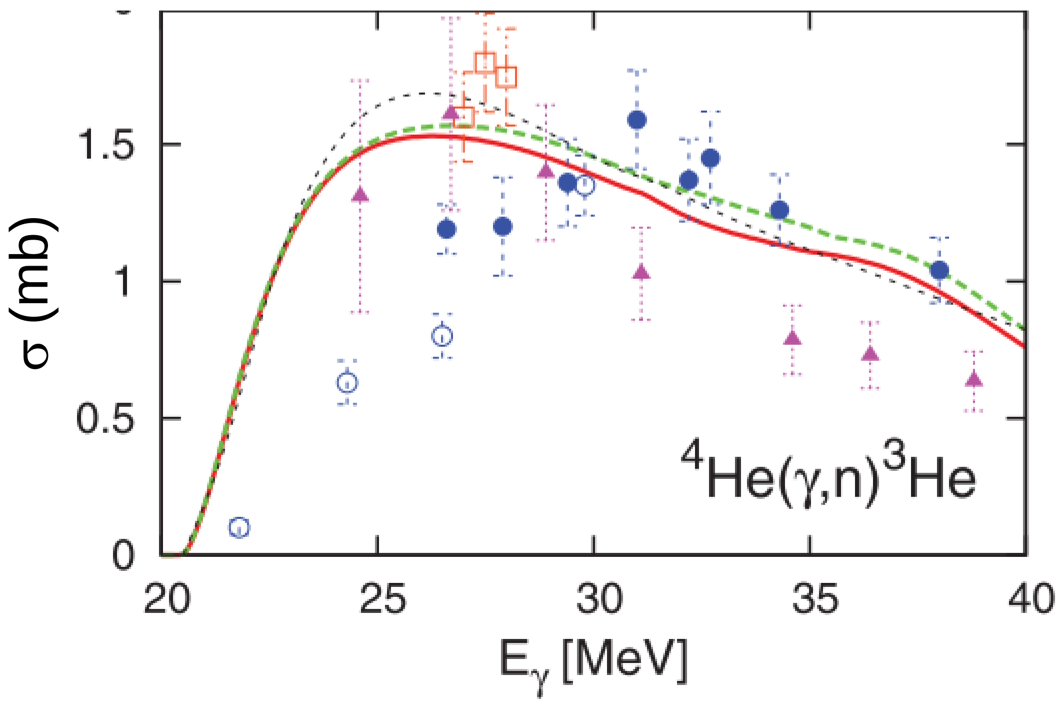
$^4He(\gamma,pt)$ at 28 MeV
p + t
Number
t
p
0
5
10
Pulse Height/Energy (MeV)



2500
2000
1500
1000
500
0
Counts
(a)
³He from ⁴He(γ,³He)n
(γ,x) on Xe, Mg and O
Tritons and partially stopped protons from ⁴He(γ,pt)
(b)
Xenon only
0
500
1000
1500
2000
2500
3000
3500
Channel



$^{4}He(\gamma,n)^{3}He$
σ (mb)
2.0
1.6
1.2
0.8
0.4
0.0
20
22
24
26
28
30
32
E_{γ} (MeV)
Present data
Shima *et al.* (2005)
Nilsson *et al.* (2007)
Quaglioni *et al.*



Circles: old data of Shima et al.
Dots: new data of Shima et al.
Triangles: Nilsson et al.

W. Horiuchi
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K. Arai

Solid: AV8' = 3NF
Dashed: G3RS + 3NF
Dotted: LIT Malfliet-Tjon

What's next ?

$^3H(\gamma,p)2n$

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

Di-neutron and the three-nucleon continuum observables

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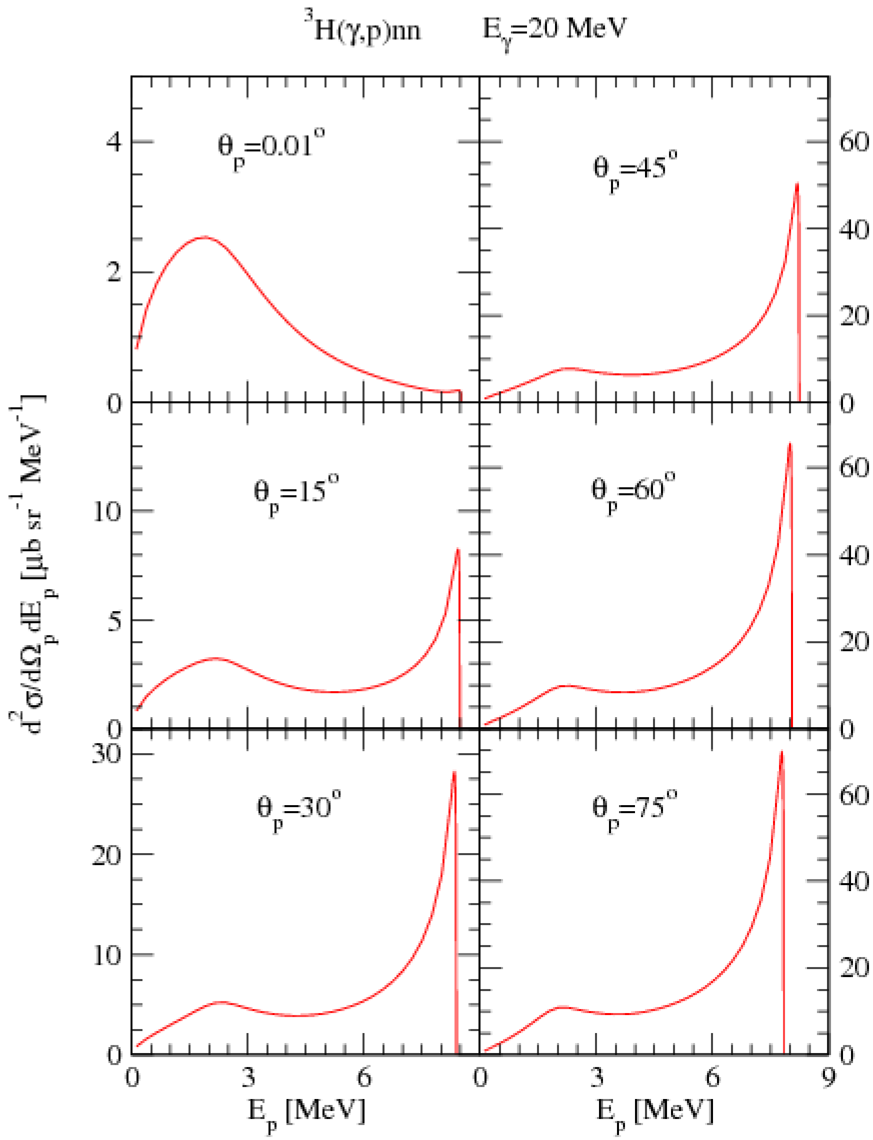
(Received 24 April 2012; published 25 June 2012)

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.

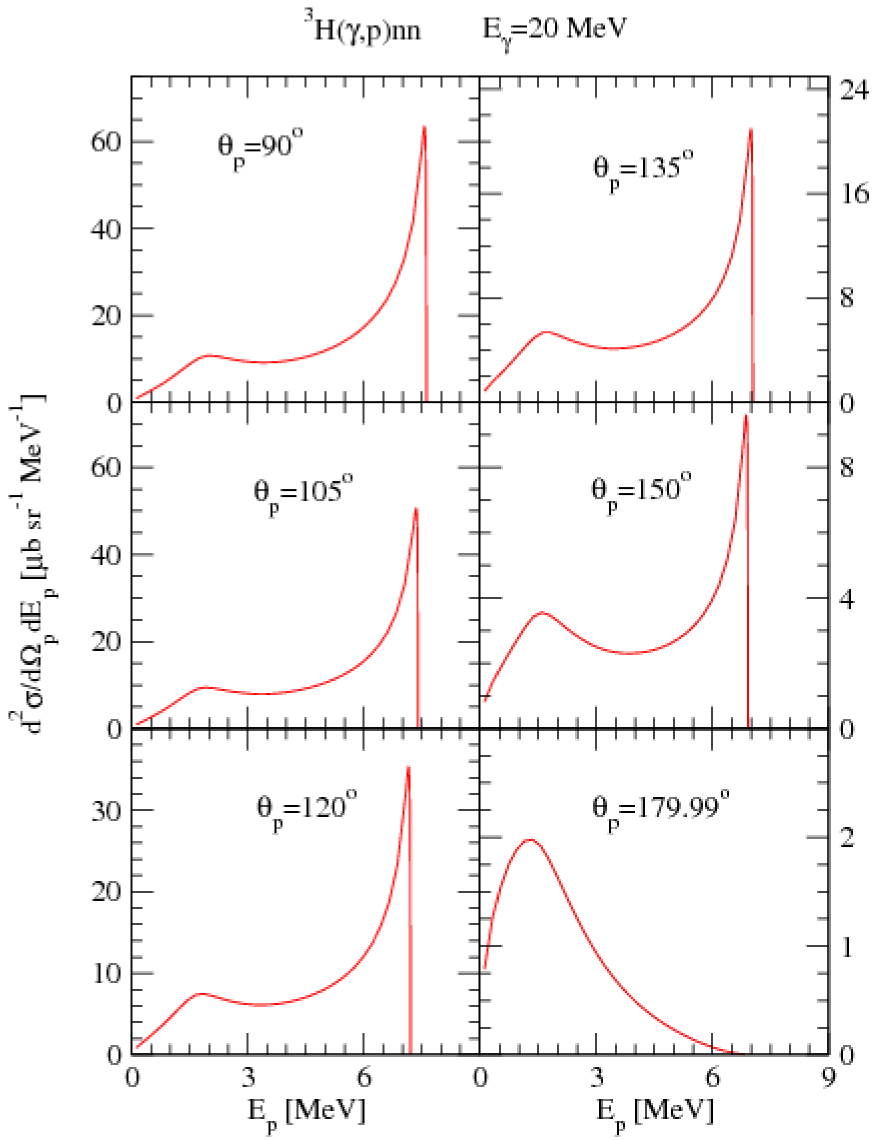
DOI: 10.1103/PhysRevC.85.064003 PACS number(s): 21.45.Bc, 25.10.+s, 25.40.Dn

TABLE I. The di-neutron binding energy ϵ_{nn}, the nn scattering length a_{nn}, and the effective range parameter r_{eff} for different factors λ by which the nn $^1S_0$ component of the CD Bonn potential was multiplied.

λ	ϵ_{nn} [MeV]	a_{nn} [fm]	r_{eff} [fm]
0.9	–	−8.25	3.12
1.0	–	−18.80	2.82
1.19	−0.099	+21.69	2.39
1.21	−0.144	+18.22	2.35
1.3	−0.441	+10.95	2.20
1.4	−0.939	+7.87	2.07



$^3H(\gamma,p)nn$ E_γ=20 MeV
θ_p=0.01°
θ_p=45°
θ_p=15°
θ_p=60°
θ_p=30°
θ_p=75°
$d^2\sigma/d\Omega_p dE_p$ [μb sr^{-1} MeV^{-1}]
E_p [MeV]
E_p [MeV]



3H(γ,p)nn E_γ=20 MeV
θ_p=90°
θ_p=135°
θ_p=105°
θ_p=150°
θ_p=120°
θ_p=179.99°
d²σ/dΩ_p dE_p [μb sr⁻¹ MeV⁻¹]
E_p [MeV]
E_p [MeV]

Changing Topics:

$A_y(\theta)$ in $^3He(n,n)^3He$ and Comparison to $^3He(p,p)^3He$ at Low Energies

p – ^{3}He

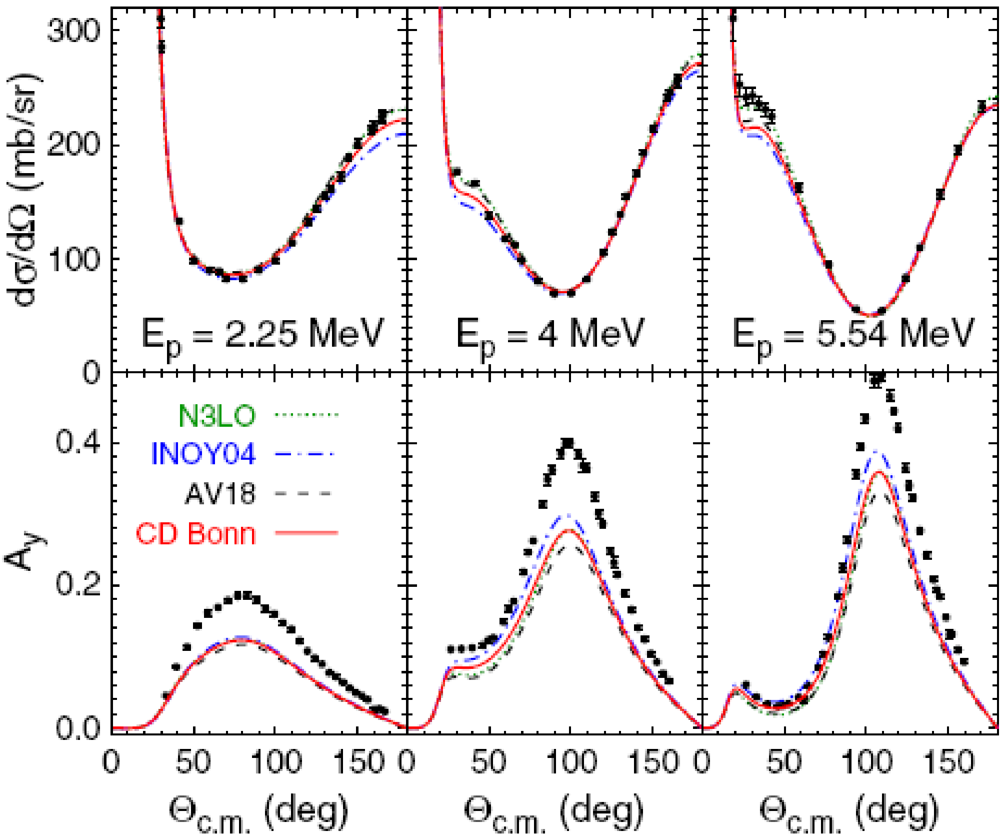
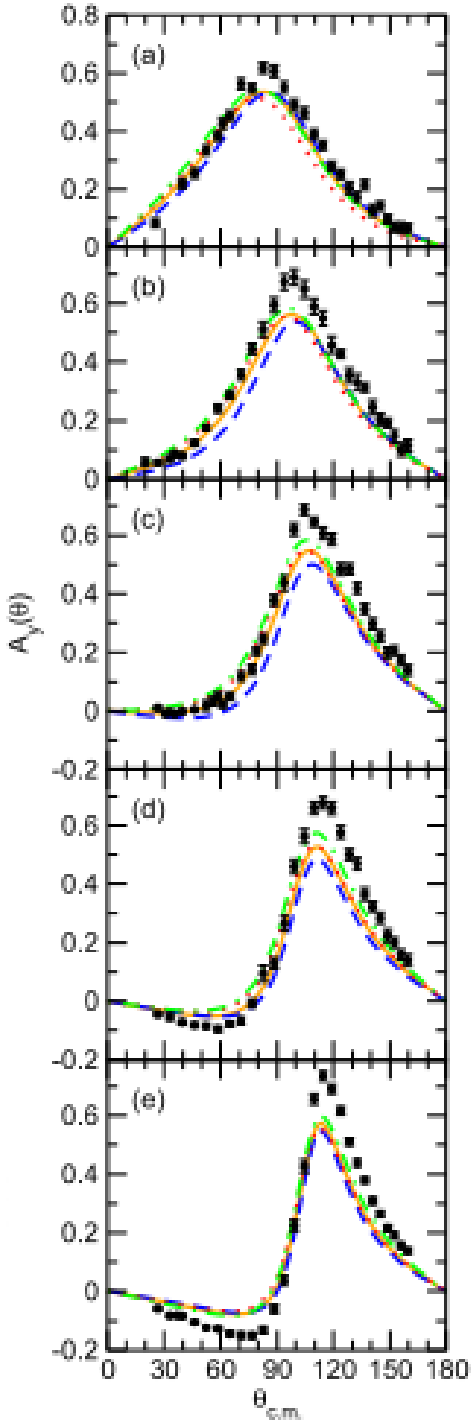


FIG. 2 (color online). The differential cross section and proton analyzing power A_y at 2.25, 4.0, and 5.54 MeV proton lab energy. Results including the Coulomb interaction obtained with potentials CD Bonn (solid curves), AV18 (dashed curves), INOY04 (dashed-dotted curves), and N3LO (dotted curves) are compared. The data are from Refs. [22,32,33].

A. Deltuva and A. Fonseca (Lisbon)



E_n=1.60 MeV

E_n=2.26 MeV

E_n=3.14 MeV

E_n=4.05 MeV

E_n=5.54 MeV

Data: $^3He(n,n)^3He$
J.H. Esterline

Dashed blue: AV18

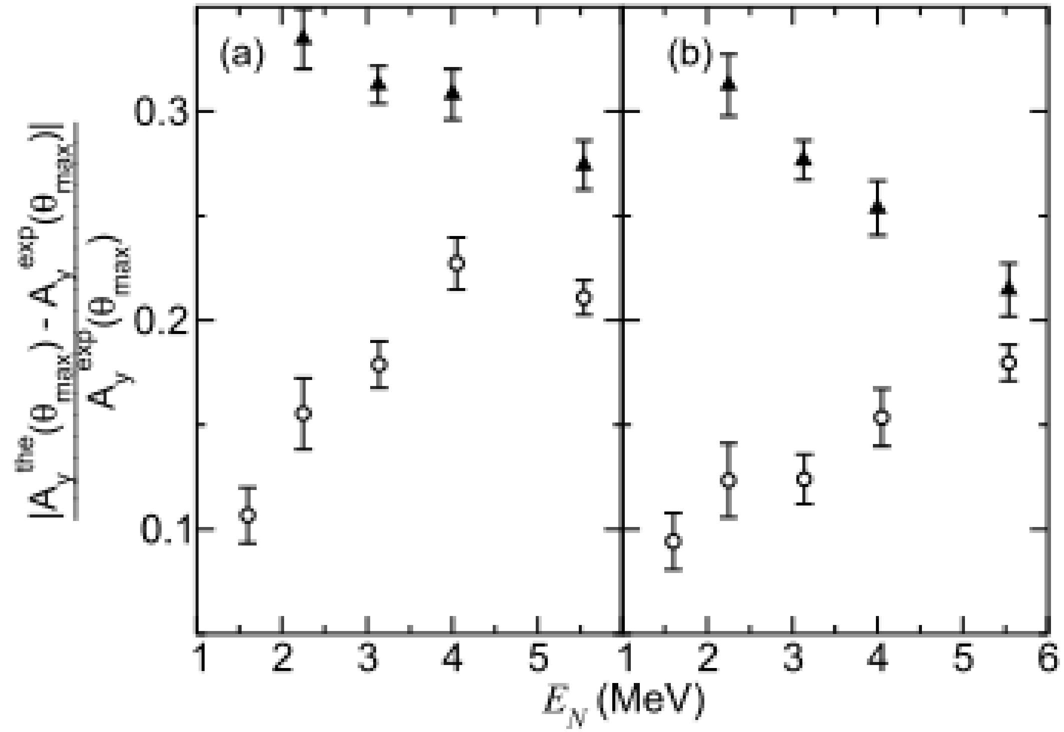
Solid orange: CD-Bonn

Dotted red: CD-Bonn + Δ

Dashed-dotted green: INOY04

Calculations:
A. Deltuva & A. Fonseca

Triangles: $^3He(p,p)^3He$
Circles: $^3He(n,n)^3He$



CD-Bonn INOY04 (Doleschall)

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