Photonuclear Reactions

Studies at Bates: 1975 -1990

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Hadronic and Electroweak Physics at MIT
Bates Retrospective and Future Prospects

September 29, 2006

Themes in photonuclear reaction studies at Bates

- Few-nucleon problems

- Photonuclear reaction mechanisms
  - (one- *vs*. two-nucleon photon absorption?)

- High momentum components in nuclear wave functions

[Pion photoproduction (A.M. Bernstein *et al*.) – will not discuss]

Themes in photonuclear reaction studies at Bates

- Few-nucleon systems
  - Photo- and electro-disintegration of the deuteron
    - Benjamin Craft, Ph.D. 1982
    - Laura Wiener, S.M. 1984
    - Troy Soos, S.M. 1989
    - Several S.B. theses
  - ^{3}He(γ,2*p*) for E_γ = 80-170 MeV
    - Carl Peridier, S.M. 1978
    - C.A. Peridier *et al*., Z. Phys. A **310**, 317 (1983)
  - ^{4}He(γ,*p*) and (γ,*n*)
    - Reinhard Schumacher, Ph.D. 1983

- Reaction mechanisms
  - Cu(γ,*p*)*X* at E_γ = 150 and 300 MeV
    - R.A. Schumacher *et al*., Phys. Rev. C **25**, 2269 (1982)
  - ^{16}O(γ,*p*)
    - Michael Leitch, Ph.D. 1979
    - R. Steven Turley, Ph.D. 1984
  - ^{40}Ca(γ,*p*)
    - M.J. Leitch *et al*., Phys. Rev. C **33**, 1511 (1986)
  - ^{16}O(γ,n_0)
    - Elizabeth Beise, Ph.D. 1988 (R.P. Redwine, supervisor)

- High momentum components
  - ^{16}O(γ,p_0), E_γ = 100 – 400 MeV
  - "Scaling" of (γ,*p*) cross section with missing momentum (R.O. Owens)

Photodisintegration of the deuteron

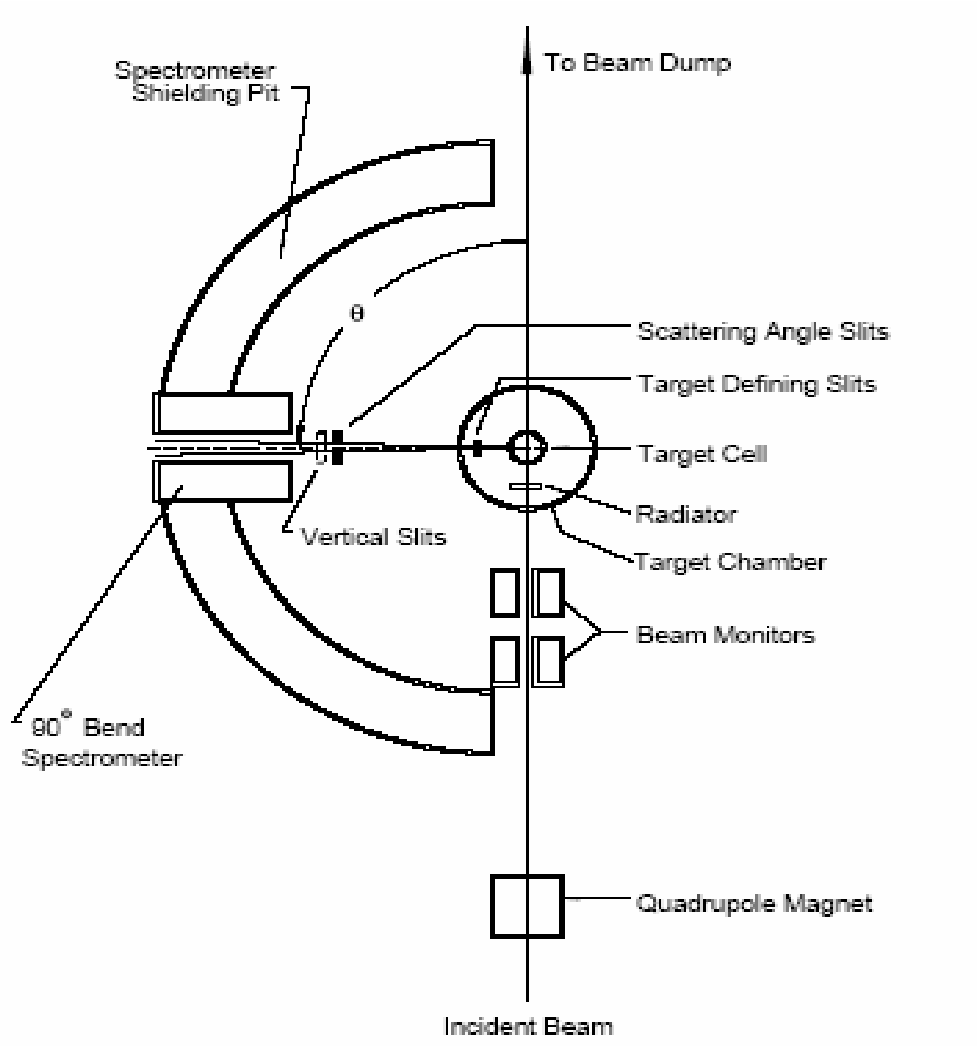
- Problems with using bremsstrahlung beams
  - Knowledge of energy spectrum
    - Modifications to theoretical spectrum due to effects of collimation and radiator thickness
  - Calibration of flux
- Goal of Bates experiment: minimize sources of error inherent in a bremsstrahlung measurement
  - Normalization to electron current, monitored concurrently with non-intercepting toroid
  - Use of full bremsstrahlung flux, no sweep magnet or collimators
  - Use of low-Z radiator, to minimize corrections to Born-approximation theoretical spectrum
  - Use of high-pressure cooled gas target
    - Density determined by pressure and temperature
  - Use of magnetic spectrometer (ELSSY) for accurate measurement of proton energy (and thus determination of incident photon energy
  - Check of target thickness, solid angular acceptance, and electron beam normalization by measurement of $p(e,p)e$

Photodisintegration of the deuteron (cont'd)

- Main drawback of experiment
  - Experiment performed as an "excitation function," measuring the cross section as a function of E_γ at one lab angle at a time
    - Only practical method: to move ELSSY to another angle one had to remove and reposition shielding, re-install and re-align collimators, re-cool D_2 target, etc.
    - Cross sections at different angles were measured in runs separated by days, months, or even years
  - Not the best technique to measure an accurate, consistently normalized angular distribution.

- Experiments with tagged photons (Mainz, LEGS) have different set of problems
  - Tagging efficiency must be known
  - Lower count rates require thick targets and/or large-acceptance detectors
  - However, since all angles measured simultaneously, angular distributions and resulting total cross sections are now thought to be more reliable than the Bates measurements

Experimental setup for (γ,*p*) measurements using ELSSY

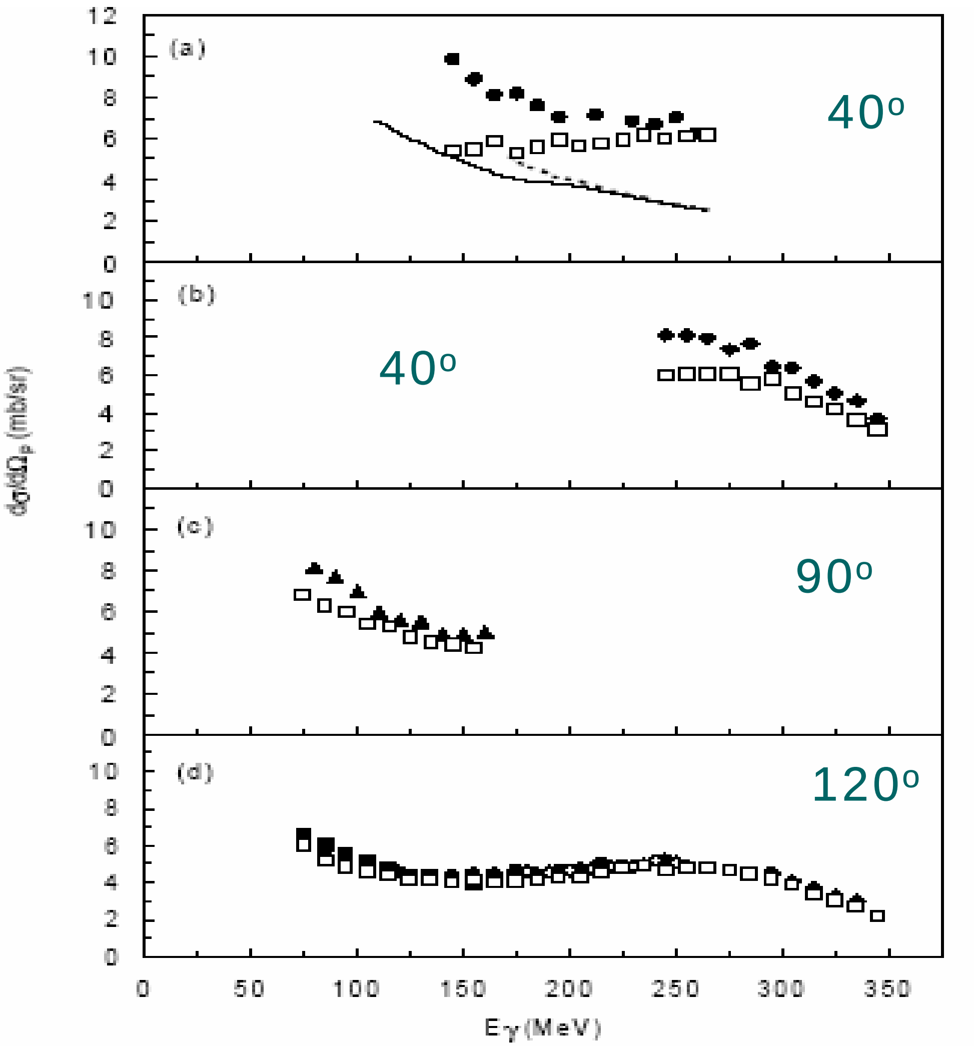


Photodisintegration of the deuteron (cont'd)

- Unique feature of Bates experiment: Use of uncollimated bremsstrahlung spectrum with radiator placed close to D_2 target
  - Residual electron beam all passed through target, must subtract electrodisintegration ("radiator-out") data from the "radiator-in" data
  - Bonus: treating the radiator-out data on their own provided a test of virtual photon theory
  - Analysis carried out as an undergraduate research project at Northwest Nazarene College supervised by former MIT graduate student Mark Yuly

- Virtual photons *vs*. real photons?
  - Given uncertainties associated with calculating and normalizing bremsstrahlung spectra, people have suggested that using virtual photons is superior way to measure photo-cross sections
  - Virtual photon spectrum concept originally suggested by Fermi; developed by Weizsäcker and Williams, Dalitz and Yennie
  - Tiator and Wright have reexamined assumptions and approximations in earlier treatments, and developed an "exact" virtual photon spectrum, for (γ,π) and (γ,*p*) reactions
    - Nucl. Phys. **A379**, 407 (1982)
    - Comput. Phys. Commun. **28**, 265 (1983)
    - Phys. Rev. C **38**, 2771 (1988)

“Experimental test of virtual photon theory via electrodisintegration and photodisintegration of the deuteron,”
M. Yuly *et al*., Phys. Rev. C **68**, 014601 (2003)

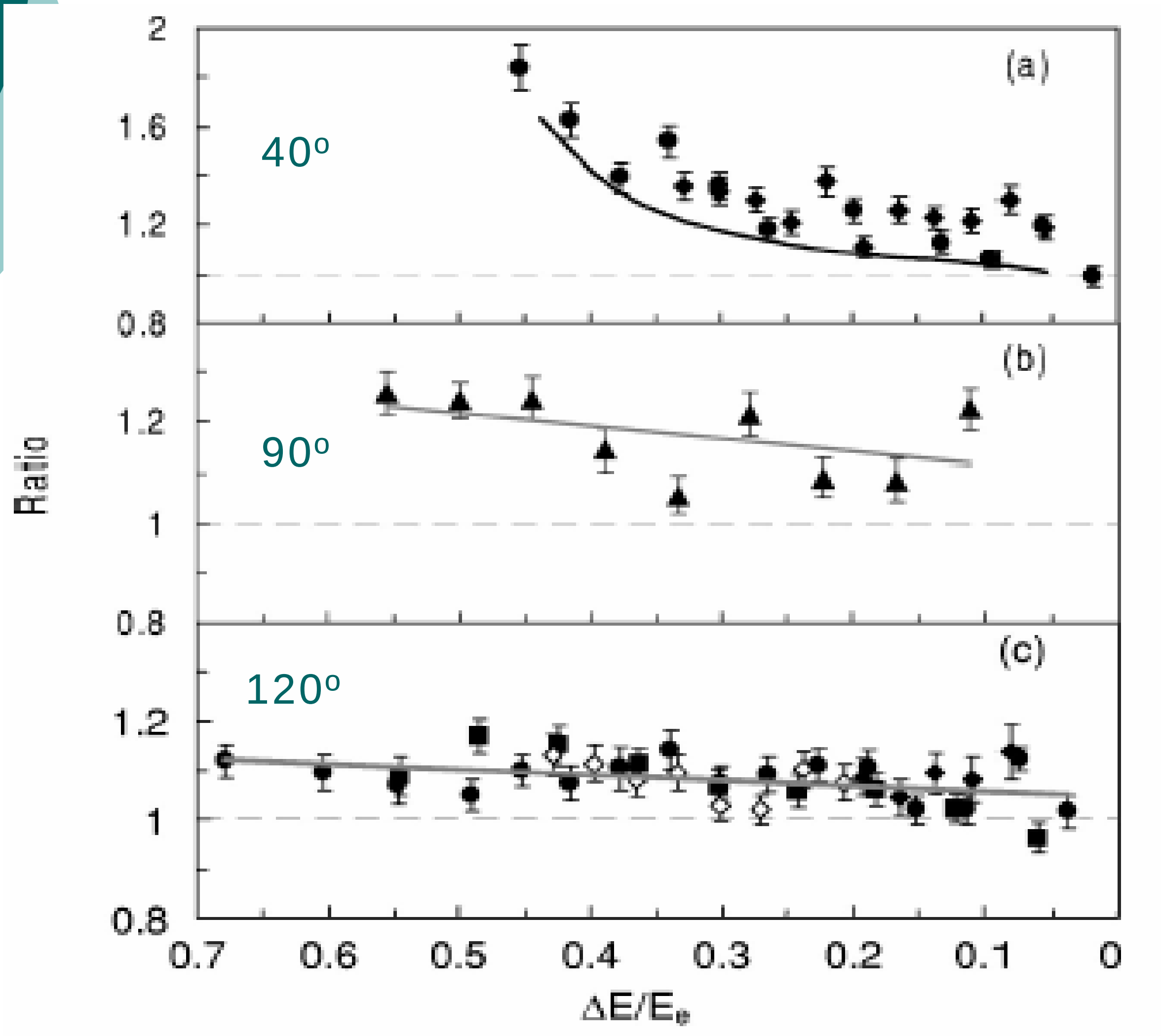


Open squares: Measured $d(\gamma,p)n$ cross section

Solid symbols: $d(\gamma,p)n$ cross section derived from $d(e,p)e'n$ measurement using virtual photon theory (VPT)

If VPT valid, solid and open symbols would lie on top of each other

“Experimental test of virtual photon theory via electrodisintegration and photodisintegration of the deuteron,”
M. Yuly *et al*., Phys. Rev. C **68**, 014601 (2003)



Dark solid curve: Wright and Tiator, Phys. Rev. C **26**, 2349 (1982)

Light lines: linear fits to data

Conclusion: ***Caveat Emptor*** when use VPT to extract (γ,*p*) cross sections from (*e*,*p*) measurements [or (γ,π) from (*e*,π)]

VPT only accurate for large angles and/or close to endpoint

Reaction mechanism(s) for photon absorption and nucleon emission

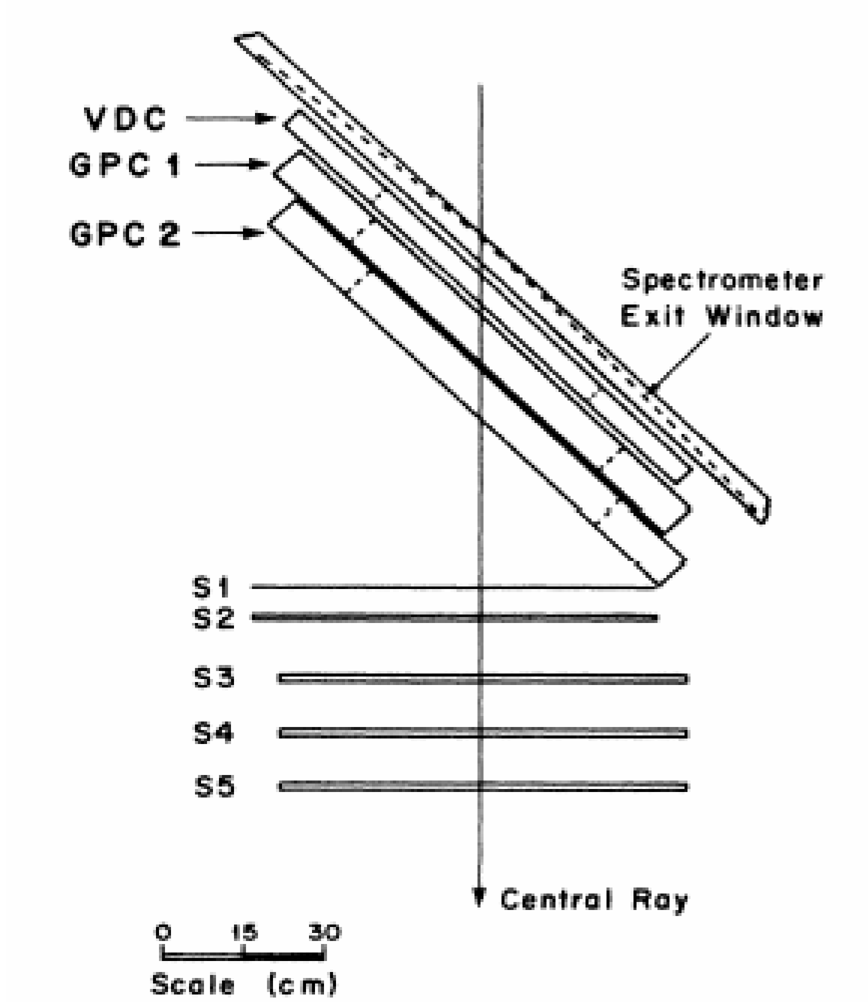
- Simplest mechanism for (γ,*p*) is direct knockout, or quasi-free knockout (QFK), in which momentum and energy of photon is absorbed by a single proton which is then ejected from the nucleus
  - Same mechanism as in (*e*,*e*'*p*) in which proton absorbs a virtual photon
- Two reasons why, for real photons, this may not be dominant mechanism
  - (γ,*n*) and (γ,*p*) cross sections are of comparable magnitude
    - Coupling of photon to neutron is much weaker than to proton
  - In (γ,*p*) reactions where residual nucleus is left in ground or low-lying excited state, there is large mismatch between momentum of incoming photon and outgoing proton.
    - In QFK, this missing momentum = initial momentum of proton
    - For E_γ = 200 MeV, initial proton momentum is 450-750 MeV/c
    - Probability of finding these high momentum components in the nuclear ground state wave function is small.
- To account for these facts, various authors have proposed reaction mechanisms in which the photon is absorbed by a pair of nucleons, e.g. a neutron-proton pair
  - This concept goes back to the quasi-deuteron model introduced by Levinger in 1951
  - There has been an extensive body of theoretical work, and many controversies, since then.
- In comparison with data, I will show a selection of calculations for both one- and two-nucleon absorption, but will not discuss any in detail

Photodisintegration of ^{4}He, 100 - 360 MeV

R.A. Schumacher *et al*., Phys. Rev. C **33**, 50 (1986)

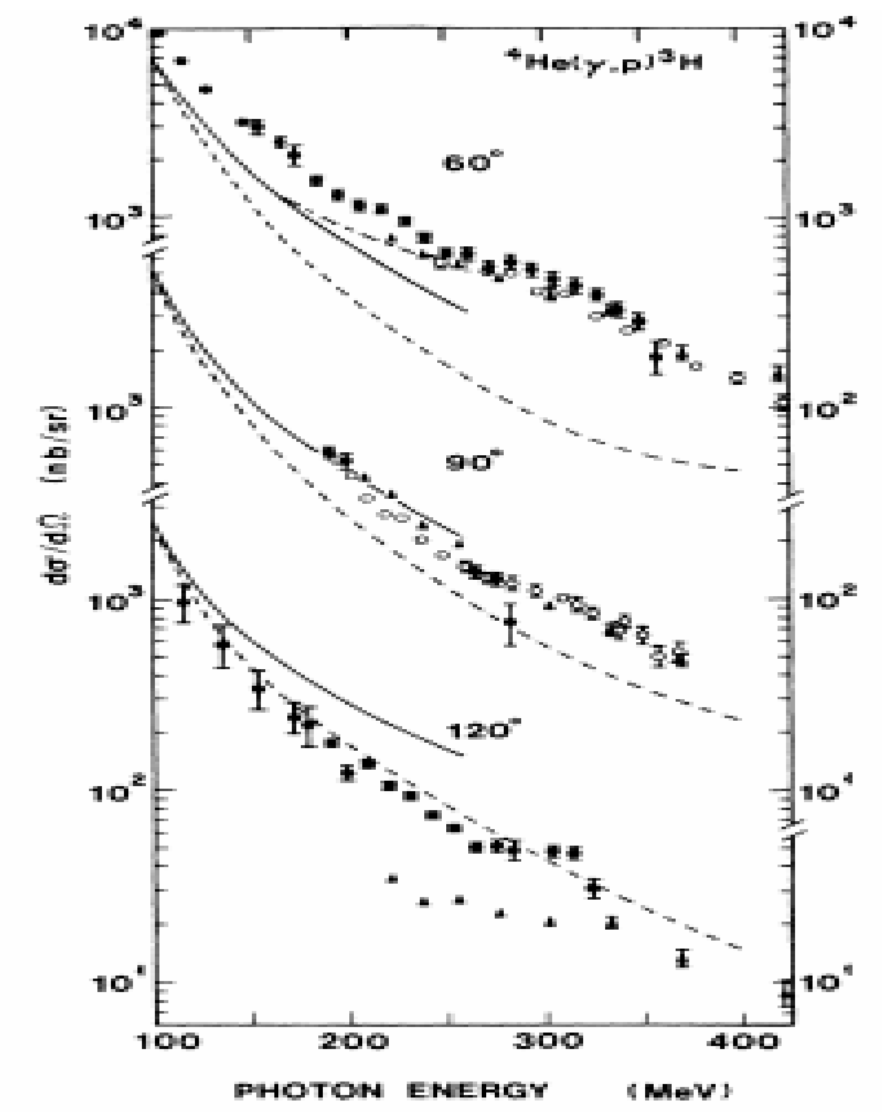
- Goal of experiment: study the two-body reactions ^{4}He(γ,*p*)^{3}H and ^{4}He(γ,*n*)^{3}He in the same experiment, by detecting recoil ^{3}H and ^{3}He nuclei
- This type of measurement had not previously been done in this energy range; very limited (γ,*n*) data existed
- Main challenge: detect heavily ionizing ^{3}He particles
  - Schumacher designed and built two multiwire gas proportional counters, inserted in front of detector stack, which had sufficient energy resolution to identify ^{3}He's
- Couldn't make measurements "really" simultaneously, as ^{3}H and ^{3}He particles had very different magnetic rigidities and thus required different spectrometer settings.
  - But this was only change between (γ,*p*) and (γ,*n*) measurements

Detector stack for ^{4}He (γ,*p*) and (γ,*n*) experiment



Photodisintegration of ^{4}He, 100 - 360 MeV

R.A. Schumacher *et al*., Phys. Rev. C **33**, 50 (1986)



Curves: calculations of Gari and Hebach, Phys. Rep. **72**, 1 (1981)

Dashed curve – direct term plus fixed-range MEC

Solid curve – variable range MEC, NN correlation terms, and center-of-mass corrections added

Dot-dashed curve – Δ(1232) current added

Open circles – data from Saclay
Triangles – data from Bonn

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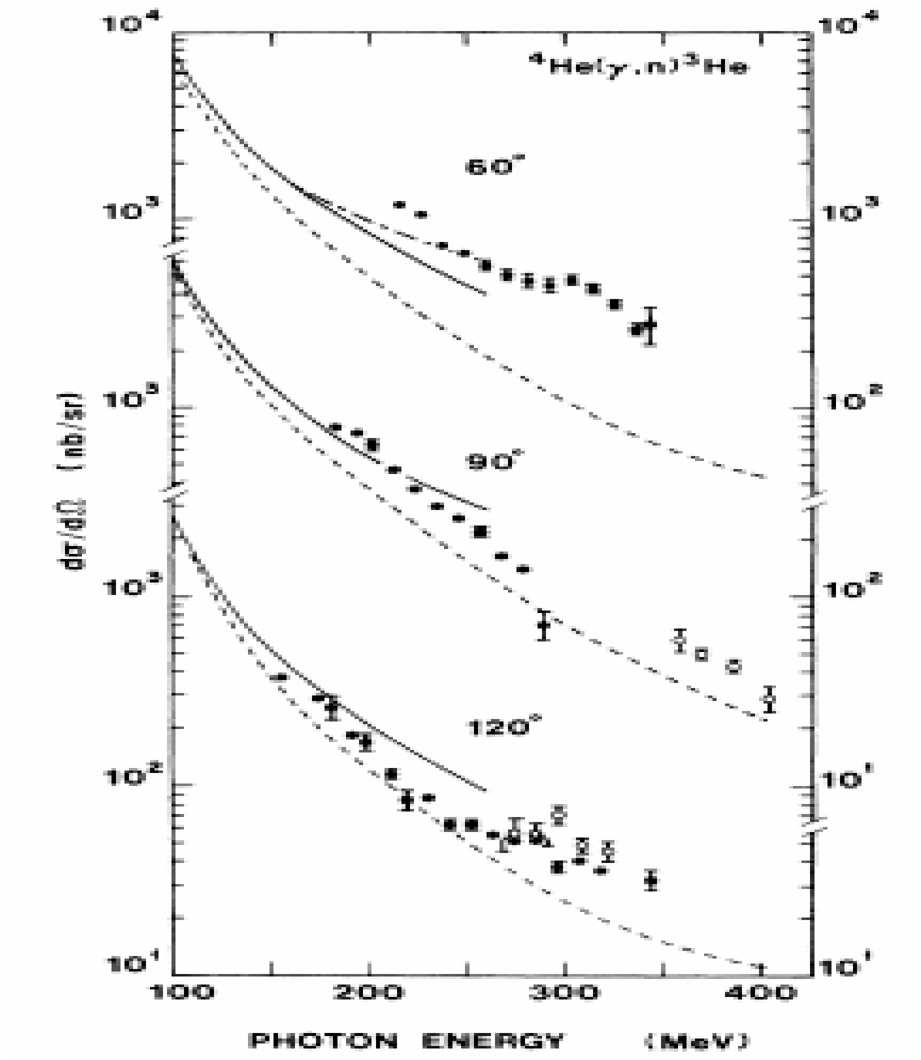
R.A. Schumacher *et al.*, Phys. Rev. C **33**, 50 (1986)



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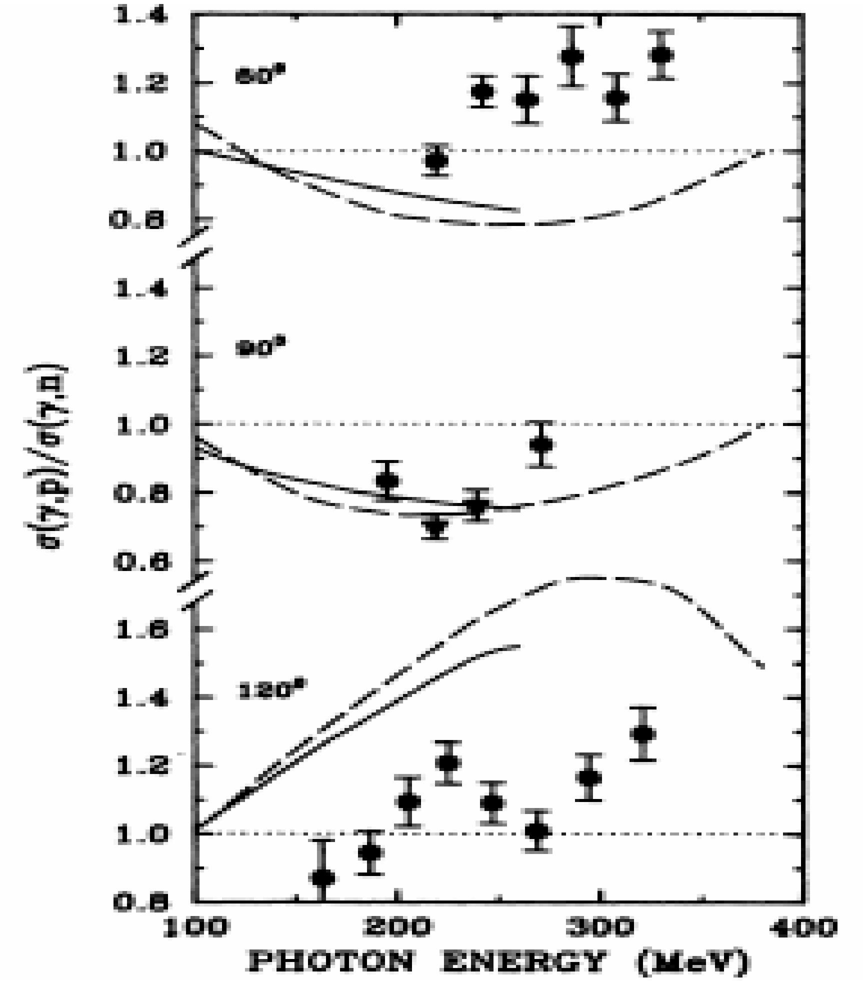


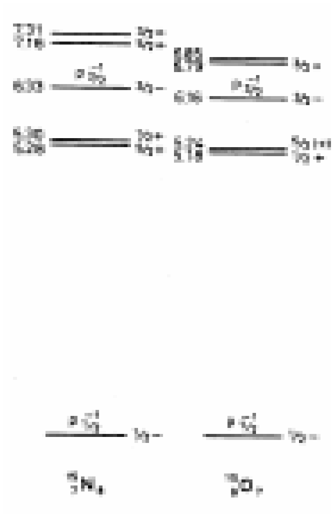
Curves: calculations of Gari and Hebach, Phys. Rep. **72**, 1 (1981)

Dashed curve – direct term plus fixed-range MEC

Solid curve – variable range MEC, NN correlation terms, and center-of-mass corrections added

(γ,N) reactions in complex nuclei

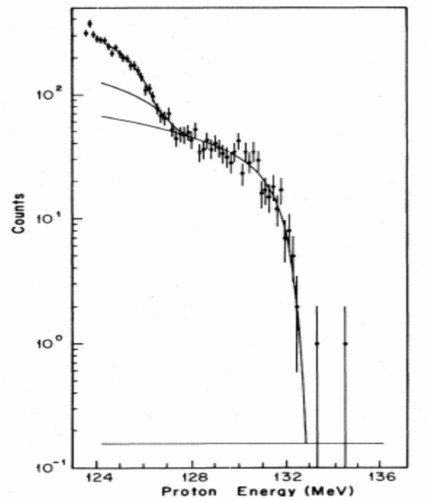
- Consider $^{16}O(\gamma, p_0)$. In simplest (QFK) picture, photon knocks out one of the $p_{1/2}$ protons from this doubly-closed-shell nucleus, leaving ^{15}N in a single hole ($1/2^-$) state
- IN PWIA, cross section is proportional to the square of the initial momentum distribution of the proton in the $p_{1/2}$ state
- If one could observe the (γ, p_3) reaction, in which ^{15}N is left in its second excited state ($3/2^-$ at 6.3 MeV), one would have a measure of the $p_{3/2}$ momentum distribution
- If this reaction proceeds by QFK, one is dealing with high momentum components
- If two-nucleon absorption is involved, then the second nucleon must be reabsorbed into the ground (or low-lying excited) state of ^{15}N.

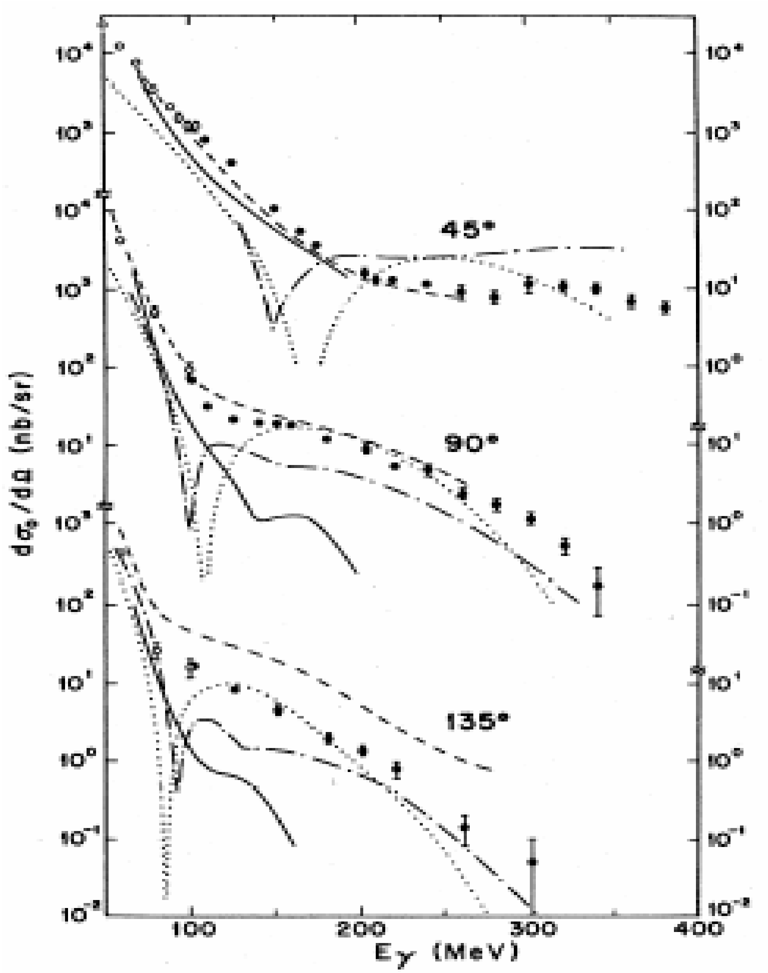


$^{16}O(\gamma,p_0)$, 100 – 400 MeV, θ_p = 45º, 90º, 135º

M.J. Leitch *et al*., Phys, Rev. C **31**, 1633 (1985)

Endpoint region of proton spectrum, with fits of data to background, $d\sigma_0/d\Omega$, $d\sigma_{1,2}/d\Omega$, and $d\sigma_3/d\Omega$





Solid curves: Boffi, Giusti, and Pacati, Nucl. Phys. **A359**, 91 (1981) – QFK

Dashed curves: Gari and Hebach, Phys. Rep. **72**, 1 (1981) – MEC

Dot-dashed curves: Londergan and Nixon, Phys. Rev. C **19**, 998 (1979) – Δ excitation

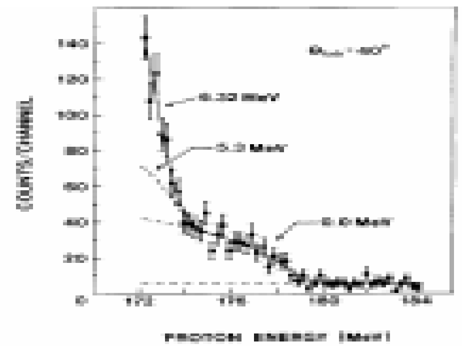
Dotted curves: B. Schoch, Phys. Rev. Lett. **41**, 80 (1978) – phenomenological quasi-deuteron model

Angular distributions for $^{16}O(\gamma,p)$, 200 – 360 MeV

R.S. Turley *et al*., Phys. Lett. **157B**, 19 (1985)
G. Adams *et al*., Phys. Rev. C **38**, 2771 (1988)

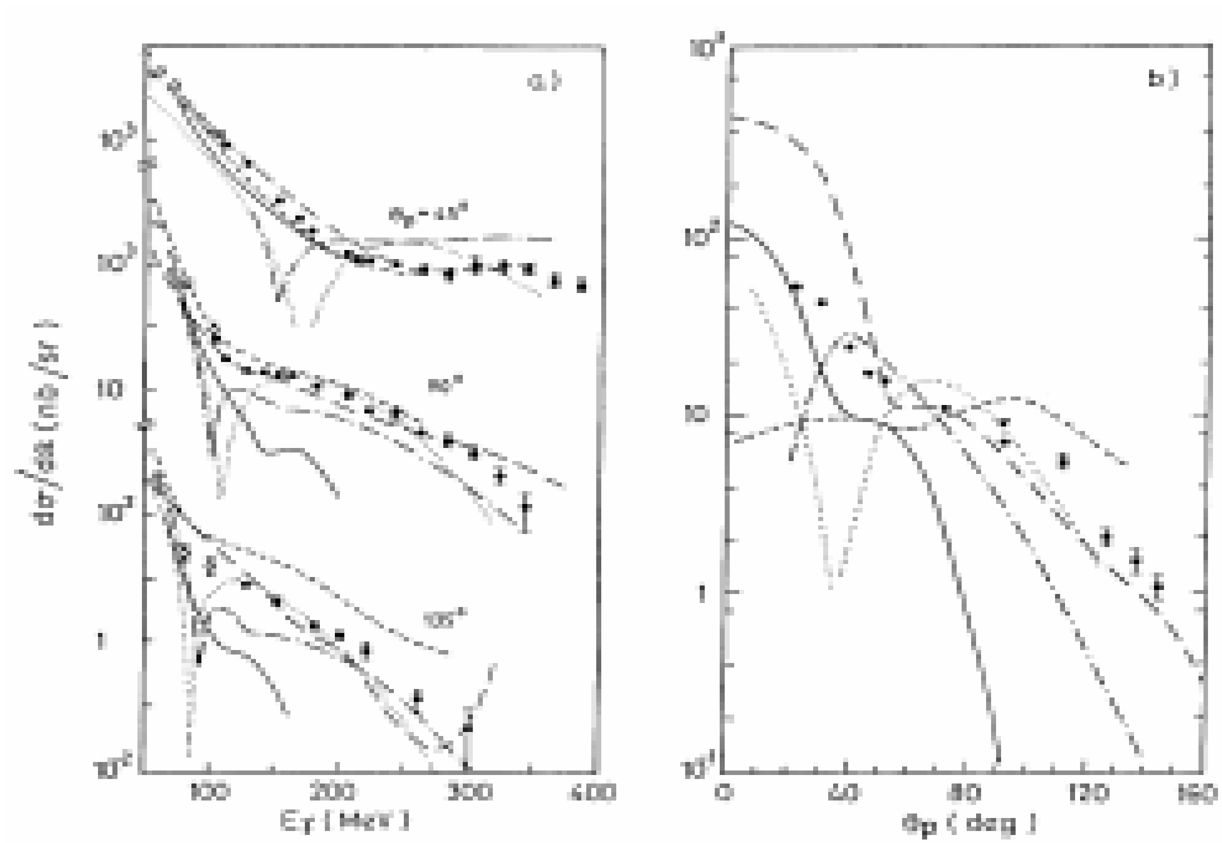
- Drawback of previous measurement: data taken at only three angles, whereas theories predict angular distributions exhibiting distinctive structure which varies quite rapidly with photon energy

- We were able to remedy this situation using OHIPS, which was more easily moveable than ELSSY



$^{16}O(\gamma,p_0)$ cross sections

Excitation functions at θ_p = 45°, 90°, and 135°
Angular distribution at $E\gamma$ = 200 MeV



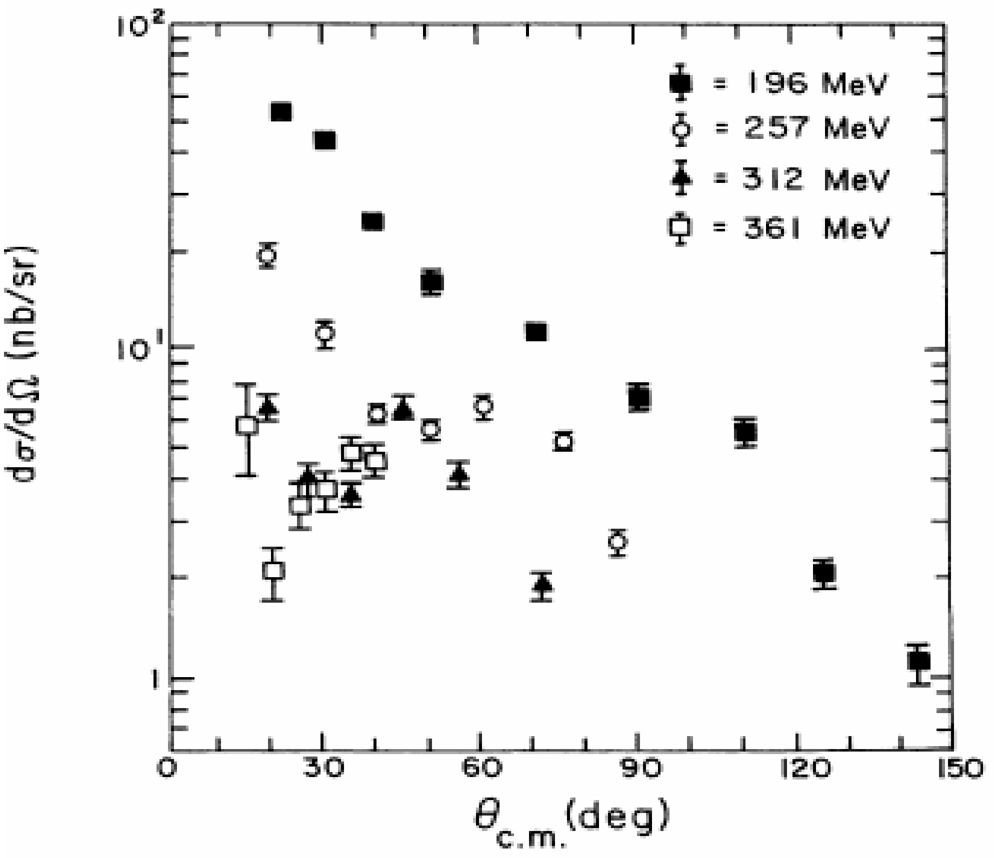
a) same as previous figure, with addition of one more theoretical calculation:
Long-dashed curve: D. Ryckebusch *et al*.
Phys. Lett. **194B**, 453 (1987)

b) angular distribution for $^{16}O(\gamma,p_o)$ at E_γ = 200 MeV

[from R.O. Owens, J.L. Matthews, and G. S. Adams, J. Phys G **17**, 261 (1991)]

Angular distributions for $^{16}O(\gamma,p)$, 200 – 360 MeV

G. Adams *et al*., Phys. Rev. C **38**, 2771 (1988)



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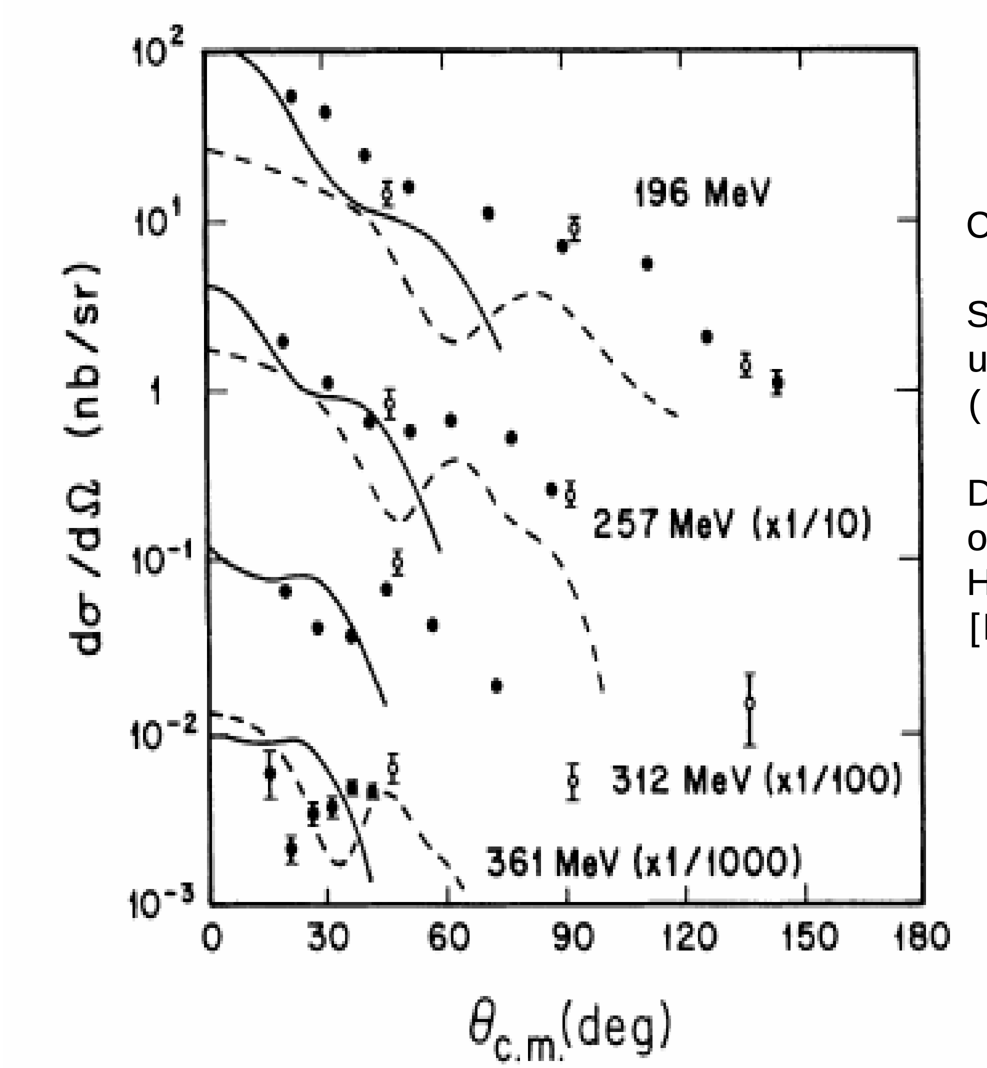

Comparison of data with QFK in DWIA

Solid curve: wave function calculated using Elton-Swift [Nucl. Phys. **94**, 52 (1966)] bound state potential

Dashed curve: wave function obtained from density-dependent Hartree-Fock calculation by Negele [Phys. Rev. C **1**, 1260 (1970)]

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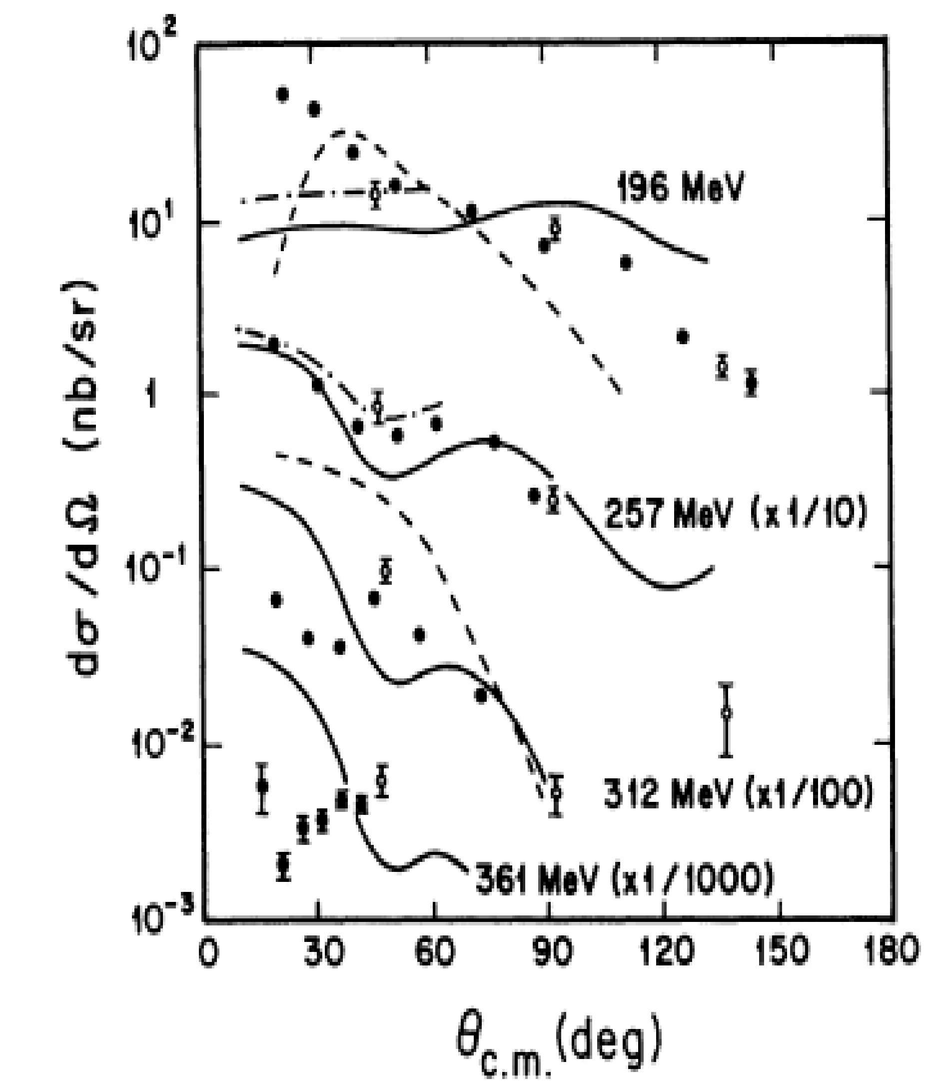
G. Adams *et al*., Phys. Rev. C **38**, 2771 (1988)



Comparison of data with two-nucleon models

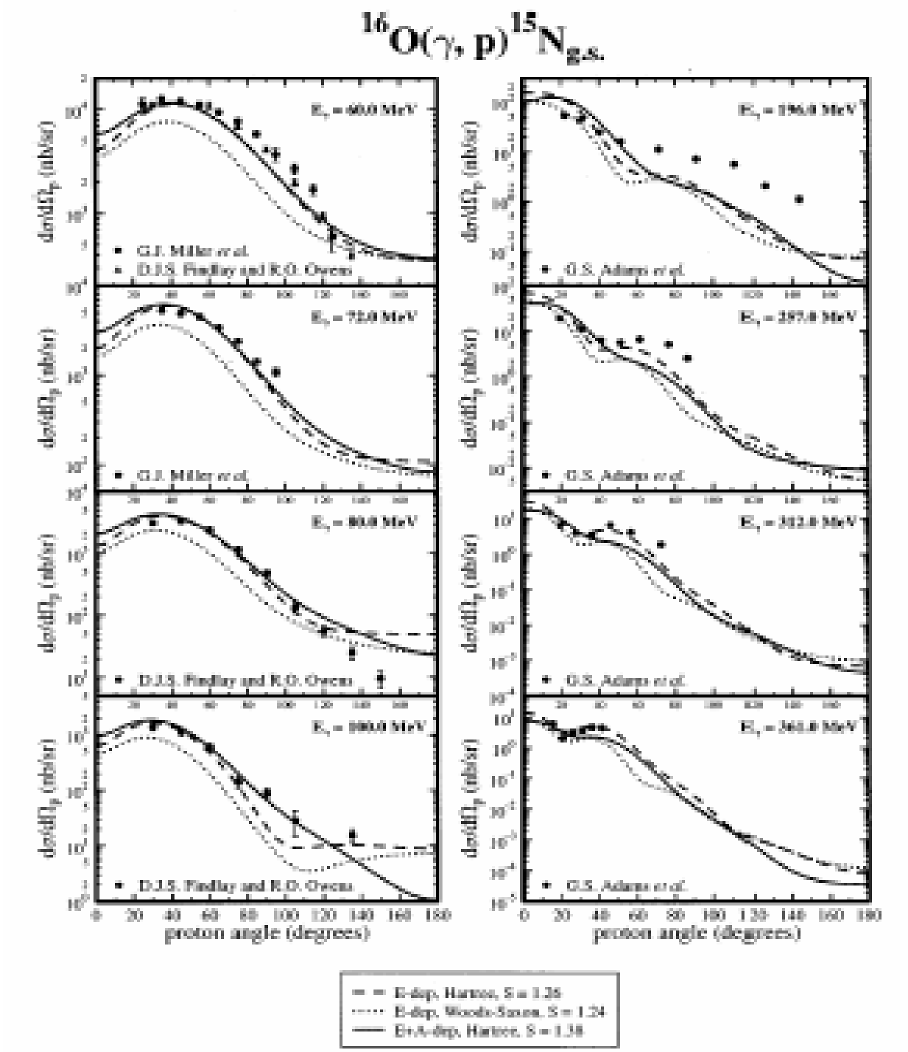
Solid curve: Gari and Hebach, no Δ

Dot-dashed curve: Gari and Hebach, including Δ

Dashed curve: Londergan and Nixon

Comparison of $^{16}O(\gamma,p_0)$ data with relativistic calculation of direct knockout mechanism

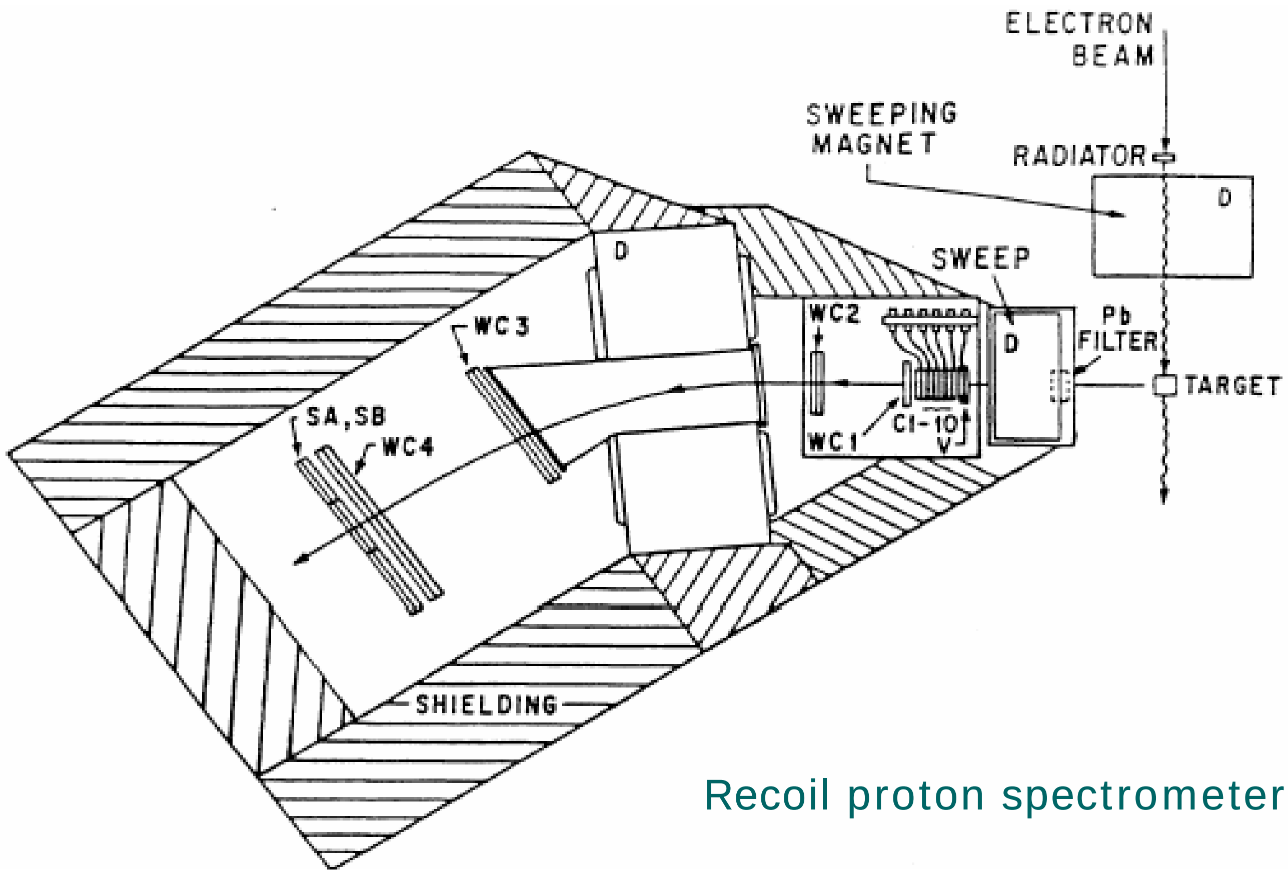
J.I. Johansson and H.S. Sherif, Phys. Rev. C **56**, 328 (1997)



Conclusion: MEC not as important when relativistic treatment used

Measurement of $^{16}O(\gamma,n)^{15}O$ at 150, 200, and 250 MeV

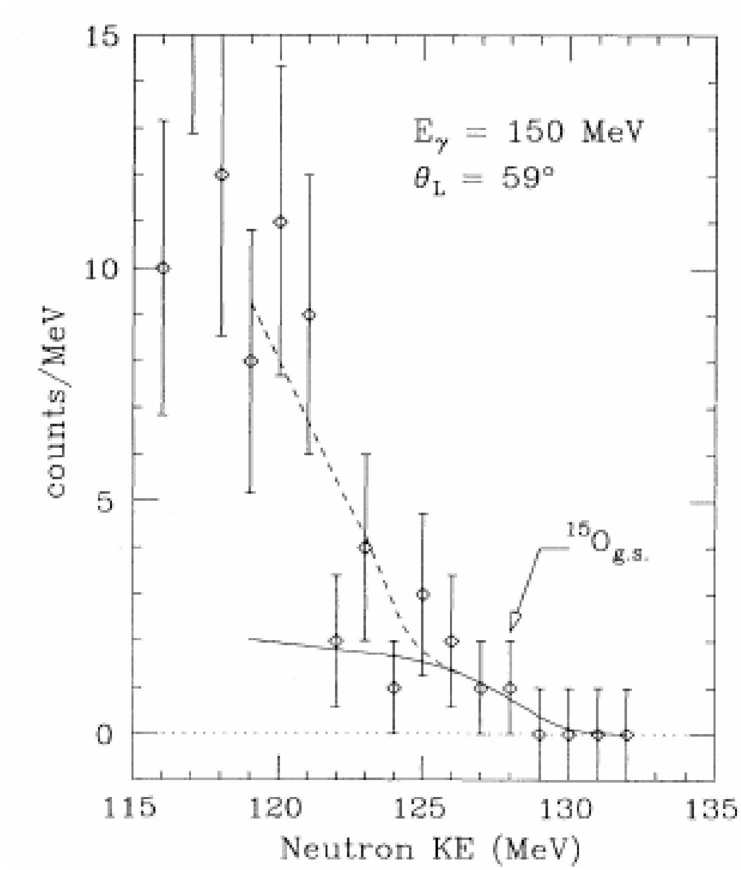
E.J. Beise *et al.*, Phys. Rev. Lett. **62**, 2593 (1989)

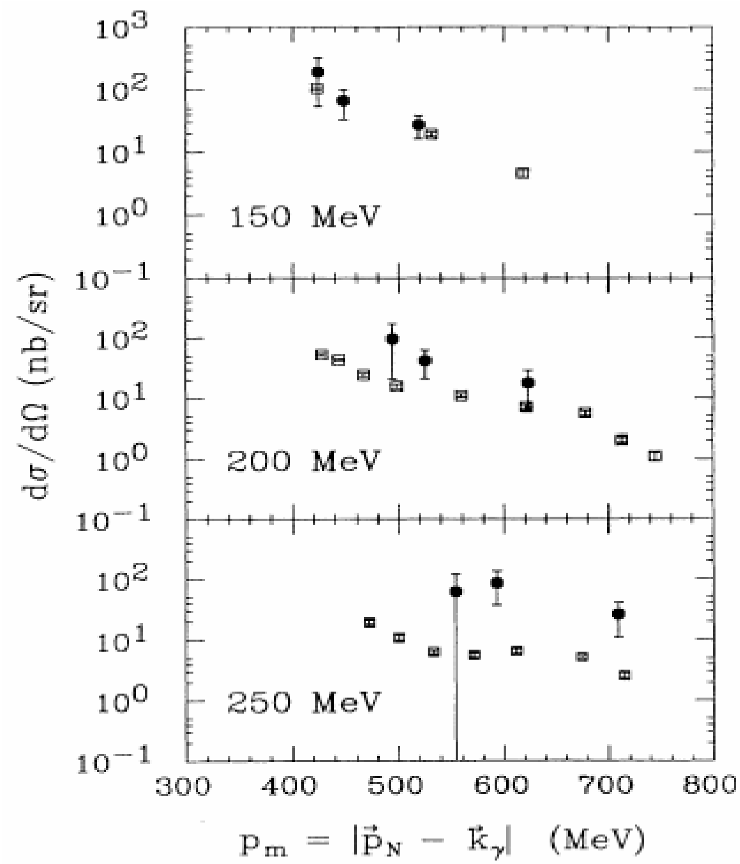


Recoil proton spectrometer

Measurement of $^{16}O(\gamma,n)^{15}O$ at 150, 200, and 250 MeV

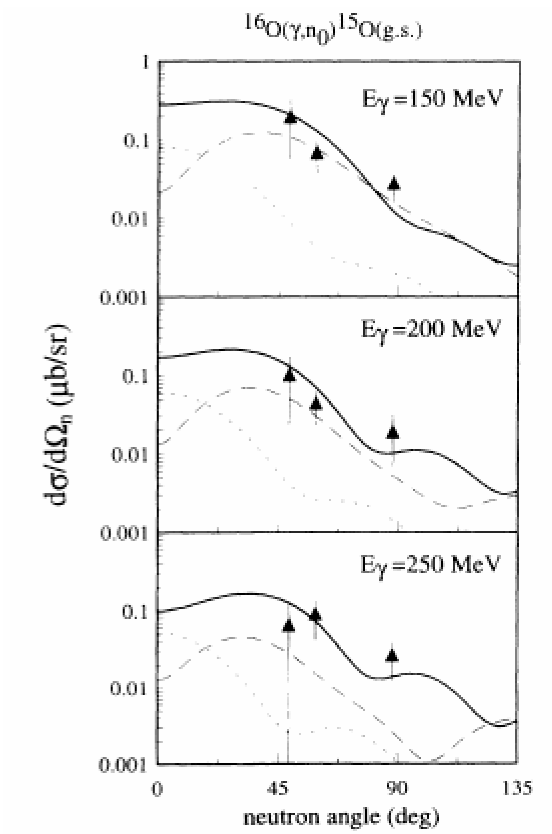
E.J. Beise *et al*., Phys. Rev. Lett. **62**, 2593 (1989)





Open squares: (γ,p)

Comparison of $^{16}O(\gamma,n_0)$ data with calculation of Ryckebusch *et al.* [Phys. Rev. C **49**, 2704 (1994)]



Self-consistent Hartree-Fock and continuum RPA calculation which aims at treating one- and two-body absorption mechanisms in a consistent way, besides accounting for distortions in the outgoing particle wave

Self-consistency: same Skyrme-type interaction which leads to the mean field is also used as the residual interaction

Bound state single particle wave functions in target nucleus taken from a Hartree-Fock calculation with an extended Skyrme force

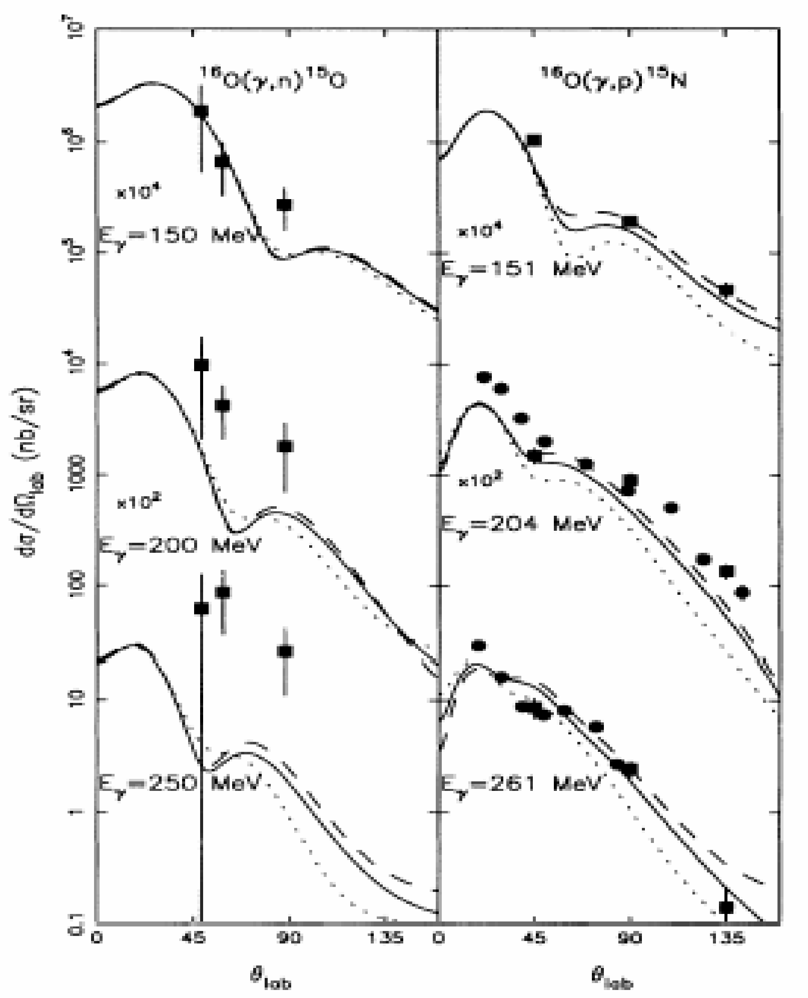
Nucleon continuum wave functions obtained by solving Schrödinger equation with the mean-field potential determined by the Hartree-Fock procedure

Dotted curve: absorption on the magnetization current

Dashed curve: absorption on the magnetization and pion-exchange current

Solid curve: absorption on the magnetization, pion-exchange, and Δ isobar current

Comparison of $^{16}O(\gamma,n_0)$ and $^{16}O(\gamma,p_0)$ data with calculation of Bright and Cotanch [Phys. Rev. Lett. **71**, 2563 (1993)]



Ab initio calculation of (γ,n) and (γ,p) using same microscopic model

Parameters taken from $^{16}O(\gamma,p)$ in giant resonance region

No MEC

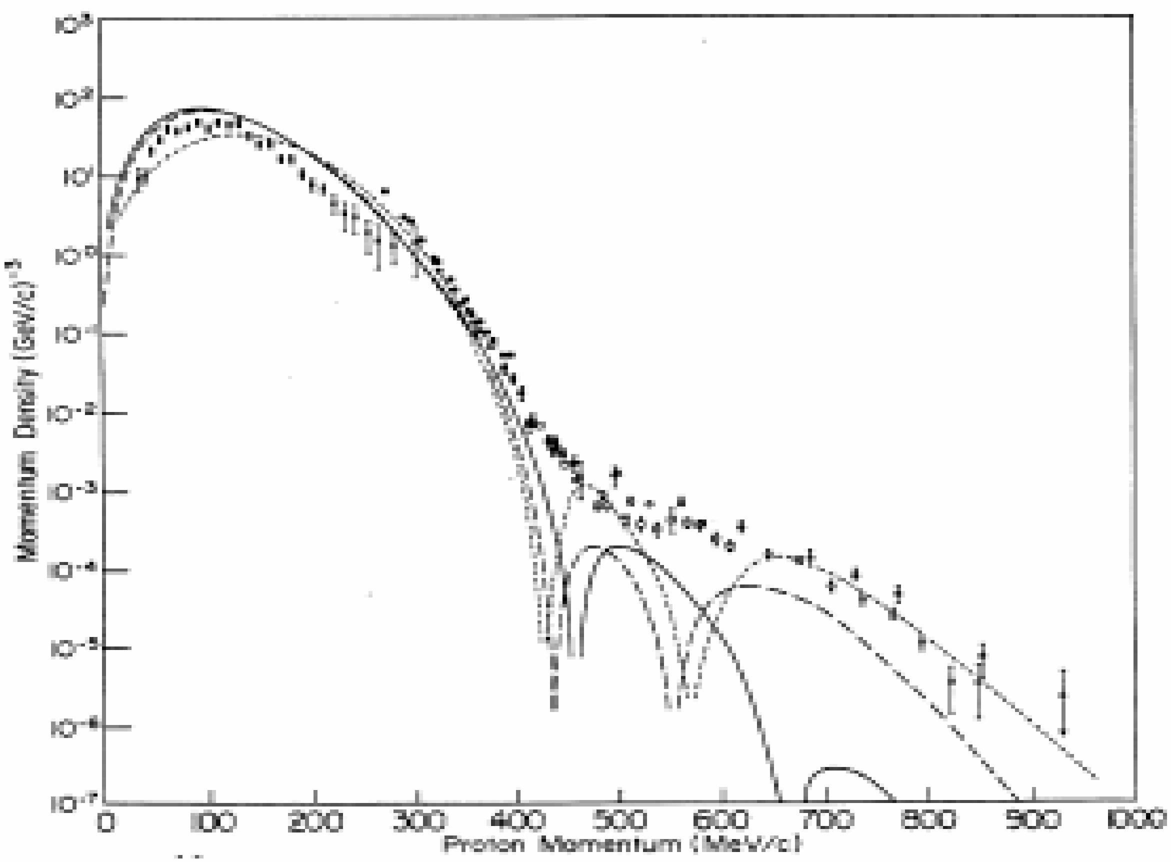
Solid and dashed curves: add Δ (different parameters) to dotted

High momentum components in nuclear wave functions

- Quasi-free knockout in PWIA: (γ,*p*) cross section proportional to square of momentum distribution with slowly-varying kinematic factors
- Findlay and Owens [Phys. Rev. Lett. **37**, 674 (1976); Nucl. Phys. **A292**, 53 (1977)] deduce momentum distributions by dividing out kinematic factors and also account for distortion in final state nuclear potential
  - Real part: shift of outgoing proton energy
  - Imaginary part: energy-dependent absorption correction
- Method validated by fact that resulting (γ,*p*) data at different energies and angles yield a self-consistent momentum distribution
- Moreover, momentum distribution derived from (*e*,*e*'*p*) and (γ,*p*) data for ^{12}C are consistent in (small) region of overlap
- For ^{16}O, (*e*,*e*'*p*) and (γ,*p*) data do not overlap

High momentum components in nuclear wave functions

Momentum Distribution for $p_{1/2}$ proton in ^{16}O from (e,$e'p$) and (γ,p) reactions



Crosses: (e,$e'p$) data (M. Bernheim *et al*., Nucl. Phys. **A375**, 381 (1982)

Solid curve: Elton-Swift [Nucl. Phys. **A94**, 52 (1967)]

Dashed curve: Density-dependent Hartree-Fock wavefunctions (J.W. Negele, Phys. Rev. C **1**, 1260 (1970)]

Dot-dashed curve: "Short-range correlations" introduced *via* Jastrow model [C. Ciofi degli Atti, Nuovo Cimento Lett. **1**, 590 (1971)]

J.L. Matthews, in Momentum Wave Functions—1982, Adelaide, South Australia, AIP Conf. Proc. No. 86, E. Weigold, ed.), p. 57.

D.J.S. Findlay *et al*., Phys. Lett. **74B**, 305 (1978)

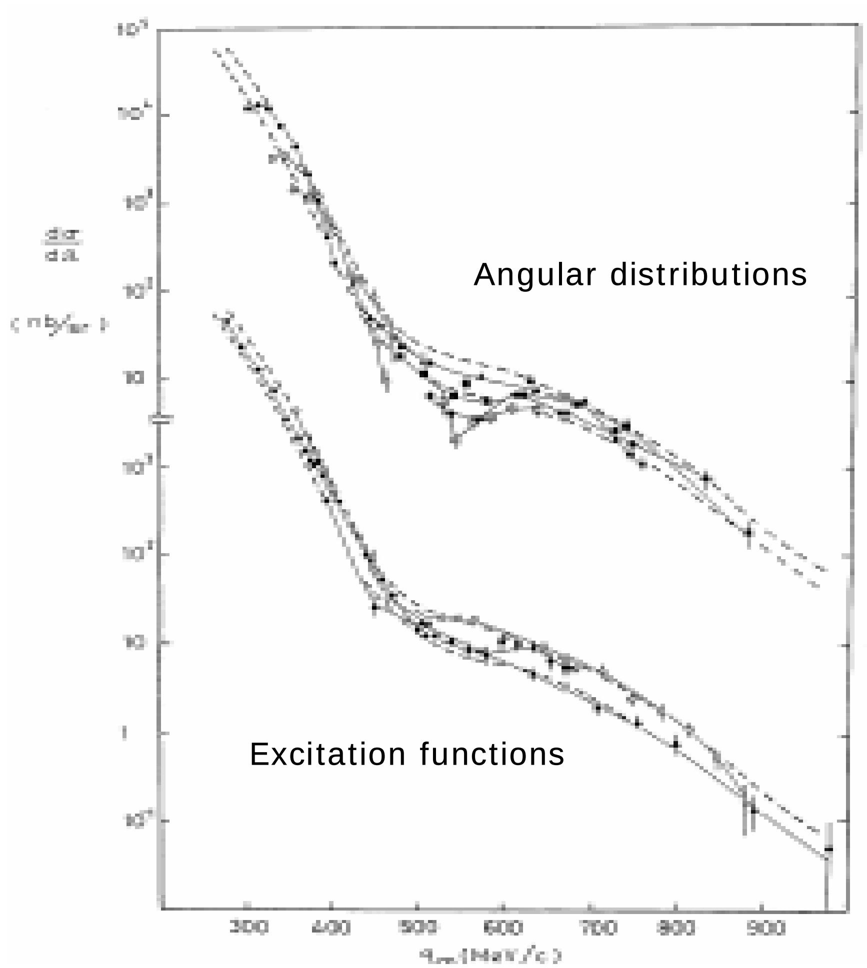
“Scaling and the mechanism of the (γ,*p*) reaction”

R.O. Owens, J.L. Matthews, and G.S. Adams, J. Phys. G **17**, 261 (1991)

- Is “scaling” of (γ,*p*) cross section with initial proton momentum surprising, given probable importance of two-nucleon mechanisms?

- Look at (γ,*p*) cross sections, plotted as a function of missing momentum, $\boldsymbol{q}_{\mathrm{m}} = \boldsymbol{p}_p - \boldsymbol{p}_{\gamma,}$,
  - p_p is the internal momentum of the outgoing proton before it emerges from the nuclear potential well
    - Estimated from asymptotic (measured) momentum using method of Findlay and Owens
  - Scaling is not as “exact” as when kinematic factors are divided out, but is still evident, over several orders of magnitude

“Scaling and the mechanism of the (γ,*p*) reaction”
R.O. Owens, J.L. Matthews, and G.S. Adams, J. Phys. G **17**, 261 (1991)



“Scaling and the mechanism of the (γ,*p*) reaction”
R.O. Owens, J.L. Matthews, and G.S. Adams, J. Phys. G **17**, 261 (1991)

- Scaling with q_m also expected for two-nucleon absorption

- Interaction mainly determined by overlap integral of the three contributing nucleon momentum wave functions

$$\int\int\int d^3q_p\; d^3q_n\; d^3q_{n'}\; \phi_p(\mathbf{q}_p)\; \phi_n(\mathbf{q}_n)\; \phi^*_{n'}(\mathbf{q}_{n'}),\quad \delta(\mathbf{q}_m = \mathbf{q}_p + \mathbf{q}_n - \mathbf{q}_{n'})$$

which measures the probability that they can provide the missing momentum q_m

- Overlap integral is a function of q_m alone, and is rapidly varying at high q_m
  - Assuming that this simple folding of nuclear momentum wave functions largely determines the shape of the cross section, can investigate effects of different types of two-nucleon correlations on (γ,*p*) cross section

"Scaling and the mechanism of the (γ,*p*) reaction"

R.O. Owens, J.L. Matthews, and G.S. Adams, J. Phys G **17**, 261 (1991)

- We performed a simple Jastrow-model calculation, following work by Weise and Huber [Nucl. Phys. **A162**, 330 (1971)]

- Correlated nuclear wave function obtained from independent particle model wave function by introducing a short-range correlation factor $G(\boldsymbol{r})$:

$$\Psi_{\rm corr} = \Psi_{\rm ipm} \prod_{i \neq j} [1 - G(\boldsymbol{r}_i - \boldsymbol{r}_j)]$$

  - Correlation factor produces a 'wound' in the wave function when the separation of a nucleon pair is small, in order to represent the effect of their mutual short-range repulsion
  - Alternatively, can picture

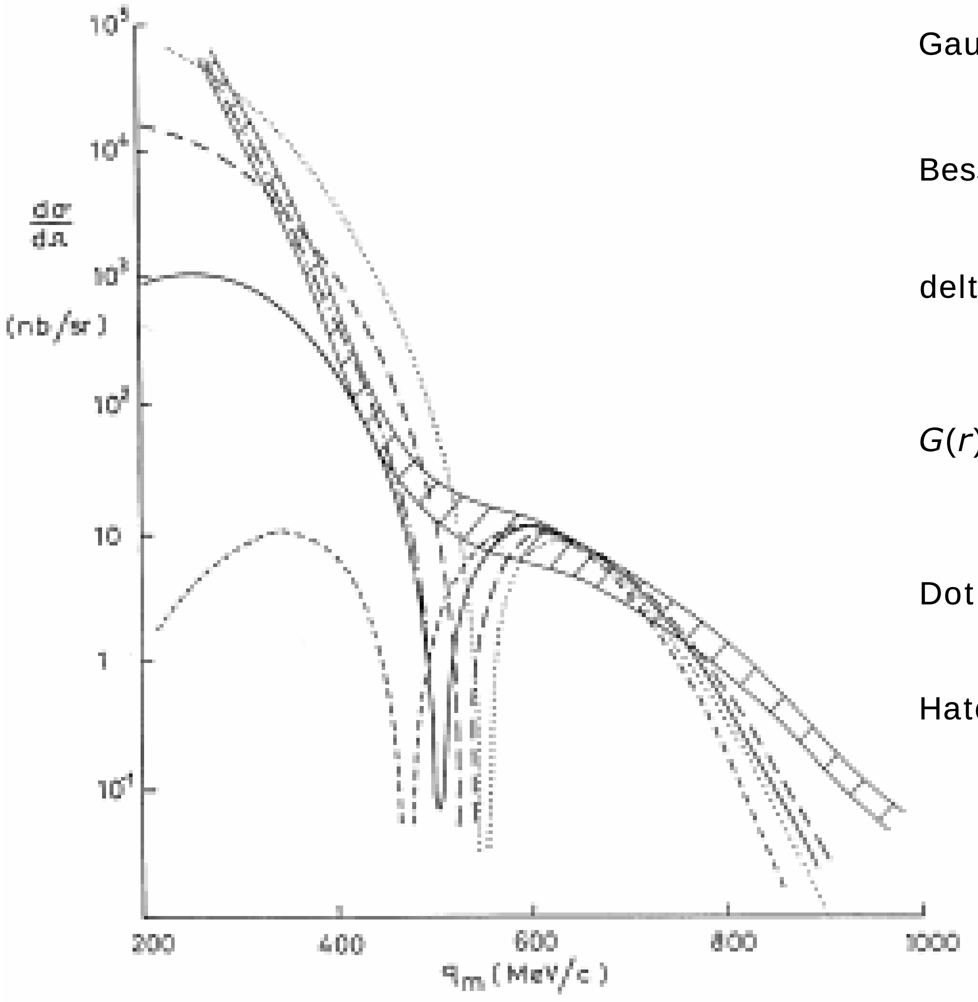
$$V(\boldsymbol{q}) \propto \int d^3r \, e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \, G(\boldsymbol{r})$$

    as a parameterization of the distribution of momenta exchanged between nucleon pairs due to their short-range interactions

- Different assumptions for correlation function
  - i) Gaussian
  - ii) Bessel function
  - iii) delta function
  - iv) Difference of two Gaussians with parameters chosen so that exchanged momentum is broadly peaked at 600 MeV/c

“Scaling and the mechanism of the (γ,*p*) reaction”

R.O. Owens, J.L. Matthews, and G.S. Adams, J. Phys G **17**, 261 (1991)



Gaussian (dotted curve): $\exp(-r^2/r_c^2)$, with r_c = 0.75 fm

Bessel function (short dashed curve): $j_0(r/r_c)$, with r_c = 0.4 fm

delta function (long dashed curve): $\delta(r - r_c)$, with wound volume corresponding to r_c = 0.8 fm

$G(r) \propto [1 - 2r^2/3r_c^2]\exp(-r^2/r_c^2)$, with r_c = 0.66 fm (solid curve)

Dot-dashed curve: result of adding one-nucleon term to solid curve

Hatched region: data (see dashed lines in previous plot of angular distributions and excitation functions)

Participants in Bates (γ,*p*) experiments

- Graduate students
  - Mike Leitch
  - Carl Peridier
  - Ben Craft*
  - Reinhard Schumacher
  - Steve Wood
  - Steve Turley
  - Laura Wiener
  - Ed Kinney
  - Freeman Lin
  - Eric Scheidker
  - Troy Soos
  - *deceased
- Postdocs
  - Lee Roberts
  - Wade Sapp
  - Dave Ingham
  - Gary Adams
  - Chris Maher
- Senior Collaborators
  - Phil Sargent
  - Hannes Jeremie (Montreal)
  - Bob Owens (Glasgow)
  - David Findlay (Harwell)
  - Mark Yuly (NNC, now Houghton College)