Nuclear Structure Information from Peripheral Nuclear Reactions

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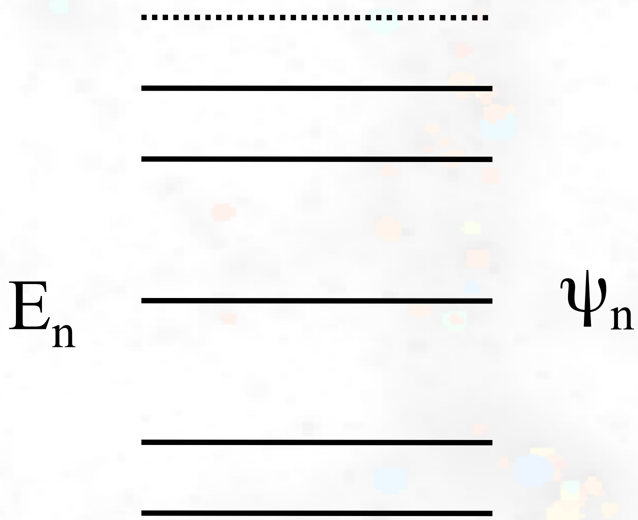
Lecture 1

Electromagnetic Excitation

Coupled-channels equations (t.d. version)



$H = H_0 + U$ solution

$$\psi = \sum_n a_n(t)\psi_n e^{-iE_n t/\hbar}$$

H_0 spectrum: $H_0\psi_n = E_n\psi_n$

$$H\psi = i\hbar\frac{\partial\psi}{\partial t}$$

$$\frac{da_k}{dt} = -\frac{i}{\hbar}\sum_n a_n(t)U_{kn}(t)e^{i(E_k-E_n)t/\hbar}$$

$$U_{kn}(t) = \int \psi_k^* U(t)\,\psi_n\, d^3r$$

1st order: $a_n \sim \delta_{n0}$

$$a_k = -\frac{i}{\hbar}\int dt\, U_{k0}(t)e^{i(E_k-E_0)t/\hbar}$$

Nuclear decay rate & Cross sections

$$a_k = -\frac{i}{\hbar}\int_0^T dt\, U_{km} e^{i(E_k - E_0)t/\hbar} = \frac{U_{km}}{E_k - E_m}\left[1 - \exp\left(i\frac{E_k - E_m}{\hbar}T\right)\right]$$

Decay rate:

$$w = \sum_{k \neq m} w_k = \frac{\sum |a_k|^2}{T}$$

$$w = \frac{1}{T}\int_{-\infty}^{\infty} |a_k|^2 \frac{dn}{dE_k} dE_k$$

$$= \frac{4}{T}\int_{-\infty}^{\infty} |U_{km}|^2 \frac{\sin^2\left[\left(\frac{E_k - E_m}{2\hbar}\right)T\right]}{\left(E_k - E_m\right)^2} \frac{dn}{dE_k} dE_k$$

$\sin^2 x / x^2$ peaks very strongly at x = 0 → $|U_{km}|^2$ and dn/dE_k can be taken out of the energy integral

$\Rightarrow$ $$w = \frac{2\pi}{\hbar}|U_{km}|^2 \frac{dn}{dE_k}$$ Fermi's Golden Rule

$$\sigma = \frac{w}{v_a} = \frac{m_a}{\hbar k_a} w$$

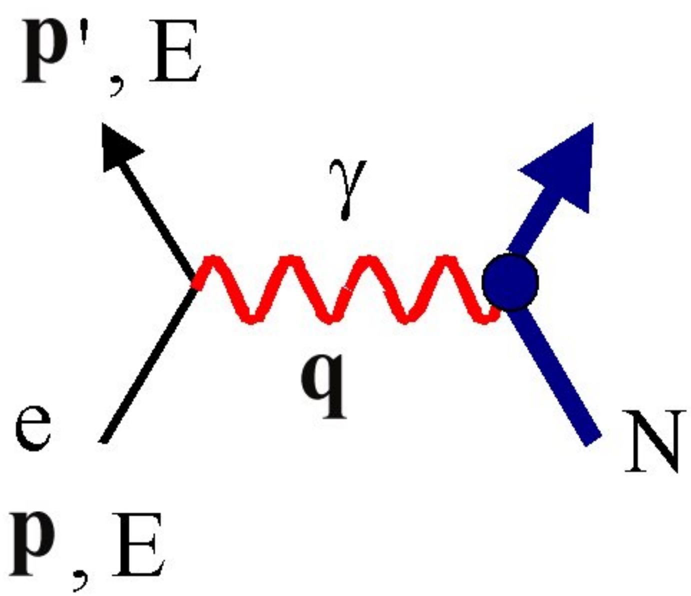
rate of transitions induced by projectiles a, divided by incident flux = v_a

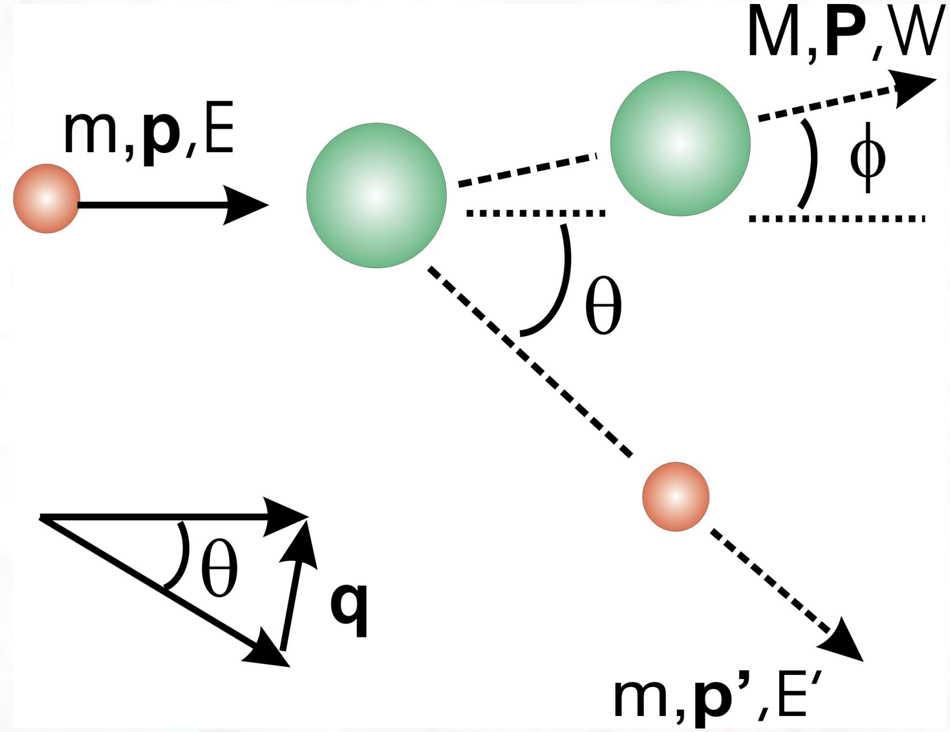
Cross section

$$d\sigma = \frac{m_a}{\hbar k_a}\frac{2\pi}{\hbar}|U_{fi}|^2 dn(E_f)$$

Electron scattering

Kinematics





$$p' \approx \frac{p}{1 + \frac{2E}{Mc^2}\sin^2\theta/2}$$

electron final momentum

$$T \approx \frac{E^2}{Mc^2}\frac{2\sin^2\theta/2}{1 + \frac{2E}{Mc^2}\sin^2\theta/2} \approx E - E'$$

nucleus kinetic energy

$$q \approx \frac{2p\sin\theta/2}{1 + \frac{2E}{Mc^2}\sin^2\theta/2}$$

momentum transfer

Spinless electron

$$w = \frac{2\pi}{\hbar}\left|\langle f,\mathbf{p}'|H|i,\mathbf{p}\rangle\right|^2 \frac{dn}{dE_f}$$

golden rule

$$H = e^2 \sum_k \frac{1}{|\mathbf{r}-\mathbf{r}_k|}$$

interaction

$$\frac{dn}{dE_f} = \frac{p'\,d\Omega L^3}{c\hbar^3}\frac{1}{1+\frac{2E}{Mc^2}\sin^2\theta/2}$$

density of states

plane wave for electrons

$$\langle f,\mathbf{p}'|H|i,\mathbf{p}\rangle = \frac{4\pi e^2}{L^3 q^2}\left\langle \Phi_f \left| \sum_1^Z e^{i\mathbf{q}\cdot\mathbf{r}_k} \right| \Phi_i \right\rangle$$

Φ = nuclear wavefunction

$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2}{2\mathrm{E}}\right)^2 \frac{1}{\sin^4\theta/2}\frac{1}{1+\frac{2E}{Mc^2}\sin^2\theta/2}\left|\left\langle \Phi_f \left| \sum_1^Z e^{i\mathbf{q}\cdot\mathbf{r}_k} \right| \Phi_i \right\rangle\right|^2$$

Electron with spin

$$\Psi_j(\mathbf{r},t) = u_j \exp\left[\frac{i}{\hbar}(\mathbf{p}\cdot\mathbf{r} - Et)\right]$$

u_j = spinor

$$u_1 = -p_z/p, \quad u_2 = -(p_x + ip_y)/p, \quad u_3 = 1, \quad u_4 = 0$$

spin up

$$u_1 = -(p_x - ip_y)/p, \quad u_2 = p_z/p, \quad u_3 = 0, \quad u_4 = 1$$

spin down

$$\frac{d\sigma}{d\Omega} = \overline{\left|\sum_1^4 u'^*_j u_j\right|^2} \times \frac{d\sigma}{d\Omega}(spinless)$$

$$\overline{\left|\sum_1^4 u'^*_j u_j\right|^2} = \frac{1}{2}(1+\cos\theta) = \cos^2\theta/2$$

spin average

$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2}{2E}\right)^2 \frac{\cos^2\theta/2}{\sin^4\theta/2} \frac{1}{1+\frac{2E}{Mc^2}\sin^2\theta/2} \left|\left\langle \Phi_f \left| \sum_1^Z e^{i\mathbf{q}\cdot\mathbf{r}_k} \right| \Phi_i \right\rangle\right|^2$$

PWBA

Elastic Scattering

$$\left\langle \Phi_i \left| \sum_{1}^{Z} e^{i\mathbf{q}\cdot\mathbf{r}_k} \right| \Phi_i \right\rangle = \int d^3r\, \rho_{ch}(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}} \equiv F(\mathbf{q})$$

charge form-factor

Mott cross section

$$\frac{d\sigma}{d\Omega} = \left(\frac{Ze^2}{2\mathrm{E}}\right)^2 \frac{\cos^2\theta/2}{\sin^4\theta/2} \frac{1}{1+\frac{2E}{Mc^2}\sin^2\theta/2} \equiv \sigma_M$$

$$F(q) = \frac{4\pi}{q}\int dr\, r\sin(qr)\,\rho_{ch}(r)$$

spherical nuclei

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_M(\theta)}{Z^2}\left|F(q)\right|^2$$

Nuclear physics

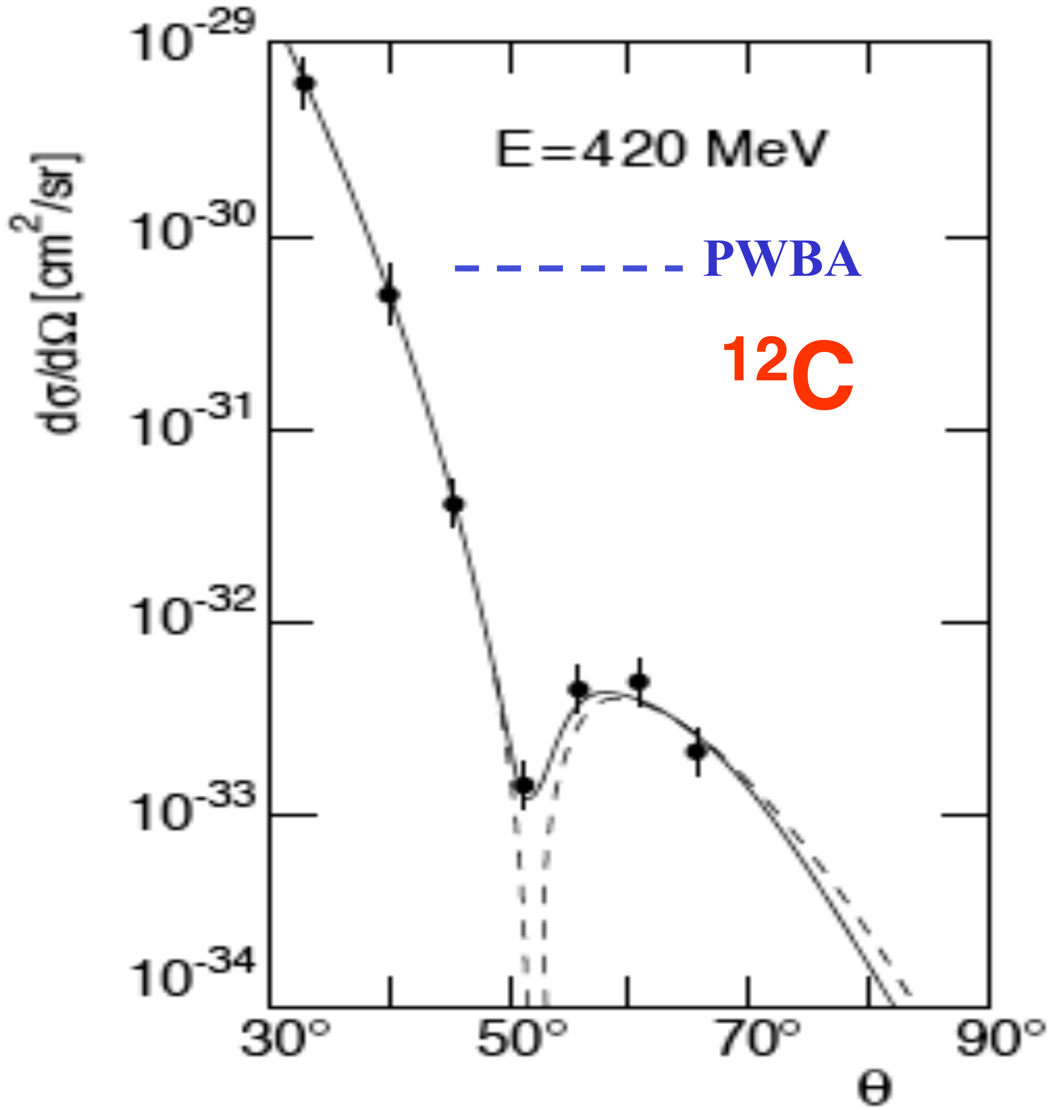
$$\rho_{ch}(r) = \int \rho_p(\mathbf{r}')f_{Ep}(\mathbf{r}-\mathbf{r}')d\mathbf{r}' + \underline{\int \rho_n(\mathbf{r}')f_{En}(\mathbf{r}-\mathbf{r}')d\mathbf{r}'}$$

f_{Ep} = charge dist. in proton

f_{En} = charge dist. in neutron

10% effect, mainly surface

DWBA corrections



Hofstadter, 1953

- electron wavefunction attracted to the nucleus
- a measured **q** probes a larger **q** = q_{eff} in F(q)

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_M(\theta)}{Z^2}\left|F\left(q_{eff}\right)\right|^2$$

Still valid. But with

$$q_{eff} = q\left(1 - \frac{V(0)}{E}\right)$$

$$= q\left(1 + 1.5\frac{Ze^2}{ER}\right), \qquad R \cong 1.2A^{1/3}\ \text{fm}$$

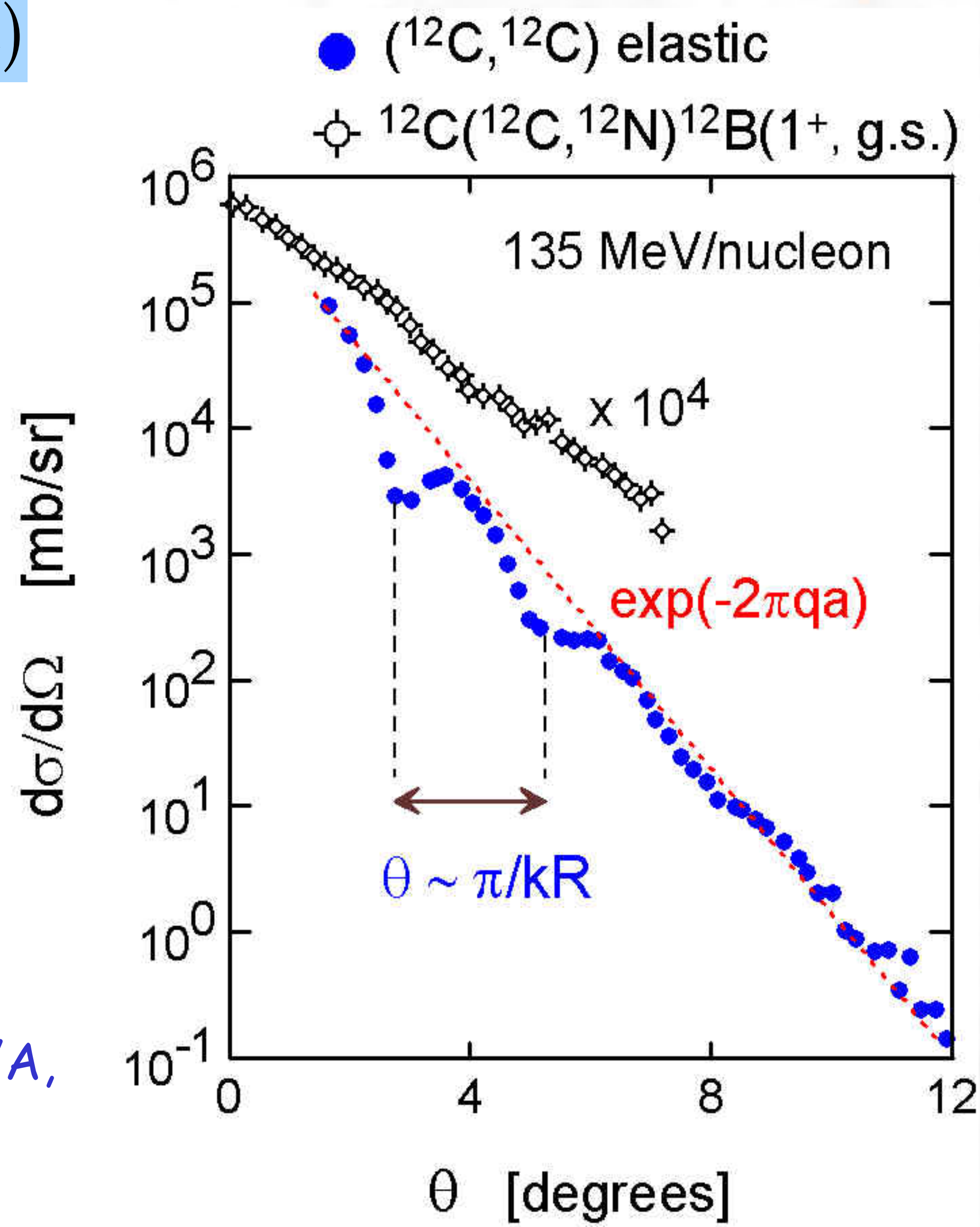
Electron (or ion) elastic (or inelastic – PWBA) scattering

$$\frac{d\sigma}{d\Omega} \sim \left|F(q)\right|^2$$

$$q = 2k\sin(\theta/2)$$

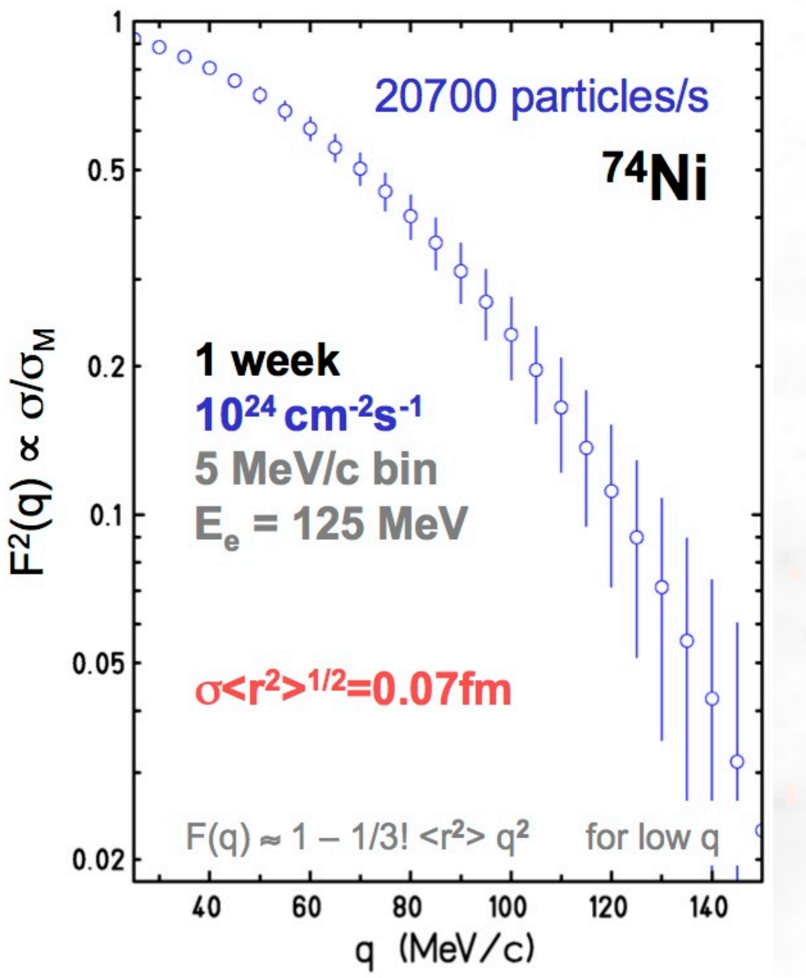
$$F(q) = \int db\, b\, J_0(qb)\, e^{iX(b)}$$
$$\sim \int db\, b\, J_0(qb) \frac{1}{1+\exp\left[\left(\frac{b-R}{a}\right)\right]}$$
$$\sim \frac{R}{q} J_1(qR)\exp(-\pi q a)$$

Neglecting coulomb distortions at low E/A,

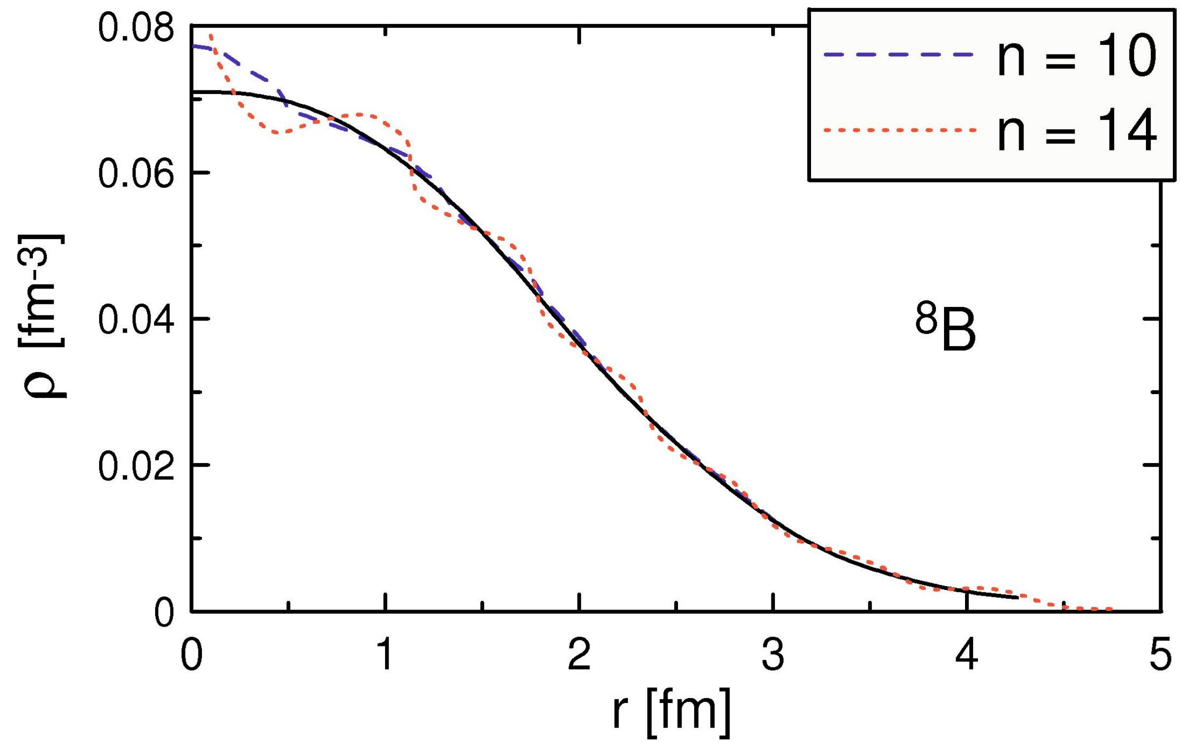


Data: Ichihara, PLB 1994, NPA 1995

experimental precision



inverse scattering problem



test case: ^{8}B

Fourier-Bessel expansion

$$\rho_{ch}(r) = \Theta(R_{\max} - r)\sum_{n=1}^{\infty} a_n j_0(q_n r)$$

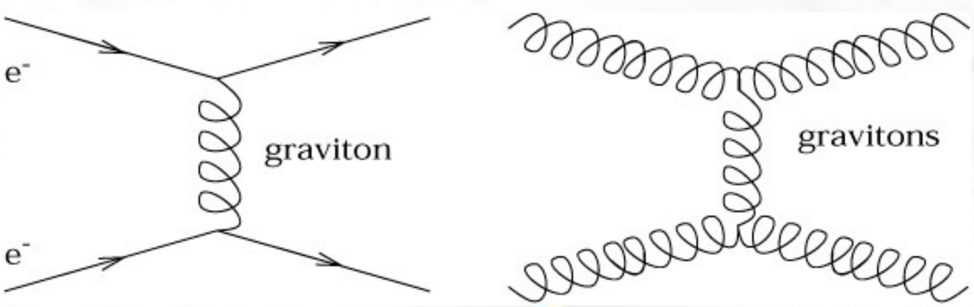
$$F_{ch}(q) = \frac{4\pi}{q}\sum_n a_n \frac{(-1)^n}{q^2 - q_n^2}\sin(qR_{\max})$$

$$q_n = \frac{n\pi}{R_{\max}}$$

Coulomb scattering

Gravity

Classical: $V = \frac{c}{r}$

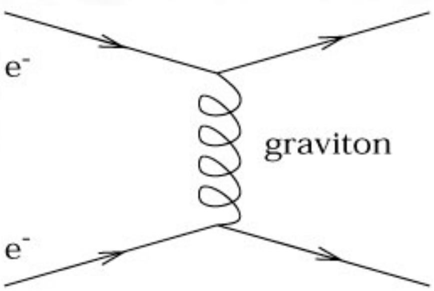


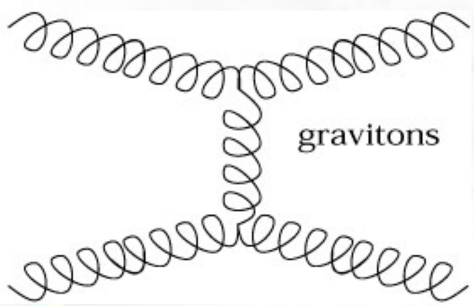
Quantum: $m_{graviton} = 0$

Non-linear

Gravity

Classical: $V = \frac{c}{r}$

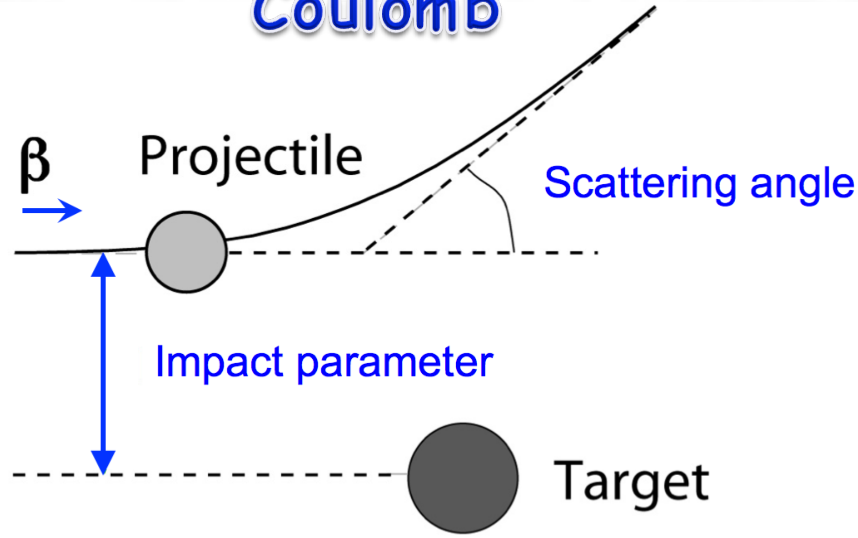




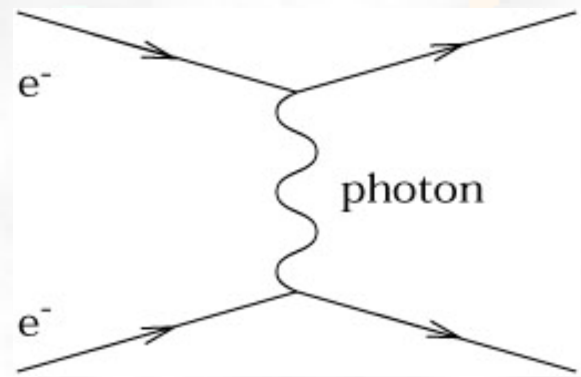
Quantum: $m_{graviton} = 0$

Non-linear

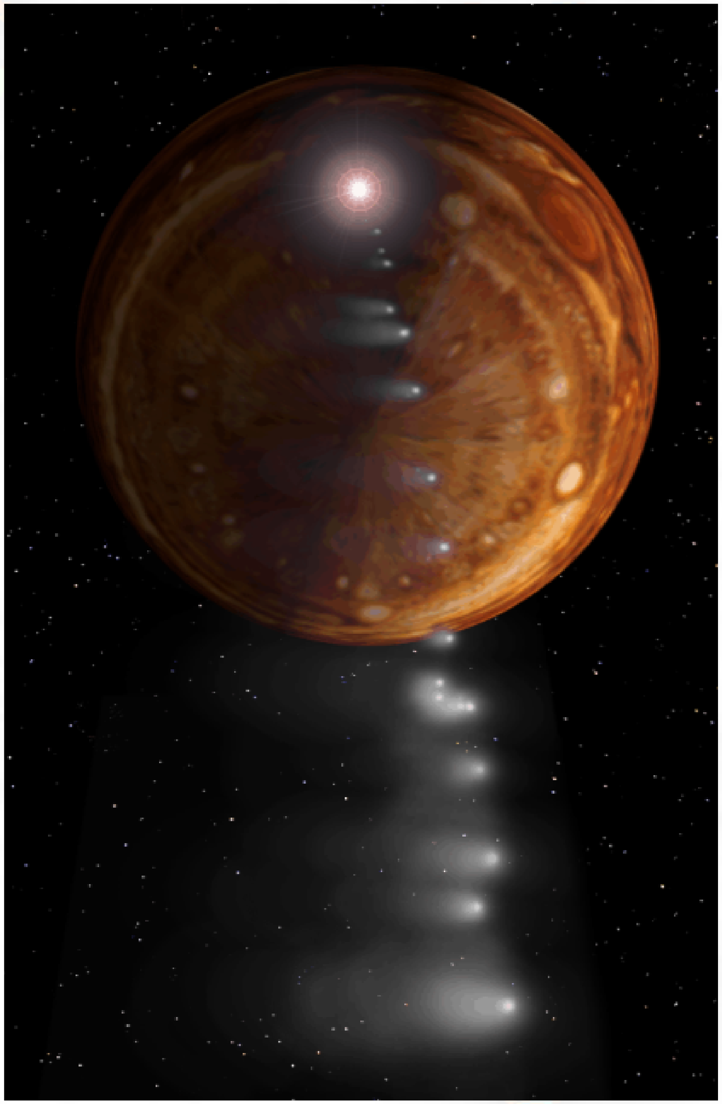
Coulomb



Classical: $V = \frac{c'}{r}$

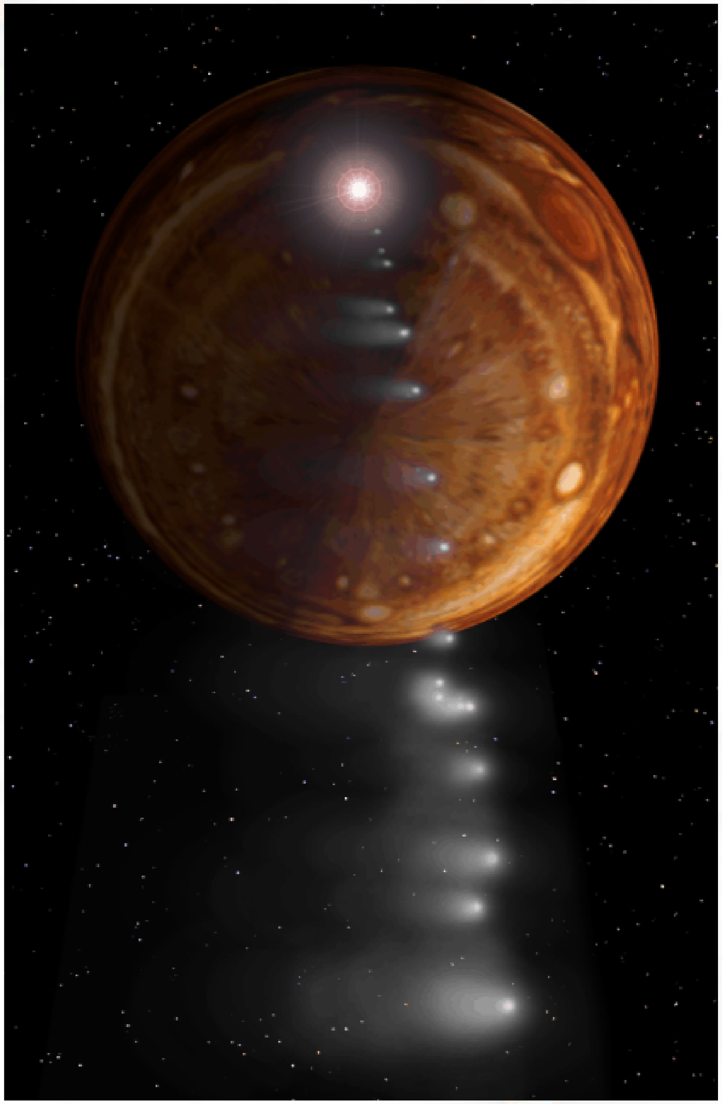


Quantum: $m_{photon} = 0$



Shoemaker-Levi comet
break into many pieces

Classical and complicated



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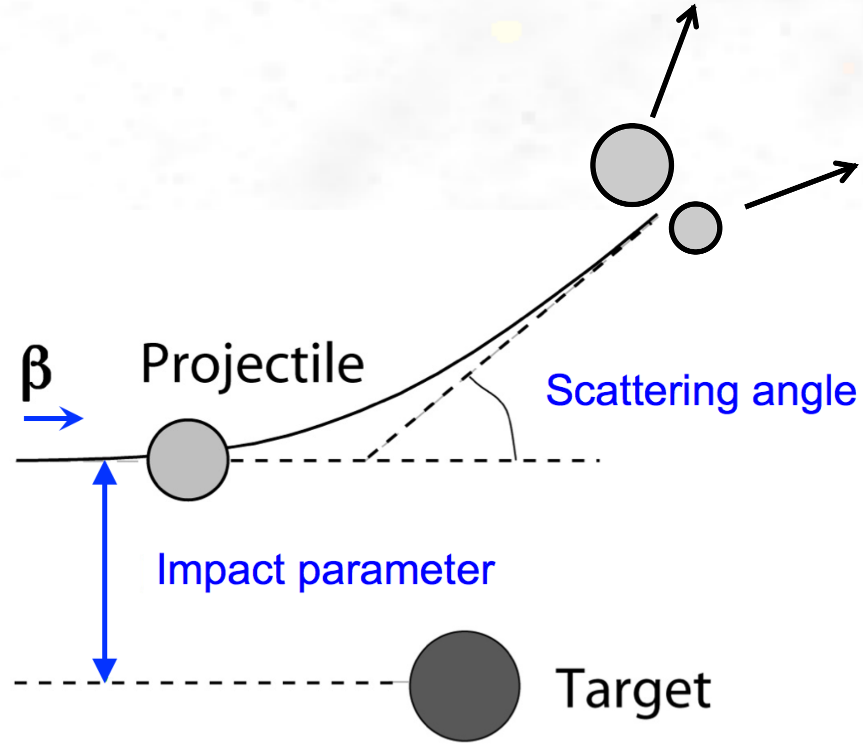
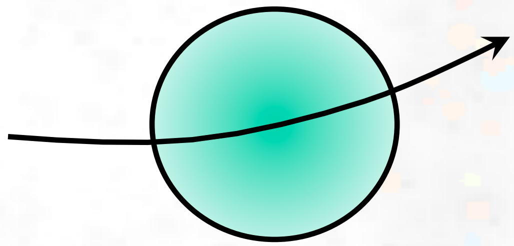


Coulomb breakup much
simpler – only few pieces

Quantum and simple

Electron scattering



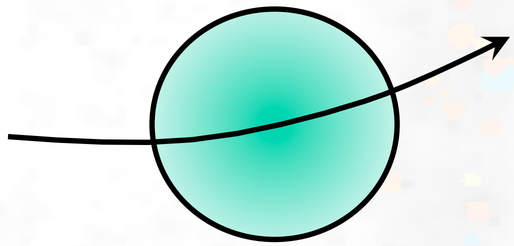
$$\frac{d\sigma}{dEd\Omega}\left(\Delta\mathbf{p},\ \Delta E\right)$$

Probes EM matrix elements
s function of Δp and ΔE

$$\frac{d\sigma}{dEd\Omega}\left(\left|\Delta\mathbf{p}\right| = \frac{\Delta E}{\hbar c} \sim 0,\ \Delta E\right) \sim \sigma_\gamma$$

Same matrix elements as real photon

Electron scattering



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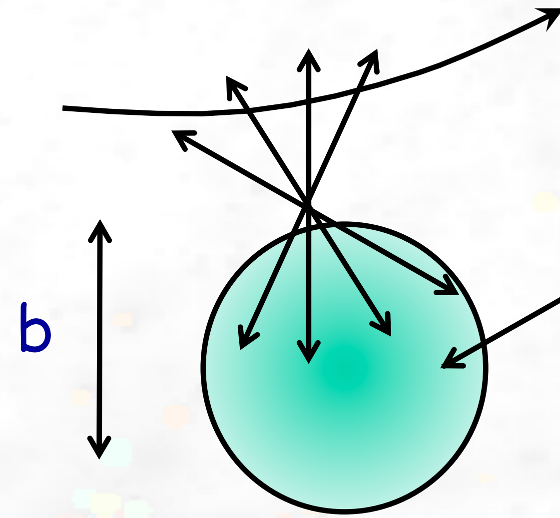
Same matrix elements as real photon

Coulomb scattering



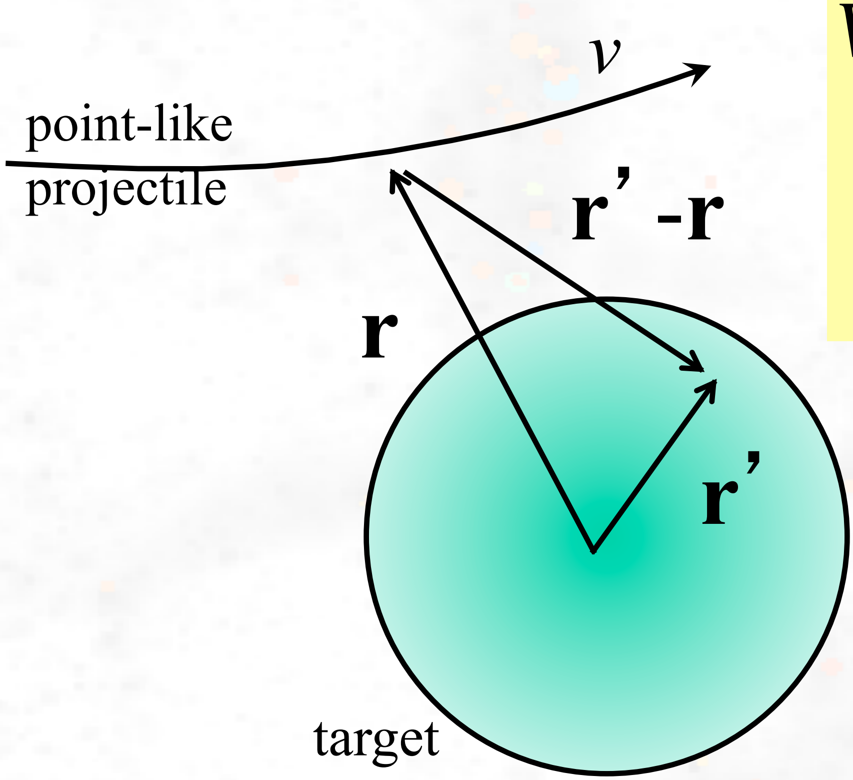
$$\nabla \cdot \mathbf{E}(t) = 0$$

$$\nabla \cdot \mathbf{B}(t) = 0$$

$$\frac{d\sigma}{dEd\Omega}\left(\Delta E\right) \sim \sigma_\gamma$$

Always probes same matrix elements as real photon

Coulomb Excitation



$$V_C(r,r') = Z_p e \int \frac{\rho(\mathbf{r}')}{|r-r'|} d^3 r'$$

$$= \frac{Z_p e}{r} + \frac{\mathbf{p}\cdot\hat{\mathbf{r}}}{r^3} + \frac{1}{2}\frac{Q_{ij} r_i r_j}{r^5} + \cdots$$

$$\mathbf{p} = \int \mathbf{r}' \rho(\mathbf{r}') d^3 r' \quad \text{(dipole)}$$

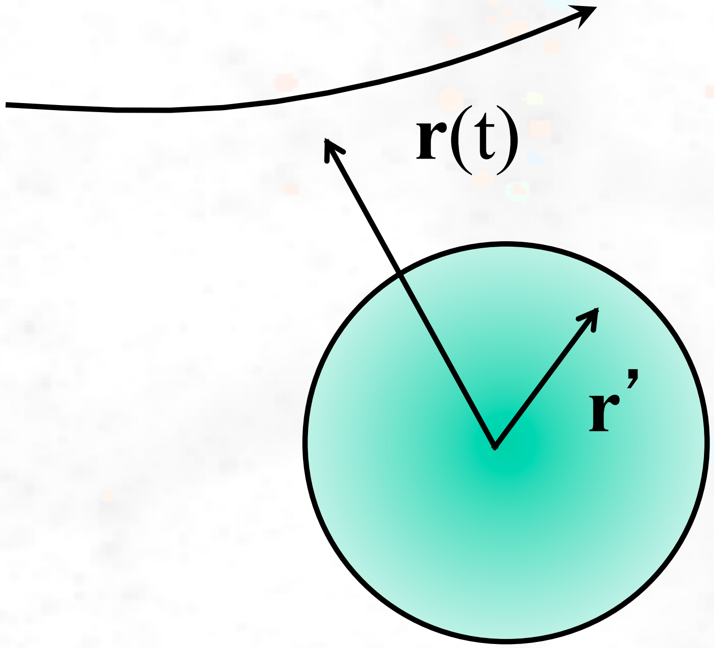
$$Q_{ij} = \int \left(3 r'_i r'_j - r'^2 \delta_{ij}\right) \rho(\mathbf{r}') d^3 r'$$

(Quadrupole)

Semiclassical method: r = r(t)

Validity: $$\eta = \frac{\text{distance of closest approach}}{\text{wavelength}} = \frac{Z_1 Z_2 e^2}{\hbar v} >> 1$$

General multipole expansion



(if r > r')

$$\frac{1}{|\mathbf{r}(t)-\mathbf{r}'|} = \sum_{L,M} \frac{4\pi}{2L+1} \frac{r'^L}{r^{L+1}(t)} Y_{LM}(\hat{\mathbf{r}}(t)) Y^*_M(\hat{\mathbf{r}}')$$

Calculate a_{fi} and average over spins:

$$w_{fi} = \frac{1}{2J_i+1} \sum_{M_i M_f} |a_{fi}|^2$$

Cross section:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_R}{d\Omega} \cdot w_{fi} = \sum_{L>0} \frac{d\sigma_L}{d\Omega}$$

orbital integral

$$\boxed{\frac{d\sigma_L}{d\Omega} \sim Z_P^2 B(EL) \left| I_L(\omega_{fi}) \right|^2}$$

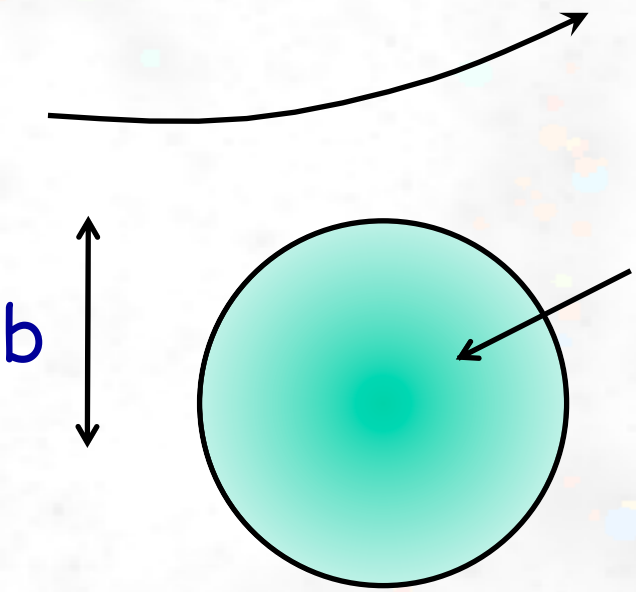
$$I_L(\omega) = \int_{-\infty}^{\infty} dt \frac{1}{r^{L+1}(t)} Y_{LM}(\hat{\mathbf{r}}(t)) e^{i\omega t}$$

$$\omega_{fi} = \frac{E_f - E_i}{\hbar}$$

$$\boxed{B(EL) \sim \left| \int r^L \delta\rho_{fi} d^3 r \right|^2}$$

reduced transition strength

Virtual photon numbers



$$\nabla \cdot \mathbf{E}(t) = 0$$
$$\nabla \cdot \mathbf{B}(t) = 0$$

E, B-field of projectile divergence free

$$\frac{d\sigma_L}{d\Omega} = \int \frac{dE_\gamma}{E_\gamma} \frac{dn_L}{d\Omega}\left(E_\gamma,\theta\right)\sigma_L^\gamma\left(E_\gamma\right)$$

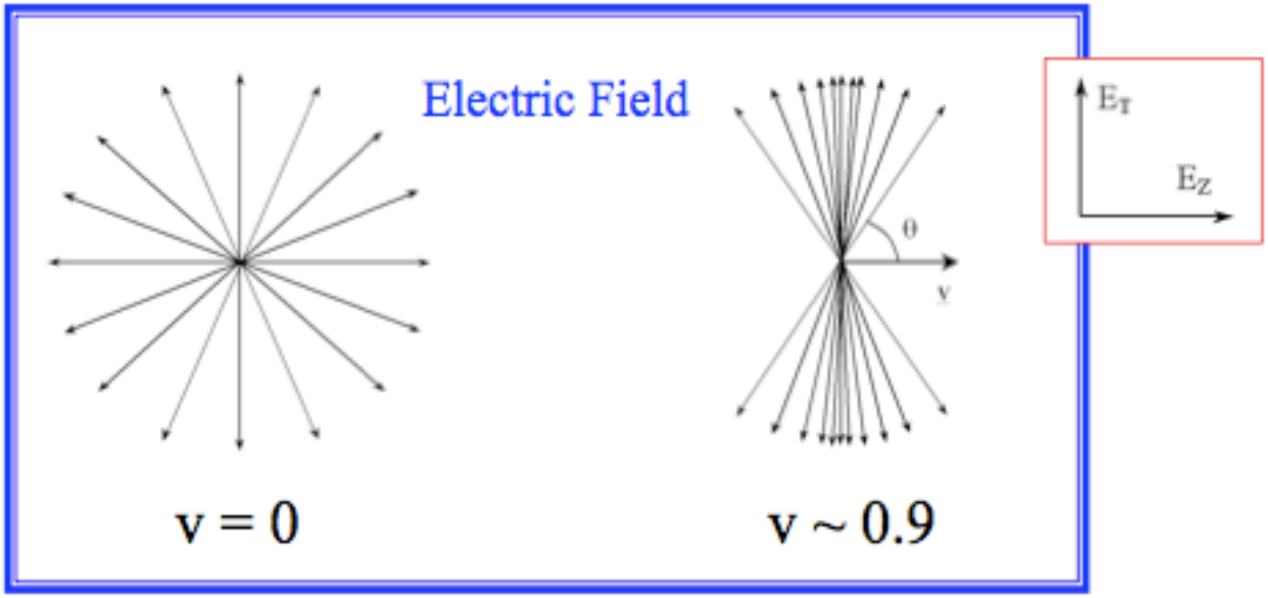
photonuclear X-section: $\sigma_L^\gamma \sim E_\gamma^{2L+1} B(EL)$ $\qquad E_\gamma = E_f - E_i$

virtual photon numbers: $\dfrac{dn_L}{d\Omega} \sim Z_P^2 \left| I_L\left(\omega_{fi},\theta\right)\right|^2$

impact parameter dependence: $\mathrm{n_L}\left(\mathrm{E_\gamma,b}\right) \equiv \dfrac{\mathrm{dn_L}}{2\pi \mathrm{bdb}} \sim \sin^{-4}(\theta/2)\dfrac{\mathrm{dn_L}}{\mathrm{d}\Omega}$

Magnetic excitations:

more complicated (involves currents, spins), but straight-forward.

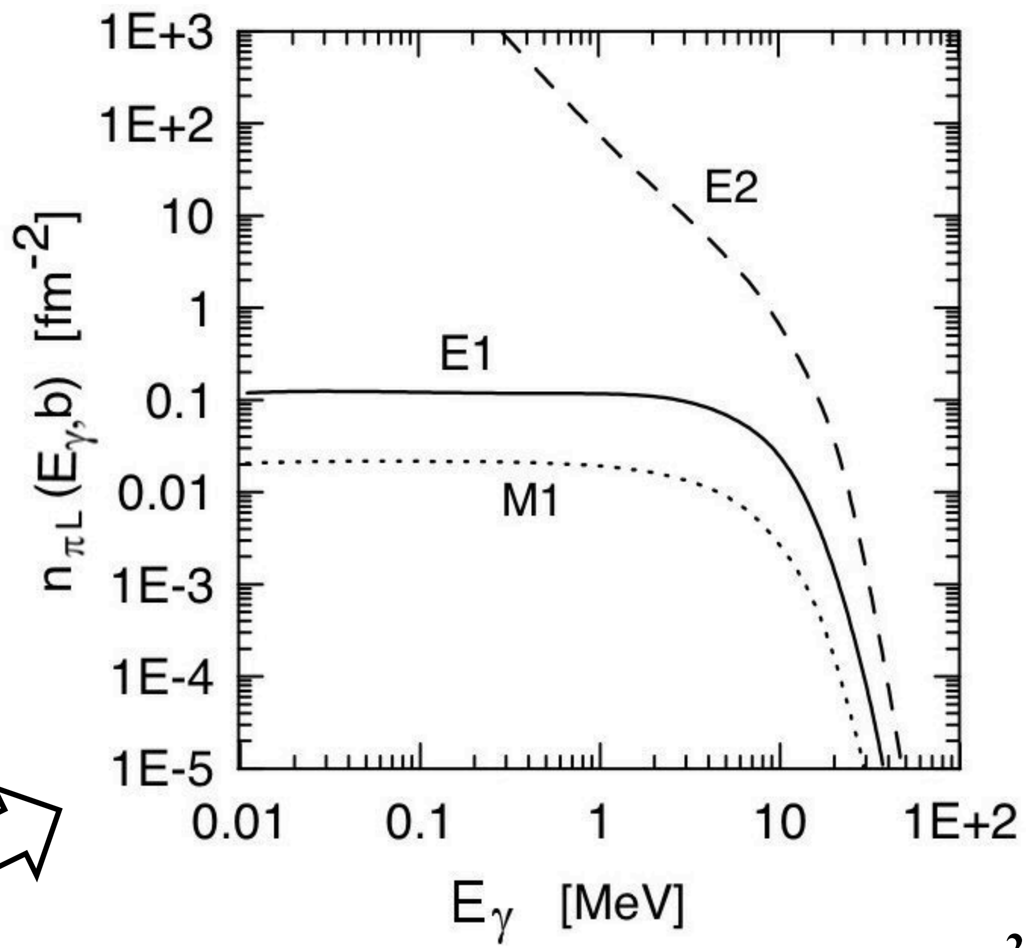


low energy scattering:

$$n_{E2} >> n_{E1} >> n_{M1} = \frac{v^2}{c^2} n_{E1}$$

Virtual photons "seen" by a Pb target due to the passage of an O projectile

at 100 MeV/nucleon and b = 15 fm

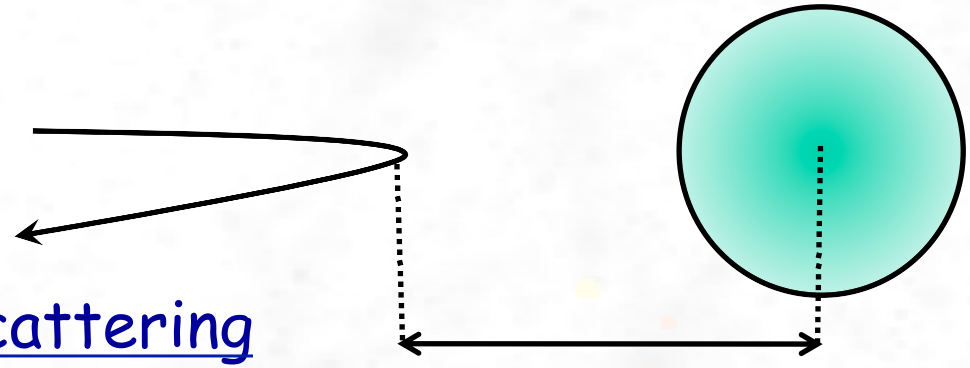


Adiabacity

$\Rightarrow$ Maximum effective excitation energy
Maximum effective impact parameter.

$$I_L(\omega) = \int_{-\infty}^{\infty} dt \, \frac{1}{r^{L+1}(t)} Y_{LM}\big(\hat{\mathbf{r}}(t)\big) e^{i\omega t}$$

orbital integral



low energy scattering

(1/2) distance of closest approach

$$a = \frac{Z_P Z_T e^2}{2E_{c.m.}}$$

if $\quad |t| > t_{exc} \sim \dfrac{1}{\omega}$ then $e^{i\omega t}$ oscillates too fast: $\quad I_L$ small

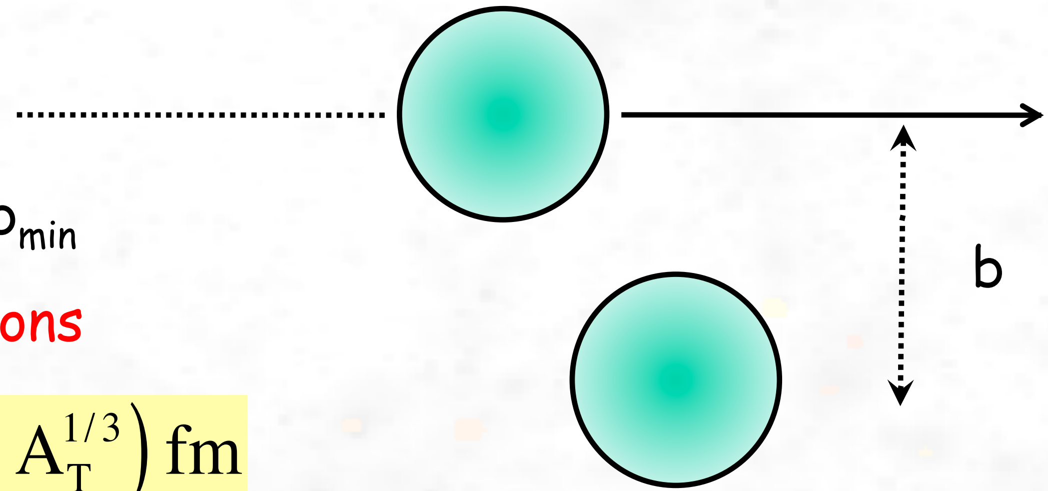
if $\quad |t| > t_{coll} \sim \dfrac{a}{v}$ then $\dfrac{1}{r^{L+1}}$ too large: $\quad I_L$ small

excitation possible if $\dfrac{t_{coll}}{t_{exc}} \tilde{<} 1 \quad \Rightarrow \quad \boxed{\zeta = \dfrac{a\omega}{v} \tilde{<} 1}$ adiabacity parameter

$$I_L(\omega) = \int_{-\infty}^{\infty} dt \, \frac{1}{r^{L+1}(t)} Y_{LM}(\hat{\mathbf{r}}(t)) e^{i\omega t}$$

orbital integral

high energy collisions



Closest approach distance = b_{min}

$b < b_{min} \rightarrow$ nuclear interactions

$$b_{mim} \sim R_P + R_T \sim 1.2\left(A_P^{1/3} + A_T^{1/3}\right) \text{fm}$$

$$t_{coll} \sim \frac{R}{\gamma v}$$

(γ due to contraction)

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Lorentz γ-factor

Excitation possible if

$$\boxed{\xi = \frac{\omega R}{\gamma v} \lesssim 1}$$

adiabacity parameter

Energy budget

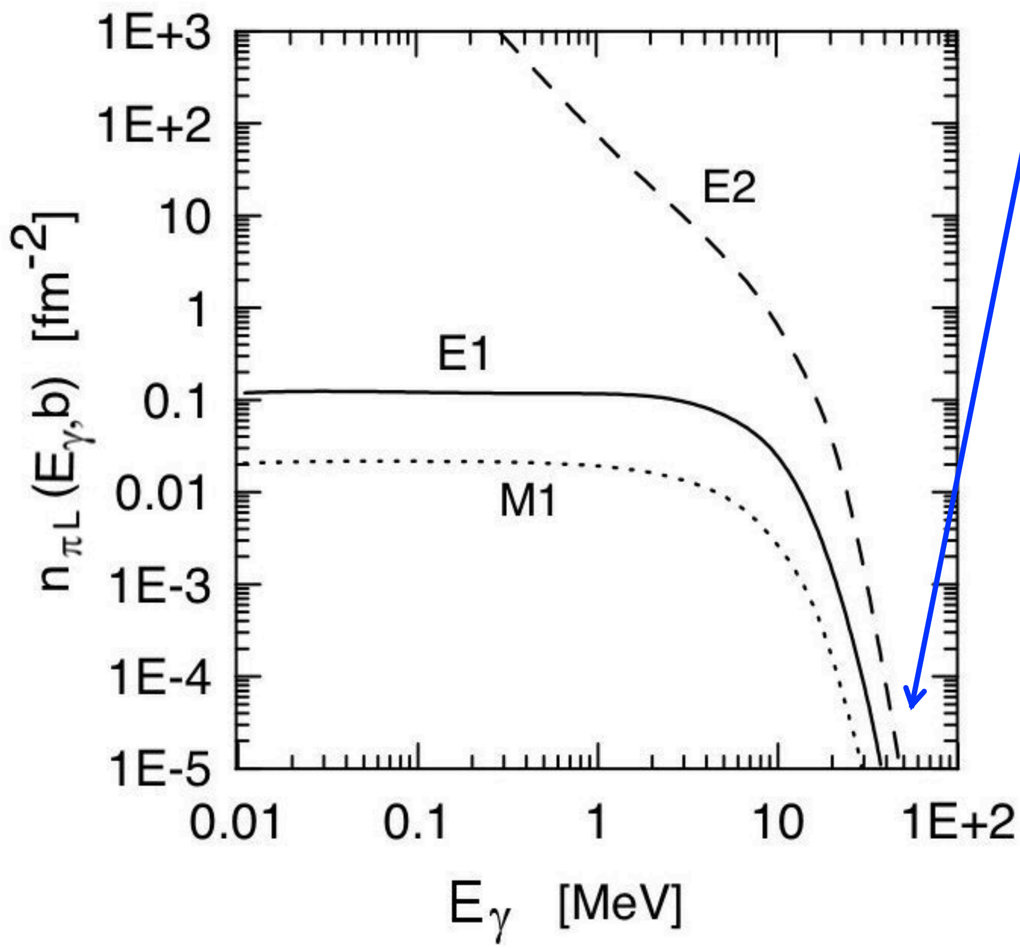
$$\zeta = \frac{E_\gamma a}{\hbar v}$$

low energy collisions

$$\xi = \frac{E_\gamma R}{\gamma \hbar v}$$

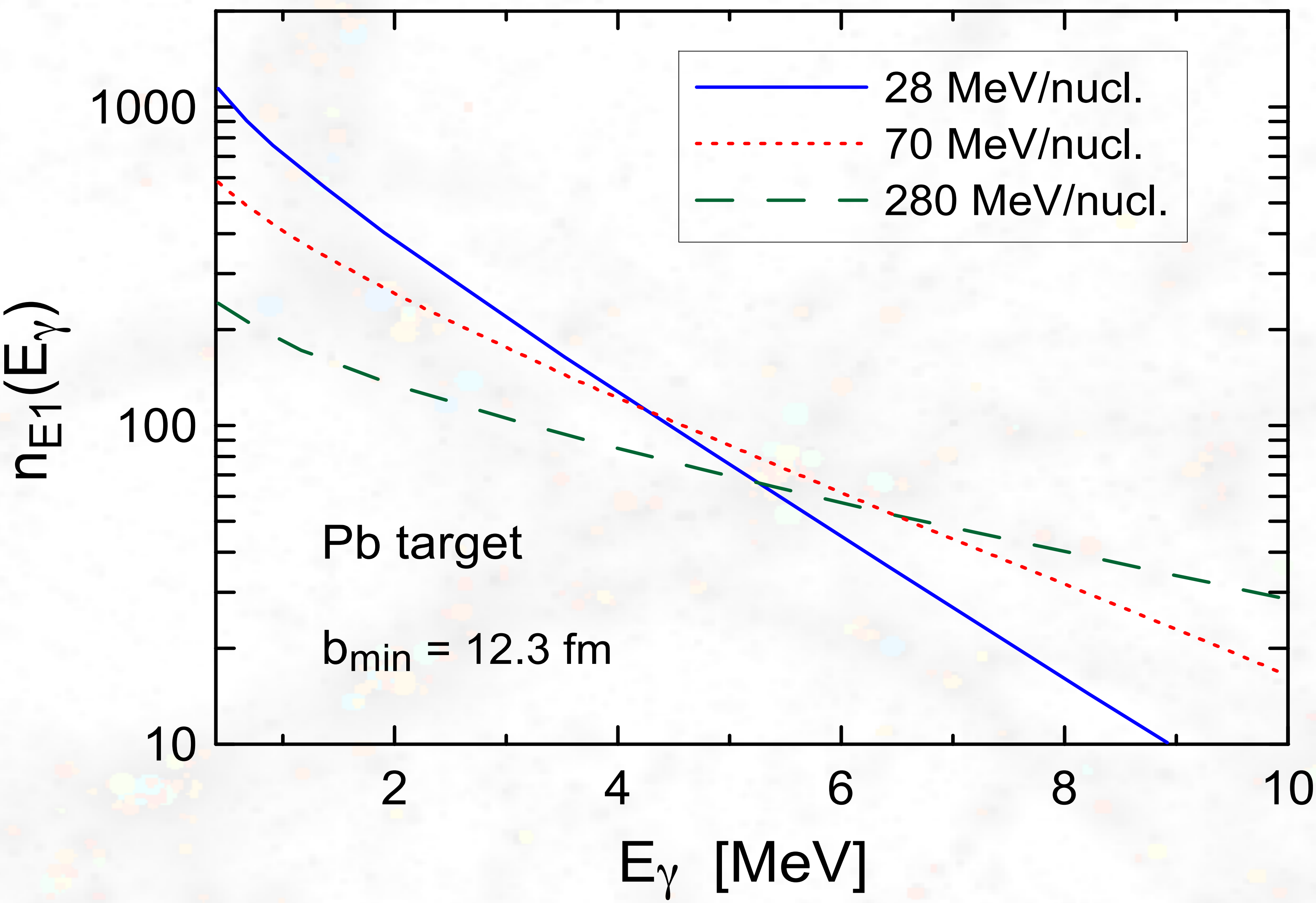
high energy collisions

$a,\ b_{min} \sim 20\ \text{fm}$ $\Rightarrow$ $$E_\gamma \tilde{<} \frac{200\,\text{MeV. fm}\,\gamma}{20\ \text{fm}} = 10\,\text{MeV.}\ \gamma$$



- small γ's: giant resonances
- large γ's: giant resonances, quasi-deuteron, deltas, mesons (ex: J/ψ)

Energy budget

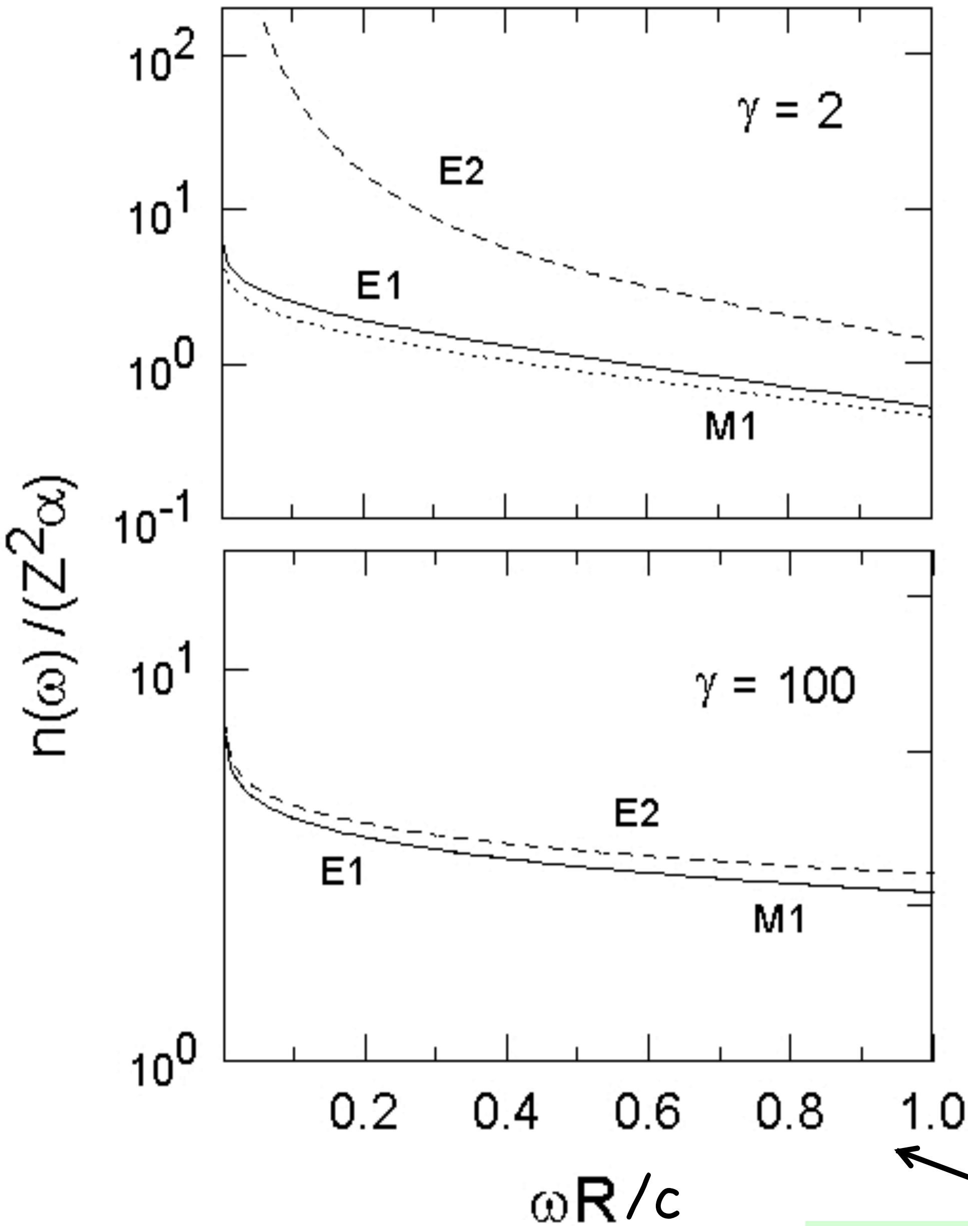


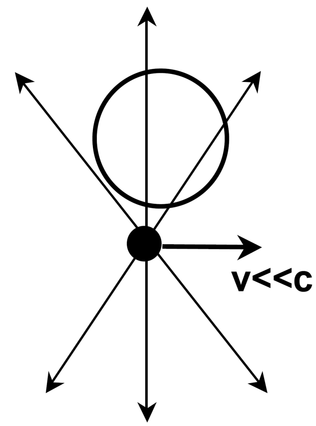
Multipolarity budget

orbital integral $$I_L(\omega) = \int_{-\infty}^{\infty} dt \frac{1}{r^{L+1}(t)} Y_{LM}(\hat{\mathbf{r}}(t)) e^{i\omega t}$$

ω large, $e^{i\omega t}$ oscillates fast: I_L small

$$n_L(E_\gamma, b) \sim \left| I_L(\omega_{fi}, \theta) \right|^2$$ also small

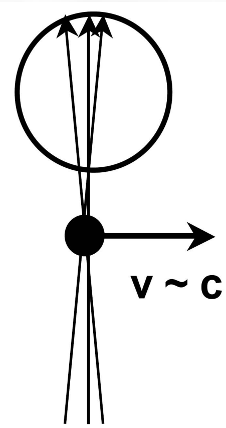




low-energy (tidal)

$$n_{E2} >> n_{E1} >> n_{M1} = \frac{v^2}{c^2} n_{E1}$$

high-energy (contraction)



$$n_{E2} \sim n_{E1} \sim n_{M1}$$

Low-energies: multipolarities of virtual photons have different weights

High energies: multipolarities have nearly same weight

$$n_L(\omega) = 2\pi \int db\, b\, n_L(\omega, b)$$

Virtual

$$\xi = \frac{\omega R}{\gamma v} \tilde{<} 1$$

Coulomb excitation: virtual photons
Each part (multipolarity) of a real photon has a different weight n_L

High-energy:

$$n_{E2} \sim n_{E1} \sim n_{M1}$$

$$\frac{d\sigma}{db} = \int \frac{dE_\gamma}{E_\gamma} n(E_\gamma, b)\,\sigma^\gamma(E_\gamma)$$

CB, Baur, Phys. Rep. 163, 299 (1988)

Real photons

$$\sigma^\gamma(E_\gamma) = \sum_L \sigma_L^\gamma(E_\gamma)$$

Real photons
All parts (multipolarities) have the same weight

Coulomb excitation for a fixed energy E_γ probes the same physics as a real photon.

But each E_γ has a different weigth.

Z_P^2 makes number of photons large.

Nuclear response to multipolarities

$$\boxed{\sigma_L^\gamma \sim E_\gamma^{2L+1} B(EL)}$$

$$\boxed{B(EL) \sim \left| \int r^L \delta\rho_{fi}\, d^3r \right|^2}$$

Estimate

$$\delta\rho_{fi} = \psi_f^* \psi_i$$

$$\psi_f \sim \psi_i \sim \frac{1}{\sqrt{R^3}}, \quad \text{if } r < R, \quad 0 \text{ otherwise}$$

$$B(EL) \sim R^{2L} \quad \Rightarrow \quad \boxed{\sigma_L^\gamma \sim (kR)^{2L}} \qquad k = \frac{E_\gamma}{\hbar c}$$

$$\frac{\sigma_{L+1}}{\sigma_L} \sim (kR)^2 << 1 \text{ for low lying states}$$

Comparison with electron scattering

Electron scattering: Magnetic interaction

$$\langle i,\mathbf{p}'|H|i,\mathbf{p}\rangle = \frac{4\pi e^2}{q^2}\left\langle i\left|\left[\left(u_i^* u_i\right)\left(U_i^* U_i\right) - \left(u_i^* \alpha_e u_i\right)\left(U_i^* \alpha_N U_i\right)\right]\right| i\right\rangle$$

averages over initial and sum over final spins

$$\overline{\left|\sum u'^*_i u_i U'^*_i U_i\right|^2} = \left(\frac{Mc^2}{E}\right) 4\cos^2\theta/2$$

$$\overline{\left|\sum u'^*_i \alpha_e u_i U'^*_i \alpha_N U_i\right|^2} = \left(\frac{\hbar^2 q^2 c^2}{E}\right) 2\tan^2\theta/2$$

"Dirac" elastic cross section of an electron on a proton (with μ = eh/Mc)

$$\frac{d\sigma}{d\Omega_d}^{\mathrm{elast}} = \left(\frac{e^2}{2E}\right)^2 \frac{\cos^2\theta/2}{\sin^4\theta/2} \frac{1}{1+\dfrac{2E}{Mc^2}\sin^2\theta/2}\left[1+\frac{\hbar^2 q^2}{4Mc^2}\left(2\tan^2\theta/2\right)\right]$$

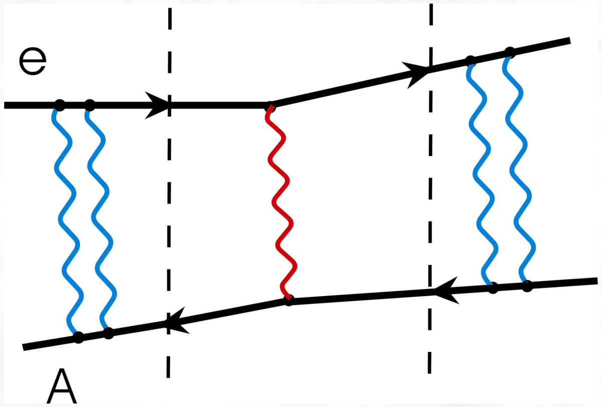
Inelastic electron scattering

$$\langle f,\mathbf{p}'|H|i,\mathbf{p}\rangle = \frac{4\pi e^2}{q^2}\left\langle f\left|\sum_{1}^{Z} e^{i\mathbf{q}\cdot\mathbf{r}_k}\left[\left(u_f^* u_i\right)\left(U_f^* U_i\right) - \left(u_f^*\alpha_e u_i\right)\left(U_f^*\alpha_N U_i\right)\right]\right|i\right\rangle$$

- **expand *exp*(i$\mathbf{q}$.r) into multipoles**
- **averages over initial and sum over final spins**

$$\boxed{\left(\frac{d\sigma}{d\Omega}\right)_{inel} = \frac{\sigma_M(\theta)}{Z^2}\left[\sum_\lambda \left|F_{C\lambda}(q_{eff})\right|^2 + \left(\frac{1}{2} + \tan^2\theta/2\right)\sum_\lambda \left|F_{E\lambda}(q_{eff})\right|^2\right]}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{inel} \cong \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$



$$F_{C\lambda}(q) \propto \int dr\, r^2\, j_\lambda(qr)\,\delta\rho_{if}(r)$$

$$F_{E\lambda}(q) \propto \int dr\, r^2\left[J^{if}_{\lambda,\lambda+1}(r)\, j_{\lambda+1}(qr) + (\lambda,\lambda-1)\right]$$

$$J^{if}_{\lambda,\lambda+1}(r) = \left\langle f\left\|\mathbf{J}_{if}\cdot\mathbf{Y}_{\lambda\lambda'1}\right\|i\right\rangle$$

Electron-ion collider mode

$$E_x \ll E, \qquad \theta \ll 1$$
$$qR \ll 1$$

Siegert's theorem

$$F_{C\lambda}(q) \cong \frac{E_x/\hbar}{q}\sqrt{\frac{\lambda+1}{\lambda}}F_{E\lambda}(q)$$

$$\frac{d\sigma}{d\Omega dE_\gamma} = \sum_\lambda \frac{dN^{(E\lambda)}(E,E_\gamma,\theta)}{d\Omega dE_\gamma}\sigma_\gamma^{(E\lambda)}(E_\gamma)$$

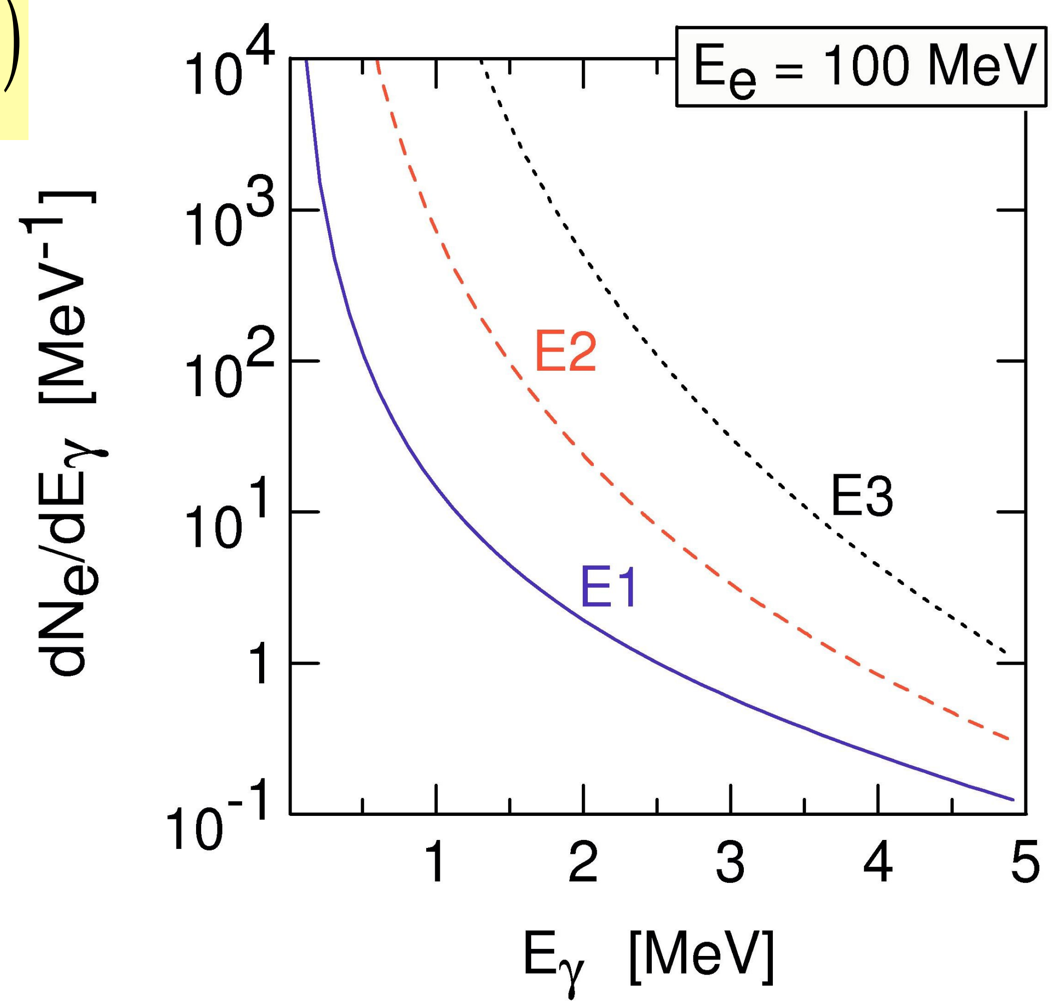
virtual photon spectrum

$$\frac{dN^{(E\lambda)}(E,E_\gamma)}{dE_\gamma} = \int_{E_\gamma/E}^{\theta_m} \frac{dN^{(E\lambda)}(E,E_\gamma,\theta)}{d\Omega dE_\gamma}$$

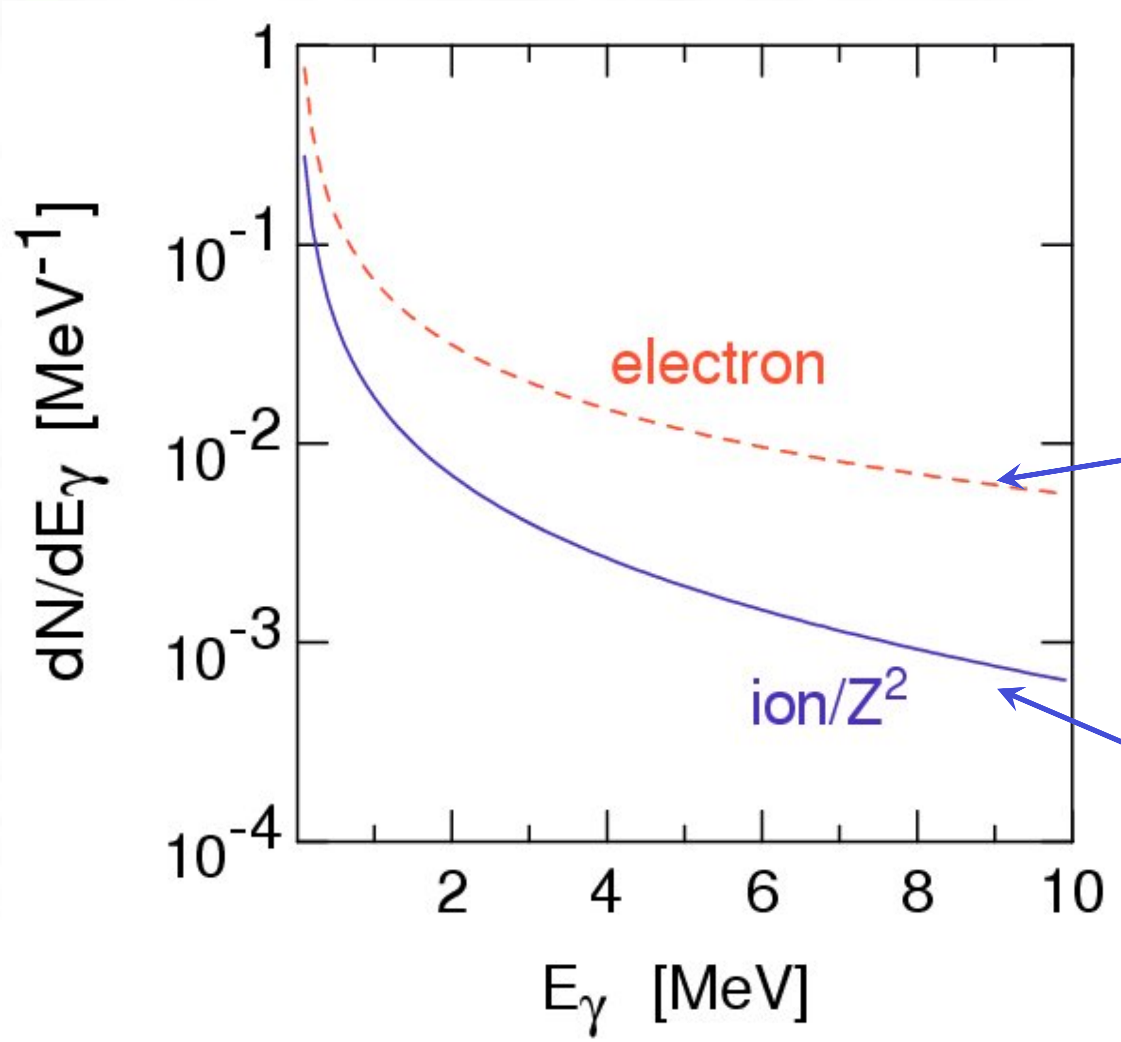
response function

$$\sigma_\gamma^{(E\lambda)}(E_\gamma) \propto \frac{dB(E\lambda)}{dE_x}$$

$$\frac{dB(E\lambda)}{dE_x} \propto \int dr\, r^2 r^\lambda \delta\rho_{if}(r)$$



Electron-ion collider mode



comparison with Coulomb excitation

$E = 1\,\mathrm{GeV}$

$E = 1\,\mathrm{GeV/nucleon}$

PLB 624, 203 (2005)

Example Applications

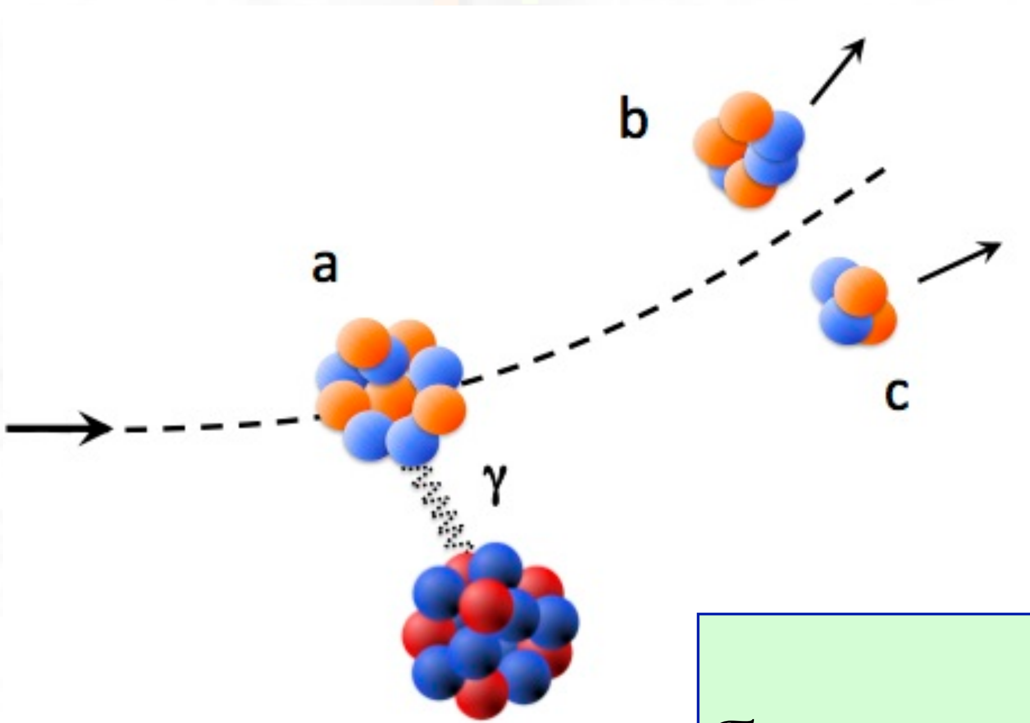
Coulomb dissociation and nuclear astrophysics

Baur, CB, Rebel
NPA 458 (1986) 188

$$\frac{d\sigma}{dE_\gamma d\Omega} = \frac{1}{E_\gamma} \sum_l \frac{dn_l(E_\gamma,\Omega)}{dE_\gamma d\Omega} \sigma_{\gamma + a \to b + c}(E_\gamma)$$

Theory

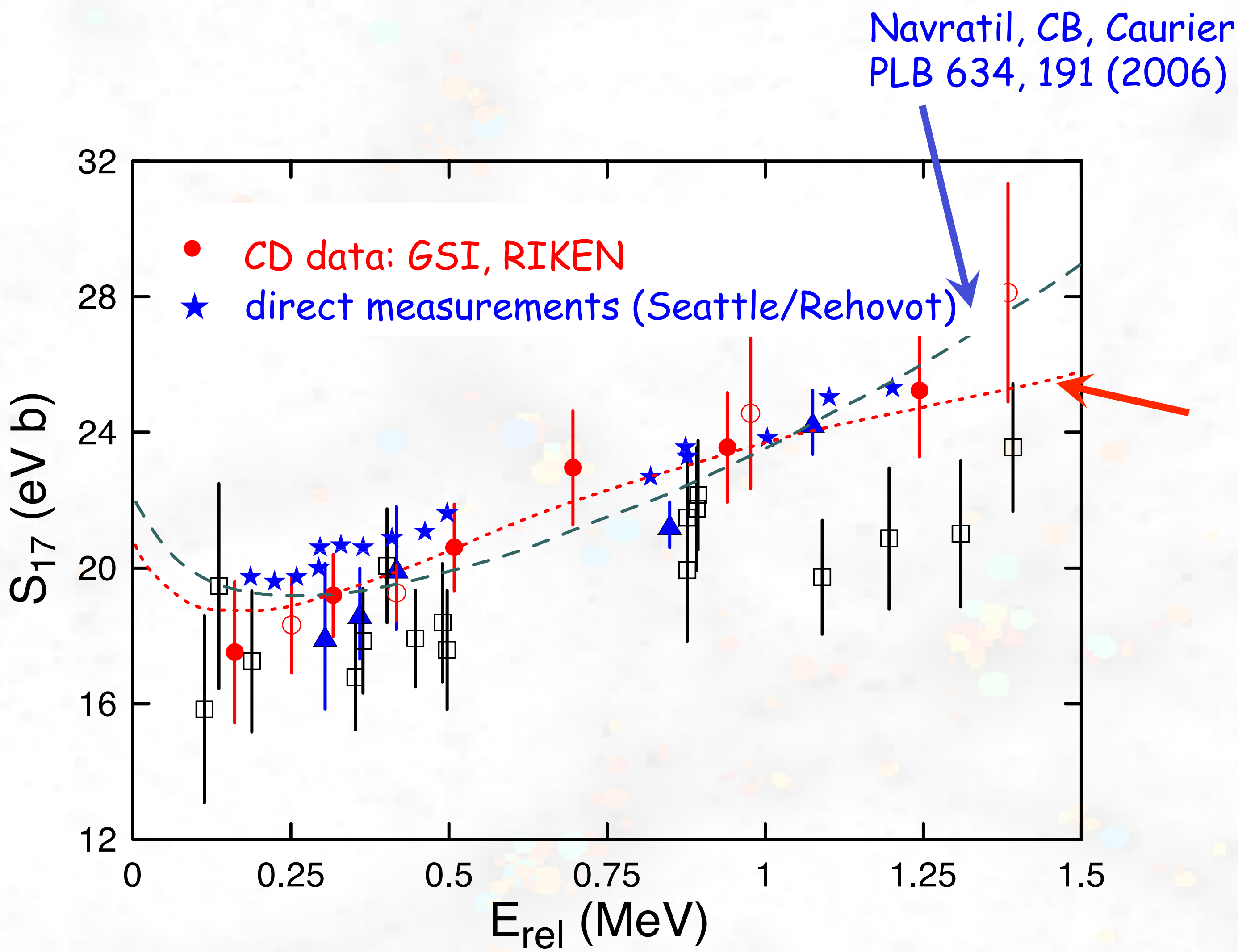
detailed balance

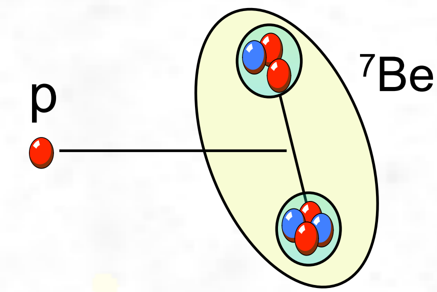


$$\sigma_{b+c \to a+\gamma} = \frac{2(2j_a+1)}{(2j_b+1)(2j_c+1)} \frac{k_{bc}^2}{k_\gamma^2} \sigma_{\gamma+a \to b+c}$$

Applications to radiative capture (n,γ) and (p,γ) reactions in nuclear astrophysics.

Solar physics: $^7Be(p,\gamma)^8B$

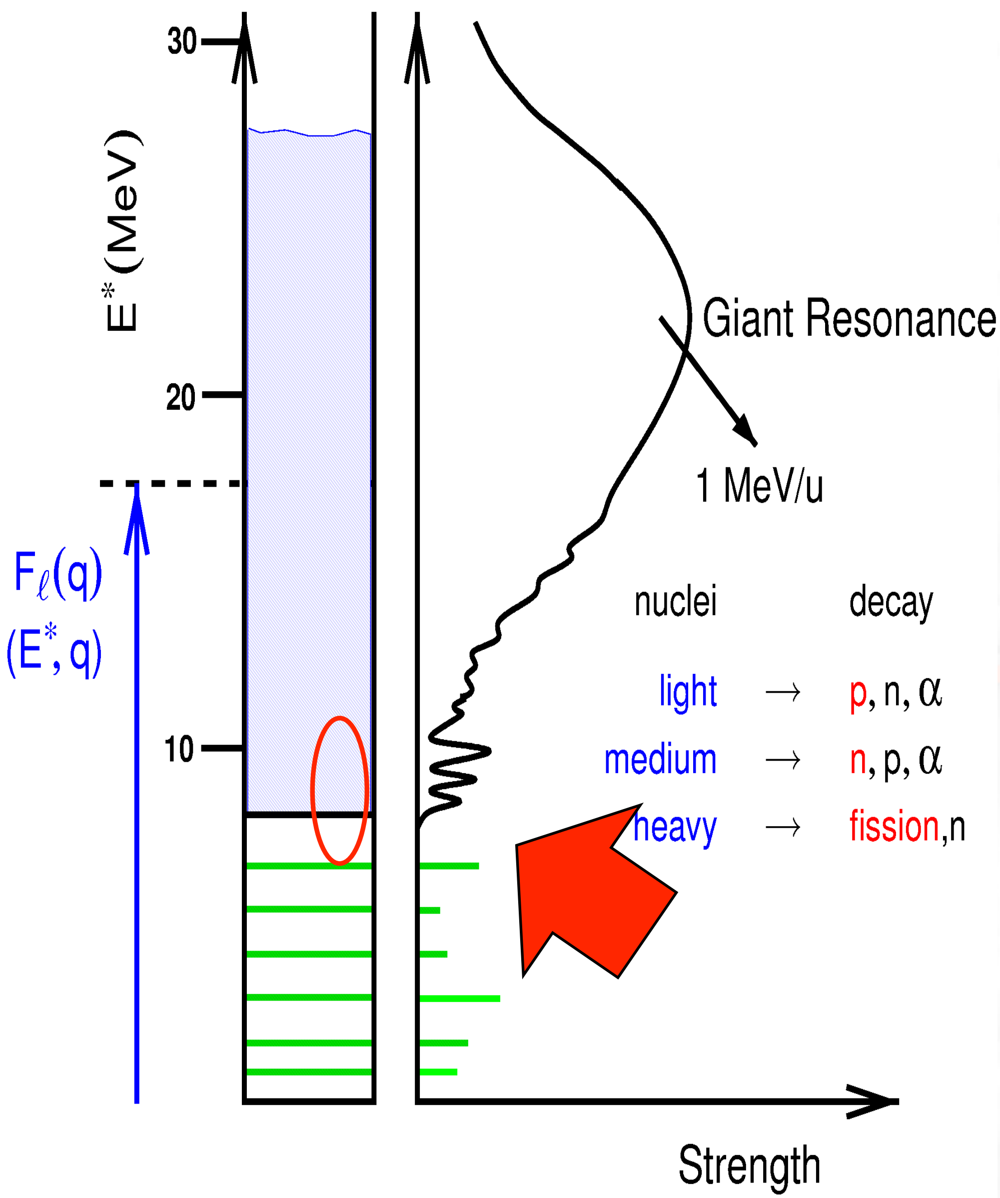




$$S_{17} \;=\; 20.8 \pm 0.7 \;(\text{exp}) \pm 1.4 \;(\text{theor})\; \text{eV b}$$

Adelberger et al.,
Rev. Mod. Phys. 83, 195 (2011)

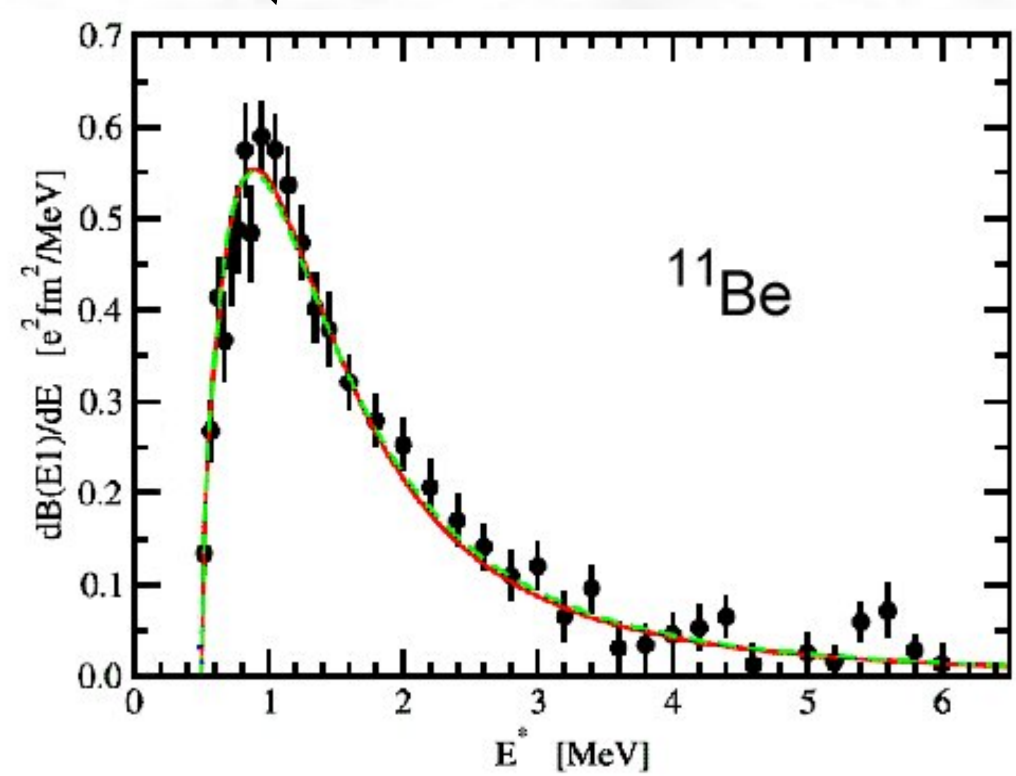
Response in exotic nuclei



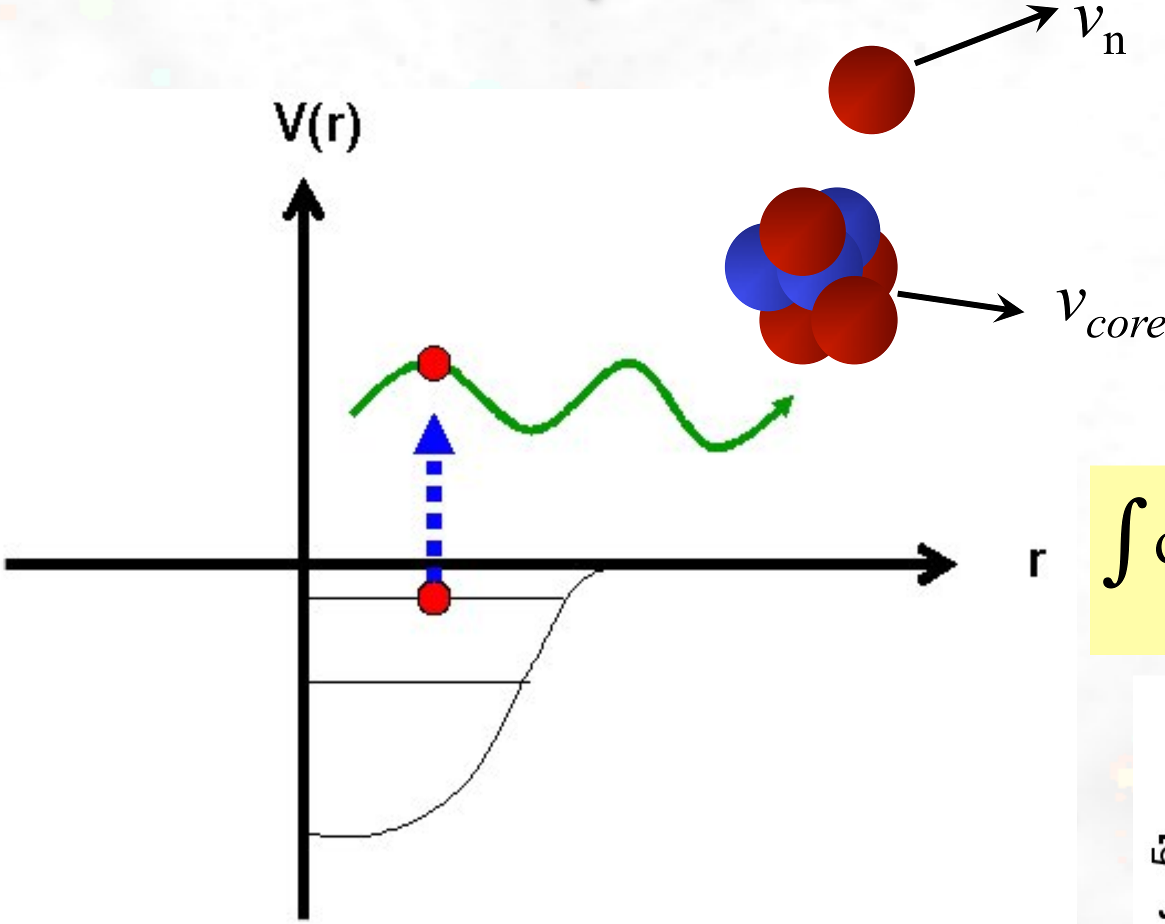
EM reponse in exotic nuclei

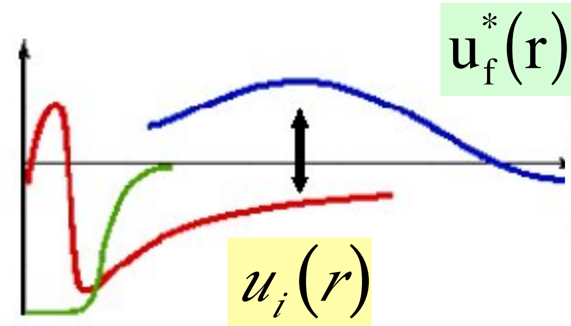
Collective response or

Direct breakup?



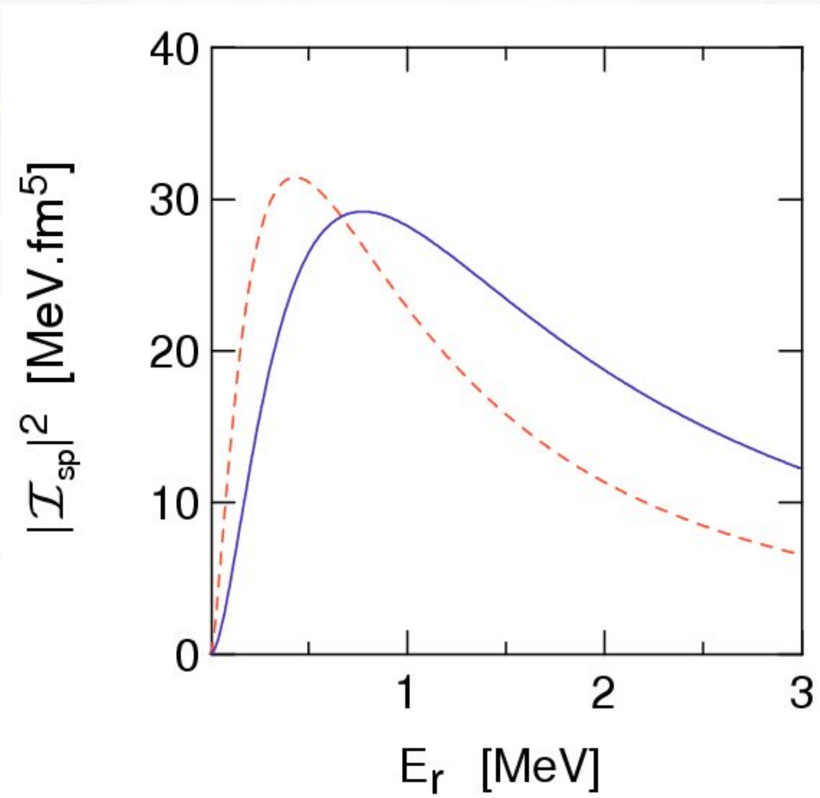
Direct breakup





$$r^2\,\delta\rho_{if}(r) \propto u_f^*(r)\,u_i(r)$$

$$\int dr\, r^{2+1}\,\delta\rho_{if}(r) \propto \frac{E_r}{\left(S_n + E_r\right)^2}\left(1+\mathrm{FSI}\right)$$

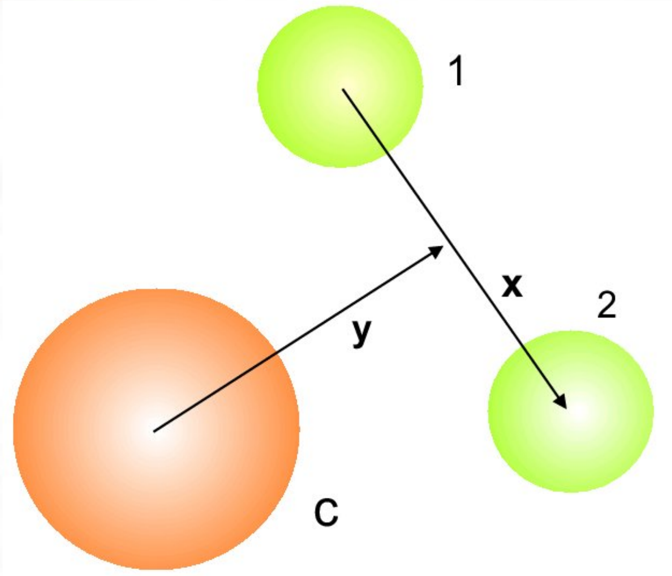


$$\frac{dB(E\lambda)}{dE_r} \propto \frac{E_r^{\lambda+1/2}}{\left(S_n + E_r\right)^{2\lambda+2}}\left(1+\mathrm{FSI}\right)^2$$

CB, Sustich, PRC 46 (1992) 2340

$$E_r^{(E\lambda)\mathrm{peak}} \cong \frac{\lambda + 1/2}{\lambda + 3/2} S_n \qquad E_r^{(E1)\mathrm{peak}} \cong \frac{3}{5} S_n$$

Direct breakup in the 3-body model



$$\Psi(\mathbf{x},\mathbf{y}) = \frac{1}{\rho^{5/2}} \sum_{KLSl_x l_y} \Phi^{l_x l_y}_{KLS}(\rho)\left[\Gamma^{l_x l_y}_{KL}(\Omega_5) \otimes \chi_S\right]_{JM}$$

$$\Omega_5 = (\theta_x, \phi_x, \theta_y, \phi_y, \theta)$$

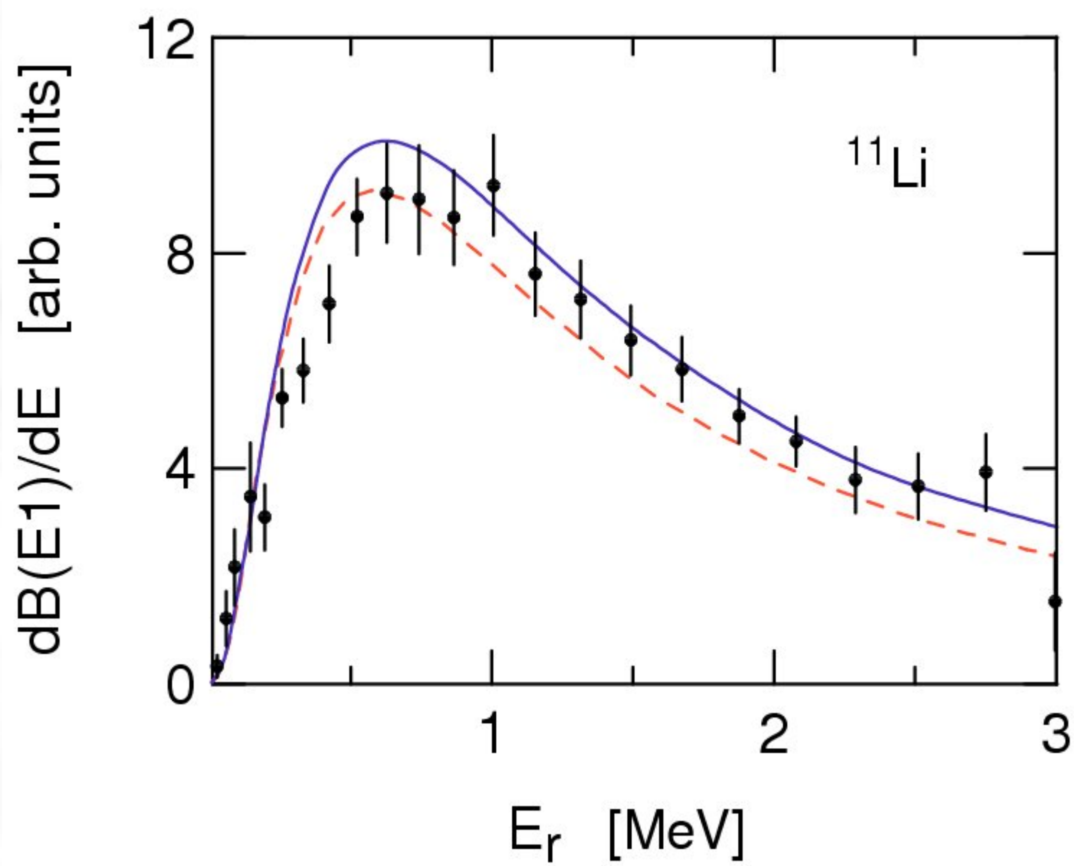
$$y = \rho \sin\theta, \qquad x = \rho\cos\theta$$

$$\delta\rho^{E1}_{fi} \propto \int dxdy \frac{\Phi_\alpha(\rho)}{\rho^{5/2}} y^2 x u_p(x) u_q(y)$$

$$E_r = \frac{\hbar^2}{2m_N}(q^2+p^2)$$

$$\frac{dB(E1)}{dE_r} \propto \frac{E_r^3}{\left(S^{eff}_{2n}+E_r\right)^{11/2}}(1+FSI)^2$$

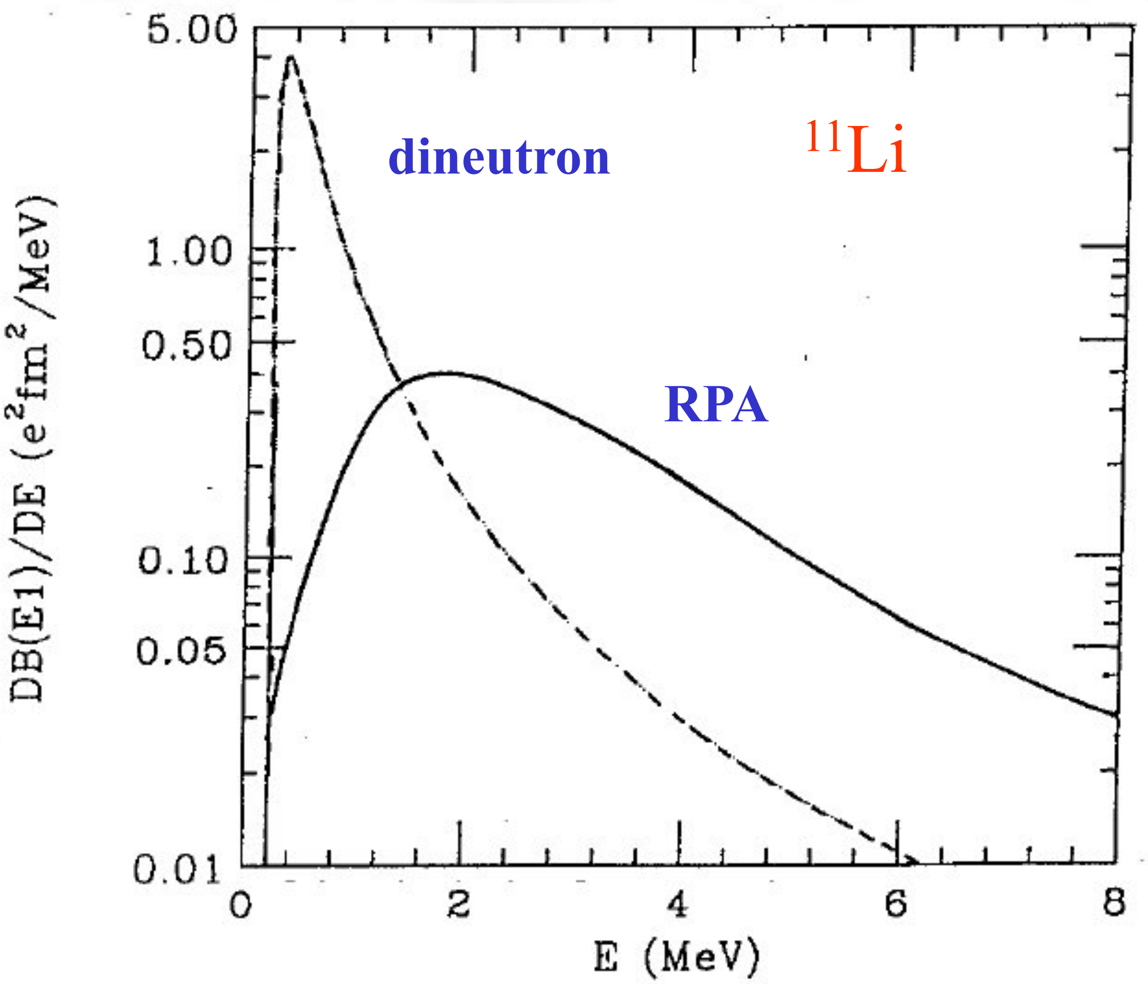
$$S^{eff}_{2n} \cong 1.8\, S_{2n}$$



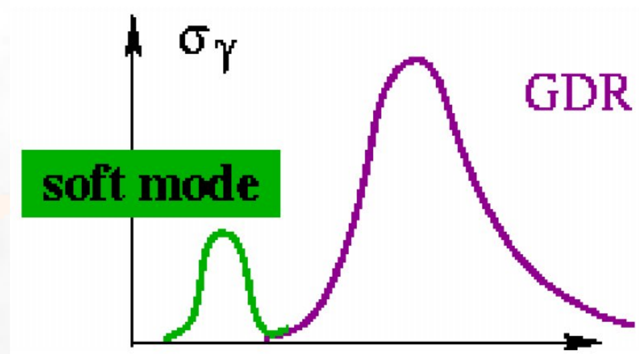
CB, PRC 75, 024606 (2007)

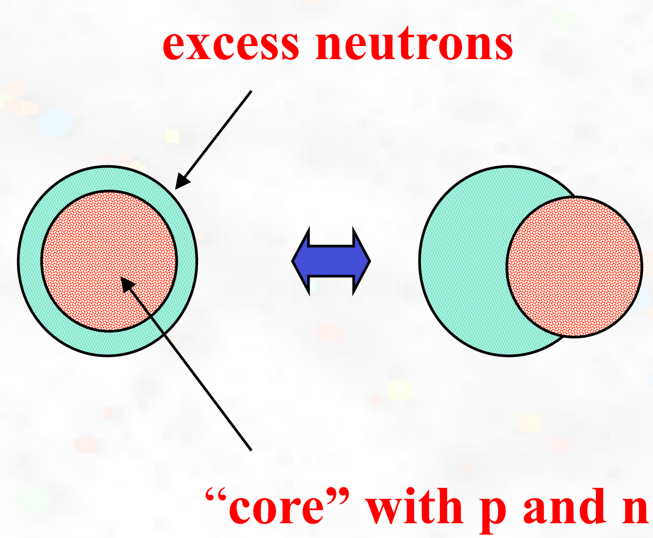
Collective response in light neutron rich nuclei

N. Teruya et al,
PRC 43, 2049 (1991)



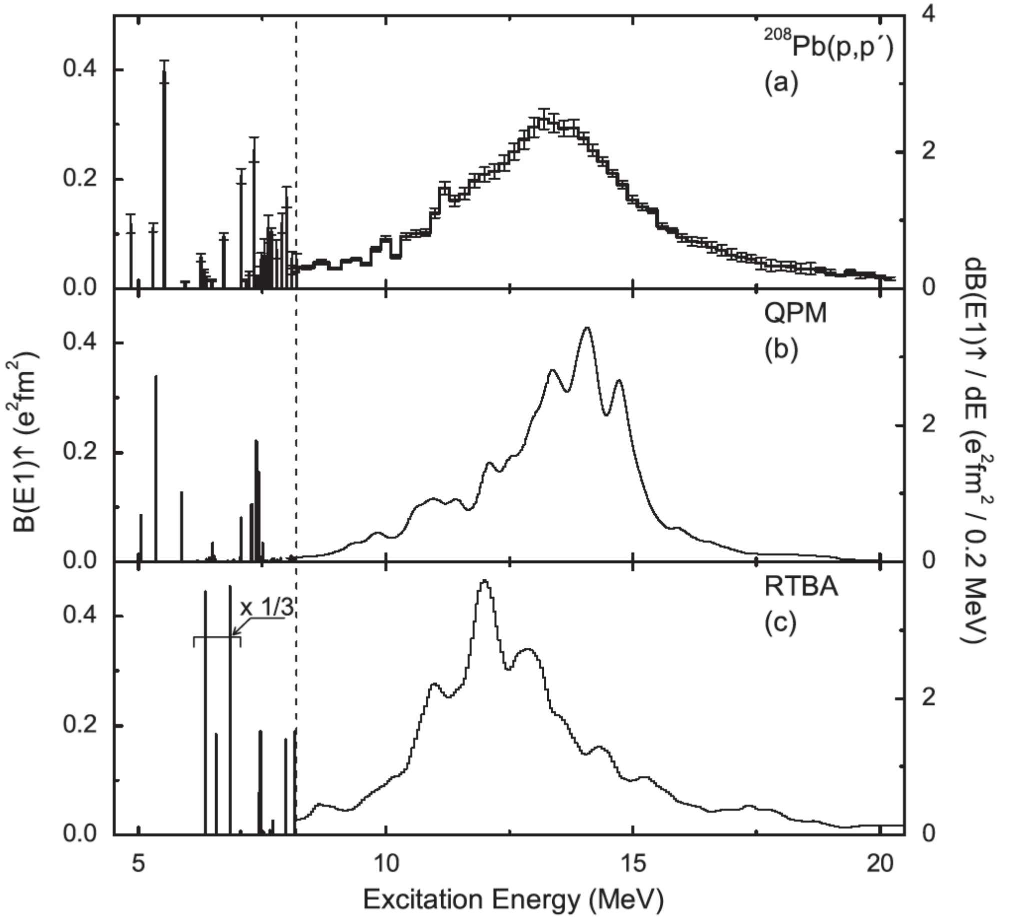
RPA + $2n_p$-$2n_h$ excitations



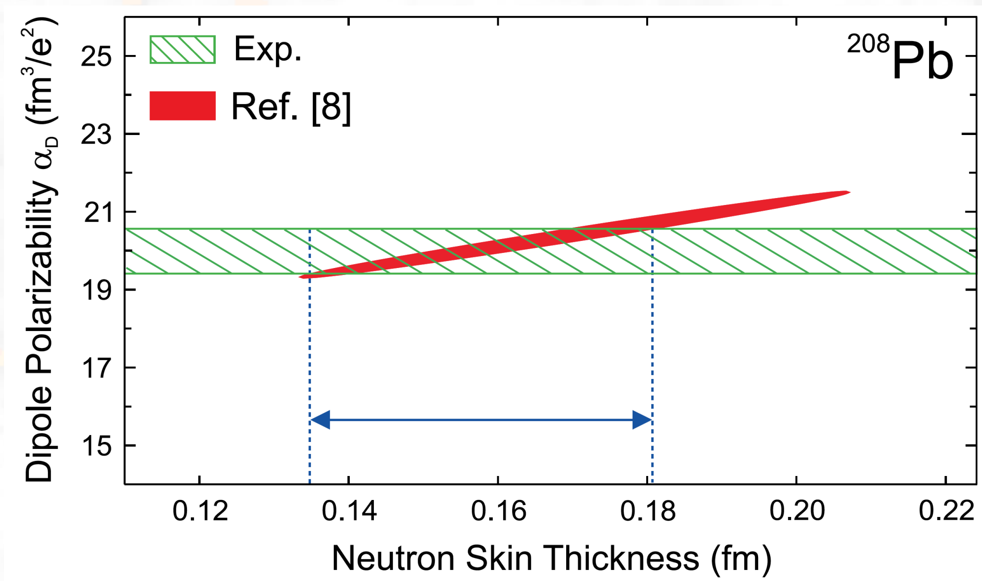


Pigmy Resonance and Neutron Skin in Pb

A. Tamii et al., PRL 107, 062502 (2011)
I. Poltoratska et al., PRC 85 (R), 041304 (2012)



$$\alpha = \frac{\hbar c}{2\pi^2 e^2} \int \frac{\sigma_{abs}}{\omega^2} d\omega$$



Constrains symmetry energy → relevant to the description of neutron stars.

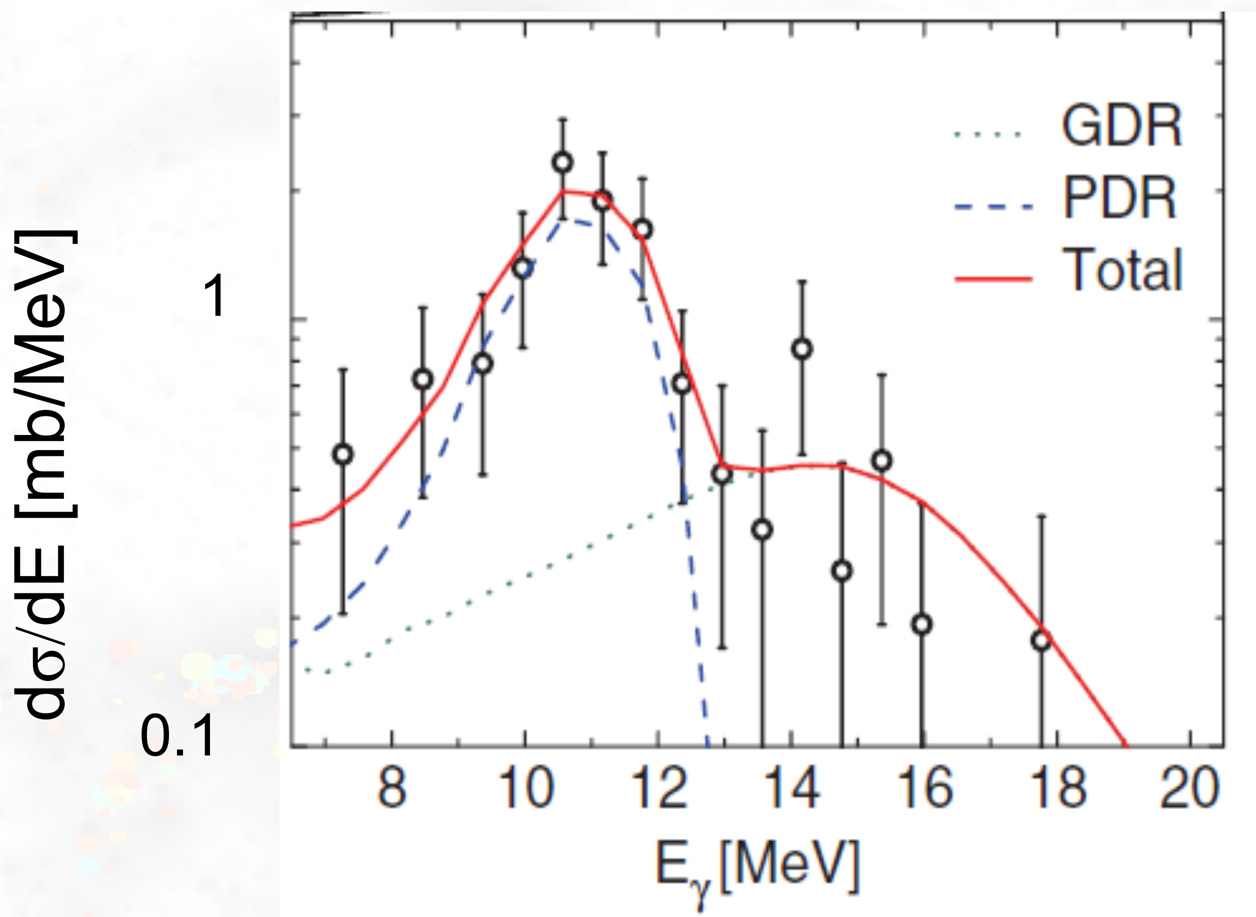
Reinhard, Nazarewicz, PRC 81, 051303(R) (2010).

Pigmy resonance in ^{68}Ni

PRL 102, 092502 (2009) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2009

Search for the Pygmy Dipole Resonance in ^{68}Ni at 600 MeV/nucleon

O. Wieland,[1] A. Bracco,[1,2] F. Camera,[1,2] G. Benzoni,[1] N. Blasi,[1] S. Brambilla,[1] F. C. L. Crespi,[1,2] S. Leoni,[1,2] B. Million,[1] R. Nicolini,[1,2] A. Maj,[3] P. Bednarczyk,[3] J. Grebosz,[3] M. Kmiecik,[3] W. Meczynski,[3] J. Styczen,[3] T. Aumann,[4] A. Banu,[4] T. Beck,[4] F. Becker,[4] L. Caceres,[4,*] P. Doornenbal,[4,†] H. Emling,[4] J. Gerl,[4] H. Geissel,[4] M. Gorska,[4] O. Kavatsyuk,[4] M. Kavatsyuk,[4] I. Kojouharov,[4] N. Kurz,[4] R. Lozeva,[4] N. Saito,[4] T. Saito,[4] H. Schaffner,[4] H. J. Wollersheim,[3] J. Jolie,[5] P. Reiter,[5] N. Warr,[5] G. deAngelis,[6] A. Gadea,[6] D. Napoli,[6] S. Lenzi,[7,8] S. Lunardi,[7,8] D. Balabanski,[9,10] G. LoBianco,[9,10] C. Petrache,[9,‡] A. Saltarelli,[9,10] M. Castoldi,[11] A. Zucchiatti,[11] J. Walker,[12] and A. Bürger[13,§]

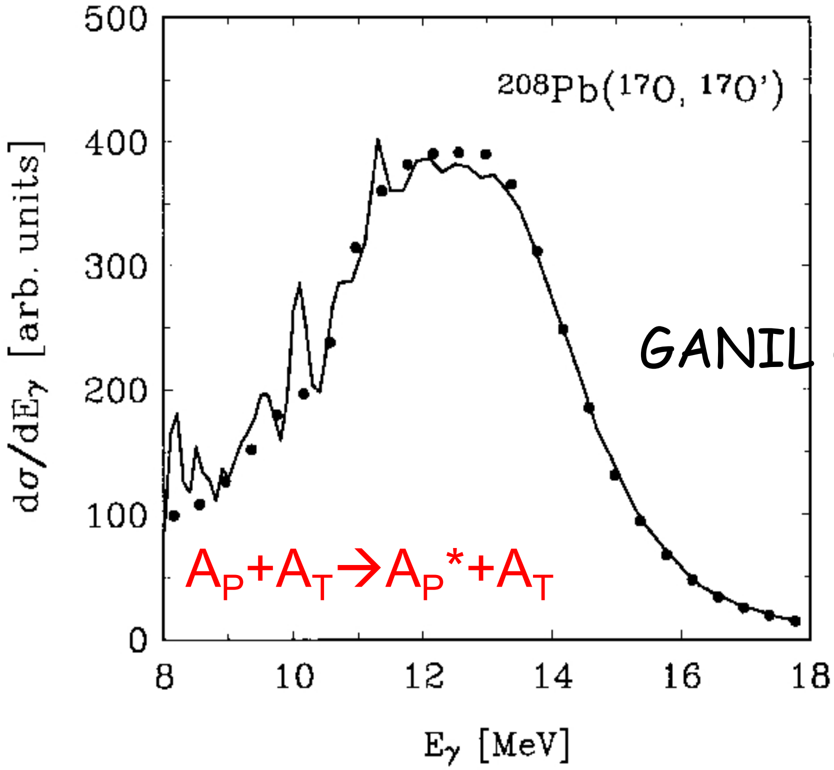


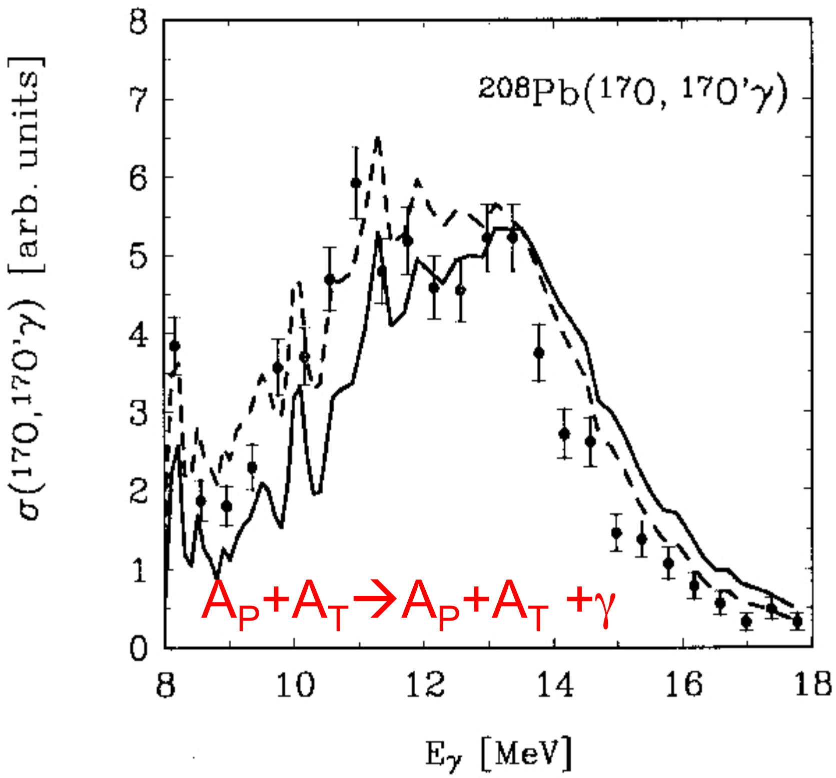
TRK percentage for the PDR: 5% +/-1.5

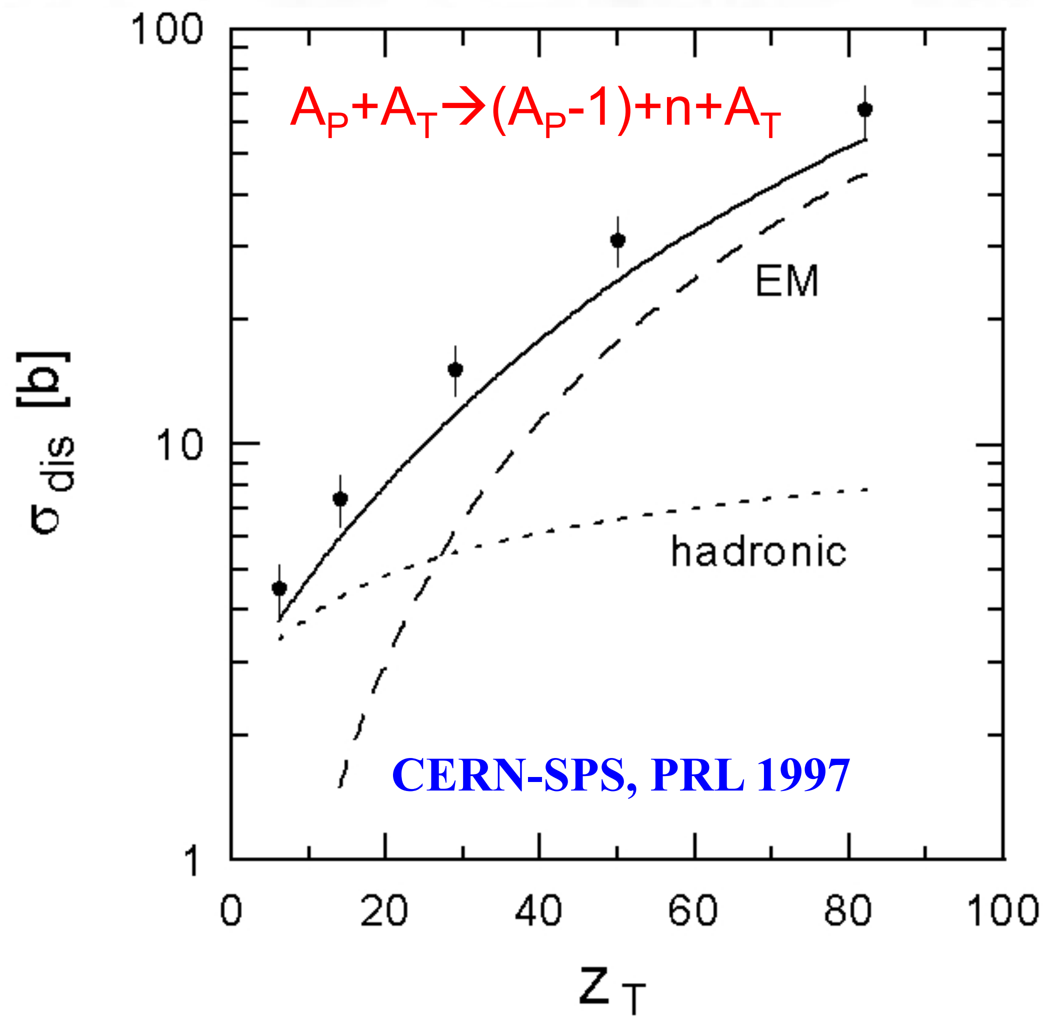
Probing more collective states

CB, Nathan, NPA 554 (1993) 158.

GANIL data, Phys. Rev. C41 (1990) 920

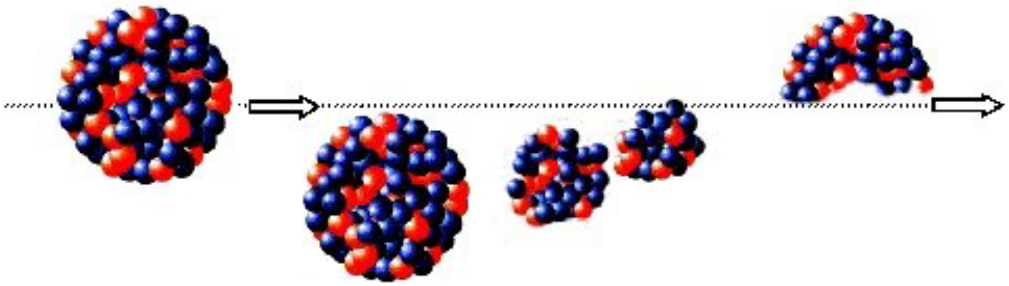




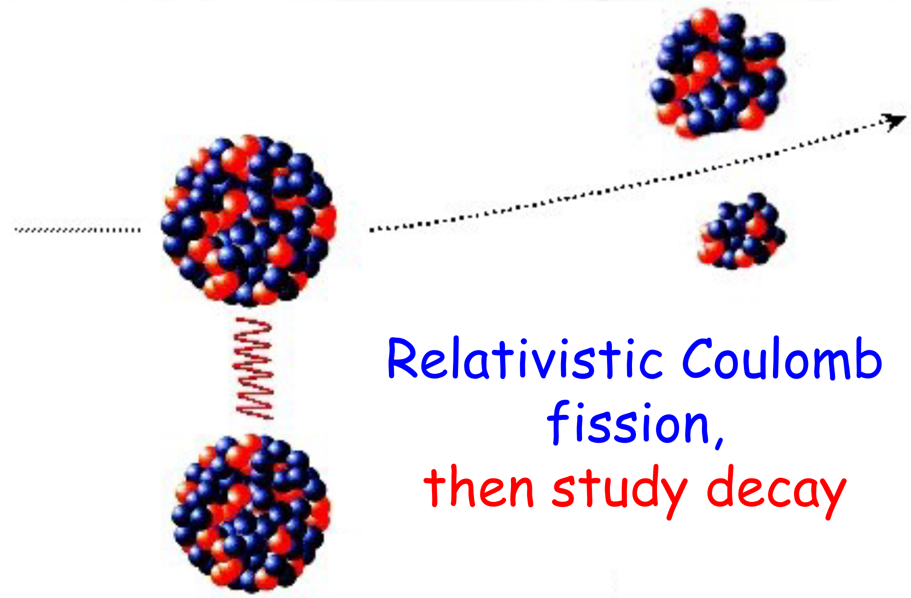


Production of rare isotopes: Coulomb fission

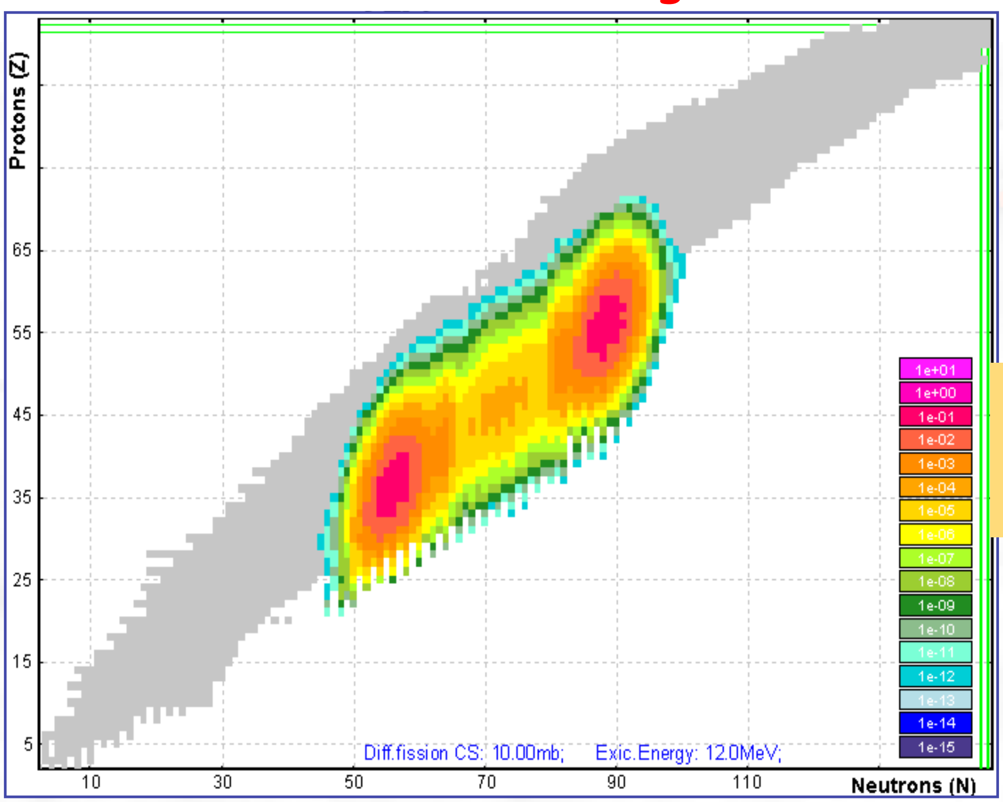
"high energy" accelerators



scrap fragments, reaccelerate,
then do something useful



Relativistic Coulomb fission,
then study decay



Calculated fission fragment differential cross sections for the fissile nucleus ^{238}U for excitation energies: of 12 MeV.

Calculations: O. Tarasov - MSU
Experiments: J. Benliure – GSI

End Lecture 1