Experimental Status of Neutral-Pion Photoproduction from Nuclei in the Threshold Region

$E_\gamma \cong 140 - 170$ MeV

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Outline

Why (γ, π^0) near threshold?

- ChPT
- Multipoles

The status of the proton.

Pursuing the neutron amplitude via the deuteron.

- Coherent: d(γ, π^0)d
- 'Quasi-free': d(γ, π^0 n)p

'Complex' nuclei

- ... from helium to lead

Chiral Perturbation Theory

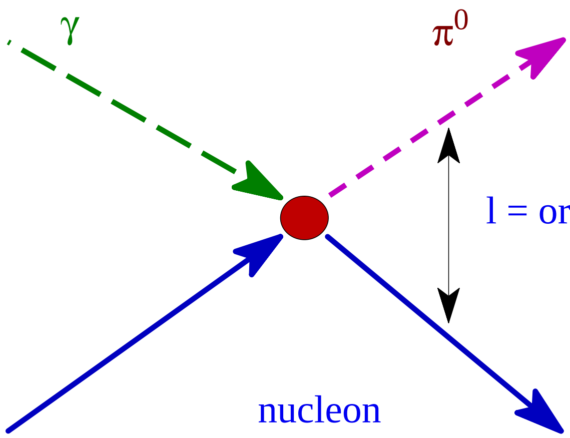
A systematic low-energy expansion about the Chiral Limit (i.e. zero quark mass).

Employs the symmetries of the Standard Model to formulate an Effective Field Theory.

Therefore CHPT is a direct consequence of the Standard Model

Provides a mechanism for testing QCD at low energies.

π^0 Photoproduction Near Threshold



Multipole amplitudes:

l = 0	E_{0+}	S-wave
l = 1	M_{1+} M_{1-} E_{1+}	P-wave

At threshold:

S-wave is finite.

P-waves vanish ~ q. (q = π^0 momentum)

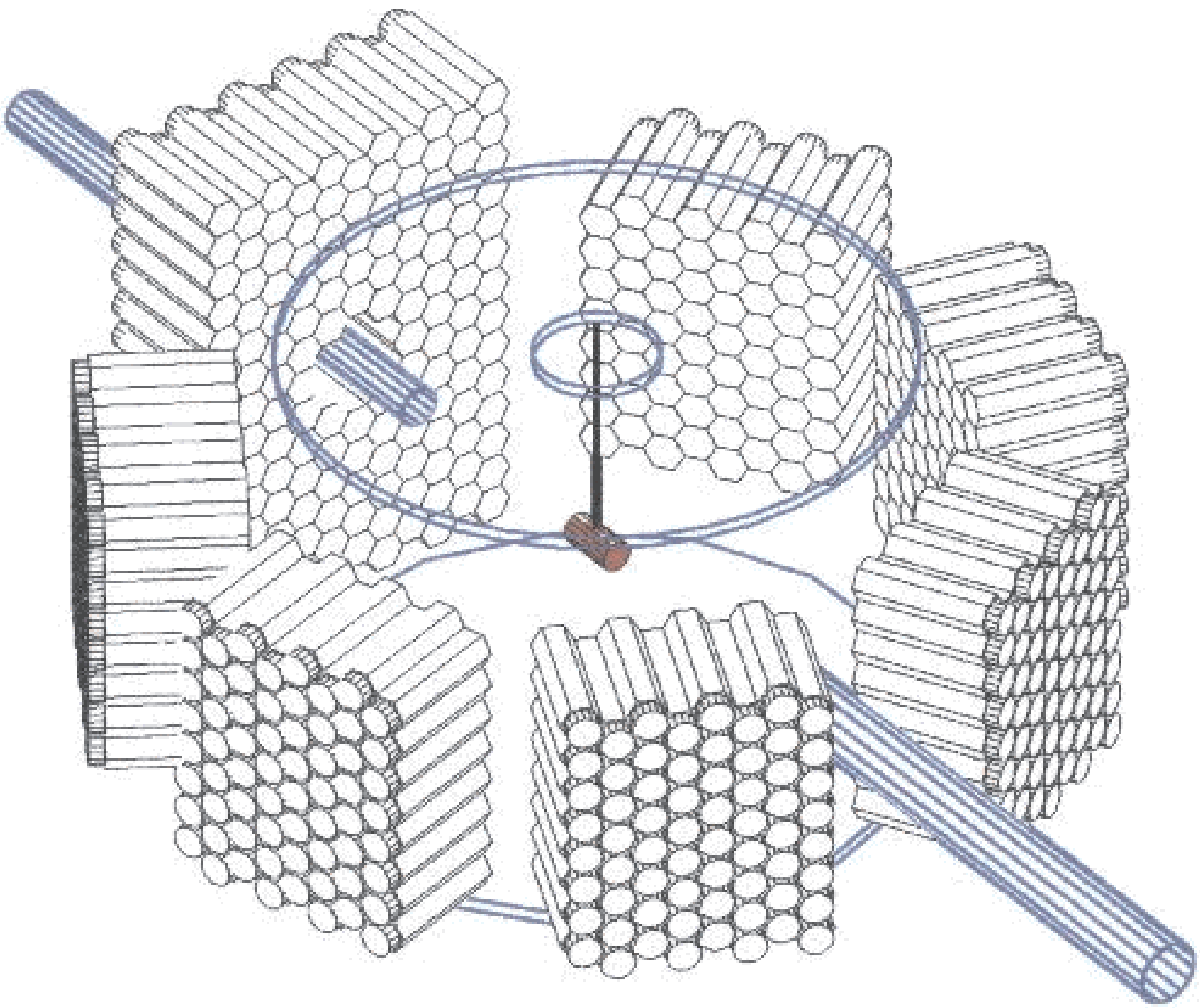
$d\sigma/d\Omega = q/k \, |E_{0+}|^2$ (k = photon energy)

E_{0+} vanishes in the Chiral limit.
Therefore
E_{0+} is very sensitive to Chiral Symmetry Breaking

TAPS π^0 Spectrometer

522 BaF_2 modules with individual vetos.

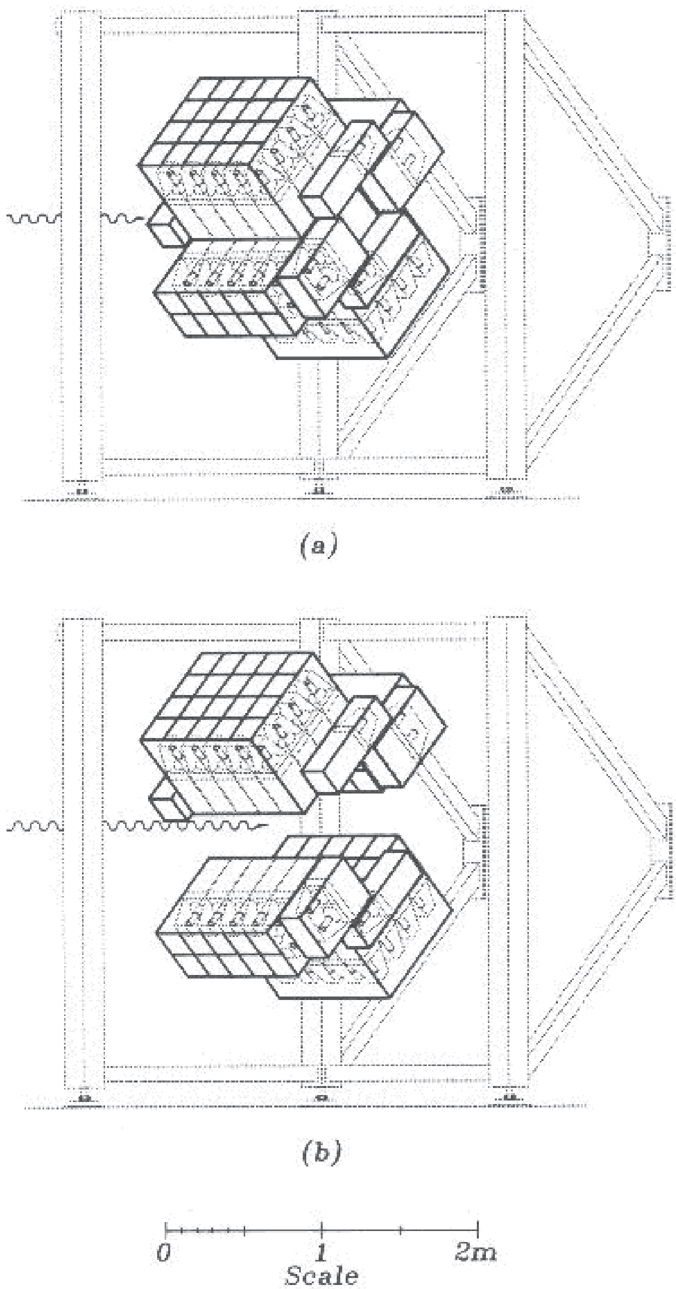
Efficiency $\leq$ 10% near threshold.



Igloo π^0 Spectrometer

68 lead-glass blocks (no vetos).

Efficiency ≤ 84% near threshold (closed).



At Threshold: Status of E_{0+}

(units of $10^{-3} / m_{\pi^+}$)

Reaction	CHPT	DR	LET	Expt
$p\,\pi^0$	−1.16	−1.22	−2.47	−1.33 ± 0.08
$n\,\pi^0$	+2.13	+1.19	+0.69	
$p\,\pi^-$	−32.7 ± 0.6	−31.7 ± 0.2	−31.7	−31.5 ± 0.8
$n\,\pi^+$	+28.2 ± 0.6	+28.0 ± 0.2	+27.6	+28.1 ± 0.3

CHPT: V. Bernard, N. Kaiser, U.-G. Meiβner, Z. Phys. **C70** (1996) 483.

DR: O. Hanstein, D. Drechsel, L. Tiator, PLB **399** (1997) 13.

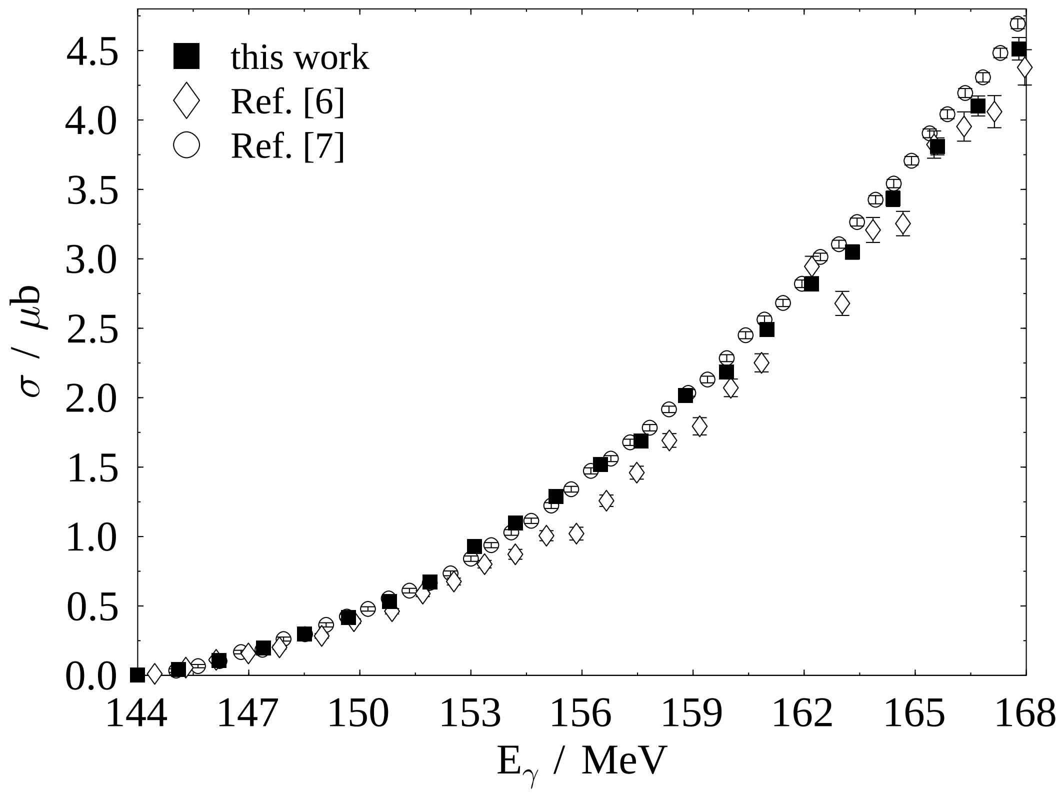
$p\,\pi^0$: A. Schmidt *et al.*, PRL **87** (2001) 232501.

$p\,\pi^-$: M. A. Kovash *et al.*, πN Newsletter **12** (1997) 51.

$n\,\pi^+$: E. Korkmaz *et al.*, PRL **83** (1999) 3609.

Latest results on p(γ, π⁰)p from Mainz

total cross section



this work: A. Schmidt *et al*., PRL **87** (2001) 232501.

Ref. [6]: M. Fuchs *et al*., PLB **368** (1996) 20.

Ref. [7]: J.C. Bergstrom *et al*., PRC **53** (1996) R1052; ibid, **55** (1997) 2016.

Near Threshold: P−waves

In the near−threshold region, only s− and p−waves contribute:

$$\frac{d\sigma}{d\Omega_\pi}\left(k,\theta_\pi\right) = \frac{q}{k}\left[A + B\cos\theta_\pi + C\cos^2\theta_\pi\right]$$

where A, B, and C are functions of E_{0+} and the p-wave amplitudes p_1, p_2, and p_3.

$$p_1 = 3E_{1+} + M_{1+} - M_{1-}$$

$$p_2 = 3E_{1+} - M_{1+} + M_{1-}$$

$$p_3 = 2M_{1+} + M_{1-}$$

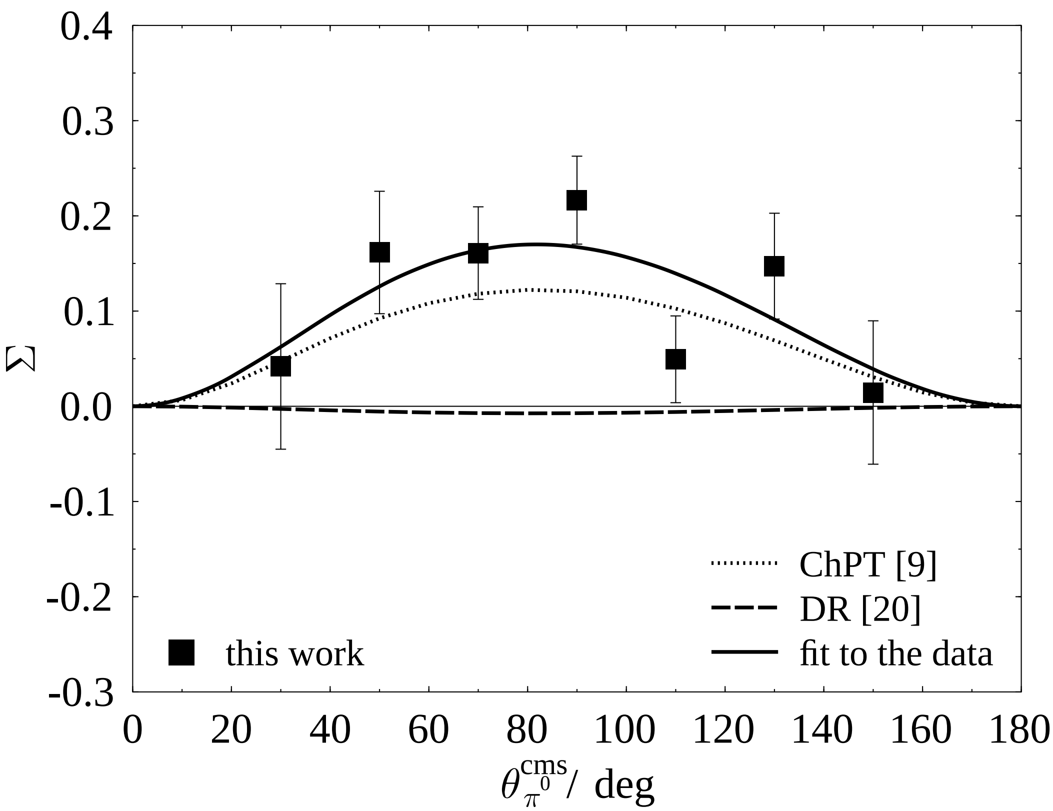
$$(p_{23})^2 = (p_2^2 - p_3^2)/2$$

With unpolarized photons can determine E_{0+} , p_1 , p_{23}.

Latest results on p(γ, π^0)p from Mainz

photon asymmetry

$$\Sigma(\theta)\frac{d\sigma}{d\Omega}=\frac{q}{2k}\left(p_3^2-p_2^2\right)\sin^2\theta$$



this work: A. Schmidt *et al.*, PRL **87** (2001) 232501.

Near Threshold: Status of P-waves

(units of $q \cdot 10^{-3} / m_{\pi^+}$)

Multipole	CHPT	DR	Mainz
p_1	9.14 ± 0.5	9.55	9.47±0.08±0.29
p_2	−9.7 ± 0.5	−10.37	−9.46±0.10±0.29
p_3	10.36*	9.27	11.48±0.06±0.35
p_{23}	11.07	9.84	10.52±0.06

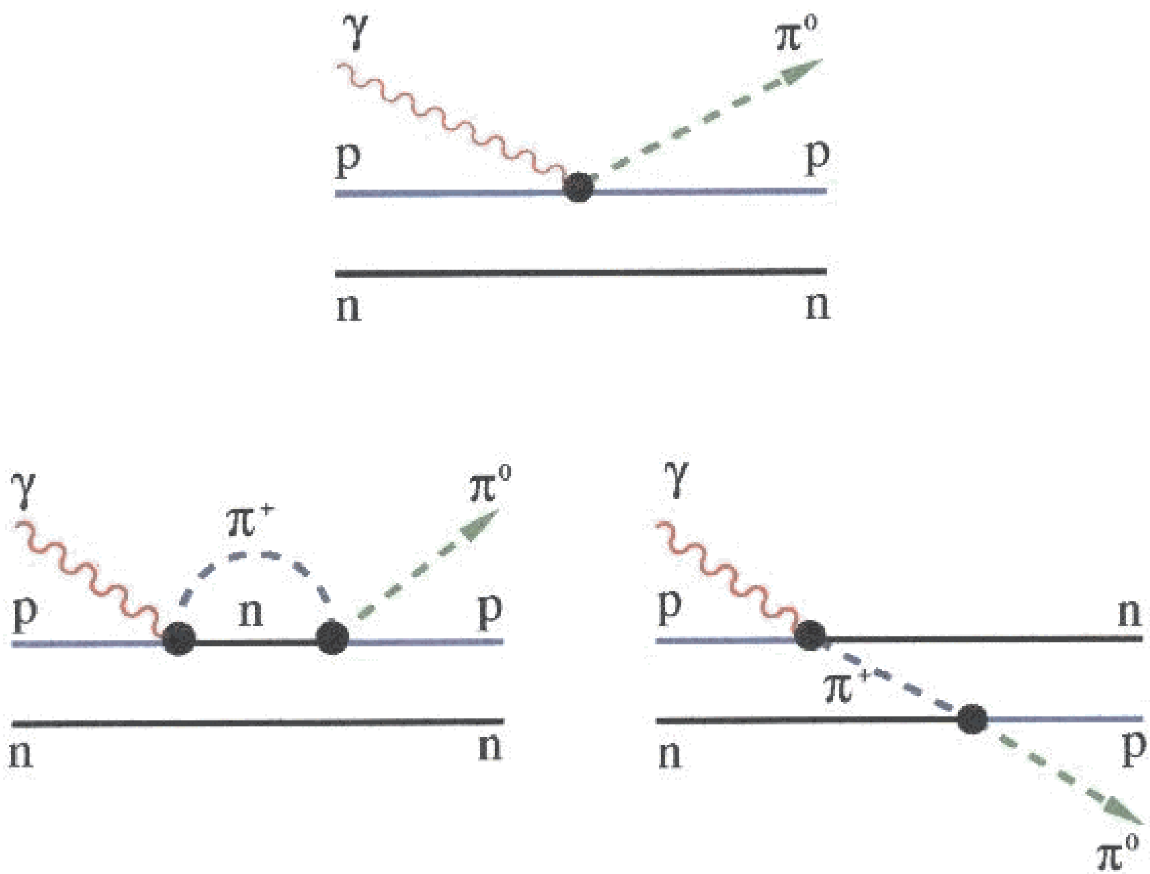
A. Schmidt *et al.*, PRL **87** (2001) 232501.

Note: p_3 is set by LEC b_p in CHPT.

Bernard, Kaiser, Meiβner, EPJA 11 (2001) 209.

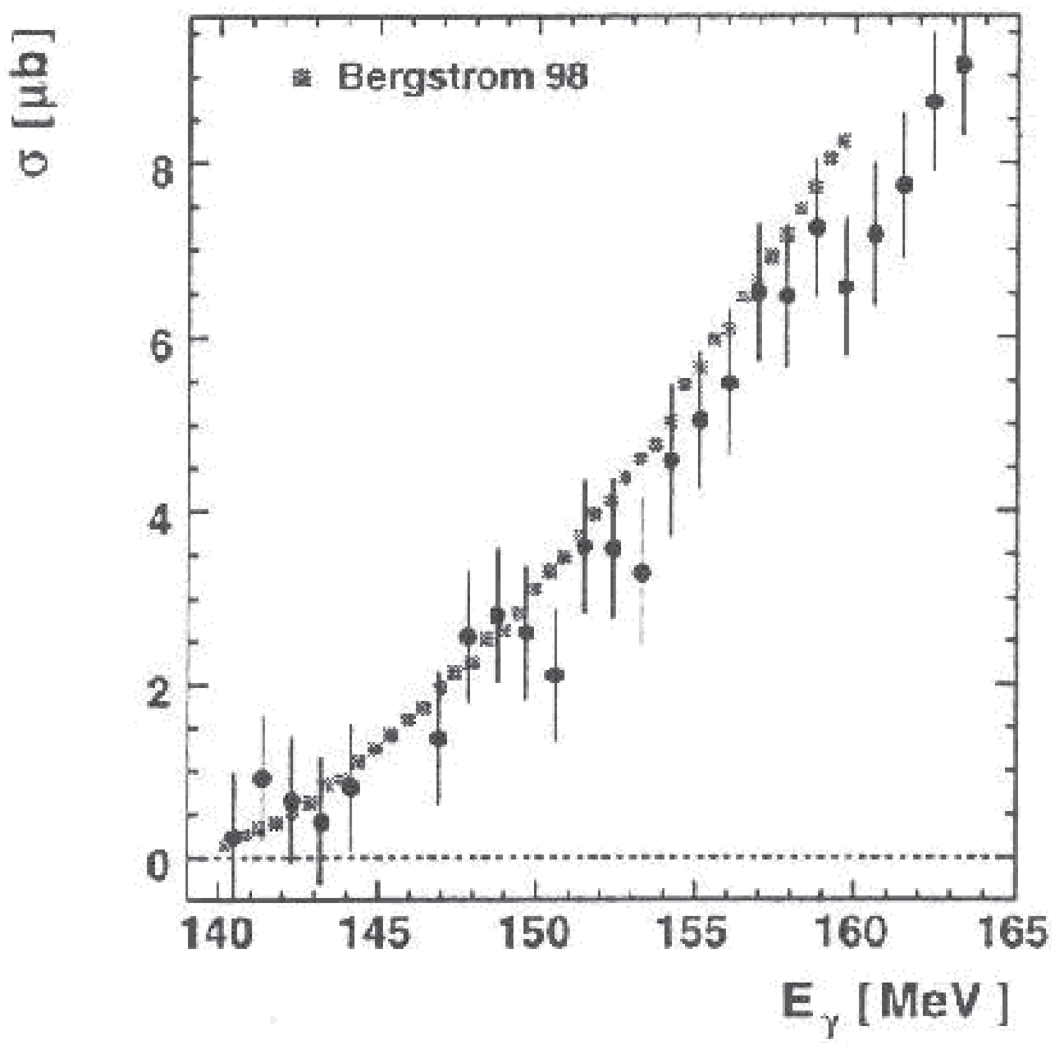
$d(\gamma, \pi^0)d$

A probe of neutron amplitudes (??)



Latest results on d(γ, π^0)X

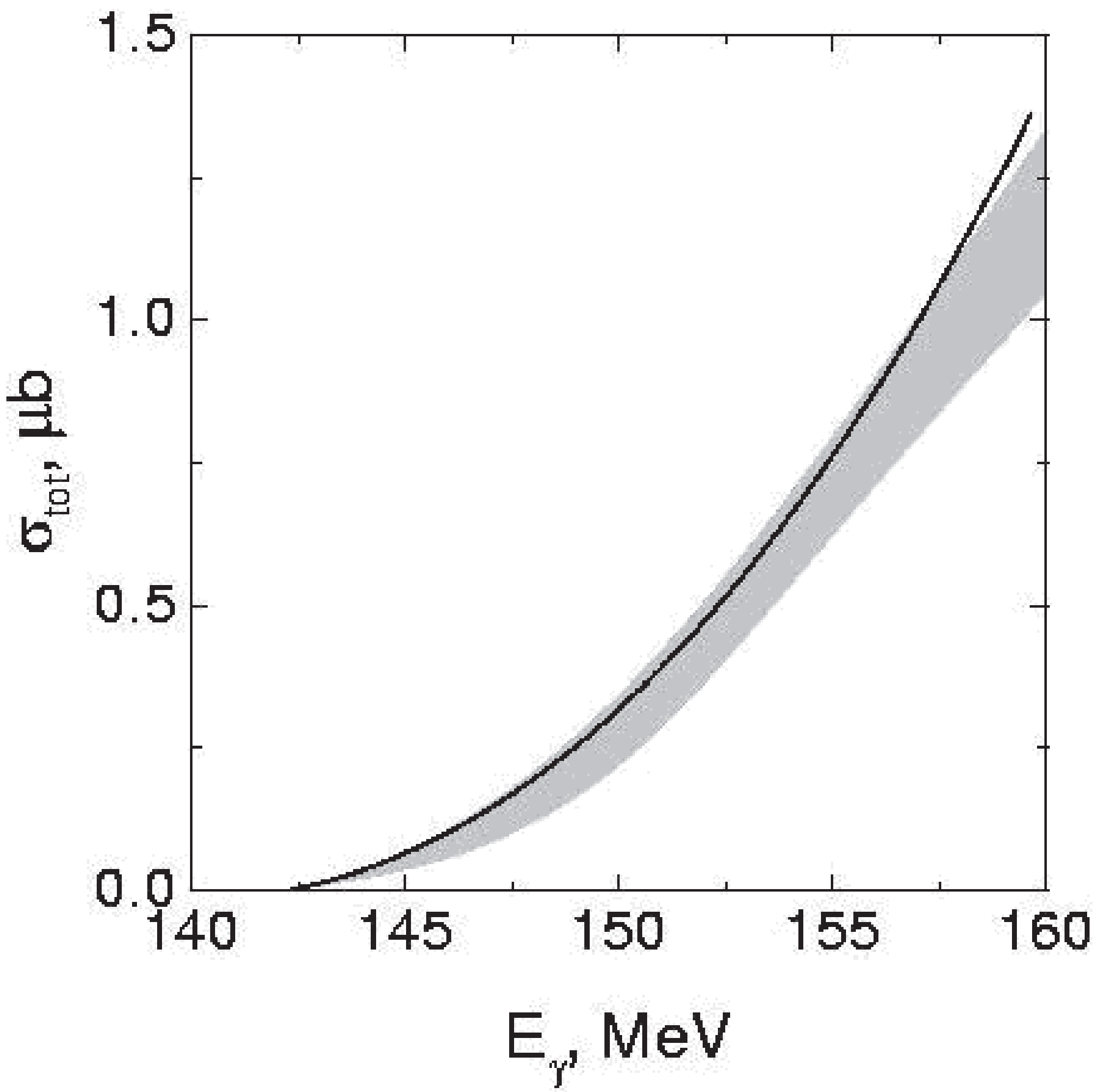
total cross section



Low stats: U. Siodlaczek *et al*., Eur. J. A **10** (2001) 365.

Hight stats: J.C. Bergstrom *et al*., PRC **57** (1998) 3203.

Contribution from d(γ, π^0)np



Shaded: Levchuk, Schumacher, Wissmann, NPA **675** (2000) 621.

Solid: Model calc. of J.C. Bergstrom *et al*., PRC **57.**

S-wave Amplitude from d(γ, π^0)d

Results for E_d:

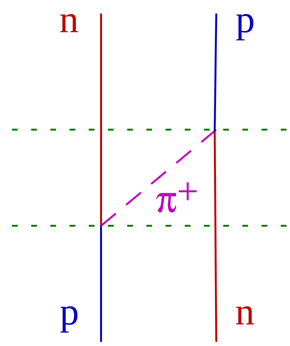
$E_{0+}(p\,\pi^0) + E_{0+}(n\,\pi^0)$	CHPT	Expt
+0.97	−1.8 ± 0.2	−1.45 ± 0.04

CHPT: S.R. Beane *et al.*, NPA **618** (1997) 381.
Expt: J.C. Bergstrom *et al.*, PR **C57** (1998) 3203.

Conclusions:

Rescattering effects are important! (also U. Siodlaczek *et al.*)

Rekalo and Tomasi-Gustafsson (nucl−th/0112063) suggest that rescattering effects vanish!

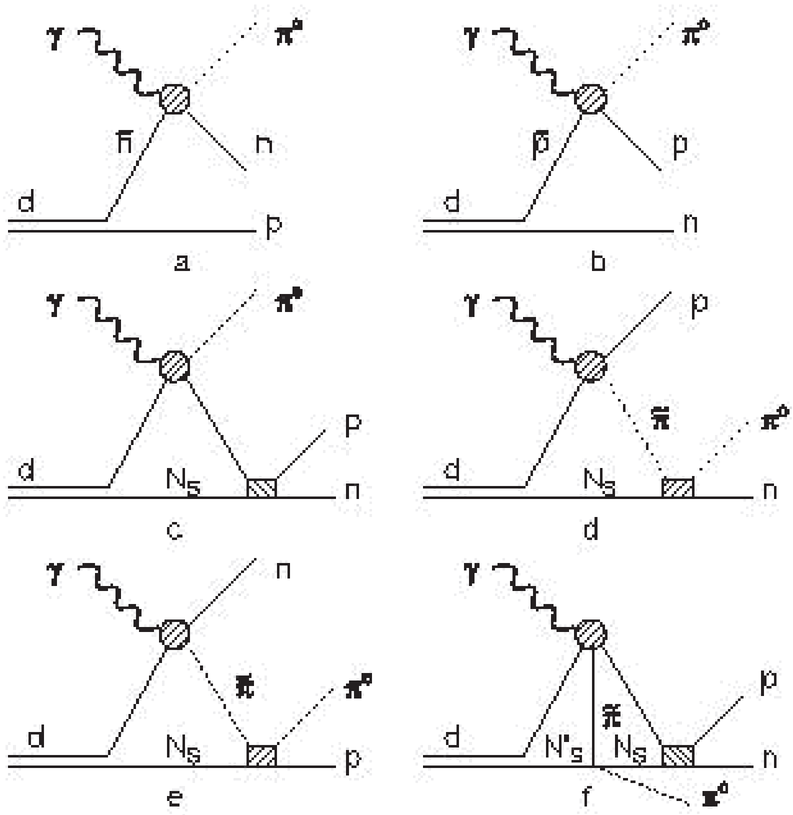


New measurement:

d(γ, π^0 n)p at Mainz to focus on the neutron amplitudes.

d(γ, π^0 n)p

A probe of neutron amplitudes(?)

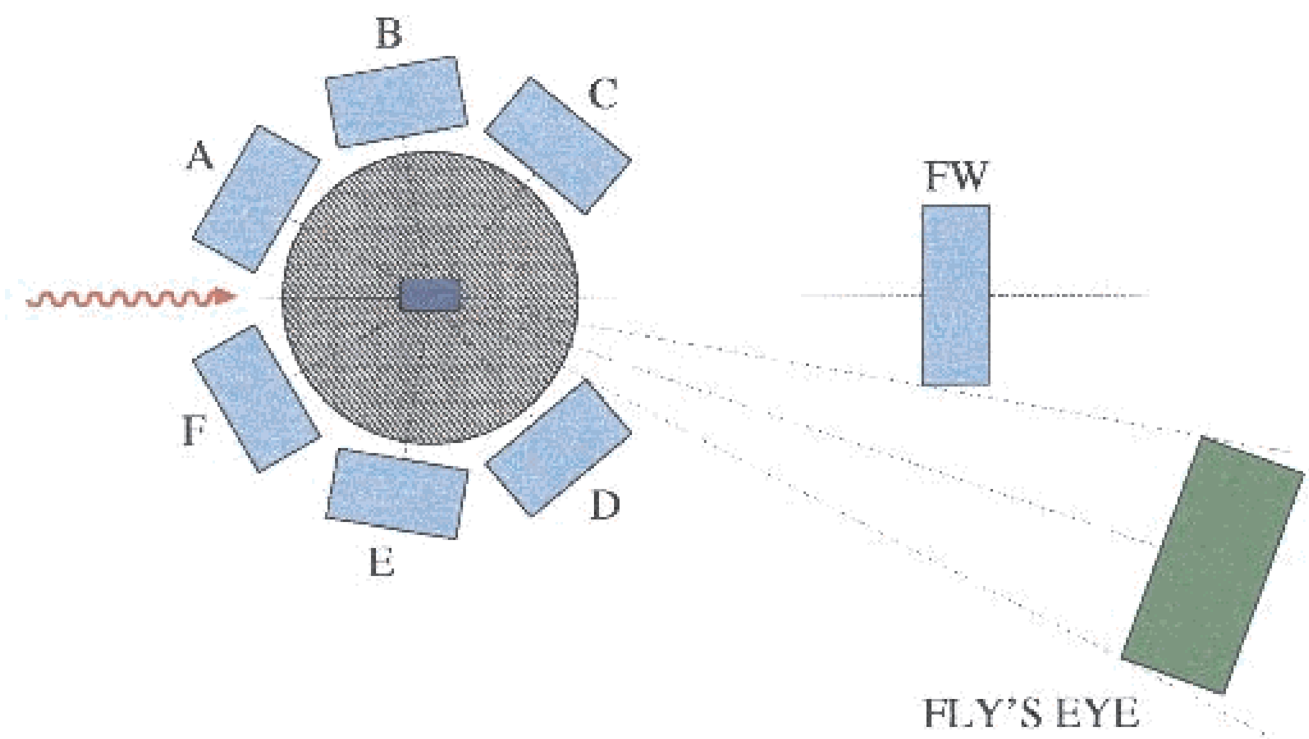


Levchuk, Schumacher, Wissmann, NPA **675** (2000) 621.

d(γ, π^0 n)p Experimental Setup

TAPS spectrometer plus parasitic neutron detector array (21°).

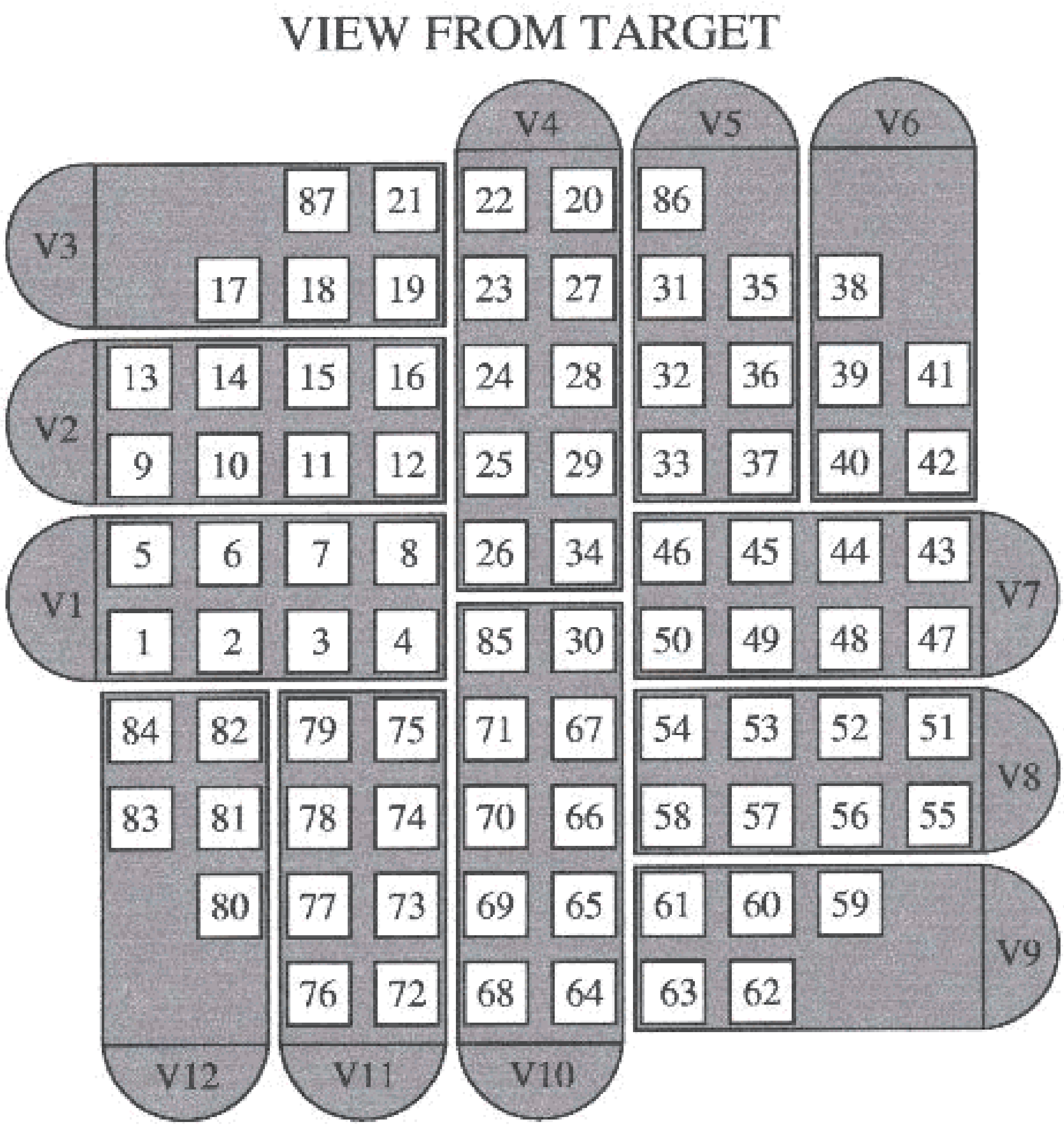
E_γ = 95 − 208 MeV.



d(γ, π ^{0} n)p Neutron Detector

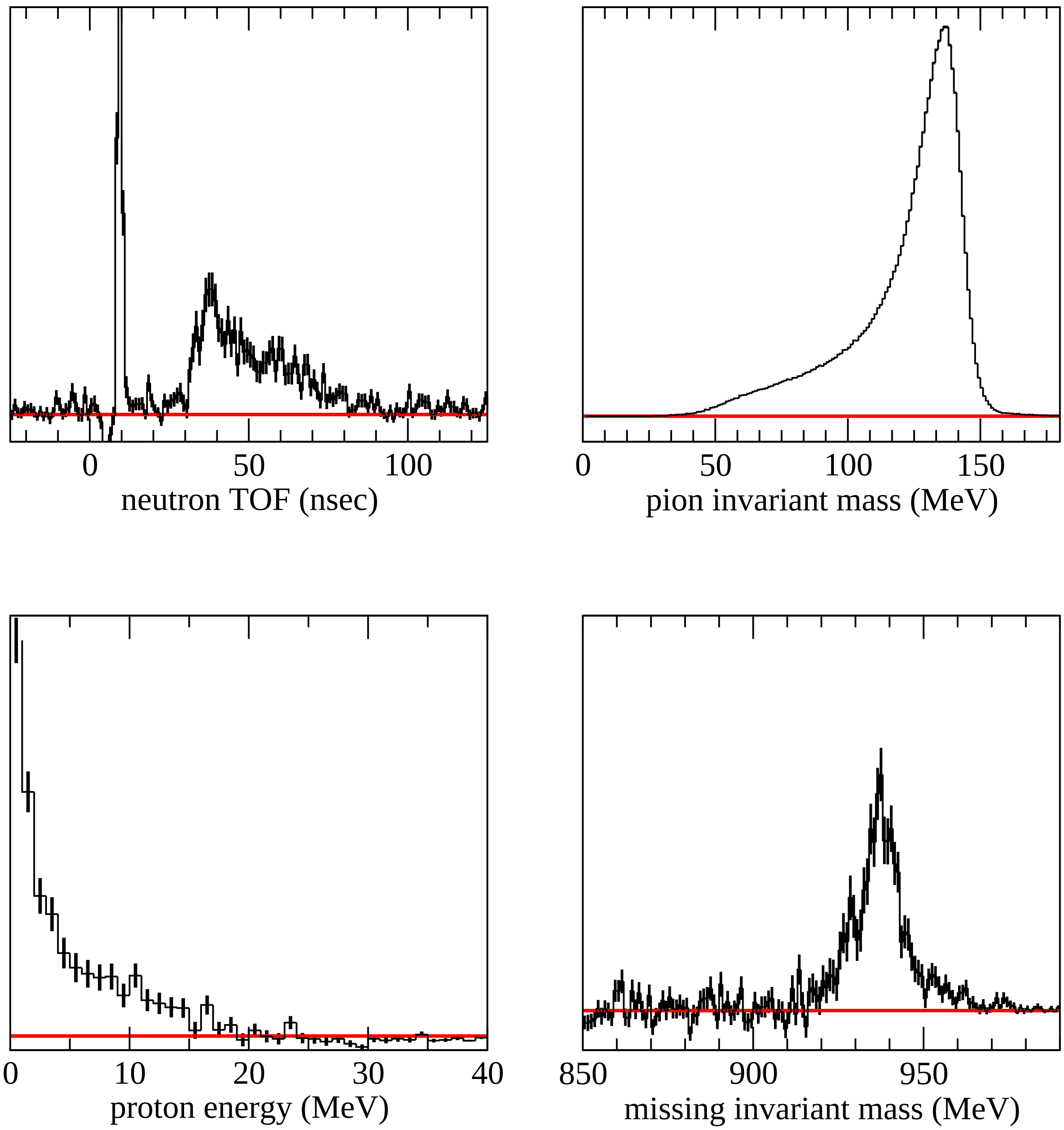
87 cells (BC−505) plus vetos.

7.6 × 7.6 × 6.4 cm^3 active volume per cell.



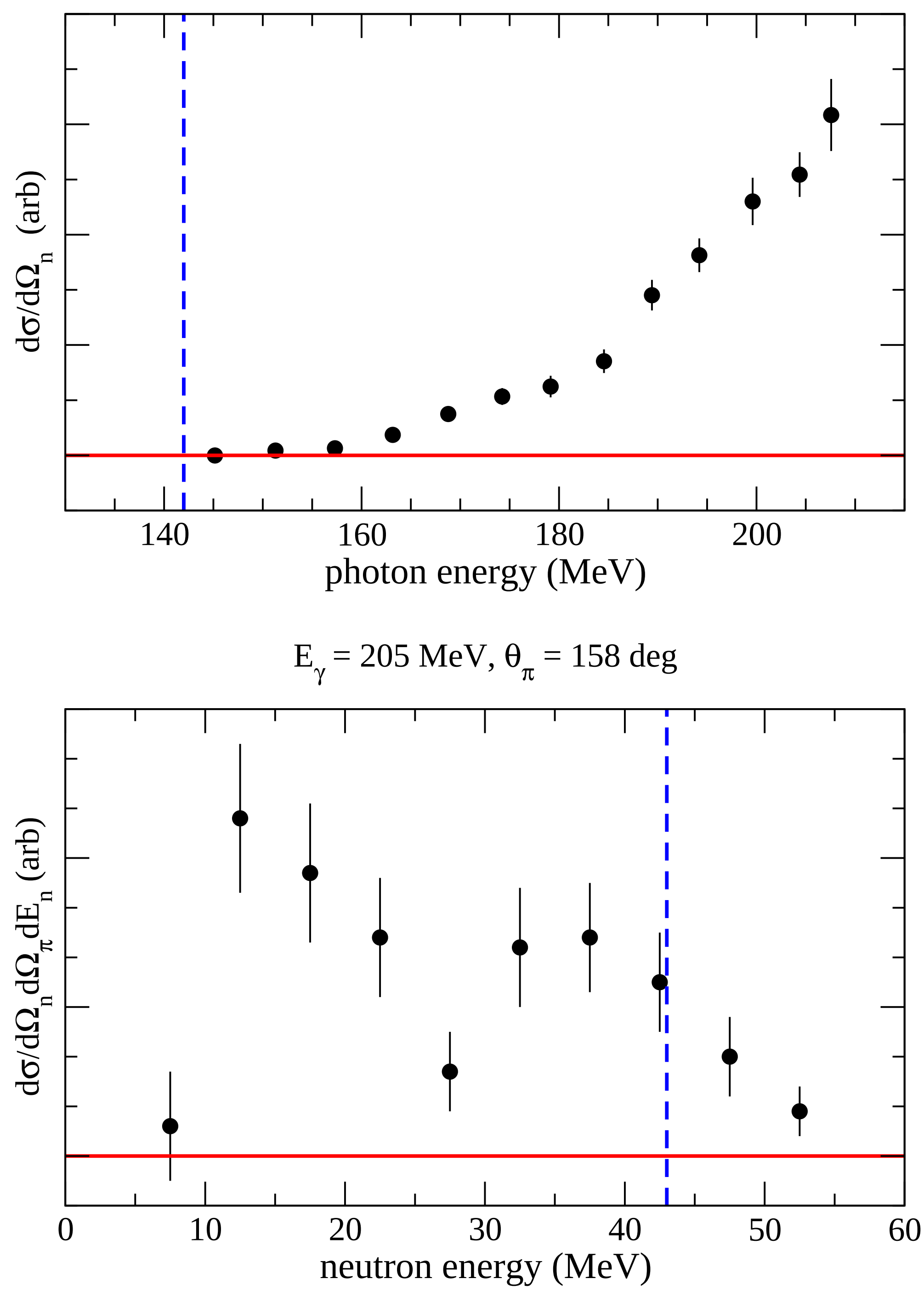
d(γ, π^0 n)p Observables

PRELIMINARY



d(γ, π ^{0} n)p Cross Sections

PRELIMINARY



Complex Nuclei

Medium modifications to nucleon amplitudes

Δ–A dynamics

Δ width

<u>Near Threshold</u> (recent)

^{1}H	SAL (96, 97), Mainz (96, 01)
^{2}H	SAL (98), Mainz (01, ?)
^{4}He	SAL (?)
^{6}Li	SAL (99)
Be	SAL (?)
^{12}C	SAL (97), Mainz (90, ?)
N	SAL (?)
O	SAL (?), Mainz (?)
Ca	Mainz (?)
^{208}Pb	Mainz (?)

$^{12}C(\gamma, \pi^0)^{12}C$

$J_\pi = 0^+$, $T = 0$ =>

Only p-waves survive near threshold.

$P_3 = P_3^{(+)} + P_3^{(0)}$ (isovector + isoscaler)

$= P_3^{(+)}$

$= p_3^{(+)} \bullet kq$ (reduced amplitude)

$p_3^{(+)}$ is determined by Δ

(also ρ and ω exchange)

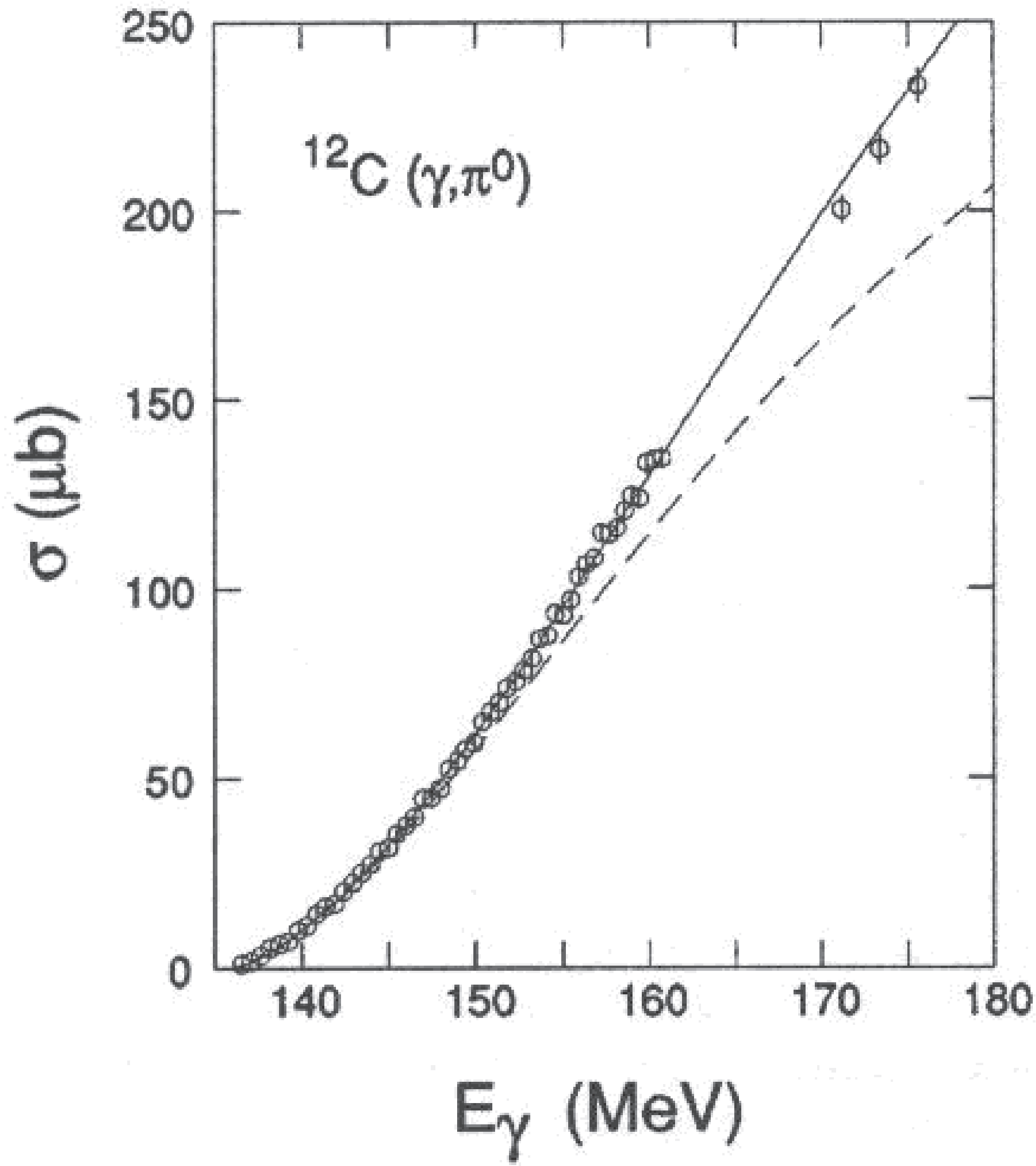
PWIA

$$\frac{d\sigma}{d\Omega} = \frac{A^2}{2}\frac{q}{k}\left(p_3^{(+)} \bullet kq\right)^2 |F|^2(Q) \sin^2\theta_\pi$$

Bergstrom, Igarashi, Vogt, PRC **55** (1997) 2923.

$^{12}C(\gamma, \pi^0)^{12}C$

Dashed line = coherent contribution
Solid line = DWIA



Bergstrom, Igarashi, Vogt, PRC **55** (1997) 2923.

$^{12}C(\gamma, \pi^0)^{12}C$

Reduced p-wave amplitude for carbon:

$p_3^{(+)} = 11.24 \pm 0.15 \;\; (10^{-3} / m_{\pi^+})$

Proton amplitude?

$p_3(\pi^0 p) = 11.5 \pm 0.4$ (Schmidt *et al.*)

$p_3^{(0)}(\pi^0 p) = 0.3$ (prediction)

=> $p_3^{(+)}(\pi^0 p) = 11.2 \pm 0.4$

The $p_3^{(+)}$ amplitude for a free nucleon

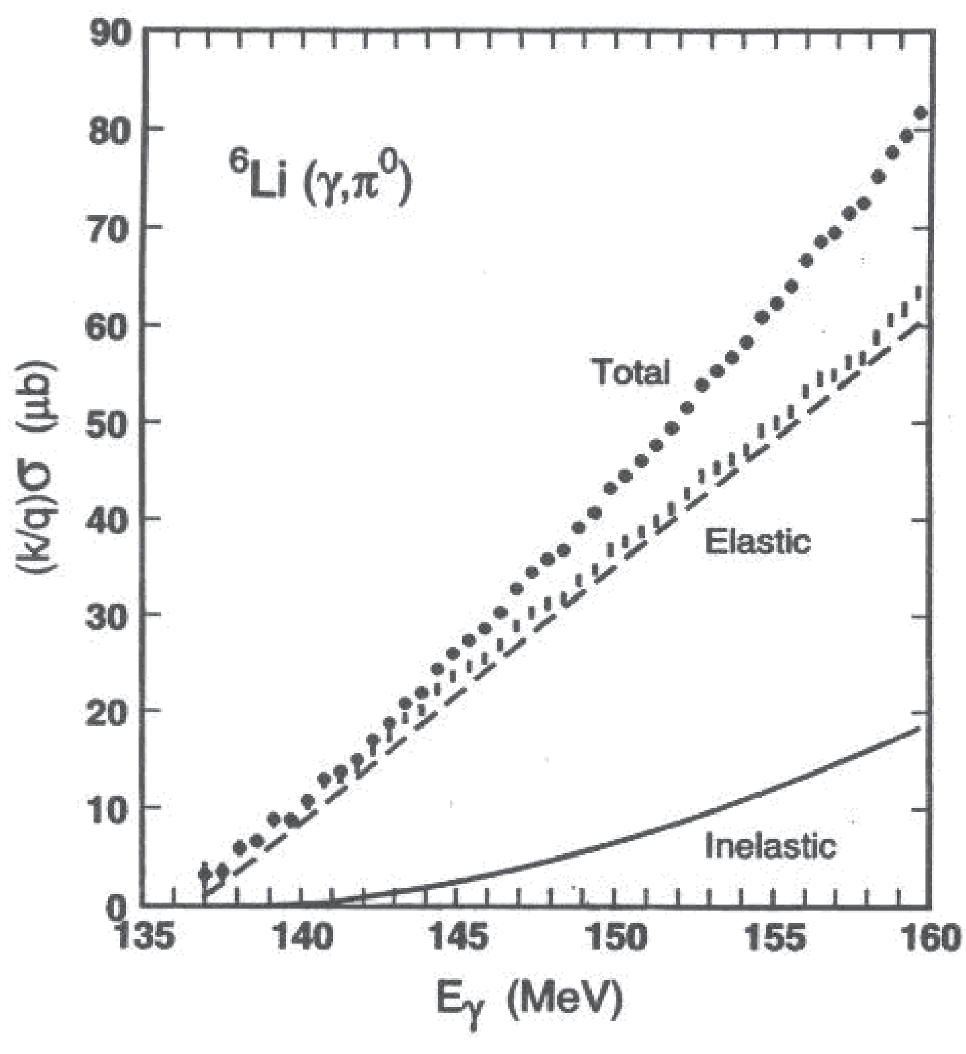
is nearly the same as for a bound nucleon.

^{6}Li(γ, π ^{0}) ^{6}Li

Motivation

$p_3^{(+)}$ medium modifications

α– d cluster model



Bergstrom, Igarashi, Vogt, PRC **59** (1999) 2588.

$^{6}Li(\gamma, \pi^{0})\,^{6}Li$

Reduced p-wave amplitude $p_3^{(+)}$

free nucleon	carbon	^{6}Li
11.2 ± 0.4	11.2 ± 0.2	11.8 ± 0.3

Inelastic contributions and imaginary parts => upper limit.

Stability of $p_3^{(+)}$ amplitude in nuclear medium.

$^6Li(\gamma, \pi^0)\,^6Li$

$E^{(+)} \equiv$ Effective s-wave amplitude (nuclear structure removed)

deuteron

$E_d = (1 - 1.5\, P_D)\, \eta\, F(k)\, E^{(+)}$

$= -1.45 \pm 0.09$

$E^{(+)} = -1.89 \pm 0.12$

^{6}Li

$E_{Li} = [\, P_S\, \eta\, F(k)\, E^{(+)}\,]\, R_d^{1/2}$

$= -1.63 \pm 0.12$

$E^{(+)} = -3.38 \pm 0.25$

Decomposition of $E^{(+)}$

$E^{(+)} = E_{0+}^{(+)} + \Delta E_p$ (p-waves) $+ \Delta E$ (charge-exchange)

ΔE is estimated from α–d model and deuteron results.

Prediction for $E^{(+)}$ for ^{6}Li is -3.9 ± 0.2.

Connection between effective

s-wave amplitudes from the deuteron and ^{6}Li.

Recent TAPS Results on Complex Nuclei

Thanks to Bob Owens at Glasgow

Tagged photon energy range from threshold to ~380 MeV

Targets: C, O, Ca, ^{208}Pb

Energy resolution of TAPS allows some separation of incoherent processes.

Analysis is 'close to complete'.

Carbon total cross section results in reasonable agreement with SAL.

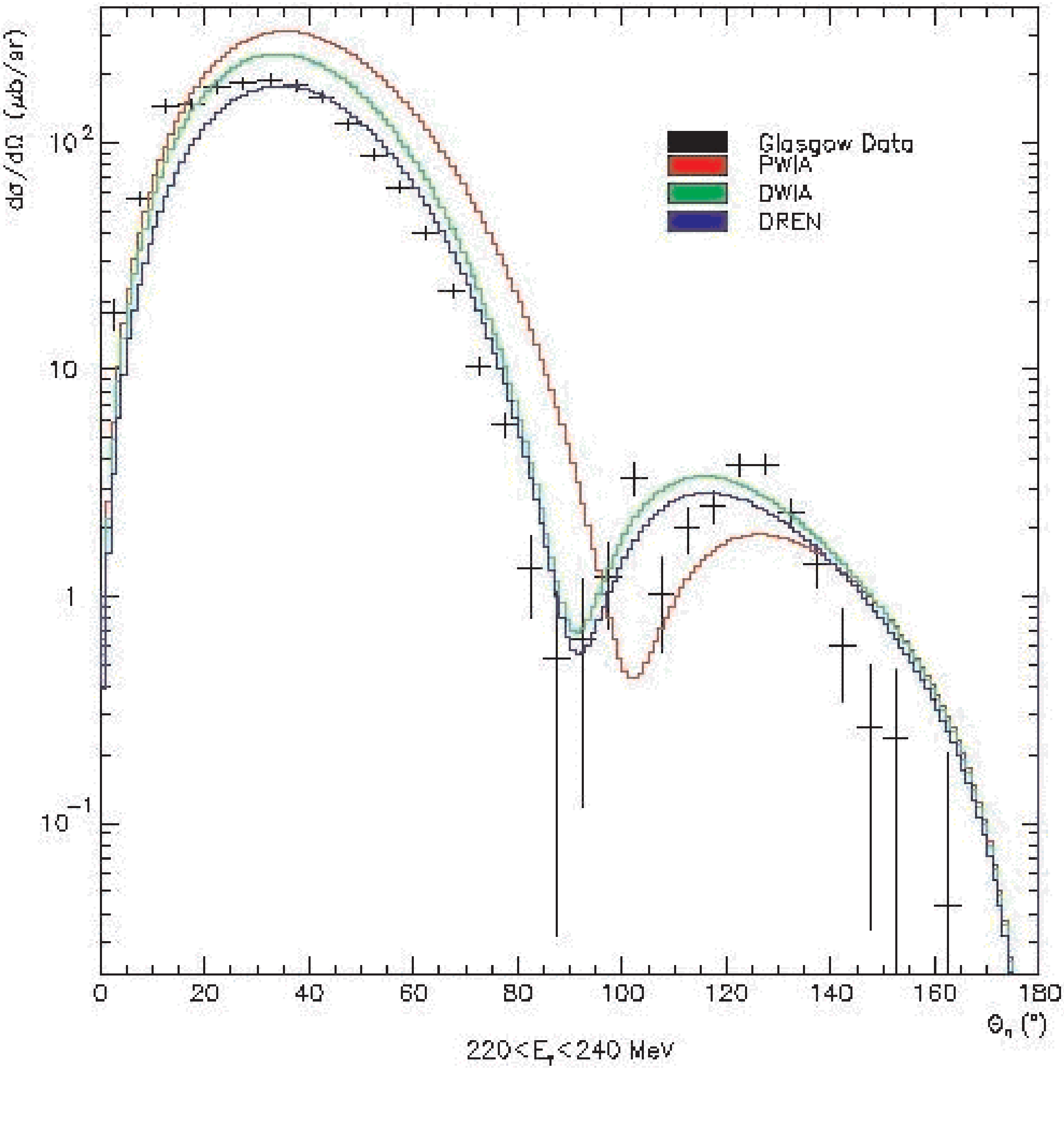
Comparisions with theoretical calculations by Kamalov.

Drechsel, Tiator, Kamalov, Yang, NPA **660** (1999) 423.

$^{16}O\ (\gamma, \pi^0)\ ^{16}O$

PRELIMINARY PRELIMINARY

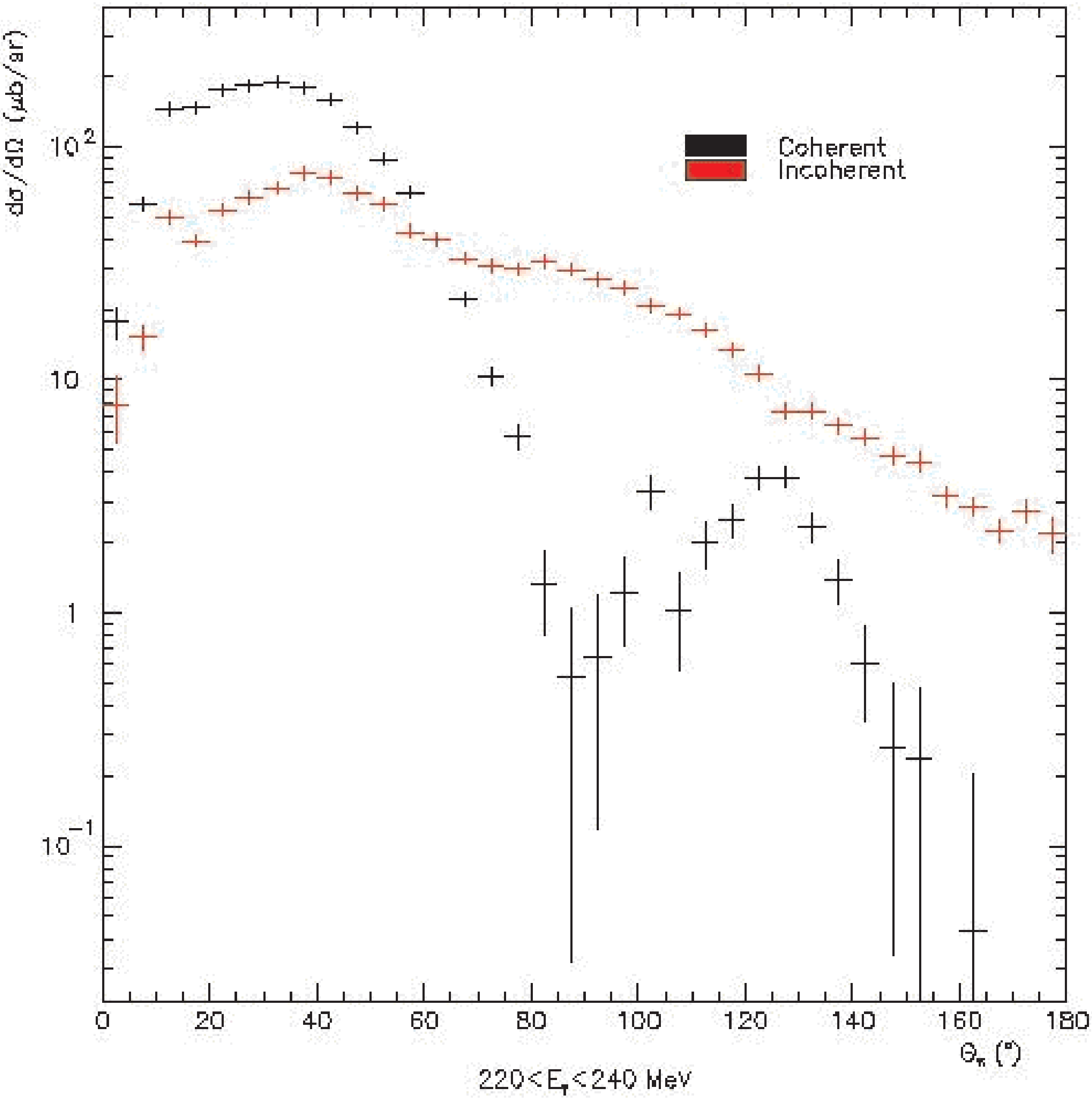
220 – 240 MeV



$^{16}O\ (\gamma, \pi^0)\ ^{16}O\ /\ ^{16}O^*$ (6 MeV)

PRELIMINARY PRELIMINARY

220 – 240 MeV

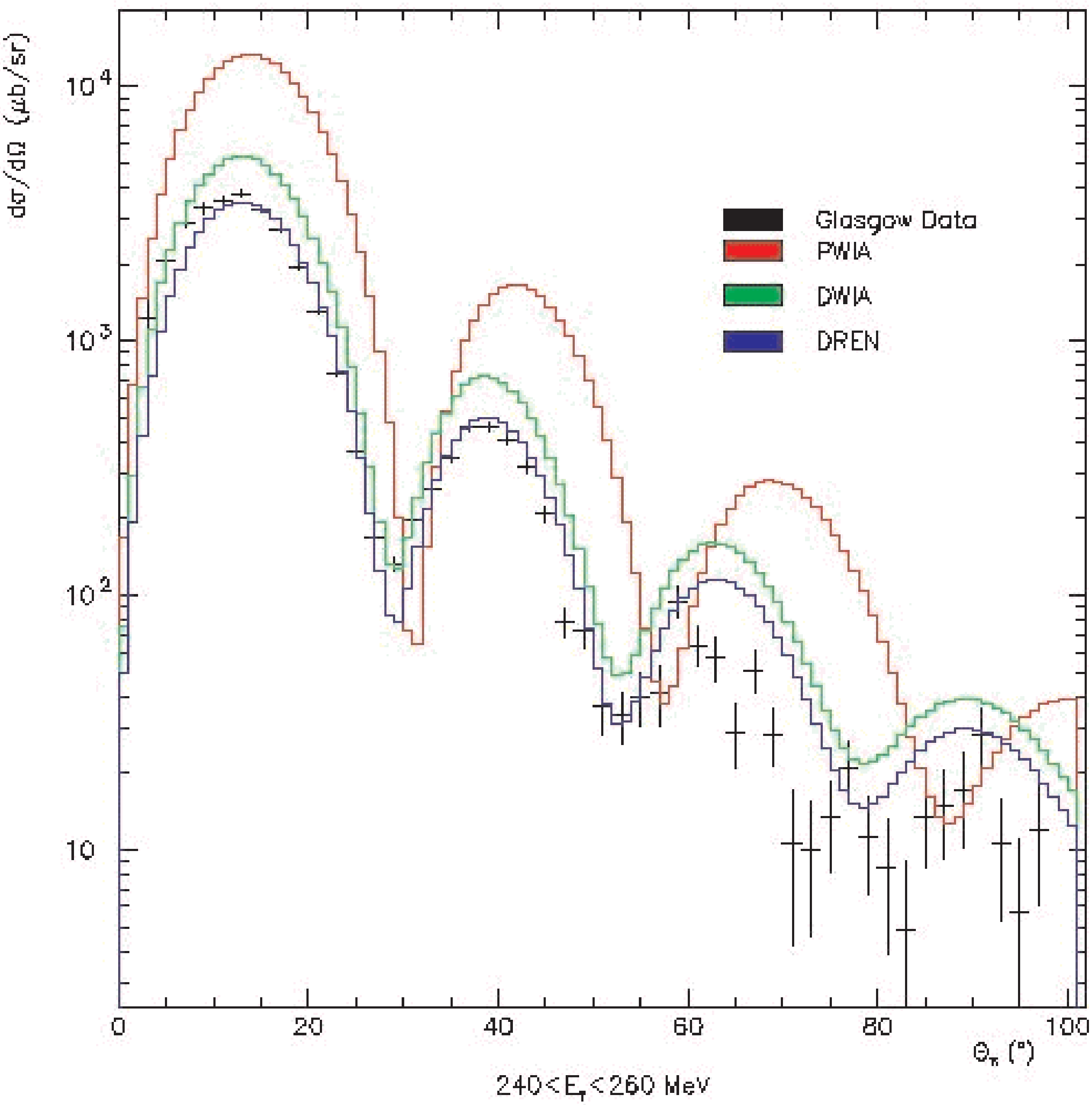


$^{208}Pb\ (\gamma, \pi^0)\ ^{208}Pb$

PRELIMINARY

PRELIMINARY

240 – 260 MeV



Summary

Success of Chiral Perturbation Theory.

Amplitudes for the proton well-understood.

- SAL and newest Mainz results in agreement.
- Future: further work with polarized beams.

Neutron amplitudes remain elusive.

- Detailed understanding of rescattering necessary.
- Can we extract neutron from deuteron data?
- Theory?

Complex nuclei.

- Need to understand/resolve incoherent contributions.
- Medium modifications of amplitudes?