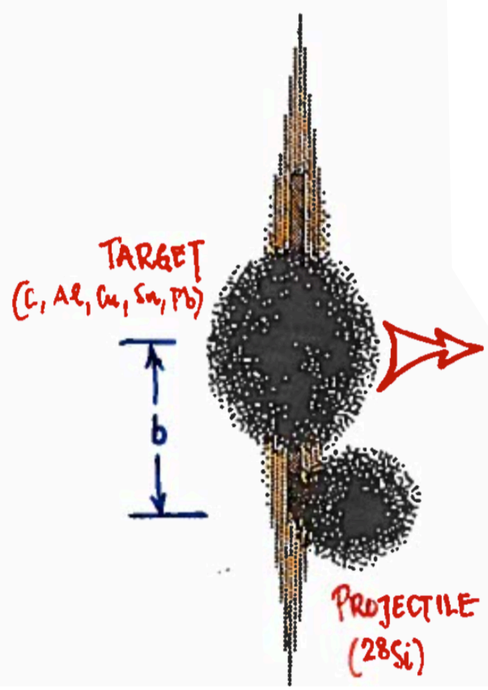
Electromagnetic dissociation of relativistic heavy-ions

W.J. Llope and P. Braun-Munzinger
& the BNL-AGS 814 collaboration

EMD in general
Unknowns in ~1980s: Multiple excitations? Exotic decays?
BNL-AGS Experiment 814
"folding model"
Results from E814
Results from other experiments
Summary

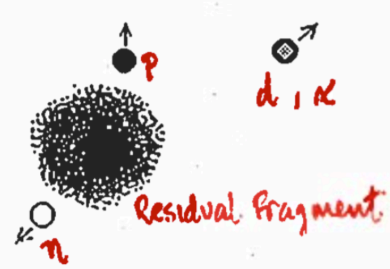
ElectroMagnetic Dissociation (EMD) as of the late-1980's…

before:



$b \gtrsim R_P + R_T$

after:



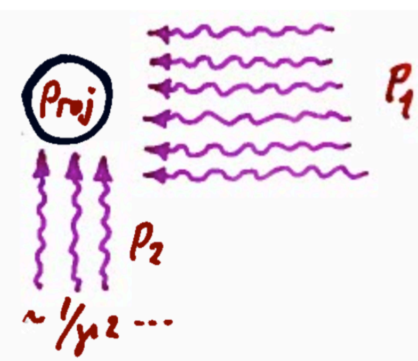
target nucleus is a strong source of (equivalent) photons *a la* Weizsäcker & Williams:

projectile absorbs photon(s) and then decays by some # of N or α emissions…

$$\mathcal{N}(E_\gamma, b) = \frac{1}{E_\gamma}\left[\frac{Z_T^2\alpha}{\pi^2\beta_P^2 b^2}\right]\left[x^2K_1^2(x) + \frac{x^2}{\gamma_P^2}K_0^2(x)\right]$$

where

$$x = \frac{E_\gamma b}{\gamma_P \beta_P \hbar c}.$$



At the time, all EMD results consistent with single γ absorption then statistical decay…

C. Brechtmann *et al.*, PRC 39, 2222 (1989),
Z. Phys. A 330, 407 (1988), Z. Phys. A 331, 463 (1988)
J.C. Hill *et al.*, PRL 60, 999 (1988)
M.T. Mercier *et al.*, PRL 52, 989 (1984), PRC 33, 1655 (1986)
H.H. Heckman *et al.*, PRL 37, 56 (1976)
J. Barrette *et al.* (E814), PRC 41, 1512 (1990)

EMD open questions (mid-1980s)

EMD has been investigated experimentally with a variety of techniques.

- using real photons
- using heavy targets & radiochemical techniques
- & foil detectors
- & "complete spectroscopy"

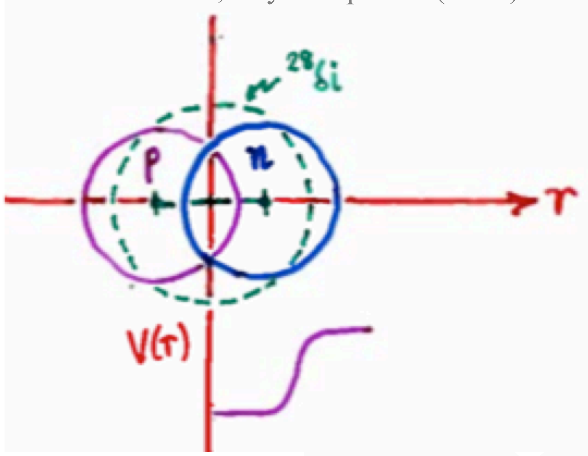
Heavy targets & relativistic light ions (^{16}O, ^{28}Si, ^{32}S, ...) allow the possibility of MULTIPLE EXCITATION.

- resultant decay mechanisms are NOT understood.

Giant Dipole Resonance:

dominates the γ absorption cross-section…

Ph. Chomaz *et al.*, Phys. Rep. 252 (1995) 275



$$\rho^{(N)} \sim 0.51 \frac{A_{proj}^{2/3}}{\sqrt{N_{proj} Z_{proj}}} \sqrt{2N+1}$$

"Average Collective Coordinate"

for ^{28}Si: $\rho^{(1)} \sim 0.6$ fm, ..., $\rho^{(4)} \sim 1.2$ fm !

Radius (^{28}Si) ~ 3.6 fm

- an efficient production mechanism for final states of many neutrons at Zero Temperature?

BNL-AGS E814

Beam: C1
Status: In progress
Approved Hours: 3600

Experiment 814 - Study of Extreme Peripheral Collisions and of the Transition from Peripheral to Central Collisions in Reactions Induced by Relativistic Heavy Ions

Brookhaven National Laboratory	M. Fatyga, R. Hogue, D. Lissauer, T. Ludlam, D. Makowiecki, E. O'Brien, V. Polychronakos, H. Takai, T. Throwe, C. Woody
CERN	W.J. Willis
Los Alamos National Laboratory	J. Boissevain, D. Fox, W. Sondheim, J. Sunier, H. van Hecke
McGill University	J. Barrette, S.K. Mark, C. Pruneau
University of New Mexico	B. Bassalleck, J. Hall, D. Wolfe
University of Pittsburgh	W. Cleland, K. Jayananda, D. Kraus, U. Sonnadara, M. Takagui, X. Zhang
State University of New York, Stony Brook	R. Bellwied, P. Braun-Munzinger, G. David, N. Herrmann, W. Llope, M. Muthuswami, J. Stachel, L. Waters, N. Xu, Y.C. Zhang
University of Tel-Aviv	R. Heifetz
Texas A&M University	J.A. Shoemaker, J. Simon, K. Wolf
Yale University (Nuclear Physics) (High Energy Physics)	S.V. Greene, T. Hemmick, R. Majka, J. Mitcheli, F. Rotondo, J. Sandweiss, B. Shivakumar
Spokesman:	**P. Braun-Munzinger**

Experiment 814 combines 4π calorimeter coverage with a high resolution forward spectrometer. Extreme peripheral collisions are investigated by making an exclusive study of projectile fragmentation processes induced by Coulomb excitation. Central collision, including transverse energy and charged particle multiplicity production and a search for hydrodynamic flow effects are also studied. In the forward spectrometer, spectra for protons, neutrons and eventually, pions and kaons are measured to provide a detailed picture of the stopping process. A search is made for neutral particles, possibly produced in central collisions. The possible production of strange matter in such collisions is studied. The target area calorimetry provides a reaction trigger while fragments are identified in the forward spectrometer by their momentum/charge, Time-Of-Flight, specific energy loss and kinetic energy. This includes a measurement of anti-proton production and a search for anti-nucleus production in such collisions.

State of the art calculations: Bertulani & Baur

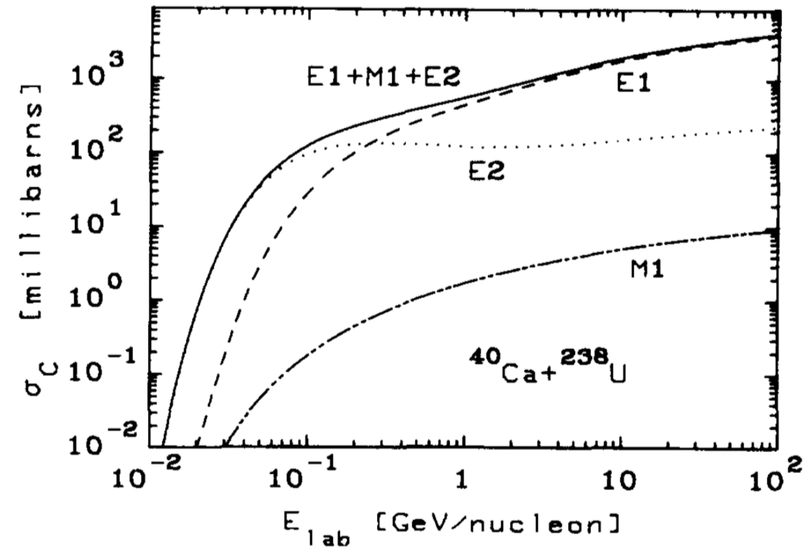
G. Baur and C. Bertulani, Phys. Rep. 163 (1988) 299.

EMD cross-section:

$$\sigma = \int_R^\infty 2\pi b\, P(b)\, \mathrm{d}b = \int n(\omega)\, \sigma_\gamma(\omega)\, \frac{\mathrm{d}\omega}{\omega}$$

Approximation for the GDR and GQR:

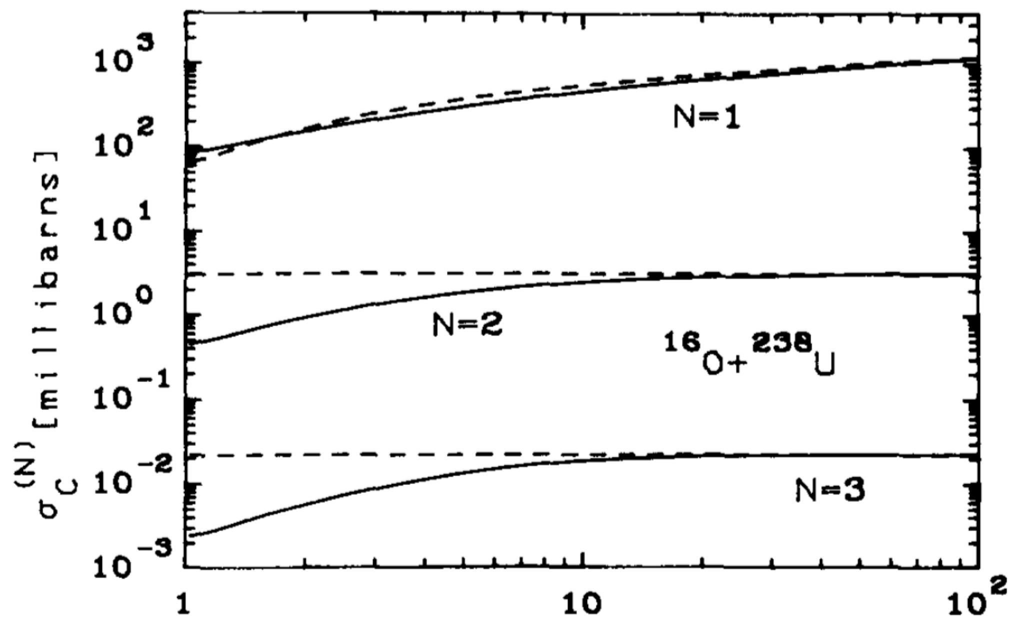
$$\sigma_C \simeq \frac{n_{E1}[E_{GR}^{(1)}]}{E_{GR}^{(1)}} \int \sigma_\gamma^{E1}(E_\gamma)\, \mathrm{d}E_\gamma + n_{E2}[E_{GR}^{(2)}]\, E_{GR}^{(2)} \int \frac{\sigma_\gamma^{E2}(E_\gamma)\, \mathrm{d}E_\gamma}{(E_\gamma)^2}$$



Evaluate prefactors at parameterized E* for GDR,GQR

$$E_{GR}^{(1)} = 80/A^{1/3}\ \mathrm{MeV}$$ <E*> for GDR

$$E_{GR}^{(2)} = 62/A^{1/3}\ \mathrm{MeV}$$ <E*> for GQR



GDR and GQR strengths from sum rules:

$$\int \sigma_\gamma^{E1}(E_\gamma)\, \mathrm{d}E_\gamma \simeq 60NZ/A\ \mathrm{MeV\ mb}$$

$$\int \sigma_\gamma^{E2}(E_\gamma)/(E_\gamma)^2\, \mathrm{d}E_\gamma \simeq 0.22\, ZA^{2/3}\ \mu\mathrm{b\ MeV}^{-1}$$

Assumes the photoabsorption cross-section is a delta function at a given E*…

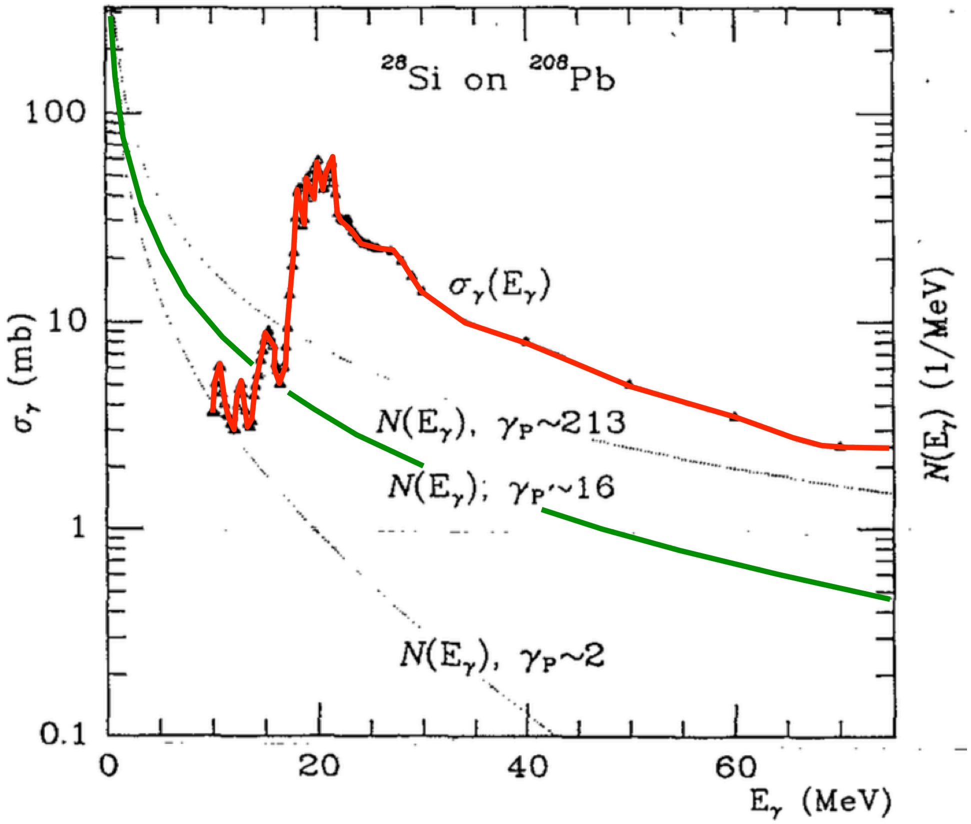
Folding model approach of PBM & wjl (single photon absorption)

WJL & PBM, PRC 41, 2644 (1990)

(real) photon absorption cross-sections taken from experiment…

$10 < E_\gamma < \hbar c \gamma_{proj}/b_{min}$

significant width due to quasi-deuteron...



eq. photons are real photons…
straight line trajectories…
all γ‘s absorbed in ground state…
numerical integration (requires care)…

mean # of ‘s absorbed at impact parameter b:

$$m_\gamma(b) = \int dE_\gamma \mathcal{N}(E_\gamma, b)\sigma_\gamma(E_\gamma) = \int dE_\gamma \Phi(E_\gamma, b)$$

In harmonic oscillator approximation, probability of single γ absorption is Poissonian:

$$\mathcal{P}^{(1)}(b) = m_\gamma(b) e^{-m_\gamma(b)} \qquad (\, m_\gamma << 1 \,)$$

Properly normalized probability that this γ has an energy E:

$$q^{(1)}(E_\gamma, b) = \frac{\Phi(E_\gamma, b)}{m_\gamma(b)}$$

Differential cross-section of absorption of exactly one γ of energy E (E*):

$$\frac{d\sigma^{(1)}}{dE^*} = \int db\, 2\pi b \mathcal{P}^{(1)}(b) q^{(1)}(E^*, b)$$

Assume the produced GDR mixes completely into compound nucleus before decaying.
Use statistical model (CASCADE) for decay BRs…

single photon cross-sections scale like $\sim Z_T^2$

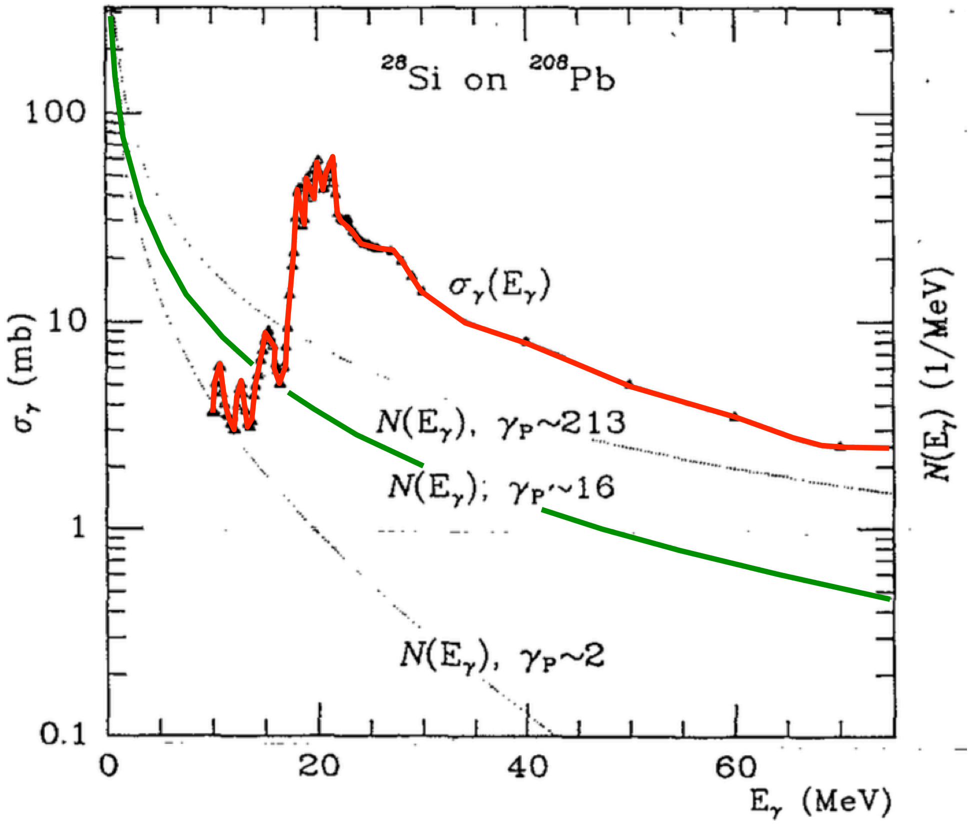
Folding model approach of PBM & wjl (multiple photon absorption)

WJL & PBM, PRC 41, 2644 (1990)

(real) photon absorption cross-sections taken from experiment…

$10 < E_\gamma < \hbar c \gamma_{proj}/b_{min}$

significant width due to quasi-deuteron...



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mean # of 's absorbed at impact parameter b:

$$m_\gamma(b) = \int dE_\gamma \mathcal{N}(E_\gamma, b)\sigma_\gamma(E_\gamma) = \int dE_\gamma \Phi(E_\gamma, b)$$

In harmonic oscillator approximation, probability of two γ absorptions is Poissonian:

$$\mathcal{P}^{(2)}(b) = \frac{m_\gamma^2(b)}{2!} e^{-m_\gamma(b)}$$

Properly normalized probability that these γ's have result in sum energy E (E*):

$$q^{(2)}(E^*, b) = \frac{\int dE_1 \Phi(E_1, b)\Phi(E^* - E_1, b)}{m_\gamma^2(b)}$$

Differential cross-section of absorption of two γ's resulting in energy E (E*):

$$\frac{d\sigma^{(2)}}{dE^*} = \frac{1}{2!}\int db\, 2\pi b e^{-m_\gamma(b)} \times \int dE_1 \Phi(E_1, b)\Phi(E^* - E_1, b)$$

Total cross-section is then the sum over N γ's:

$$\sigma = \int dE^* \left[\frac{d\sigma^{(1)}}{dE^*} + \frac{d\sigma^{(2)}}{dE^*} + \frac{d\sigma^{(3)}}{dE^*} + \cdots \right]$$

n-photon cross-sections scale like $\sim Z_T^{2n}$

Importance of realistic photoabsorption cross-section

WJL & PBM, PRC 41, 2644 (1990)

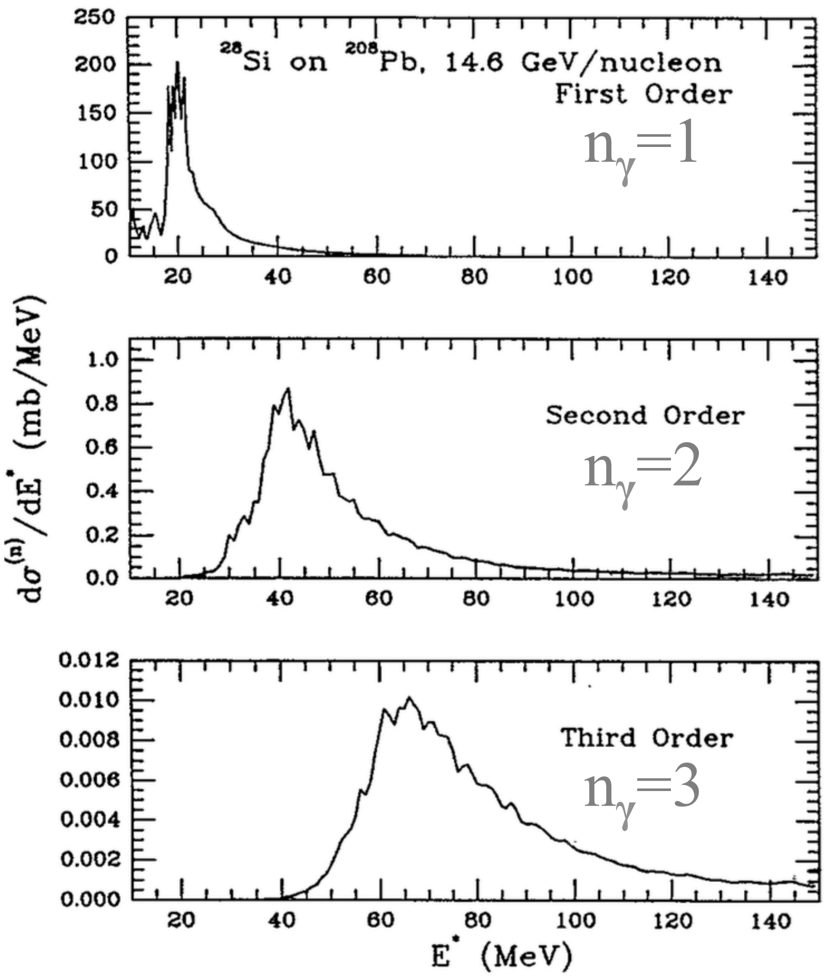
	Bertulani & Baur	WJL&PBM narrow σ_γ	WJL&PBM real σ_γ	
Order	σ (Ref. 20)	$\sigma(\sigma_\gamma^G)$	$\sigma(\sigma_\gamma^{expt})$	
	^{16}O on ^{238}U at 100 GeV/nucleon			
1	N/A	1.03 b	2.5 b	→ ×2.5
2	3.1 mb	3.16 mb	20.6 mb	→ ×6.5
3	22 μb	22.9 μb	328 μb	→ ×14
4	160 nb	164.3 nb	4.8 μb	→ ×30
	^{32}S on ^{238}U at 100 GeV/nucleon			
1	N/A	2.63 b	4.3 b	→ ×1.7
2	17 mb	17.5 mb	46.3 mb	→ ×2.6
3	250 μb	273 μb	1.1 mb	→ ×4
4	4 μb	4.3 μb	26.6 μb	→ ×6.2

calculated cross-sections for EMD are significantly larger when using a realistic photoabsorption cross-section!

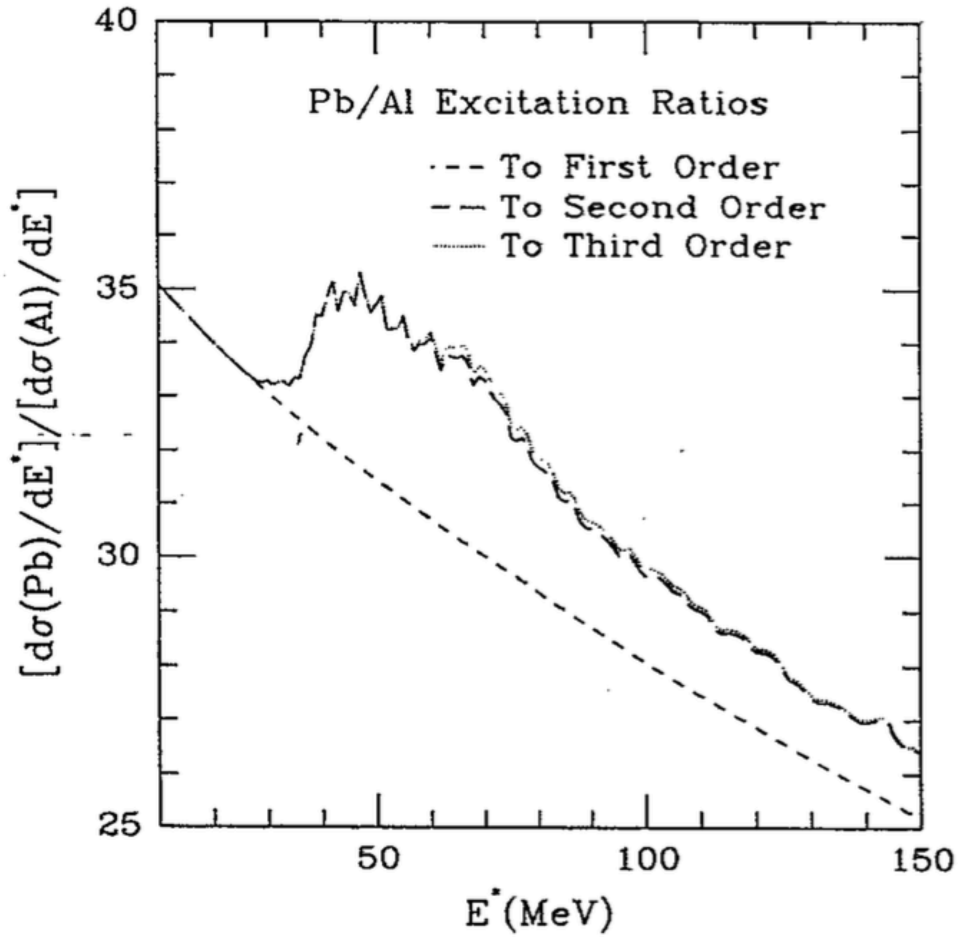
Signatures of multiple photon absorption

WJL & PBM, PRC 41, 2644 (1990)

GDR dominates the photoabsorption, so n-fold absorption at $E^* \sim nE_{GDR}$



n-photon cross-sections go like $\sim Z_T^{2n}$



study ratios of cross-sections for high- and low-Z targets for decay channels near the peak of the n-fold photoabsorption cross-section!

look for enhancements in decay channels w/ Q-values near n^*E_{GDR}…

Signatures of multiple photon absorption

WJL & PBM, PRC 41, 2644 (1990)

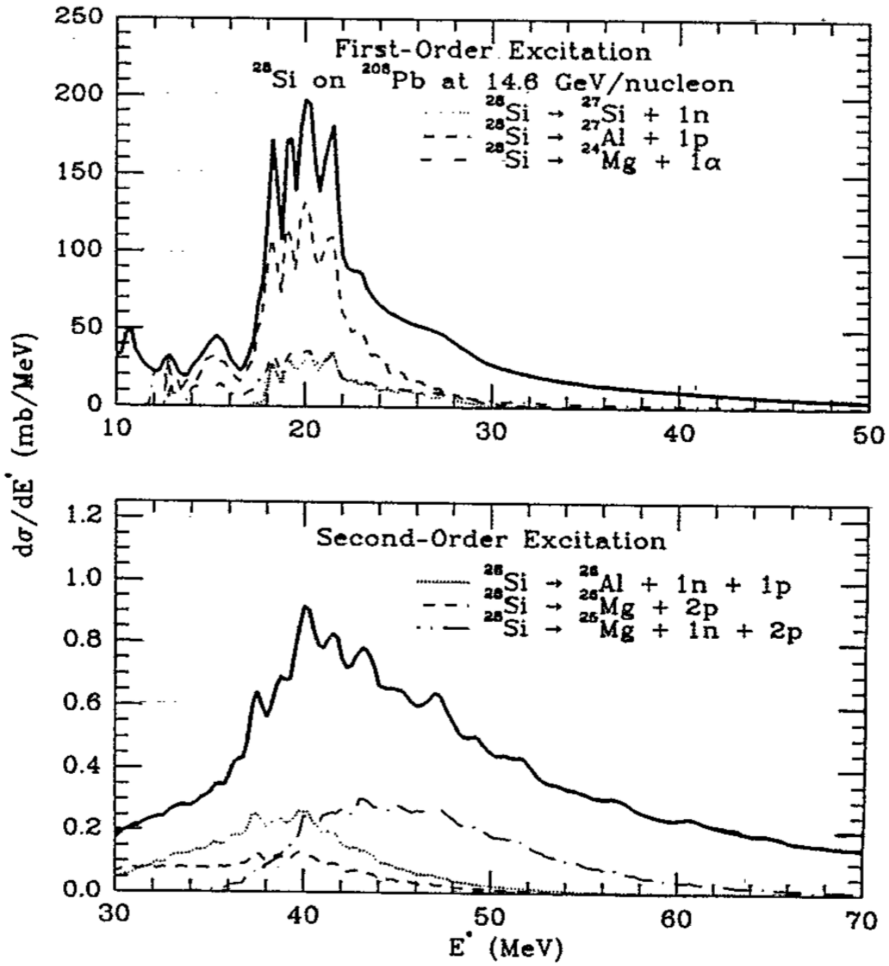


FIG. 8. The differential first-order (top plot, solid line) and second-order (bottom plot, solid line) excitation cross sections versus the excitation energy. The dashed lines indicate the contributions from the important decay channels, labeled in the appropriate figure.

E814 ratios from 1988 test run…

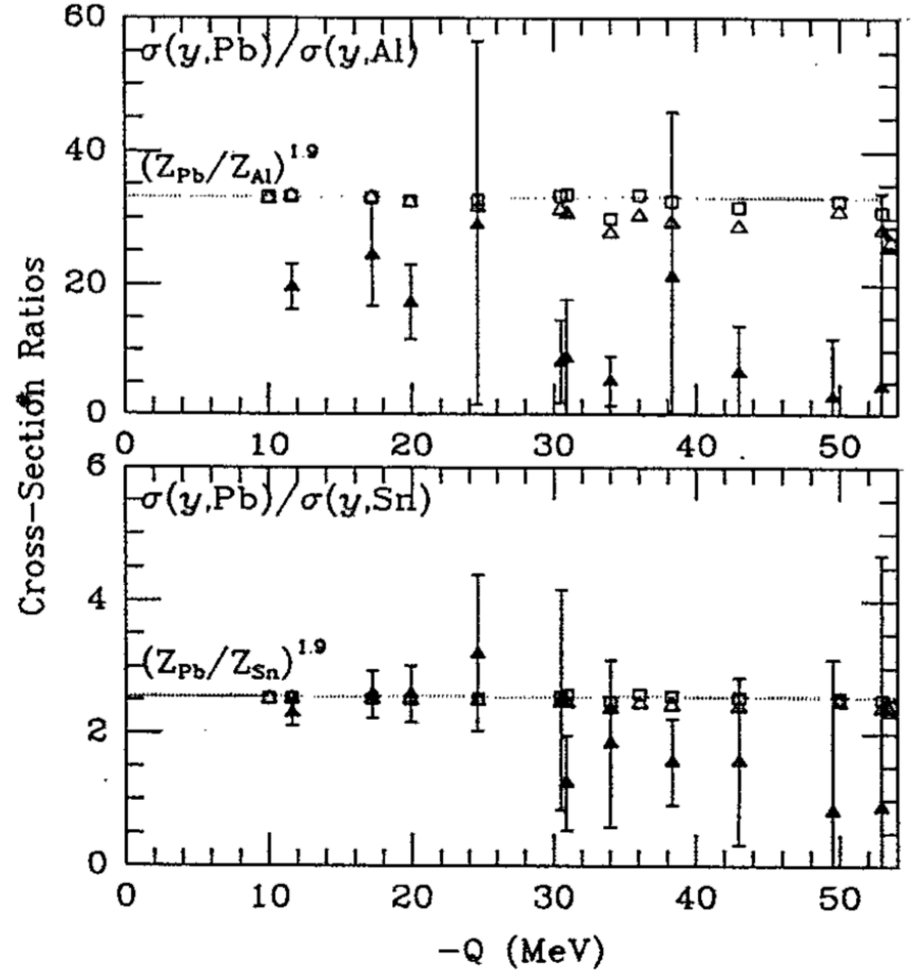


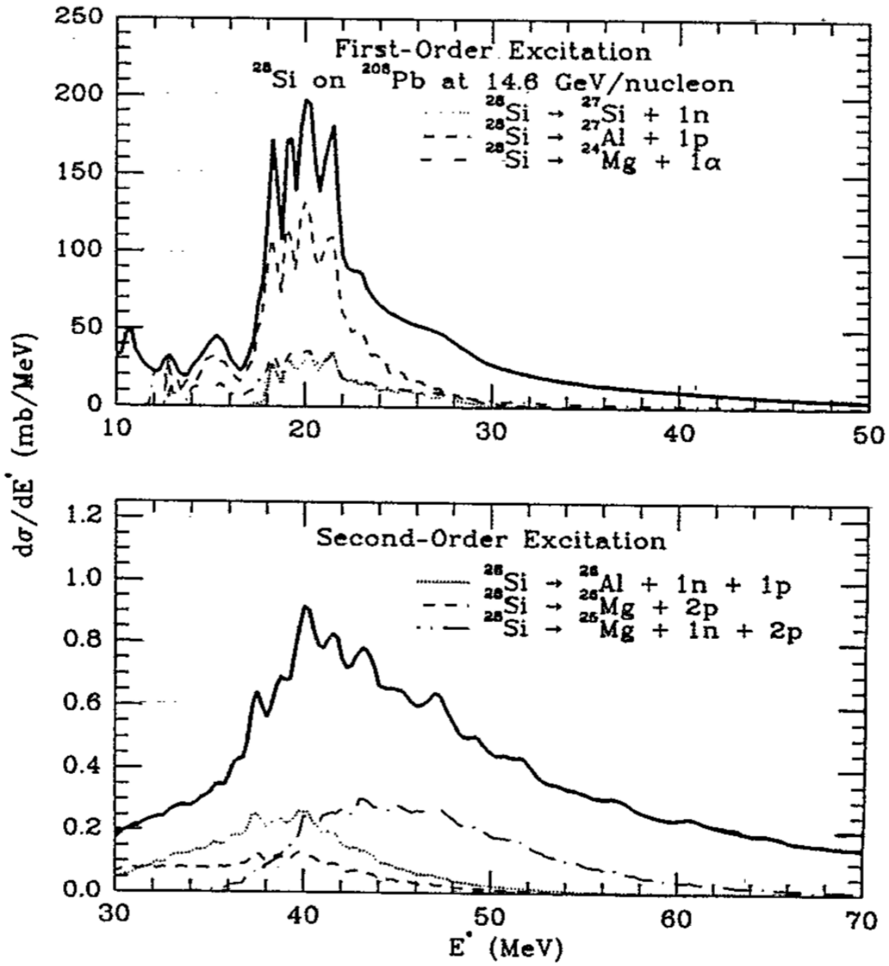
FIG. 10. The ratios of the E814 cross sections, Ref. 10, for the electromagnetic dissociation of 14.6 GeV/nucleon ^{28}Si projectiles (solid points), the calculated ratios to first order (open triangles) and to third order (open squares). The dotted line gives the ratio expected for first-order excitation.

E814 1988 data: significant nuclear contamination… Error bars need to be *much* smaller…

Signatures of multiple photon absorption

$(Z_1/Z_2)^{1.9}$

WJL & PBM, PRC 41, 2644 (1990)



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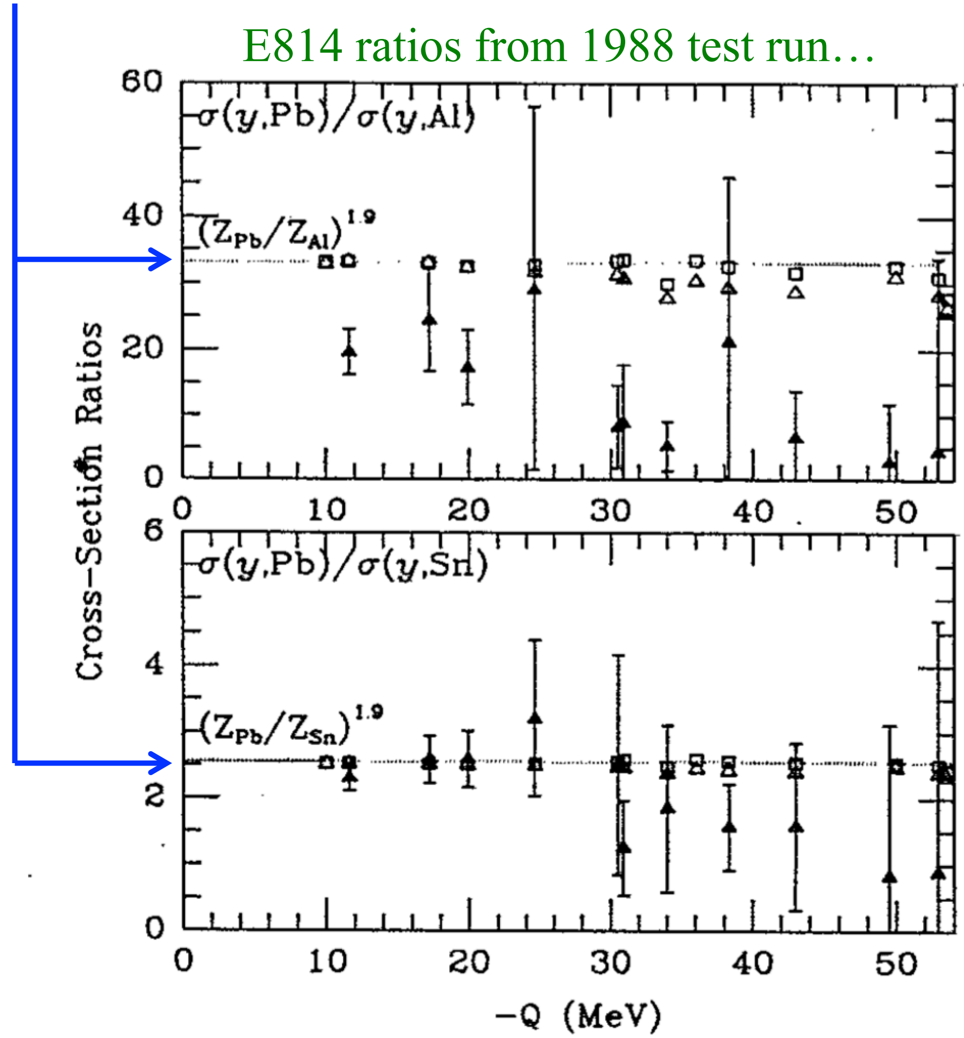

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E814 1988 data: significant nuclear contamination… Error bars need to be *much* smaller…

Goals of the E814 "extreme peripheral collisions" program

Accurate separation between EM and nuclear excitations in experimental data taken by the E814 experiment for ^{28}Si on C, Al, Cu, Sn, Pb targets at 14.6 GeV/c/N

use many detectors to reject nuclear interactions and redundantly measure all FS particles

Compare measured EMD cross-sections with those from a semi-classical Weizsäcker-Williams framework which incorporates the statistical model for the nuclear decay to look for discrepancies possibly related to exotic non-statistical decay mechanisms

Establish with precision the scaling of the cross-sections for EM and nuclear excitations with the target species

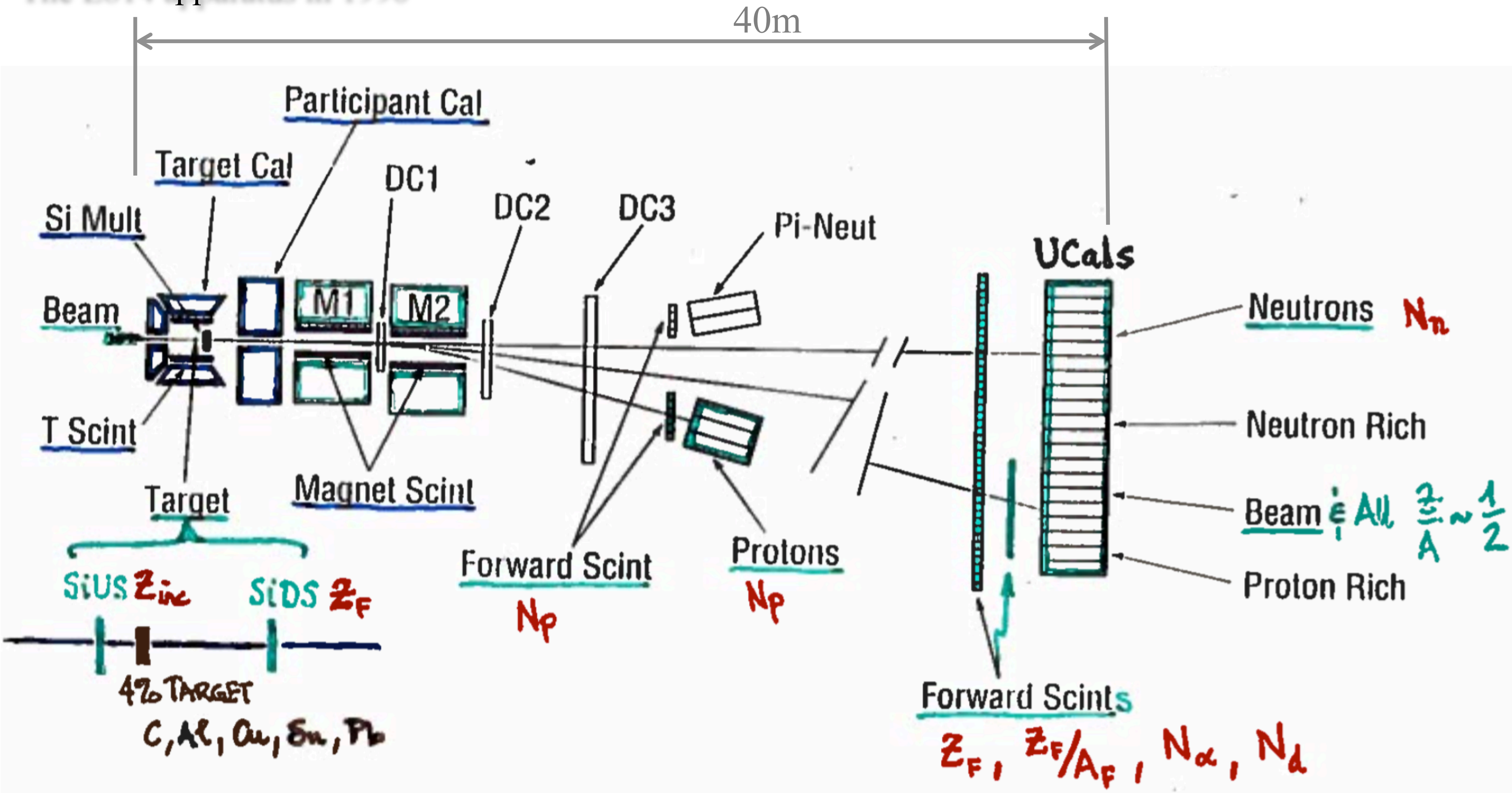
nuclear cross-sections $\sigma \sim (A_P^{1/3} + A_T^{1/3})$

EMD cross-sections $\sigma_n \sim Z_T^{1.9n}$ $n = \#$ of γ's absorbed

Establish or deny that multiple electromagnetic excitations contribute to the measured cross-sections

study how the EMD cross-sections scale with the target charge Z_T

The E814 apparatus in 1990



"4π calorimetry" hermetically surrounding the target…

separate EMD from peripheral nuclear reactions

Forward magnetic spectrometer and calorimetry…

(redundantly) exclusive measurements of the final state

Unit Z (or A) resolution on all nucleons and nuclei in the final state required at the trigger level … Otherwise E814 only measures down-stream interactions…

May 1987: test run
B. Bassalek, *et al.* (E814), Z. Phys. C 38, 45 (1988)

December 1988: test run
J. Barrette *et al*. (E814), PRL 64 (1990) 1219
J. Barrette *et al*. (E814), PRC 41 (1990) 1512
J. Barrette *et al*. (E814), PLB 252 (1990) 550

June 1989: nearly final apparatus testing DCs and PCal

June 1990: apparatus complete emphasis on peripheral events… much more detailed triggering…

RUNNING CONDITIONS:

"1p (w/ ONLINE VETO)"

Pretrigger:
- E ≳ 3 GeV in UCal – proton region
- Z ≳ 12 in Upstream Silicon
- 6 ≲ Z ≲ 13.5 in Downstream Silicon

Second-Level:
- E ≳ 7.5 in UCal – proton region
- Multiplicity ≲ 2 in "Veto" Wall
- Z ≳ 6 in DS FSci
- 4π Veto → TCal, PCal, MSci

"1n (w/ ONLINE VETO)"

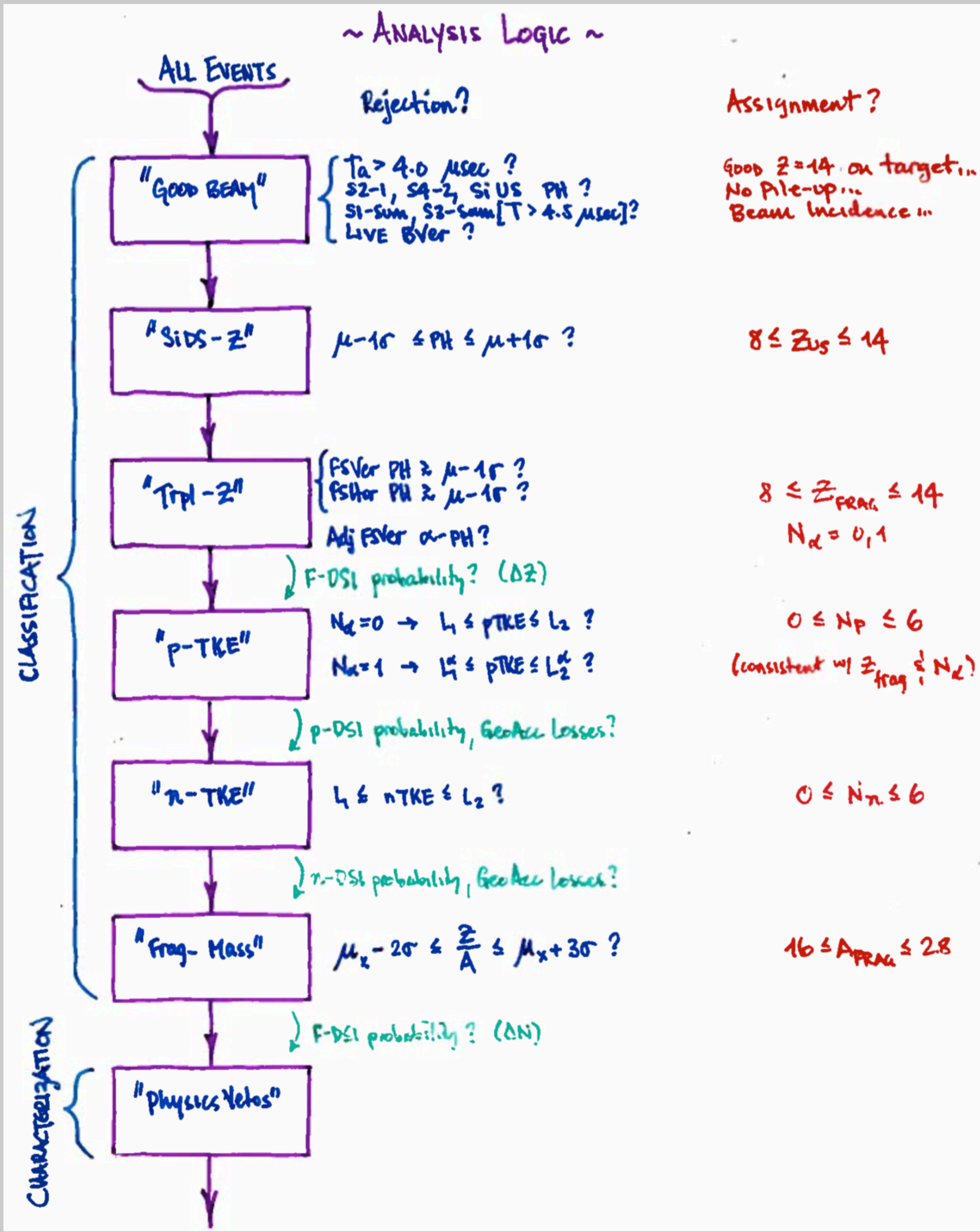
Pretrigger:
- E ≳ 3 GeV in UCal – neutron region
- Z ≳ 12 in Upstream Silicon
- Z ≳ 11 in Downstream Silicon

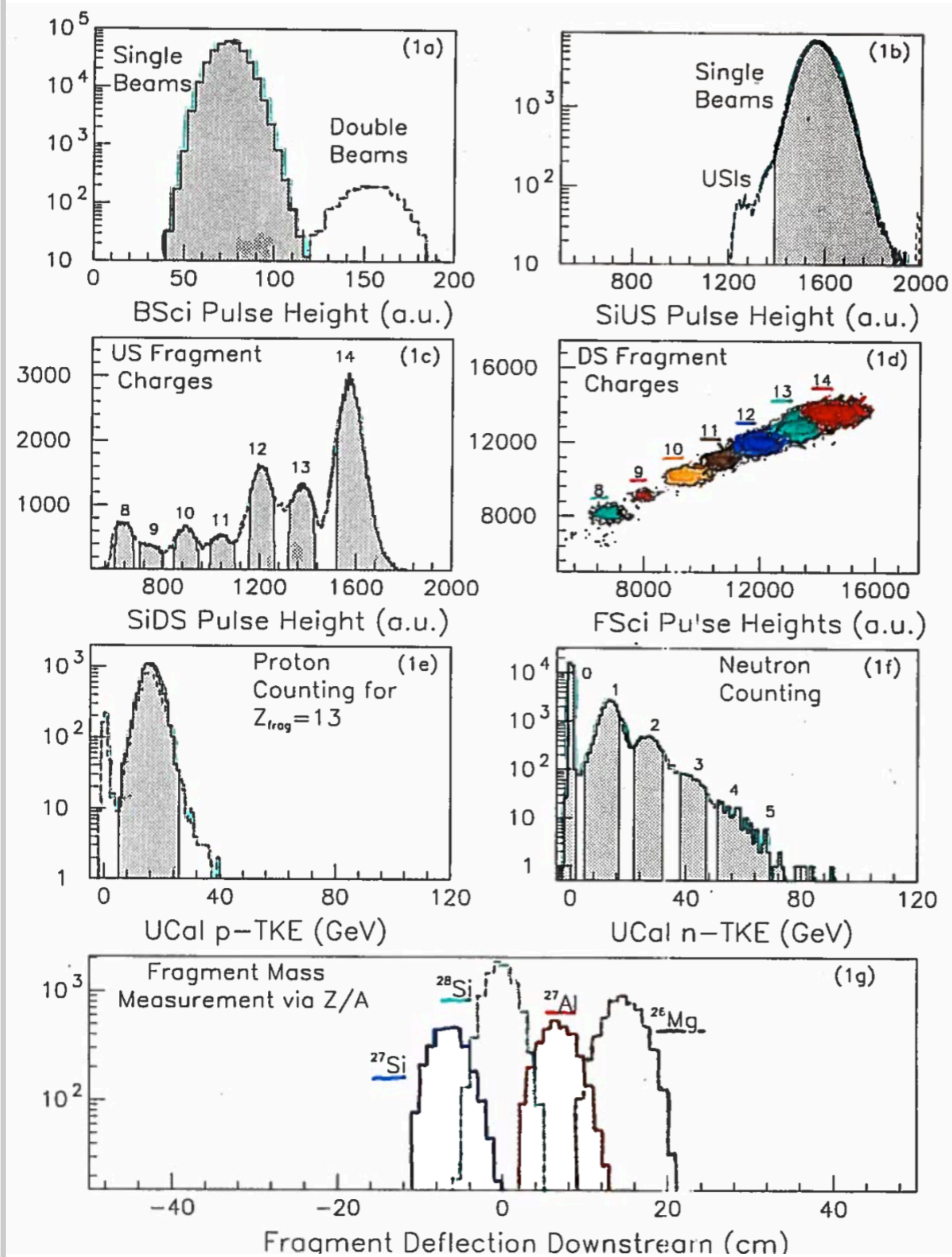
Second-Level:
- E ≳ 7.5 GeV in UCal – neutron region
- Multiplicity ≲ 2 in "Veto" Wall
- Z ≳ 9 in FSci
- 4π Veto → TCal, PCal, MSci

	December '88	June '90
Yield: $^{28}Si(^{208}Pb) \to {}^{27}Al + 1p$	~2500	~750,000
Integrated luminosity	~100 μb	~1 μb

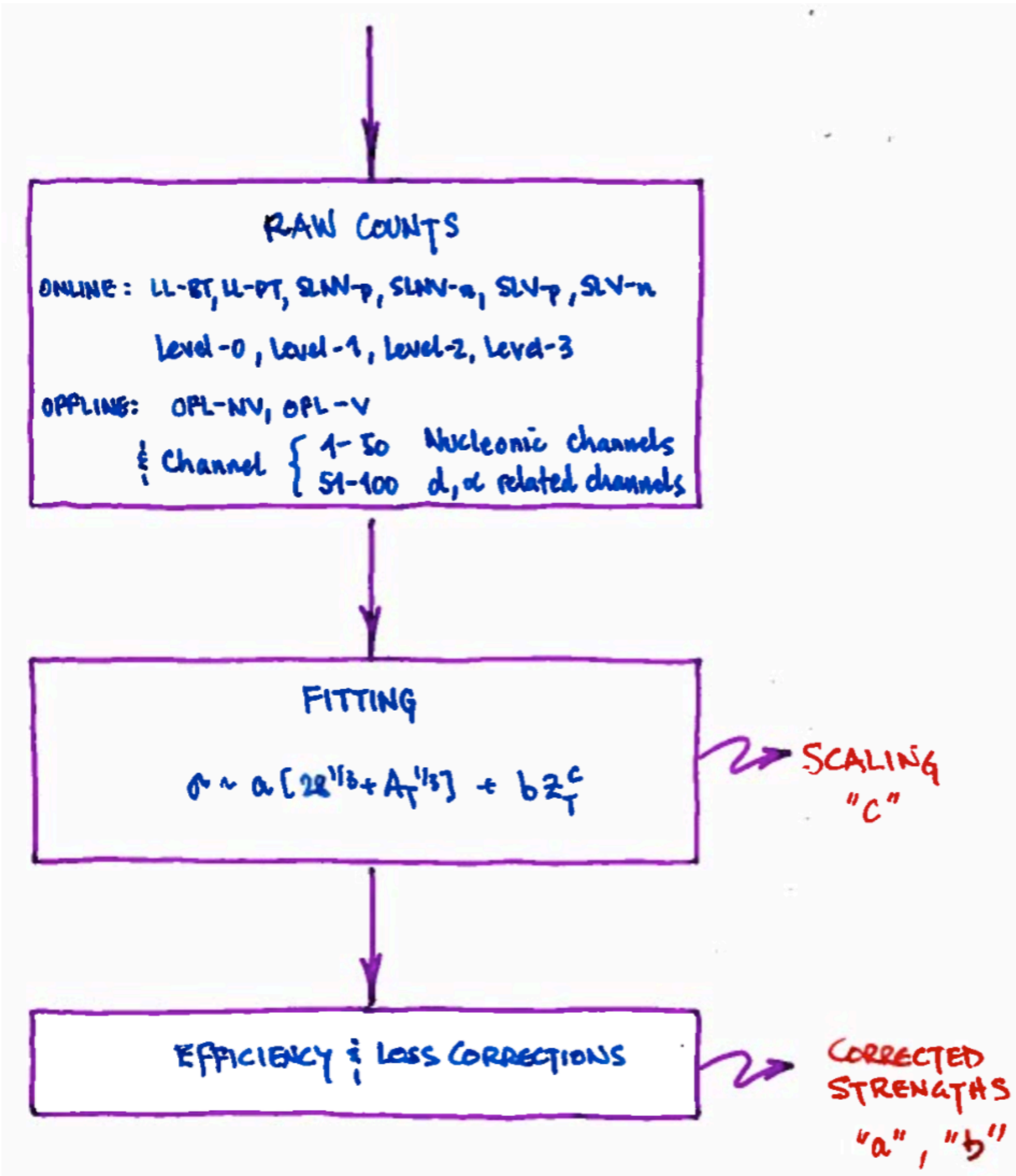
i.e. a factor of 5∅ in "tape-writing" efficiency!

Measuring exclusive final states with E814





Measuring exclusive final states with E814



Look for multiple photon absorption: $\sigma \sim Z_T^X$ & $X>1.9$

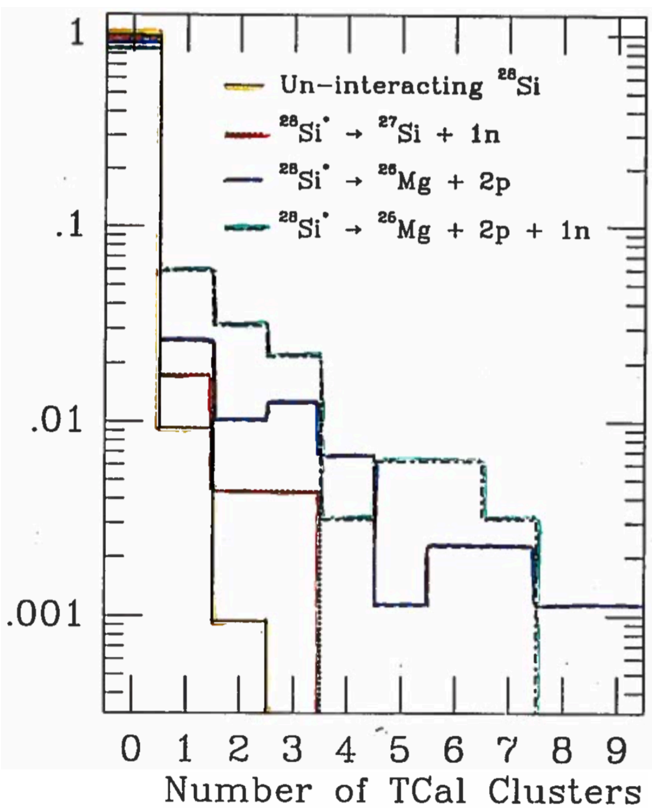
Look for possibly exotic decay mechanisms: compare σ to folding model + CASCADE

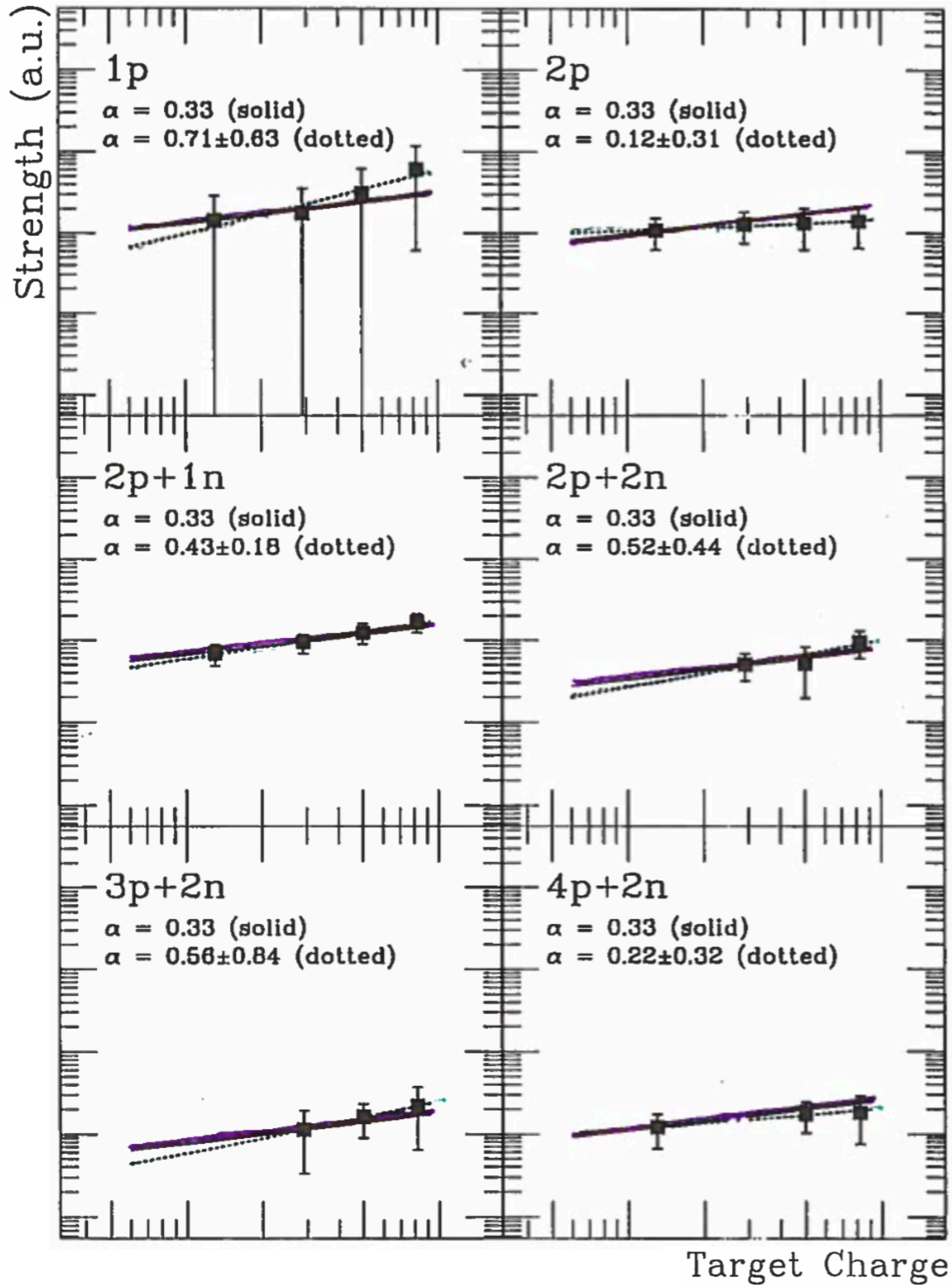
Making sure we understood the obviously nuclear excitations

for nuclear excitations, expect:

$$\sigma \sim (28^{1/3} + A_T^{1/3})$$

select exclusive events accompanied by activity in target calorimeter





EMD cross-sections

now concentrate on EMD…

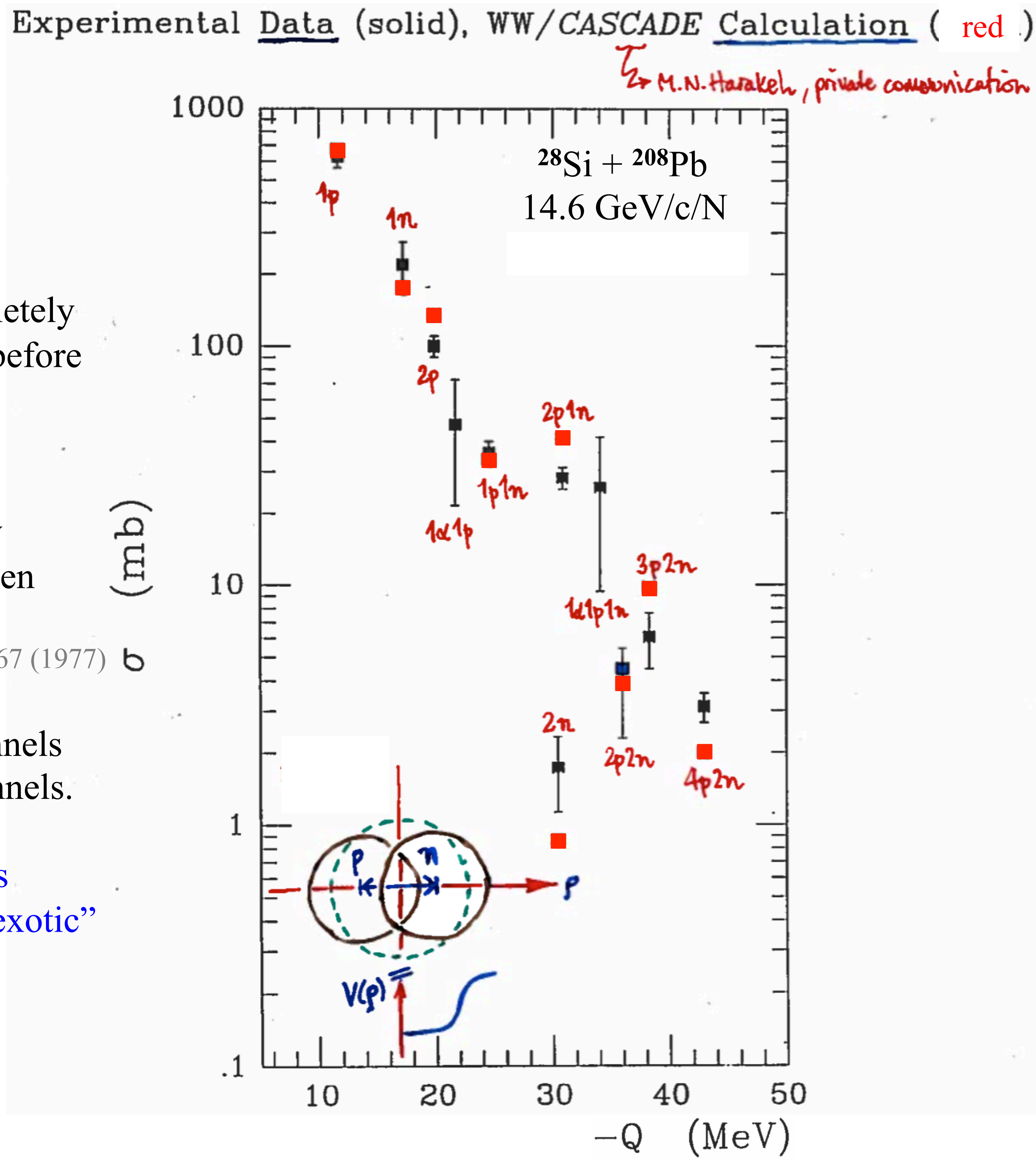
Assume nGDR mixes completely into the compound nucleus before decaying

Use a statistical model (CASCADE) to give the decay branching fractions for a given final state...

F. Pühlhofer, Nucl. Phys. A280, 267 (1977)

tends to overestimate p-channels
and underestimate n-channels.

some factor ~2 discrepancies
but nothing considered "exotic"



EMD cross-sections

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Assume nGDR mixes compl
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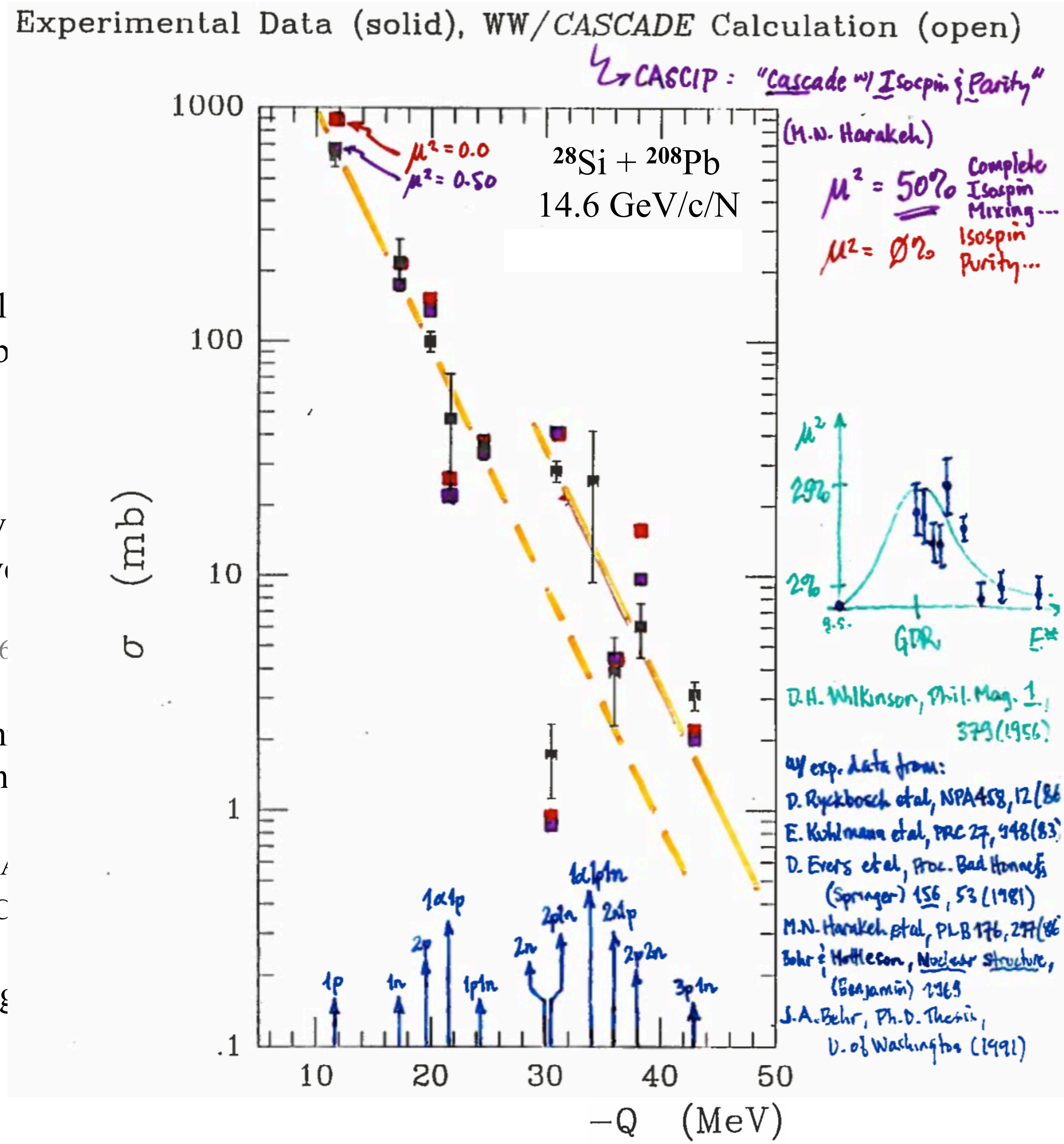
final state...

F. Pühlhofer, Nucl. Phys. A280, 26

tends to overestimate p-chan
and underestimate n-chan

Also tried a version of CASCA
including isospin & parity (C
from M. Harrakeh...
...generally small chang



Z_T scaling

nuclear excitations still contribute even after careful cuts in the target region… "quiet nuclear component"

Rejected what I could, then fit cross-sections *vs.* Z_T with:

$$\sigma \sim a(28^{1/3}+A_T^{1/3}) + bZ_T^{c}$$

a,b: cross-sections

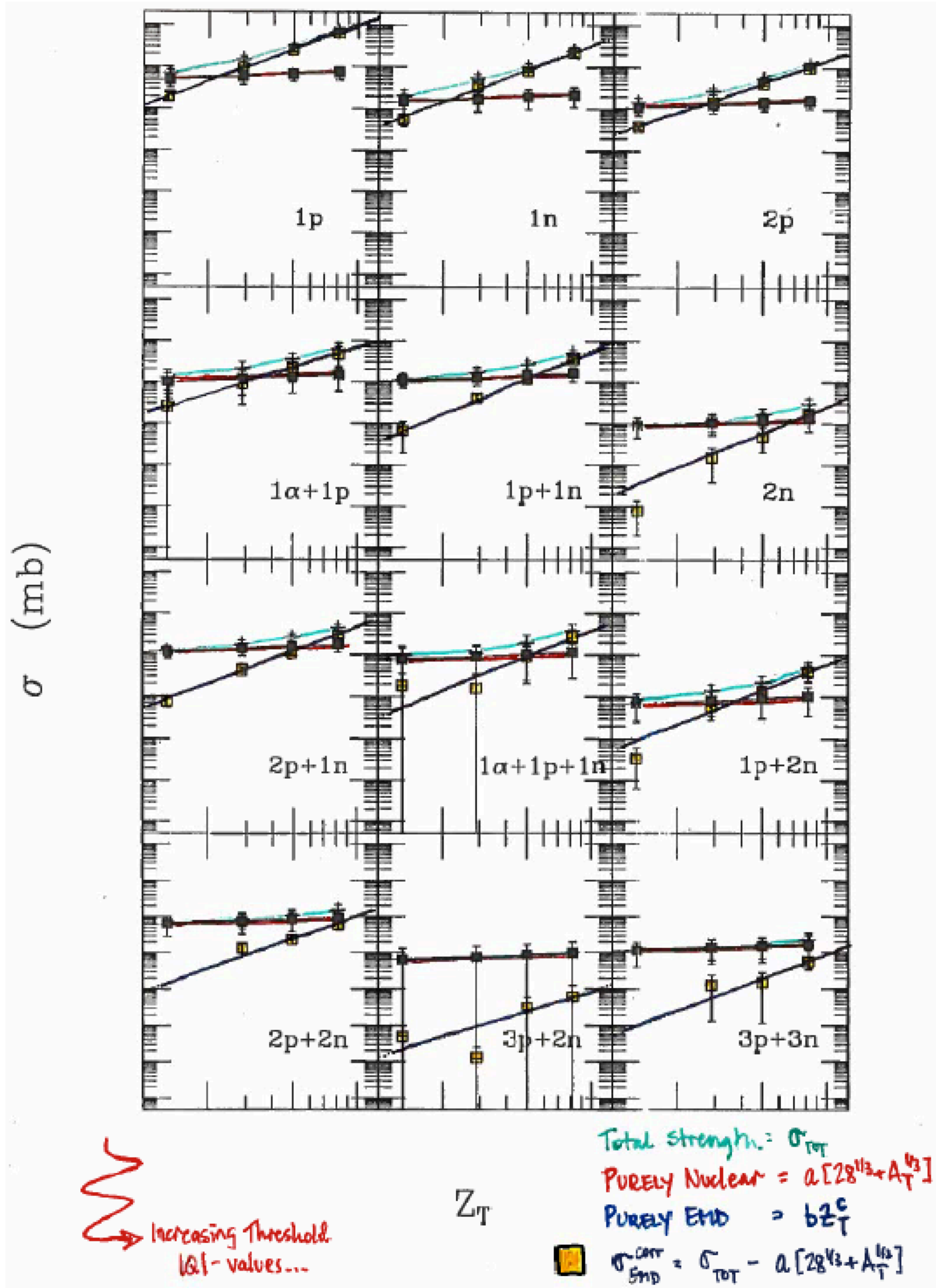
c: scaling

For single photon absorption:

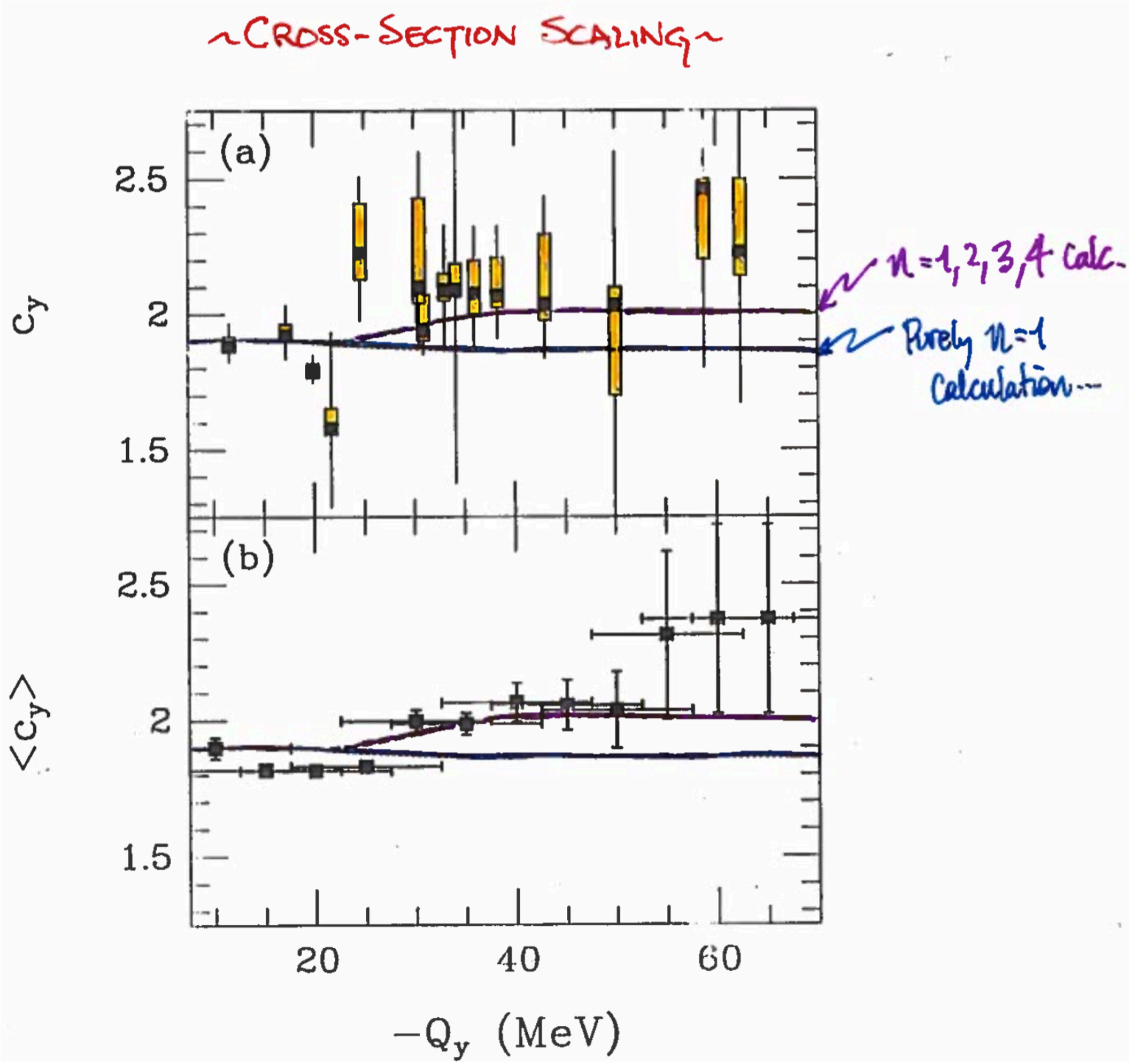
$c \sim 1.9$

due to different ranges of impact parameters sampled for different targets

WJL & PBM, PRC 41, 2644 (1990)



Observation of two photon absorption

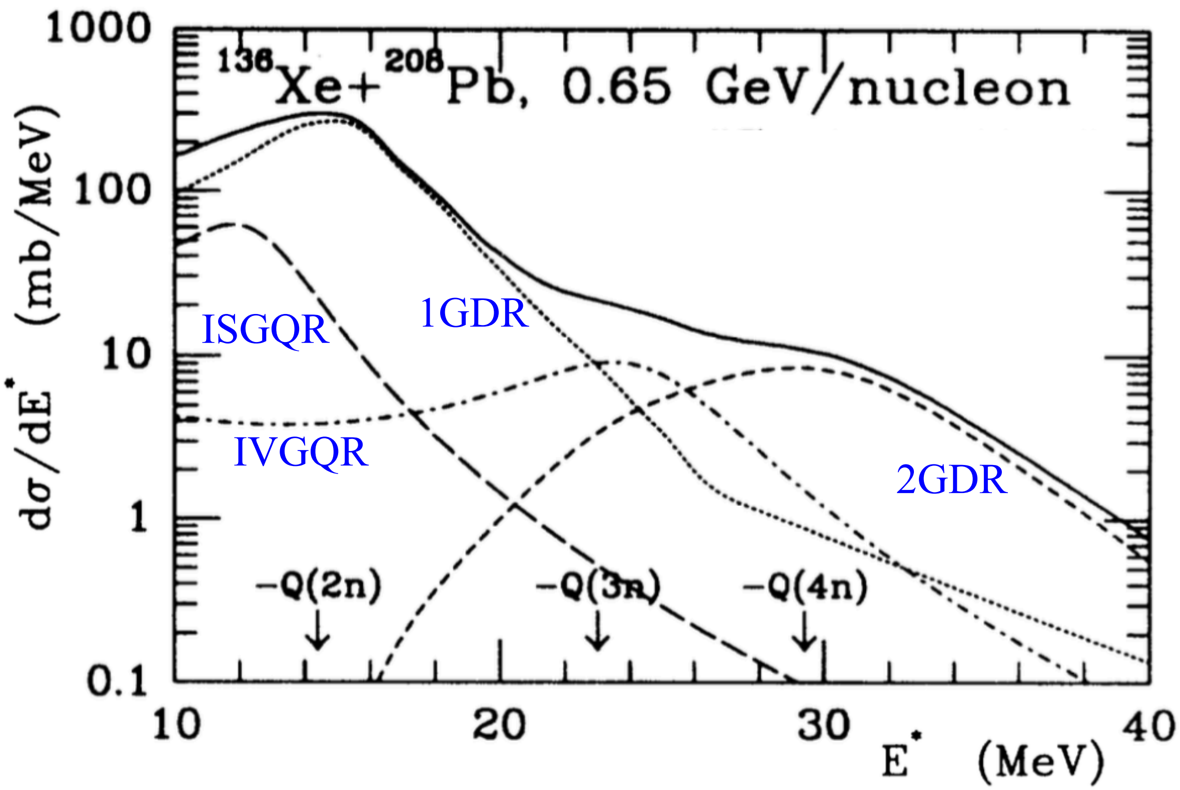


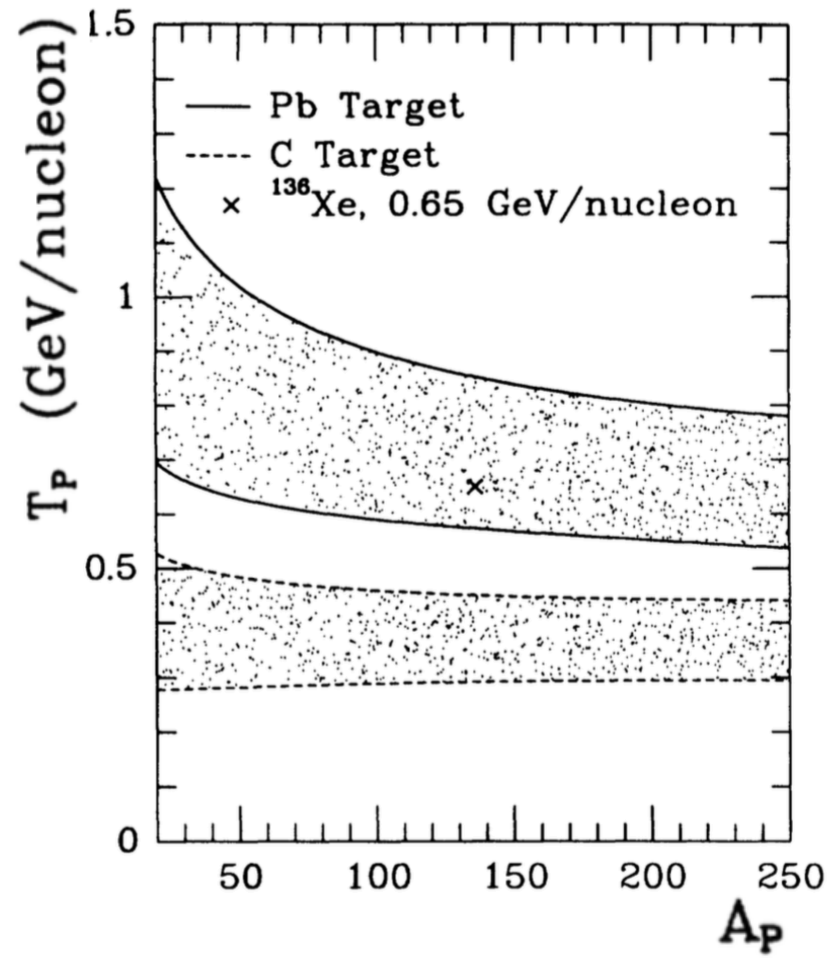
Lower beam energies should make the signal of 2-photon absorption easier to see…

WJL & PBM, PRC 45, 799 (1992)

Use adiabaticity in WW photon spectrum to limit contribution from single photon absorption in the region of the double GDR…

$$E_{GDR} + \Gamma_{GDR} \lesssim \frac{\hbar c \gamma_P \beta_P}{b_{min}} \lesssim 2E_{GDR} - \Gamma_{GDR}$$

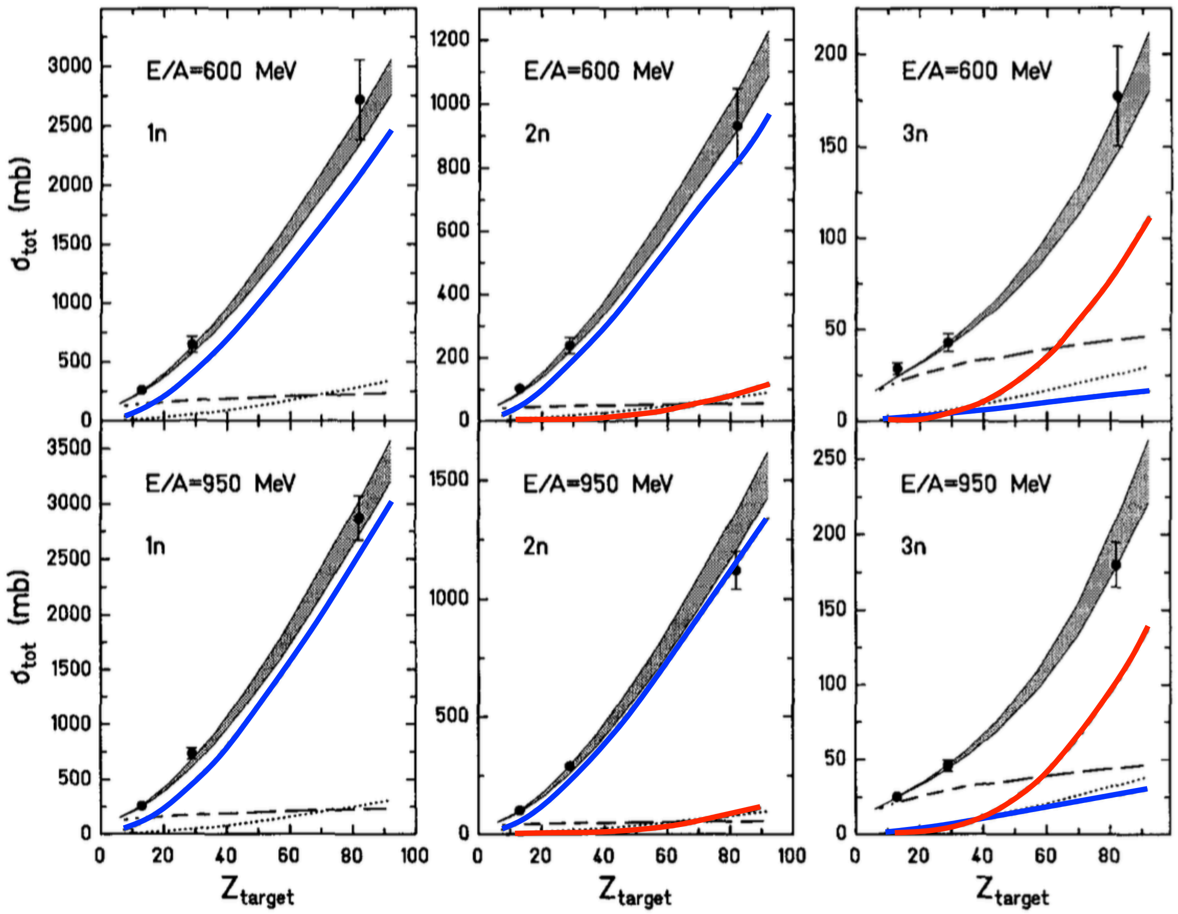




Beam energies near 0.6-1 GeV/N can emphasize 2-photon w.r.t. 1-photon…

Experimental results at lower beam energies

^{197}Au+X, T. Aumann *et al.*, Nucl. Phys. A569, 157c (1994)
^{238}U+X, T. Aumann *et al.*, Nucl. Phys. A599, 329c (1996)
see also K. Boretzky *et al.* (LAND), PLB 384, 30 (1996)



lines: nuclear, GDR, GQR, DGDR

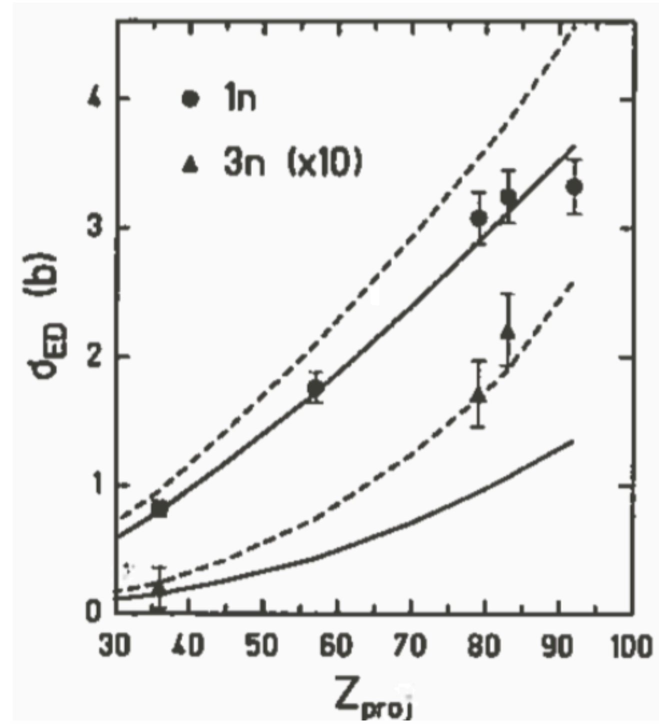


Figure 4. Calculated ED cross sections using different parametrizations for the minimum impact parameter b_{min}. The solid curves are obtained with the Kox parametrization [11], the dashed one with $b_{min} = 1.2(A_{proj}^{1/3} + A_{targ}^{1/3})$ fm.

It is obvious that it is not possible to describe simultaneously the 1n and the 3n cross sections by varying the minimum impact parameter. A better approach would be to replace the fixed value of b_{min} by a smooth transition as suggested by Llope and Braun-Munzinger [4].

at low beam energies, trickiest part is getting b_{min} right…

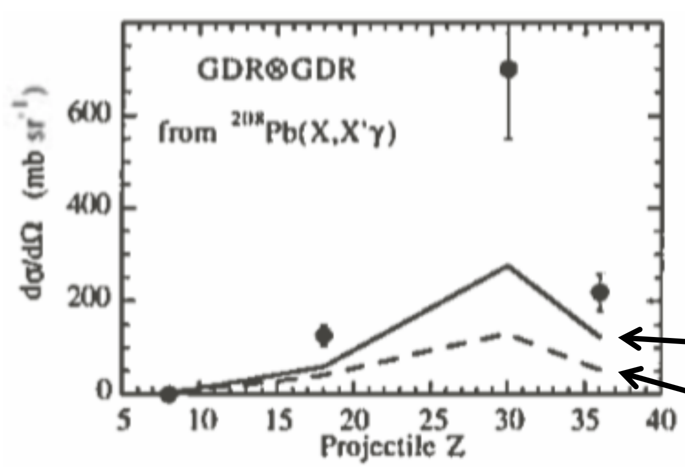
Now even lower! E/A ≤ 95 MeV/N

Data taken at GANIL with high resolution magnetic spectrograph "SPEG"

Forward magnetic spectrometer and BaF_2 crystals around the target to measure γ's

Measure dexcitation of nGDR via γ emission and E* in magnetic spectrometer.

The solid lines on the Fig. 7 are calculations for the excitation cross sections using the simplest possible model of the DGDR [24], which considers the DGDR strength distribution to be determined completely by the single photon E1 photo absorption cross section; additional damping and other broadening effects are ignored.



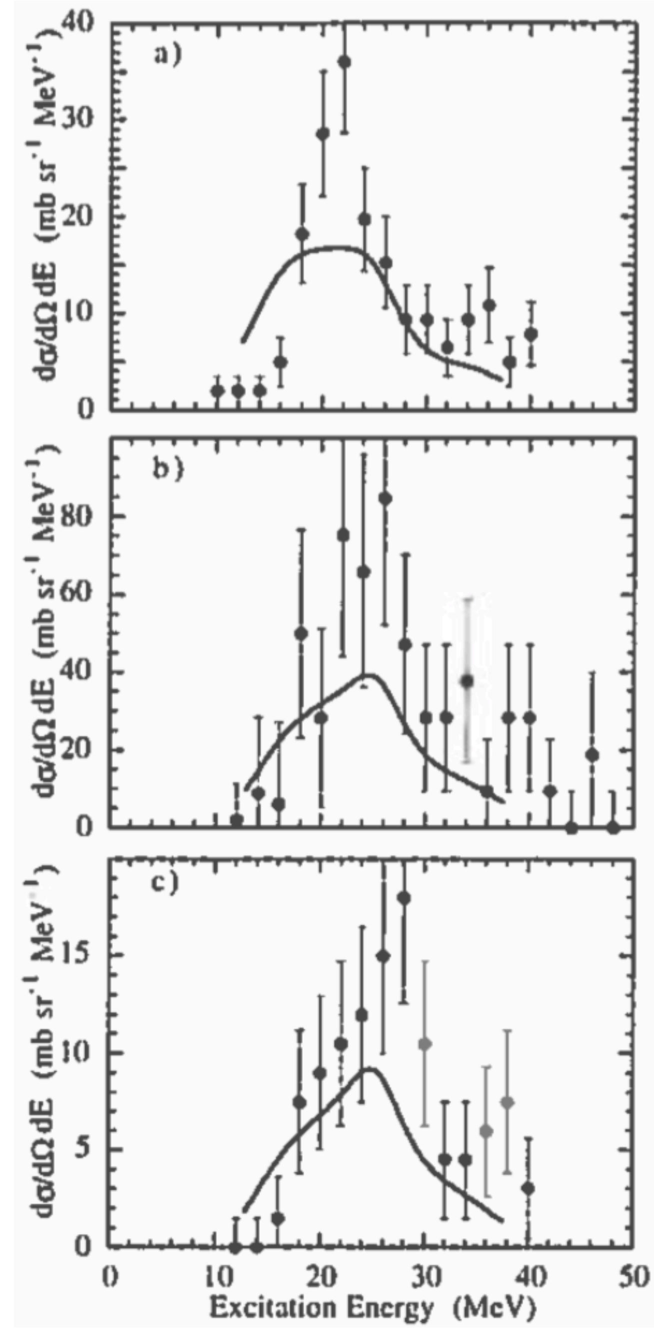
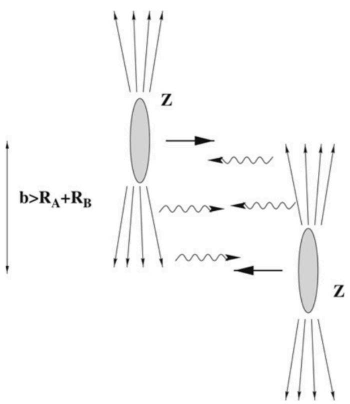


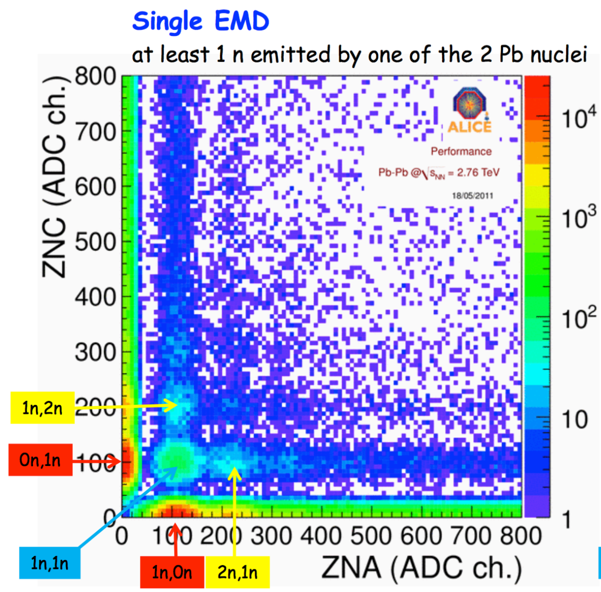
Figure 7. Experimental (points) and theoretical (curves) cross sections for DGDR excitation in target nuclei: a) 60*A MeV ^{86}Kr on ^{208}Pb, b) 80*A MeV ^{64}Zn on ^{209}Bi, c) 95*A MeV ^{36}Ar on ^{208}Pb.

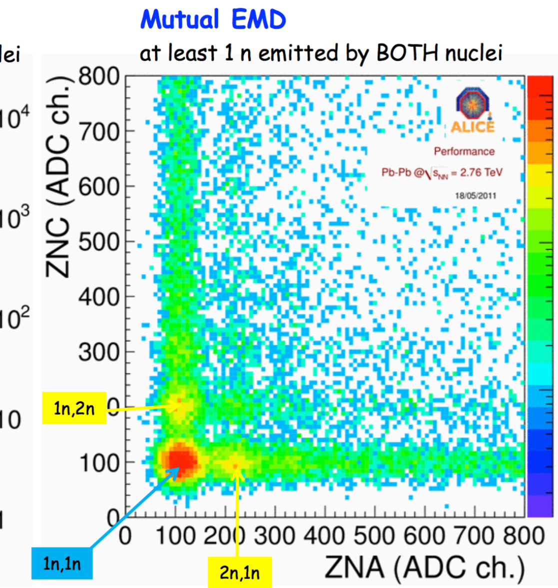
Modern EMD

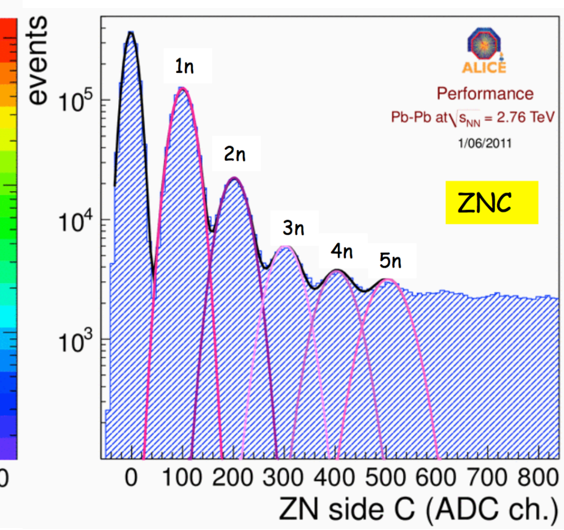
N. DeMarco, PLHC2011, Perugia
ALICE, PRL 109, 252302 (2012)

EMD at RHIC and LHC is an important contibution to beam lifetime.









Compare to RELDIS model — I.A. Pshenichov *et al.,* Phys. Rev. C 60 044901 (1999)

- single and double virtual photon absorption by nuclei "following Llope and Braun-Munzinger"
- intranuclear cascades of produced hadrons
- statistical decay of excited residual nuclei (evaporation, fission and multifragmentation)

	DATA (PRELIMINARY)	RELDIS MODEL
$\sigma^{sEMD} + \sigma^{had}$	$(195.6 \pm 0.1$ stat. $^{+24.2}_{-11.7}$ syst.) b	$(192.9 \pm 9.2$ syst.) b
$\sigma^{sEMD} - \sigma^{mEMD}$	$(176.9 \pm 0.1$ stat. $^{+21.6}_{-10.6}$ syst.) b	$(179.7 \pm 9.2$ syst.) b
σ^{mEMD}	$(5.7 \pm 0.2$ stat. $^{+0.7}_{-0.3}$ syst.) b	$(5.5 \pm 0.6$ syst.) b
σ^{sEMD}	$(185.7 \pm 0.2$ stat. $^{+22.6}_{-11.1}$ syst.) b	$(185.2 \pm 9.2$ syst.) b

Summary

Peter and I developed a "folding model" for the cross-sections for n-photon EMD, $n \geq 1$

- one must use realistic photoabsorption cross-sections in EMD σ calculations

With the E814 collaboration, we looked for any hints of multiple γ absorption

- look closely at decay channels with Q-values near $n{*}E_{GDR}$
- look closely at the scaling of the cross-sections with the target charge Z_T

Saw a hint of 2-photon EMD in 14.6 GeV/c/N ^{28}Si + A (but did not claim "observation")

- an independent analysis was consistent, but the scaling enhancement was not quite as strong

We suggested lower beam energies as the adiabatic cutoff reduces the 1γ near the DGDR.

Unambiguous double GDR photoexcitation seen in experiments at GSI and later elsewhere…

At higher beam energies, all data consistent with the folding model and statistical decay

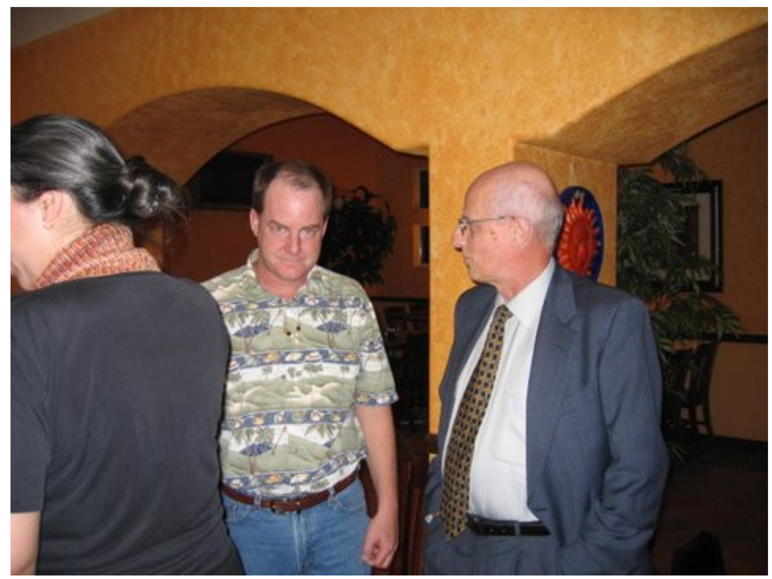
- no "exotic" decays seen

At lower beam energies, the results depend strongly on the choice of b_{min}, and the total cross-sections are underestimated (many assumptions we used are breaking down).

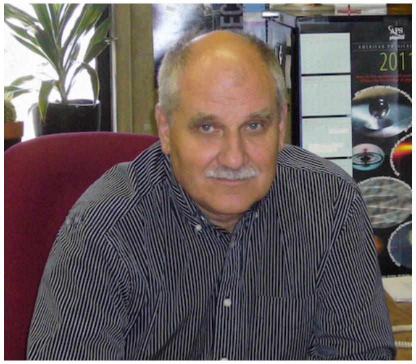
Birthday party for Jimmy Dee (~2007)

Just one night in a quite average Mexican restaurant northwest of Houston TX.

Peter and Johanna flew all the way around the world for this.



Greetings and best wishes from the Wayne State heavy-ion group!



Sergei Voloshin

ALICE & STAR
Flow, CME, vorticity
Λ polarization

Claude Pruneau

ALICE
Flow
Correlations

From all of us at WSU:
All the best & many thanks for everything Peter!

Jörn Putschke

ALICE & STAR
Jets in HI
Jetscape topical group

+6 postdocs (2 at CERN)
+5 graduate students

W.J. Llope

ALICE & STAR
GEM framing for ALICE TPCU
rapidity correlations in RHIC BES

BACKUP

M.N. Harakeh, Joliet-Curie School, La Colle Sur Loup, France; 12-17 September 2011