Nuclear Astrophysics with Radioactive Beams

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Part II

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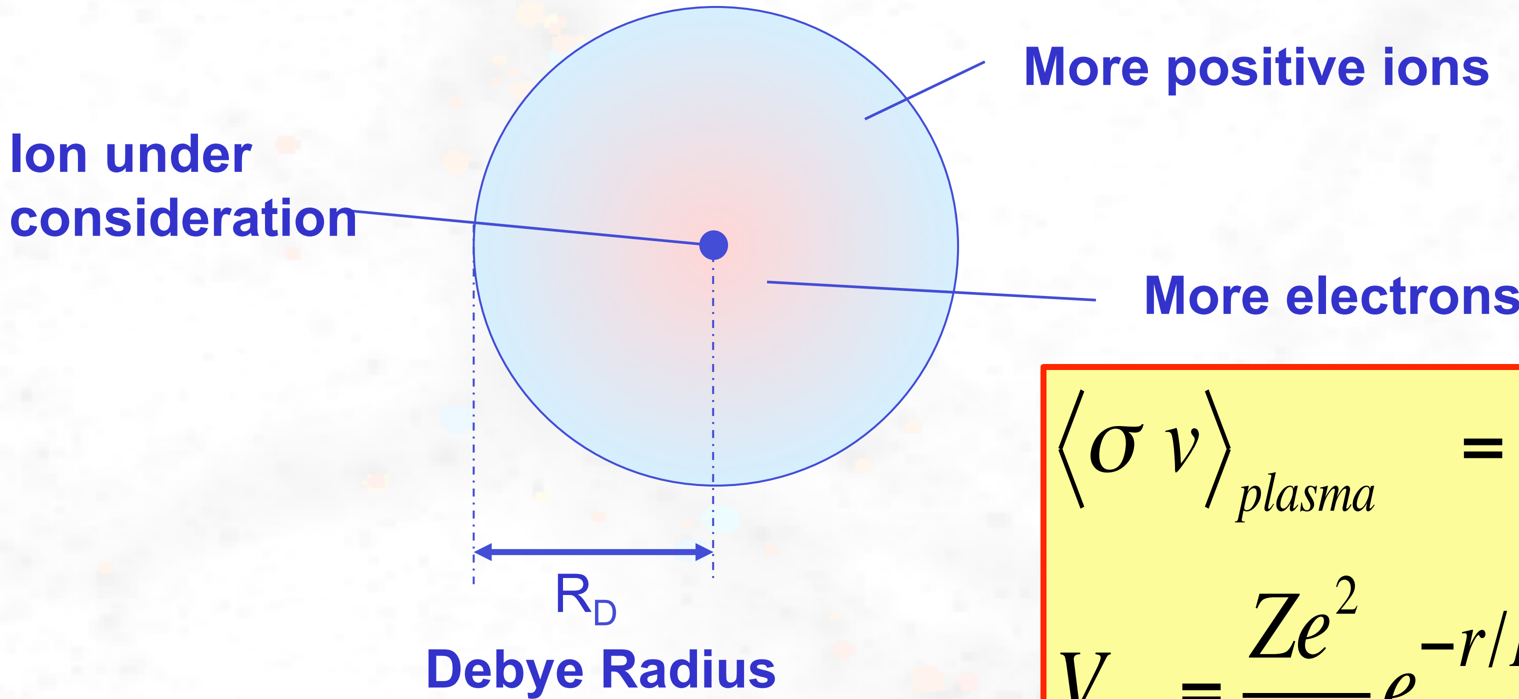
Electron screening in plasmas and in experiments

Electron screening (in stars)

Debye-Hueckel screening (Salpeter 1959)

$$n\, R_D^3 >> 1$$



$$\langle \sigma v \rangle_{plasma} = f(E) \langle \sigma v \rangle_{bare}$$

$$V_{eff} = \frac{Ze^2}{r} e^{-r/R_D}$$

$$f(E) = e^{U_e/kT}, \qquad R_D \sim \sqrt{kT/\rho} \sim 0.218 \overset{0}{\mathrm{A}} \,(\mathrm{Sun})$$

$$^7\mathrm{Be(p,}\gamma)^8\mathrm{B} \;\; (T \sim 10^7 \mathrm{K}): \qquad f(E) \sim 1.2$$

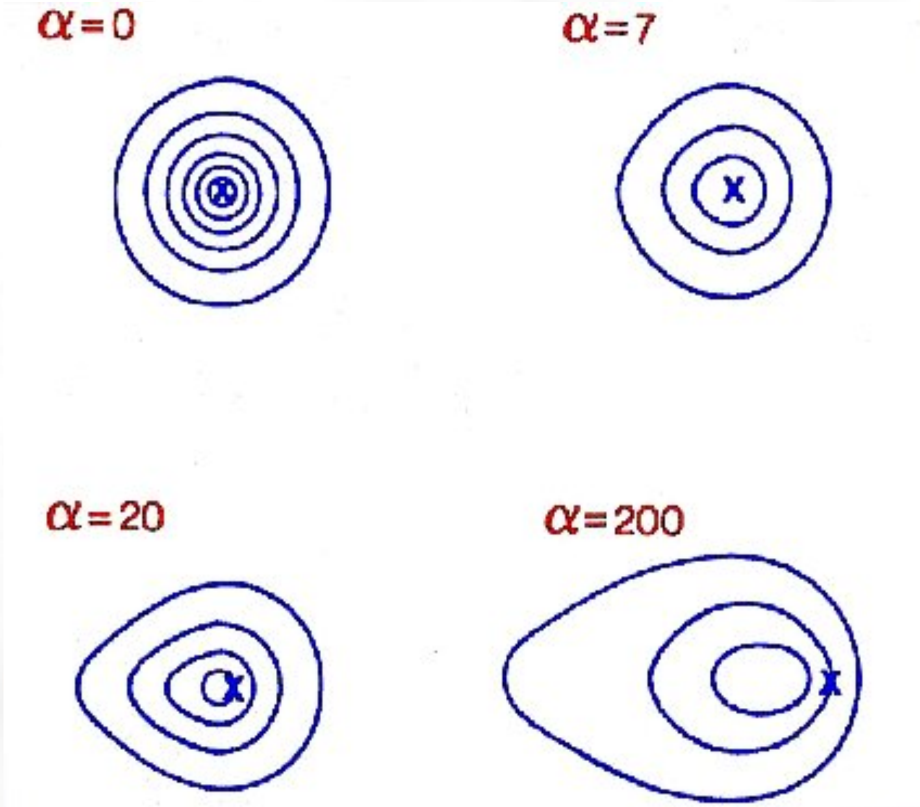
(20 % effect)

Gamow energy >> thermal energy (dynamical screening)

Carraro, Schaefer, Koonin, ApJ 1988

$$\alpha = v / v_{thermal} \; , \qquad s_{12} = dynamic / Debye$$

Reaction	Gamow Energy (E_g/T)	s_{12}
p–p	4.6	0.76
^{3}He–^{3}He	16.6	0.75
^{3}He–^{4}He	17.3	0.76
p–^{7}Be	13.9	0.80
p–^{14}N	20.6	0.82

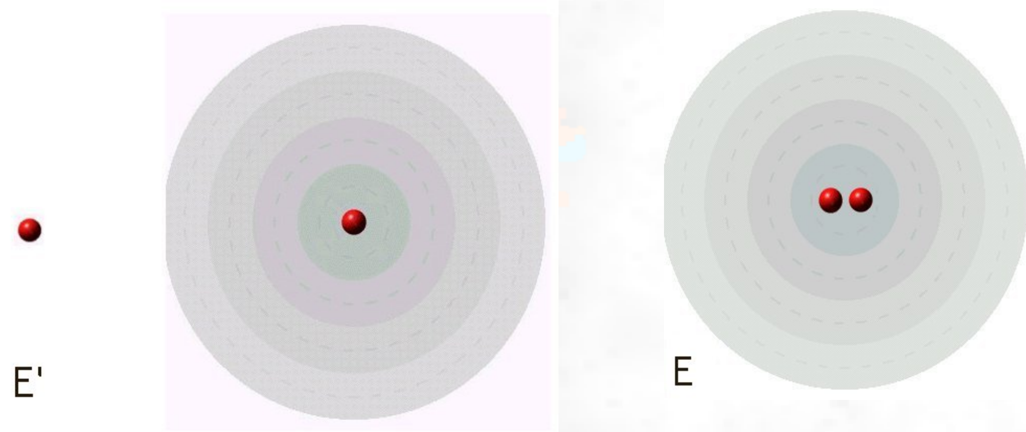


Fluctuations in the Debye sphere

$$n\, R_D^3 \sim 3 - 5$$

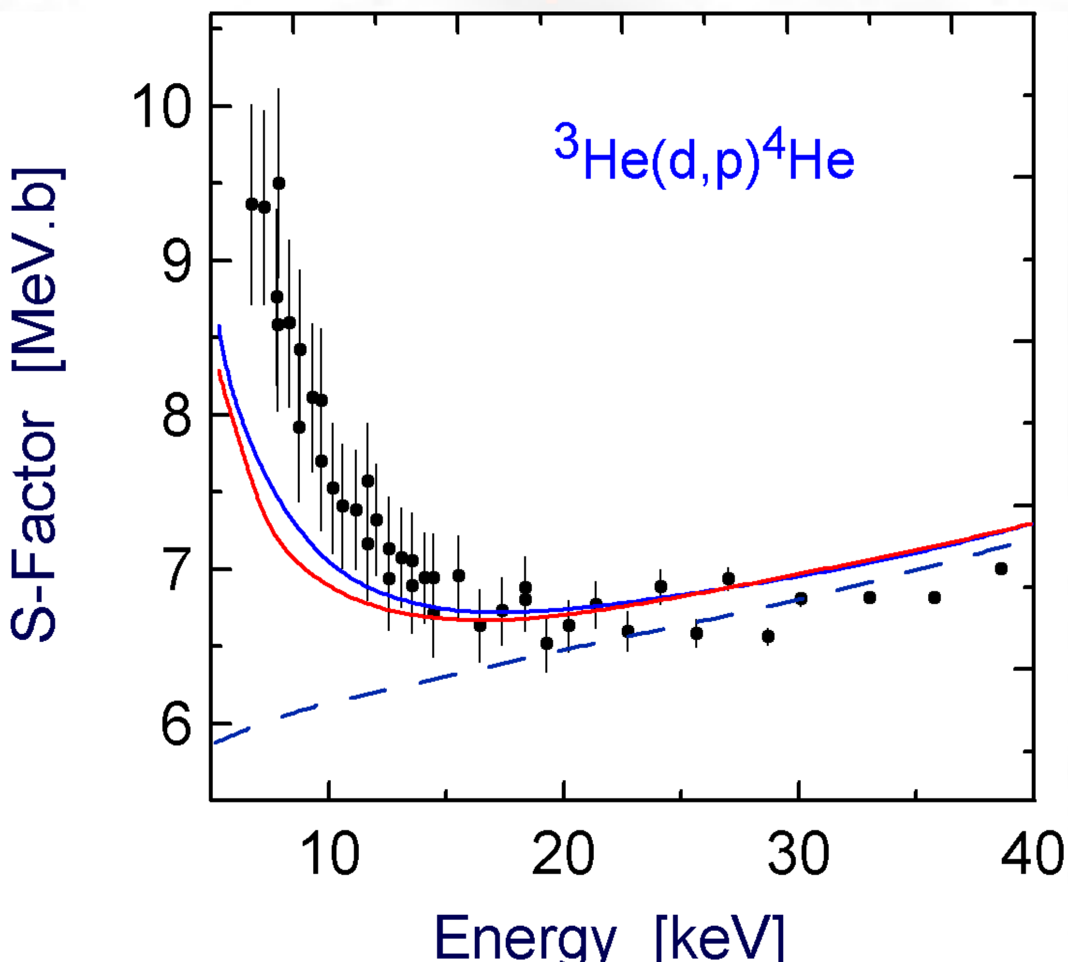
- One cannot derive the screening from thermodynamics but one has to resort to kinetic equations.
- Deviations from Debye-Hueckel can be large.

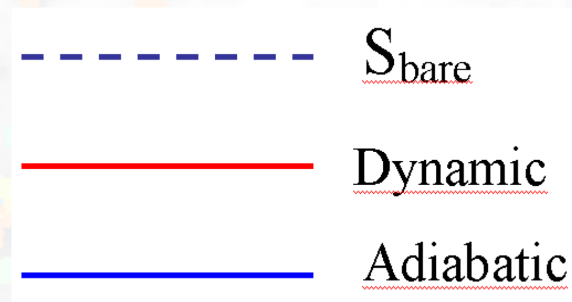
Electron screening (in the laboratory)



Adiabatic model: $\Delta E = E' - E$

$$\sigma_{lab}^{fusion} \sim \sigma_{bare}(E+\Delta E)$$
$$\sim \exp\left[\pi\eta(E)\frac{\Delta E}{E}\right]\sigma_{bare}(E)$$





Reaction	ΔE [eV] experiment	ΔE [eV] adiabatic limit
$d(^3\mathrm{He},p)^4\mathrm{He}$	180 ± 30	119
$^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$	470 ± 150	186
$^6\mathrm{Li}(d,\alpha)^4\mathrm{He}$	380 ± 250	186
$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$	300 ± 280	186
$^{11}\mathrm{B}(p,\alpha)2^4\mathrm{He}$	620 ± 65	348

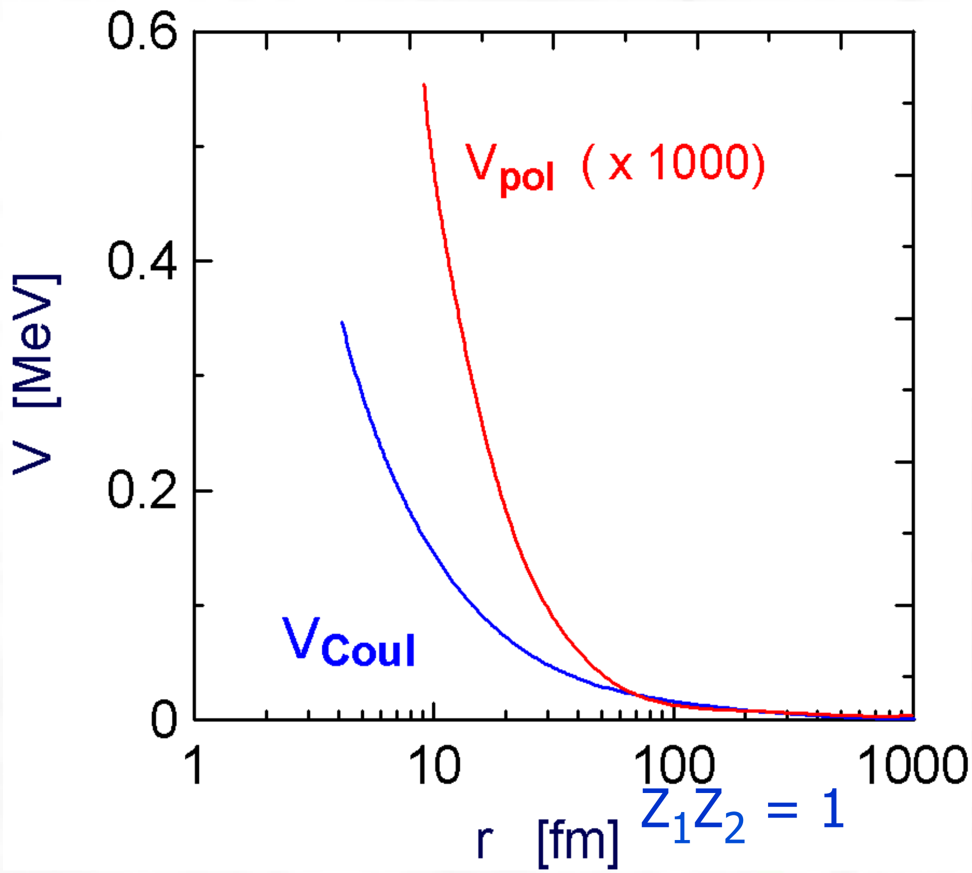
Amplification of small effects

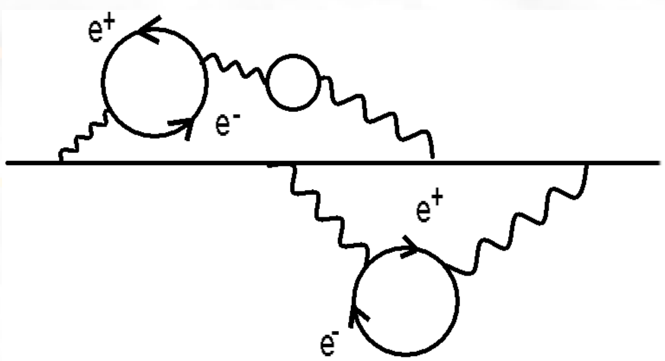
- Thermal motion, lattice vibrations, beam energy spread
- Nuclear breakup channels (in weakly-bound nuclei)
- Dynamics of tunneling

Balantekin, Bertulani, Hussein
NPA 627, 324 (1997)

Corrections	
Vaccuum Polarization	$\sim 1\%$
Relativity	10^{-3}
Bremsstrahlung	10^{-3}
Atomic porarization	10^{-5}
Nuclear polarization	$<10^{-10}$

all $\leq$ 1%

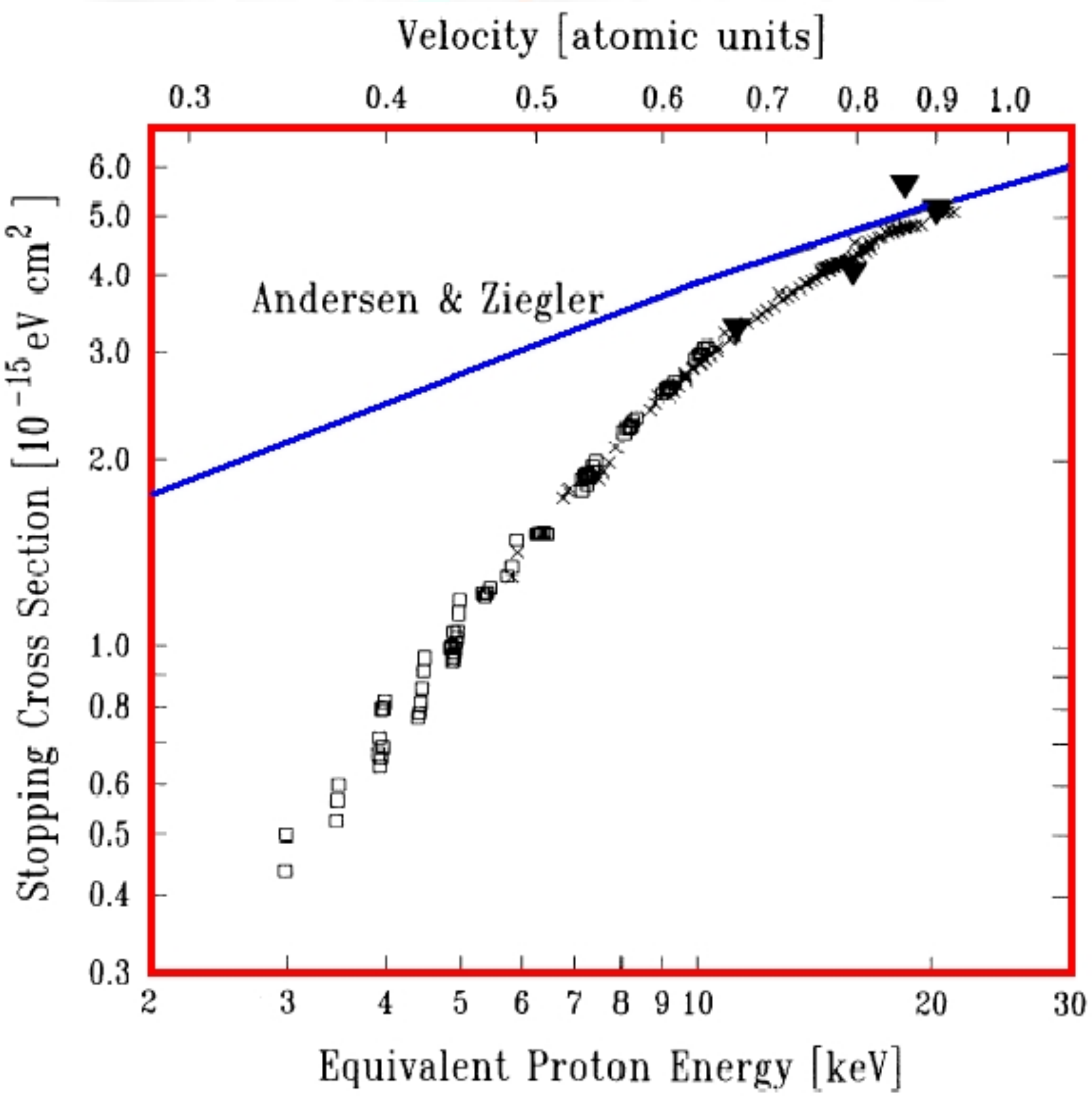


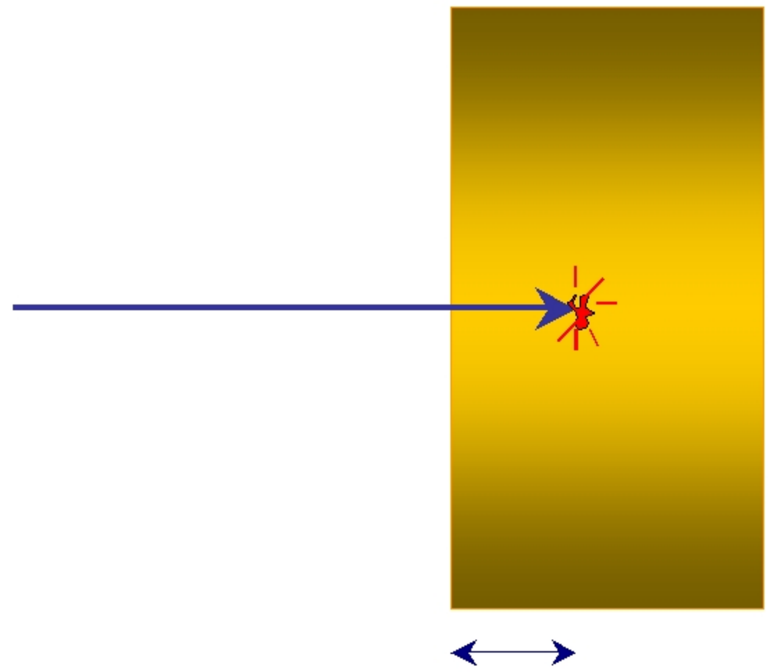


Vacuum polarization

Not a solution! (we need ~ 100%)

Stopping power





$$S = -\frac{dE}{dx}$$

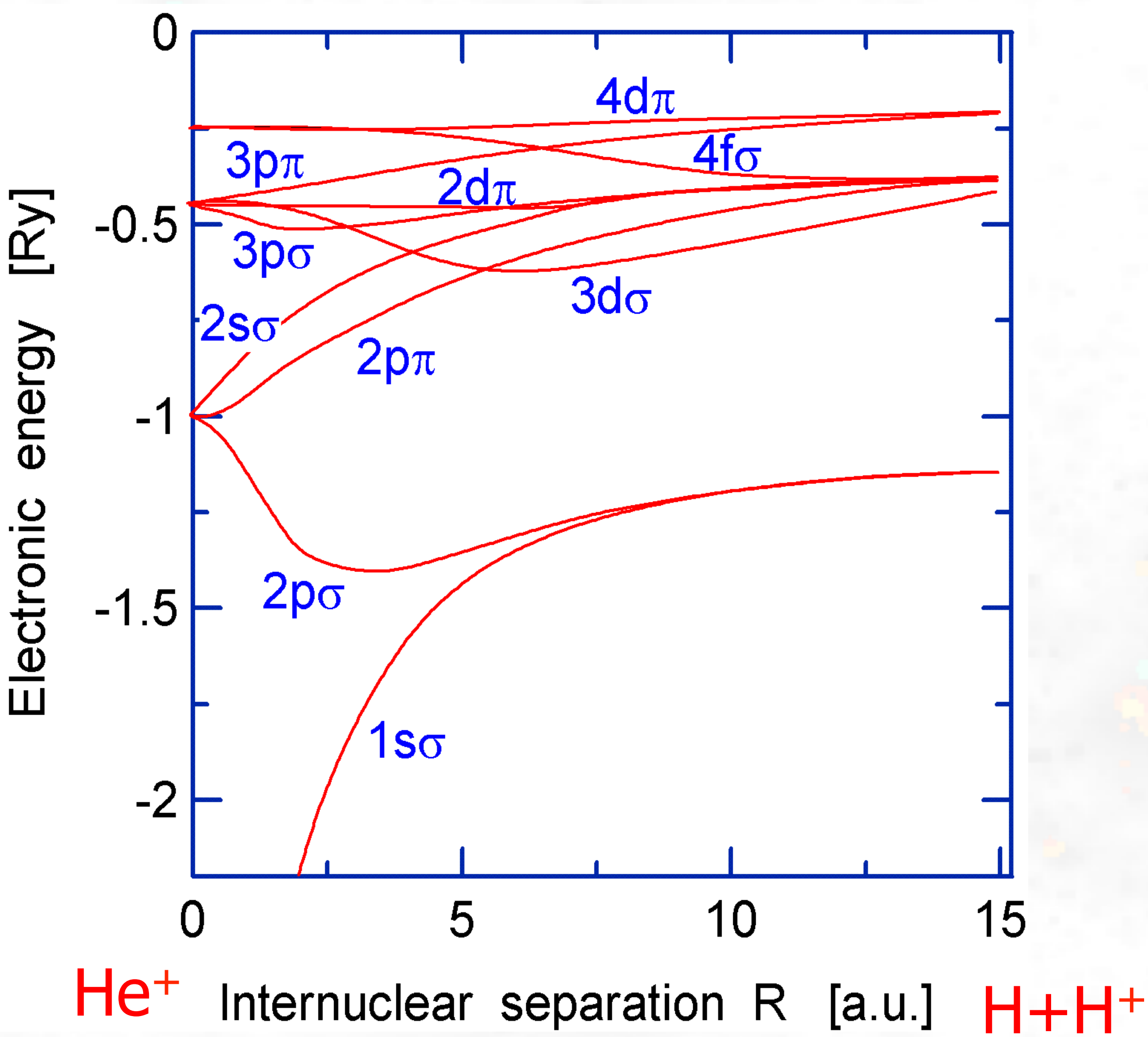
Golser, Semrad, PRL 1991

$E' = E - S_p.\Delta x$

H + He

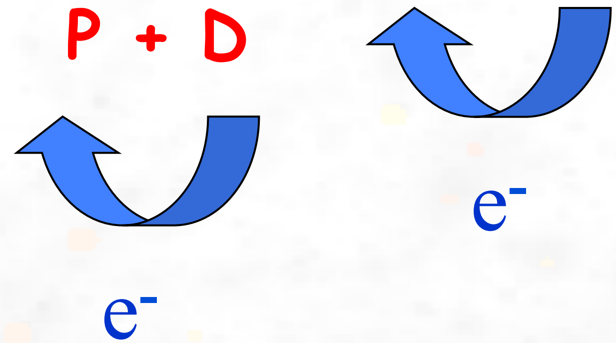
Mainly charge-exchange

Theory for the simplest systems



p + H   p + He

P + D



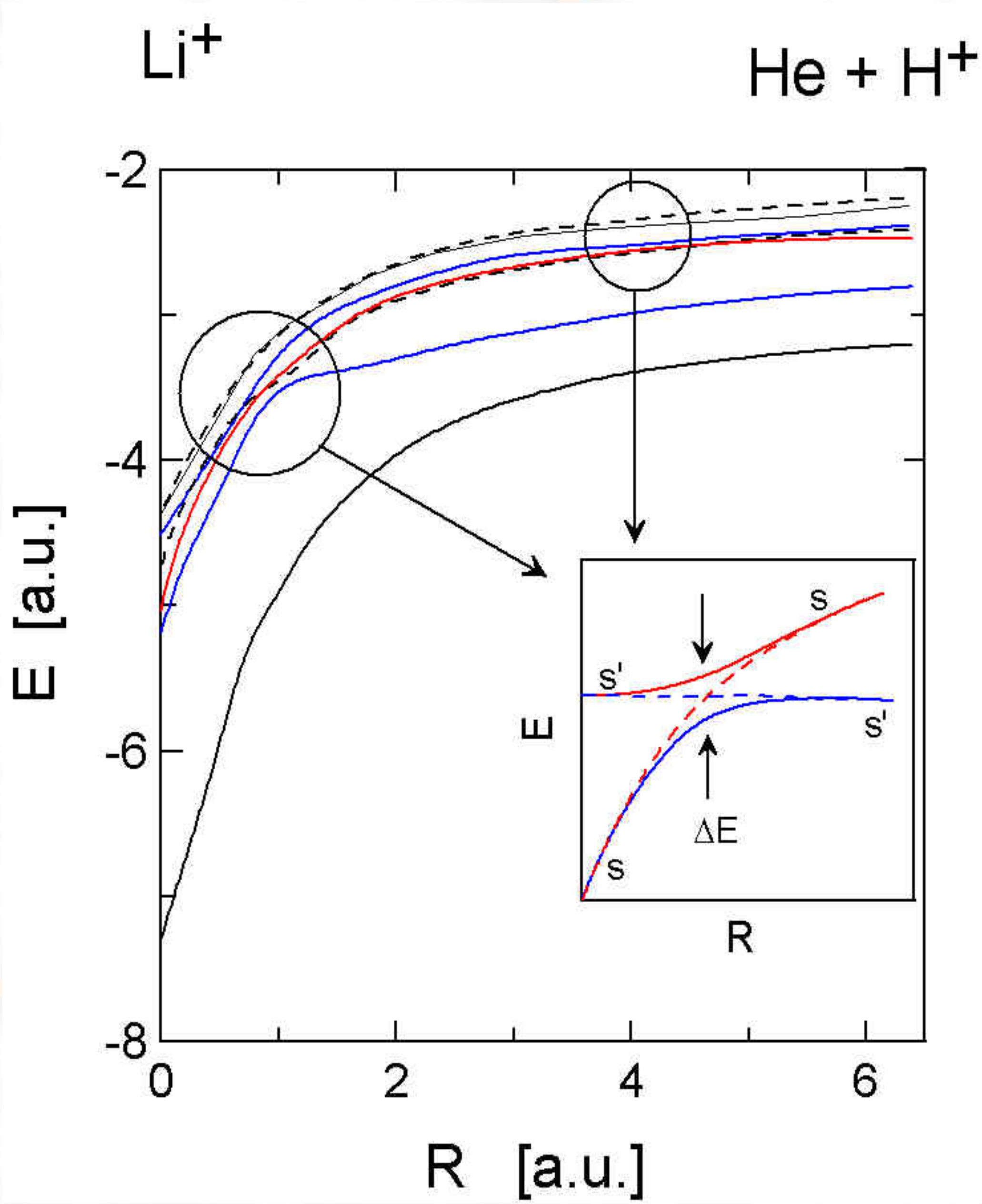
Elliptic coordinates
Molecular orbitals
Hellman-Feynmann relation
TDSE (for p + He)

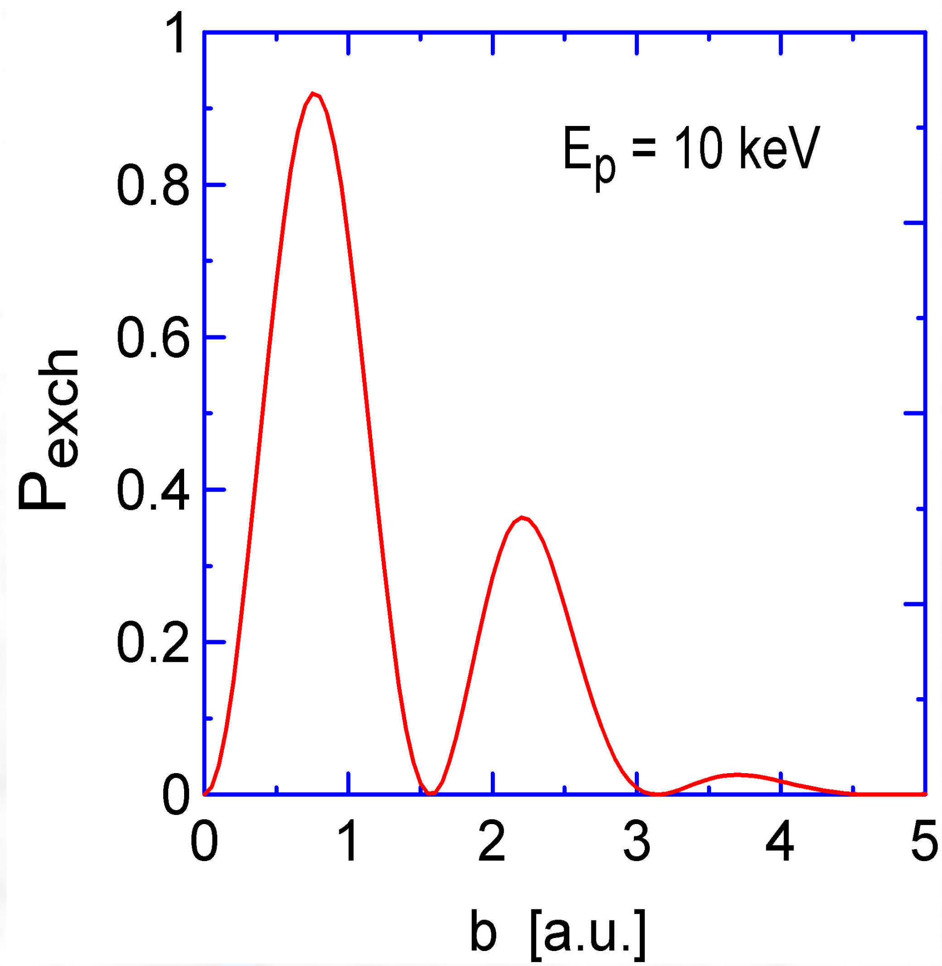
Coupled-channels

Bertulani, de Paula, PRC 62, 045802 (2000)
Bertulani, PLB 585, 35 (2004)

Damping of resonant exchange

H(1s) ⇔ He(1s2s)





Landau-Zener

$$P = e^{-\Gamma\,\Delta t_{coll}} \cos^2\left[\frac{H_{12}\,a}{2\mathrm{v}}\right]$$

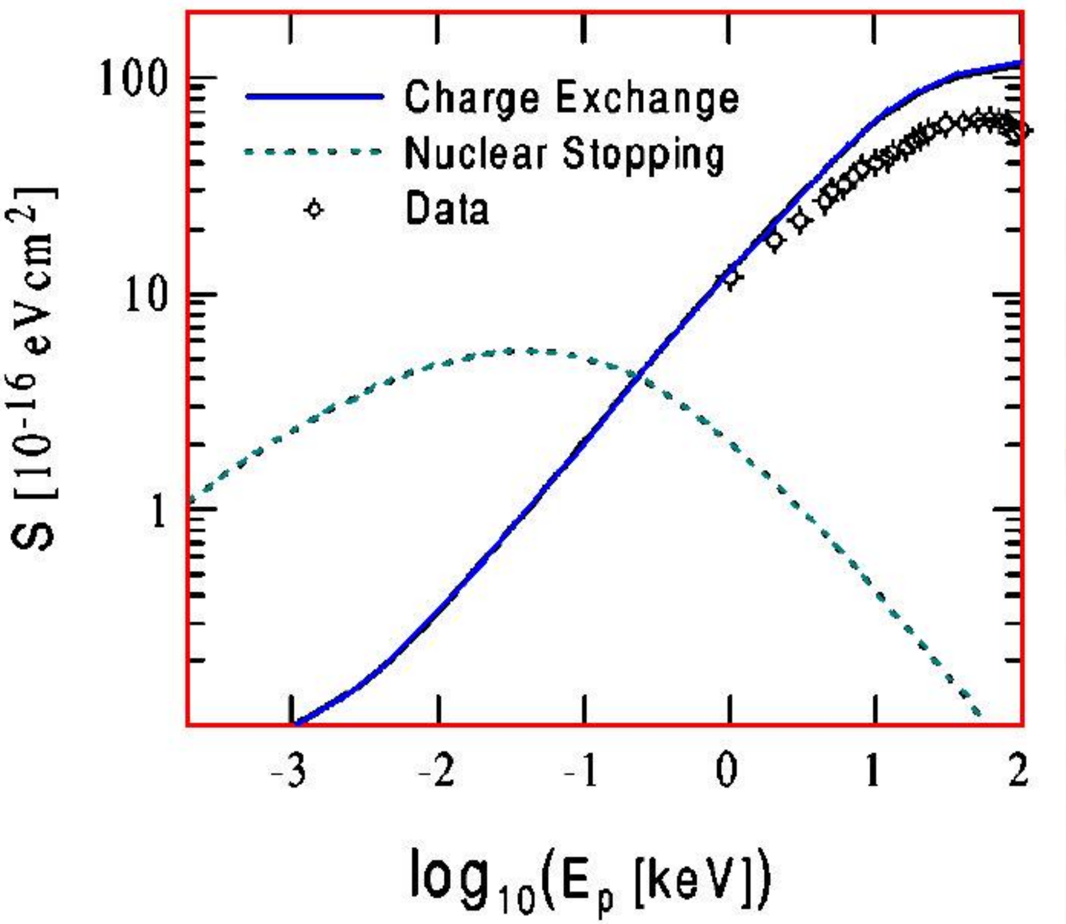
Stopping power at very low energies

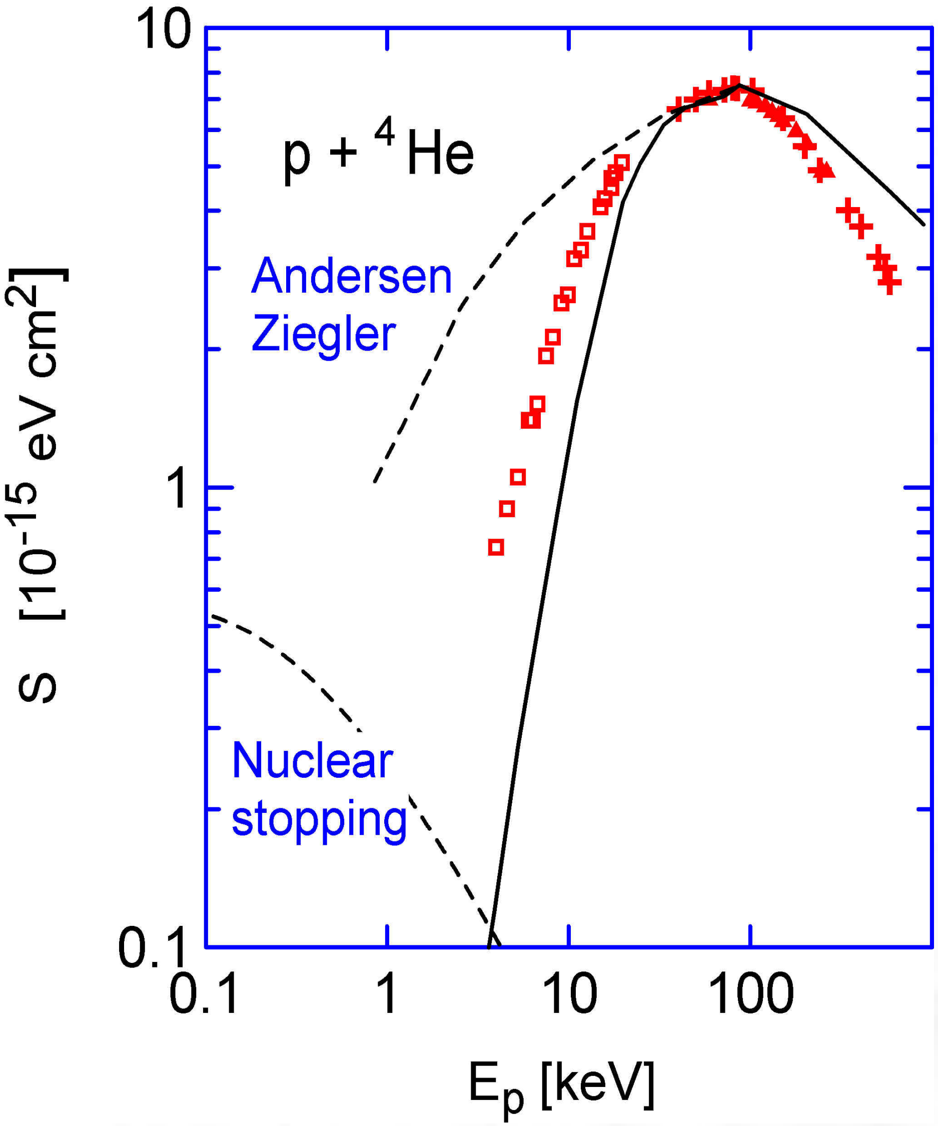
Threshold effect

$$E_P \geq \frac{\mu^2}{4M_P m_e}\Delta E \geq 8 \quad \text{keV}$$

Bertulani, PLB 585, 35 (2004)

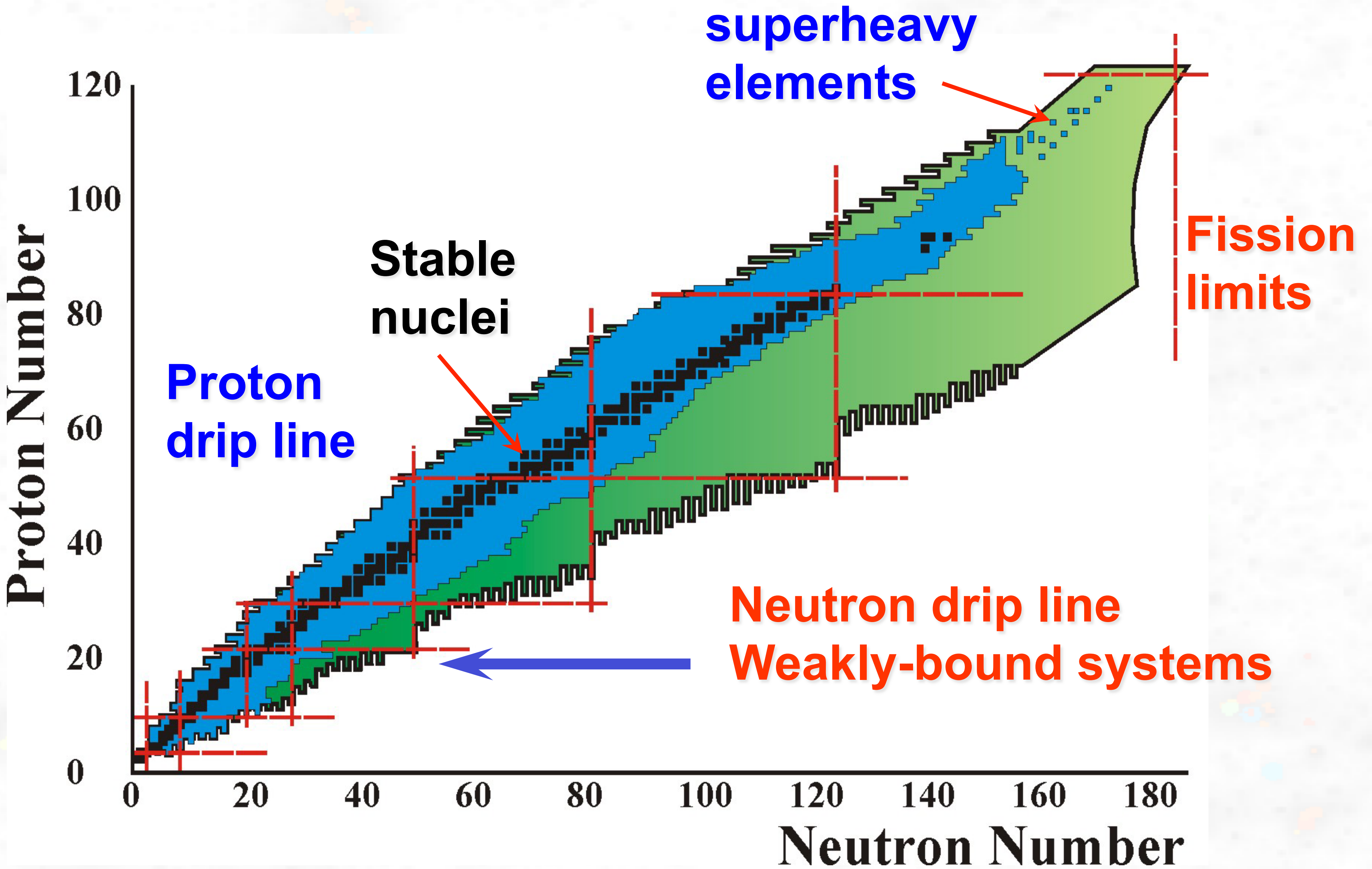
He: $1s^2 \rightarrow 1s2s$: 19.8 eV



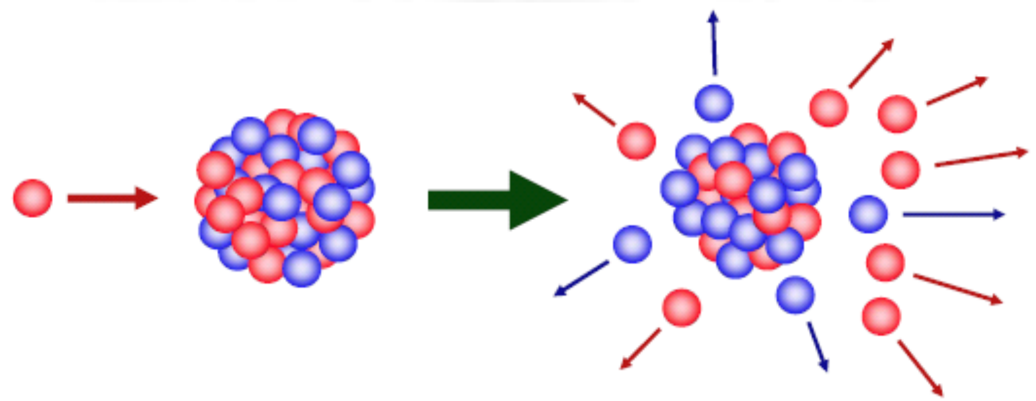


Nuclear Astrophysics with Radioactive Beams

Limits of nuclear stability

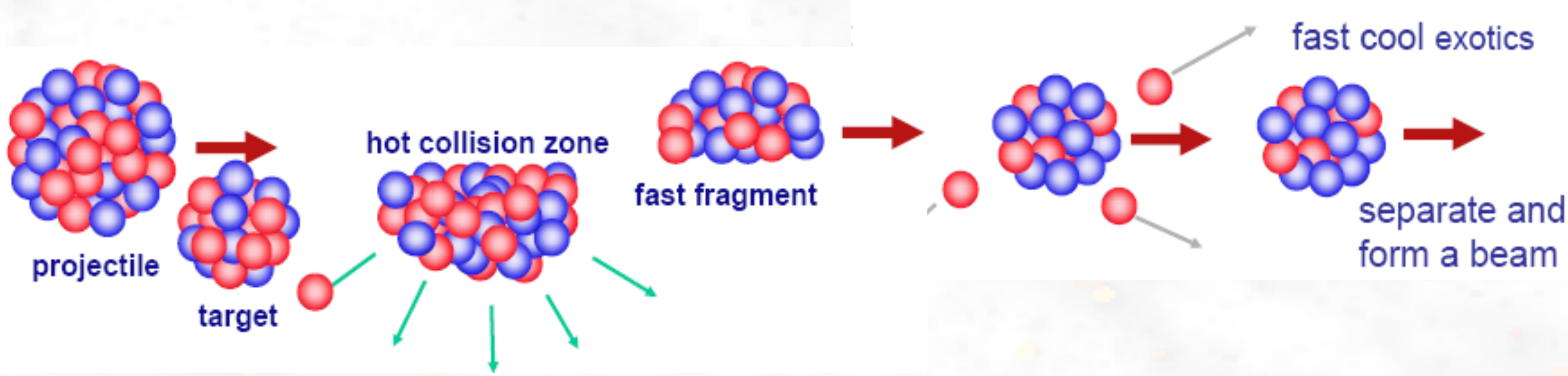


Exotic nuclei production



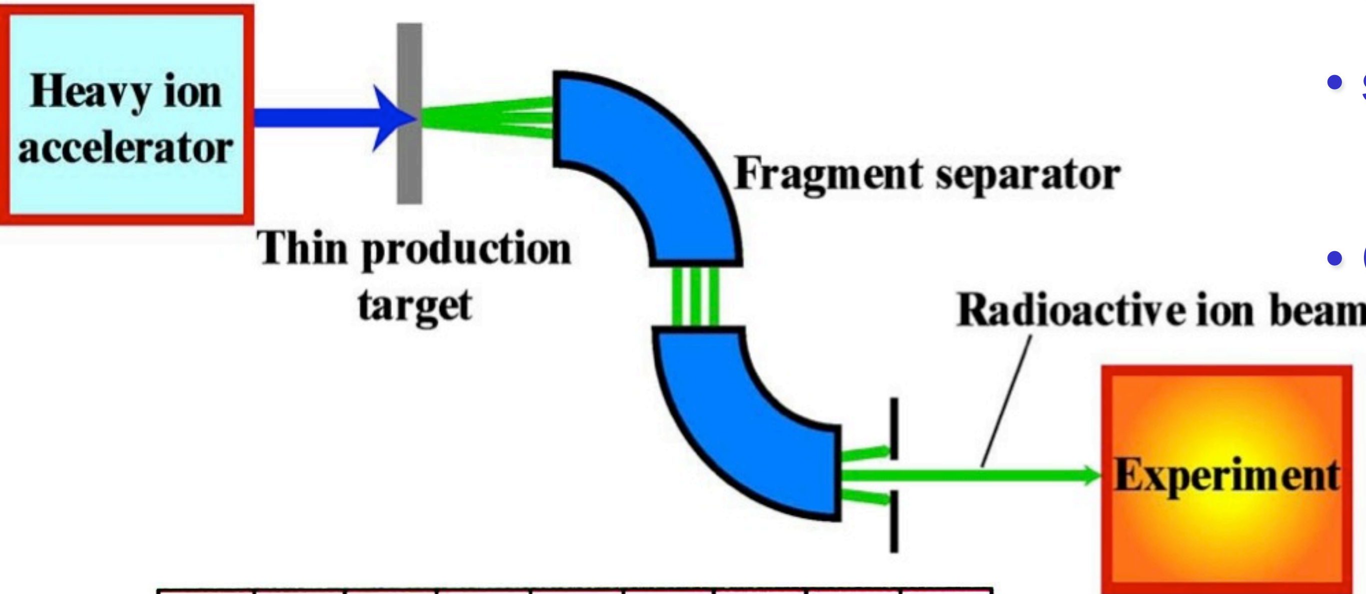
Target fragmentation: ISOL-facilities

- quality beams
- limited species, slow extraction

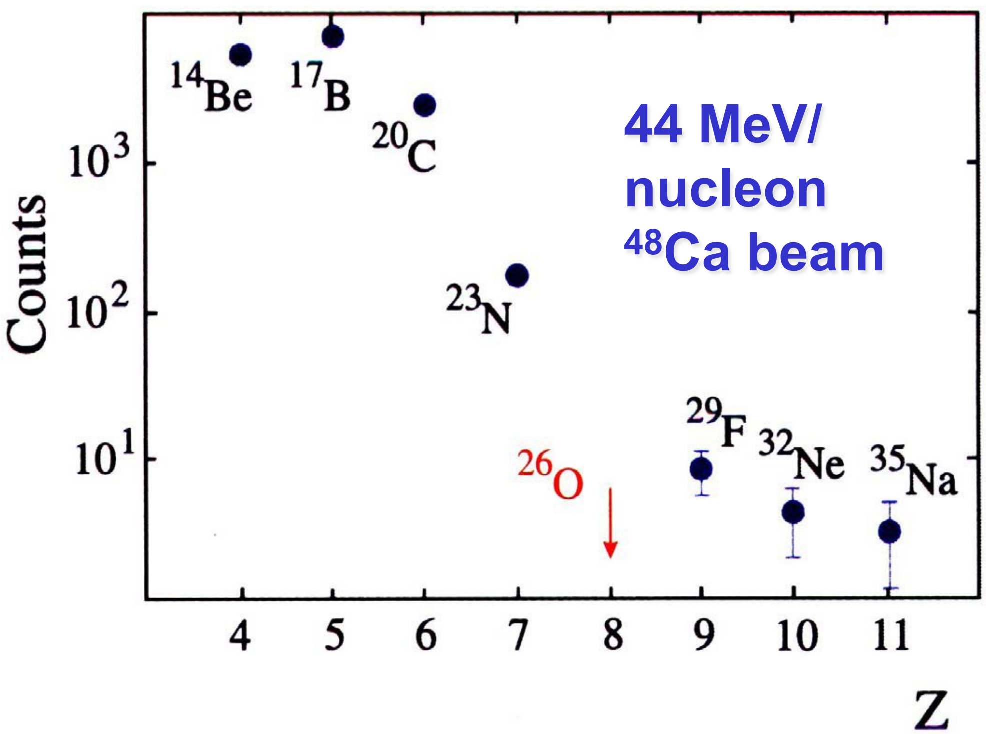


Projectile fragmentation (~ 100 MeV/nucleon)

Production of radioactive beams



- beams of modest quallity
- short-lived isotopes with $T_{1/2} > 10^{-6}$ s
- GANIL, GSI, MSU, RIKEN



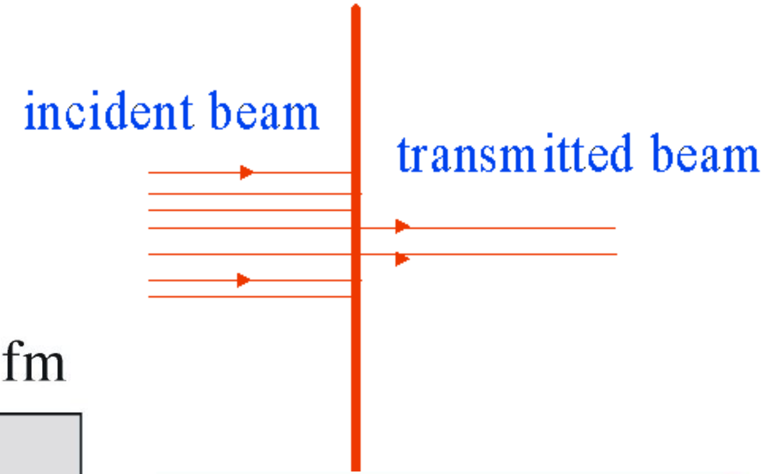
D. Guillemaud-Mueller et al. PRC 41 (1990), 937

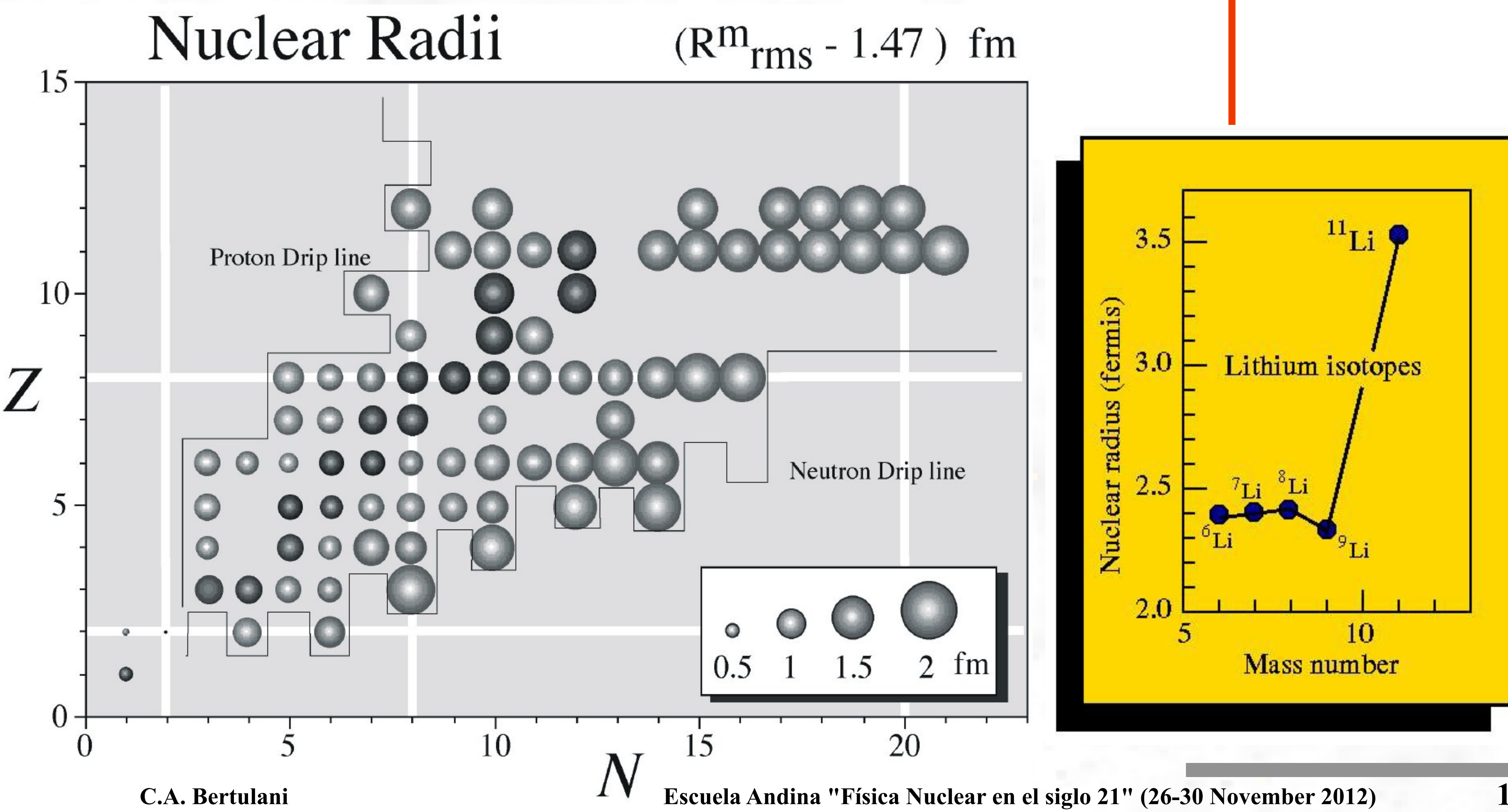
How the program of radioactive beams began

First experiments: (a) nuclear radii, (b) momentum distributions

Isao Tanihata, PRL, PLB 1985

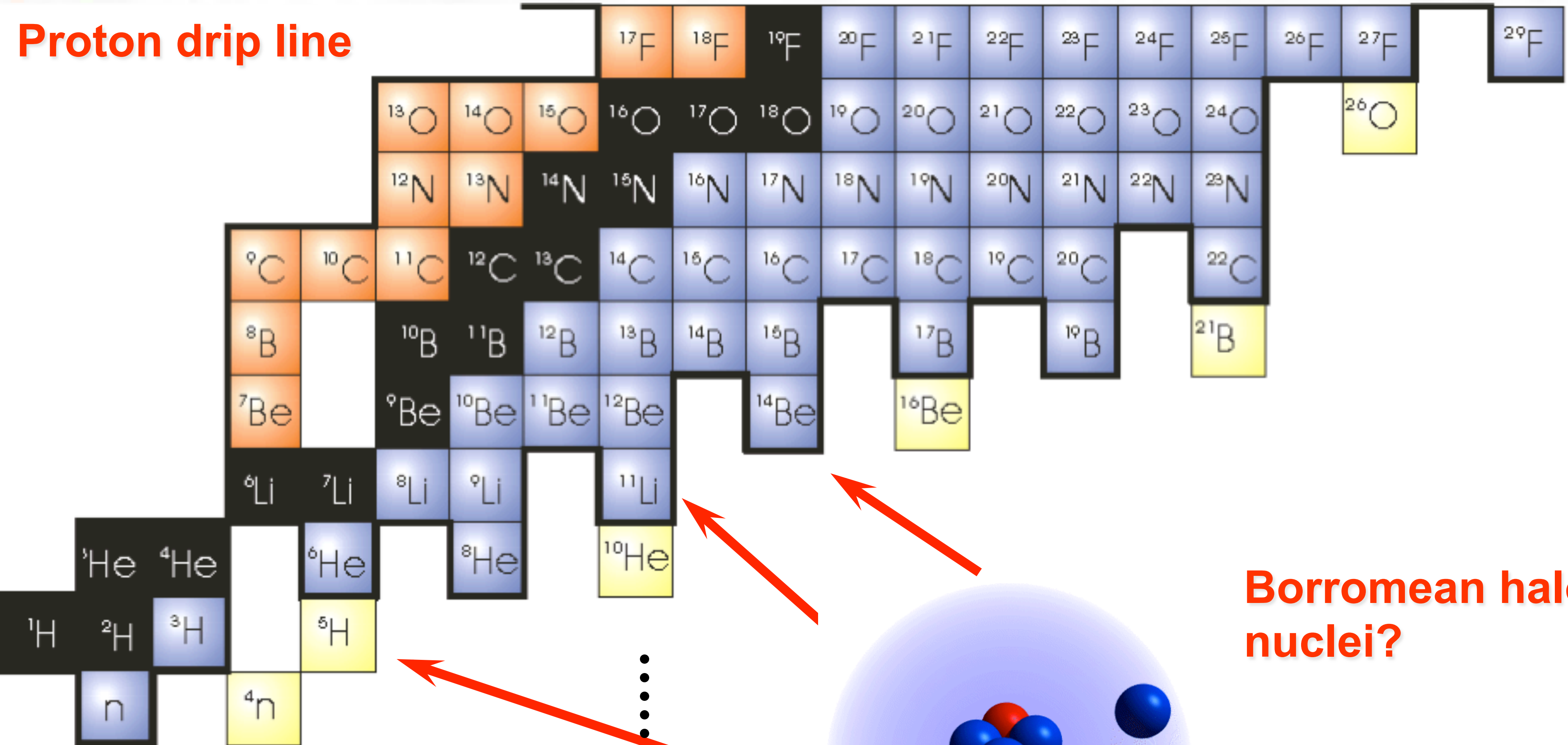
$$\sigma_I = \pi R_I^2$$

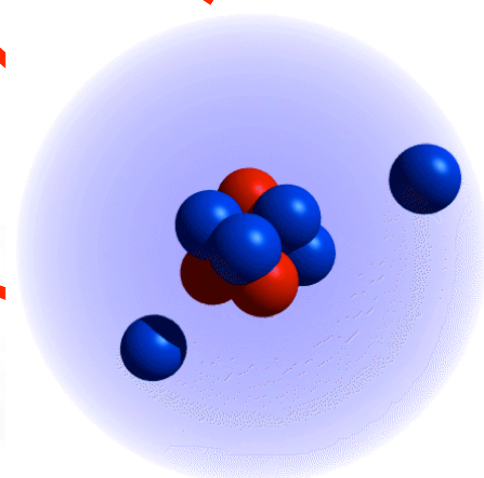




Neutron dripline in light nuclei

Proton drip line



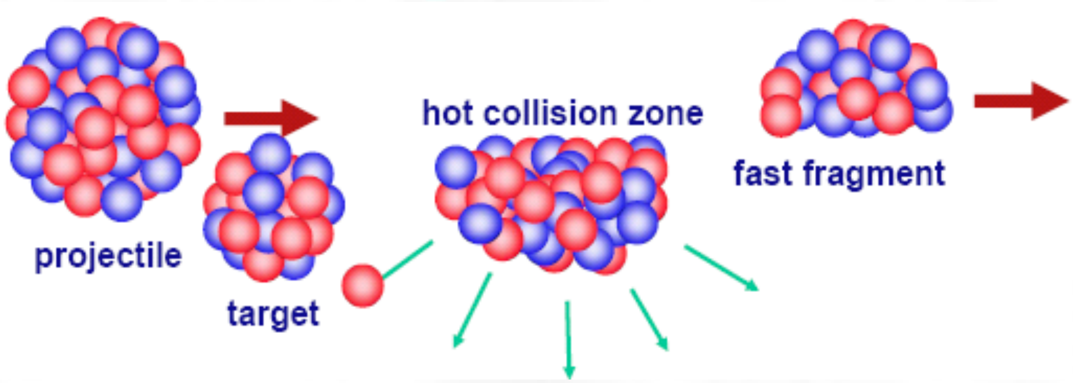


Borromean halo nuclei?

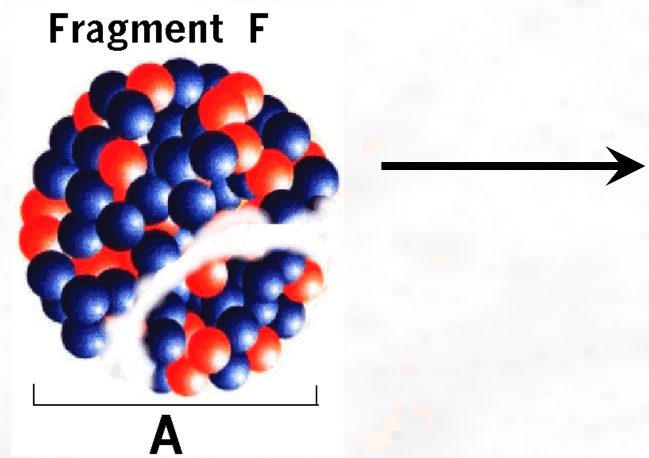
N=8

Tetra-neutron?

Momentum distributions of fragments



Goldhaber model, PLB 53, 306 (1974)



$$\sigma^2 = \left\langle \left[\sum_{i=1}^{F} p_i \right]^2 \right\rangle = A_F \langle \mathbf{p}_i^2 \rangle + A_F (A_F - 1) \langle \mathbf{p}_i \cdot \mathbf{p}_j \rangle = 0$$

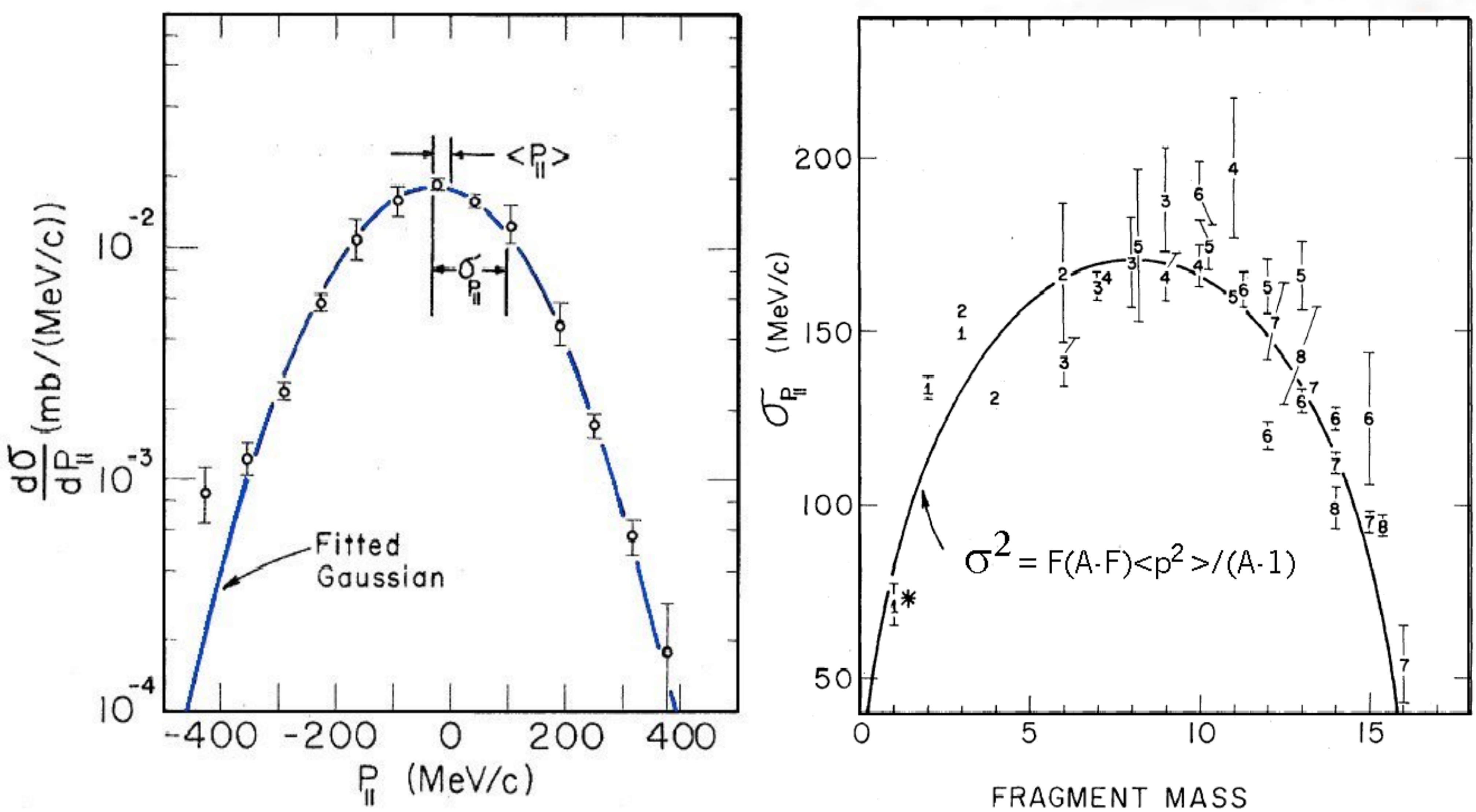
$$\left[\sum_{i=1}^{F} p_i \right]^2 = A \langle \mathbf{p}_i^2 \rangle + A(A-1) \langle \mathbf{p}_i \cdot \mathbf{p}_j \rangle = 0$$

nucleon fermi momentum

$$\sigma^2 = \frac{A_F (A - A_F)}{A - 1} \langle p_i^2 \rangle$$

$$\langle p_i^2 \rangle = \frac{3 p_F^2}{5}$$

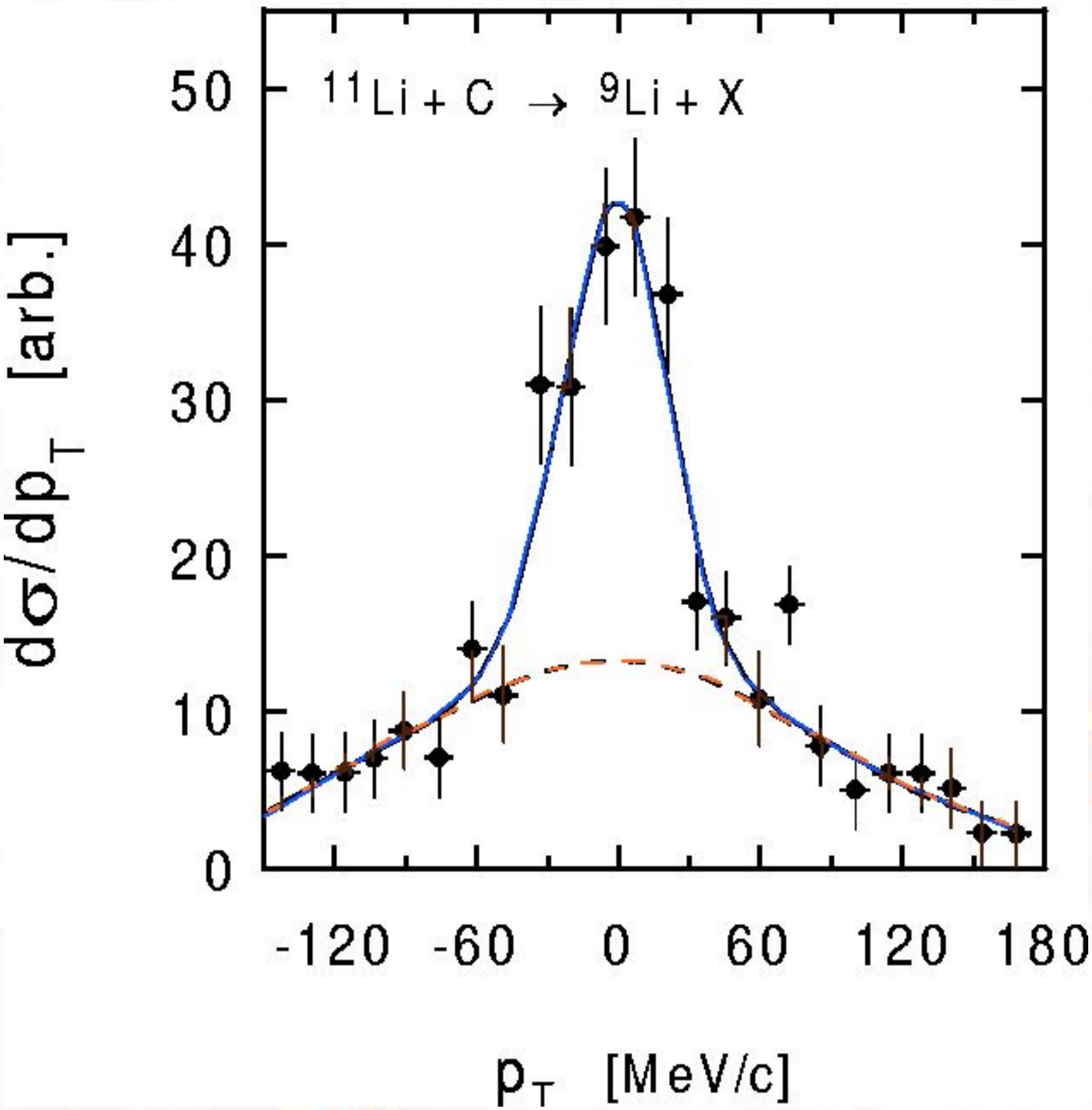
Momentum distributions of fragments (stable projectiles)



Well described by Goldhaber formula,
Goldhaber, PLB 53, 306 (1974)

$$\sigma^2 = \frac{A_F(A-A_F)}{A-1}\langle p_N^2 \rangle$$

Momentum distributions (unstable projectiles)

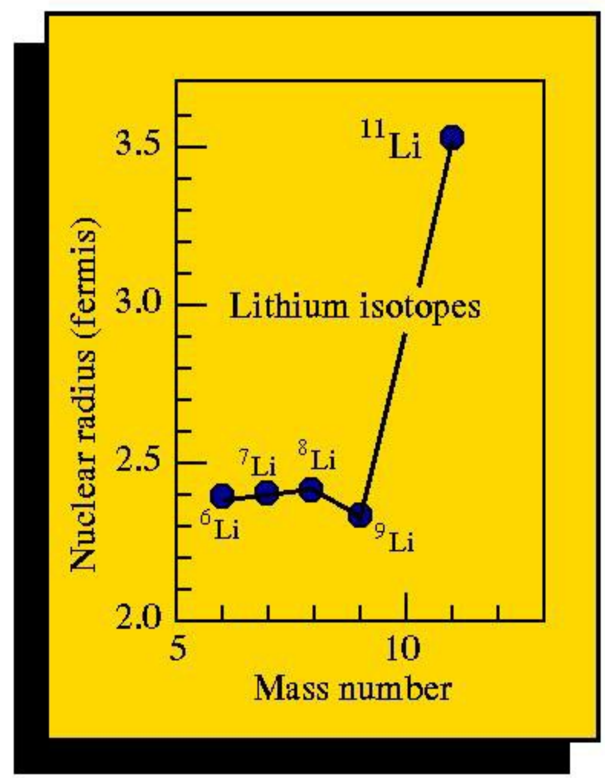


$$\sigma^2 = \frac{A_F(A-A_F)}{A-1}\left\langle p_N^2 \right\rangle$$

Small σ^2

➡ Small $\left\langle p_N^2 \right\rangle$

Large R



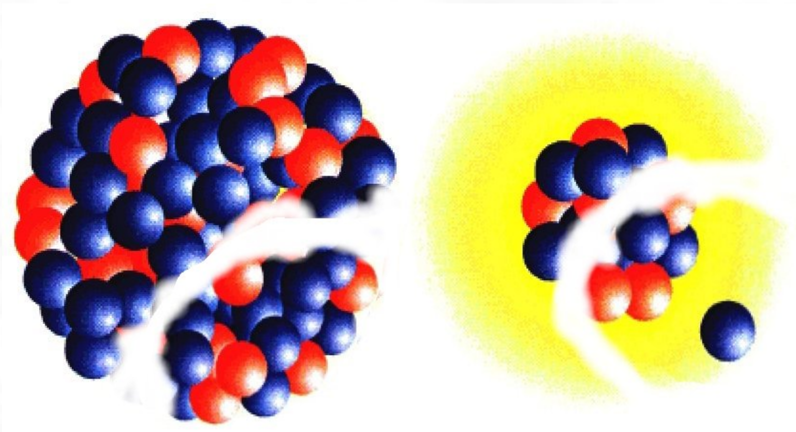
Tanihata,
Bevalac, Berkeley, 1985

Momentum distributions (unstable projectiles)

Size due to binding, not Fermi motion Goldhaber model with two fluids

Valence nucleons + core nucleons
Bertulani, K. McVoy, PRC 48, 2534 (1993)

Two fluids: valence (1) + core (2) + interaction or binding (K)



$$\sigma^2 = \frac{A_F(A-A_F)}{A-1}\left[\frac{A_1}{A}\langle p^2\rangle_1 + \frac{A_2}{A}\langle p^2\rangle_2 + \frac{\langle K^2\rangle}{A_1 A_2}\right]$$

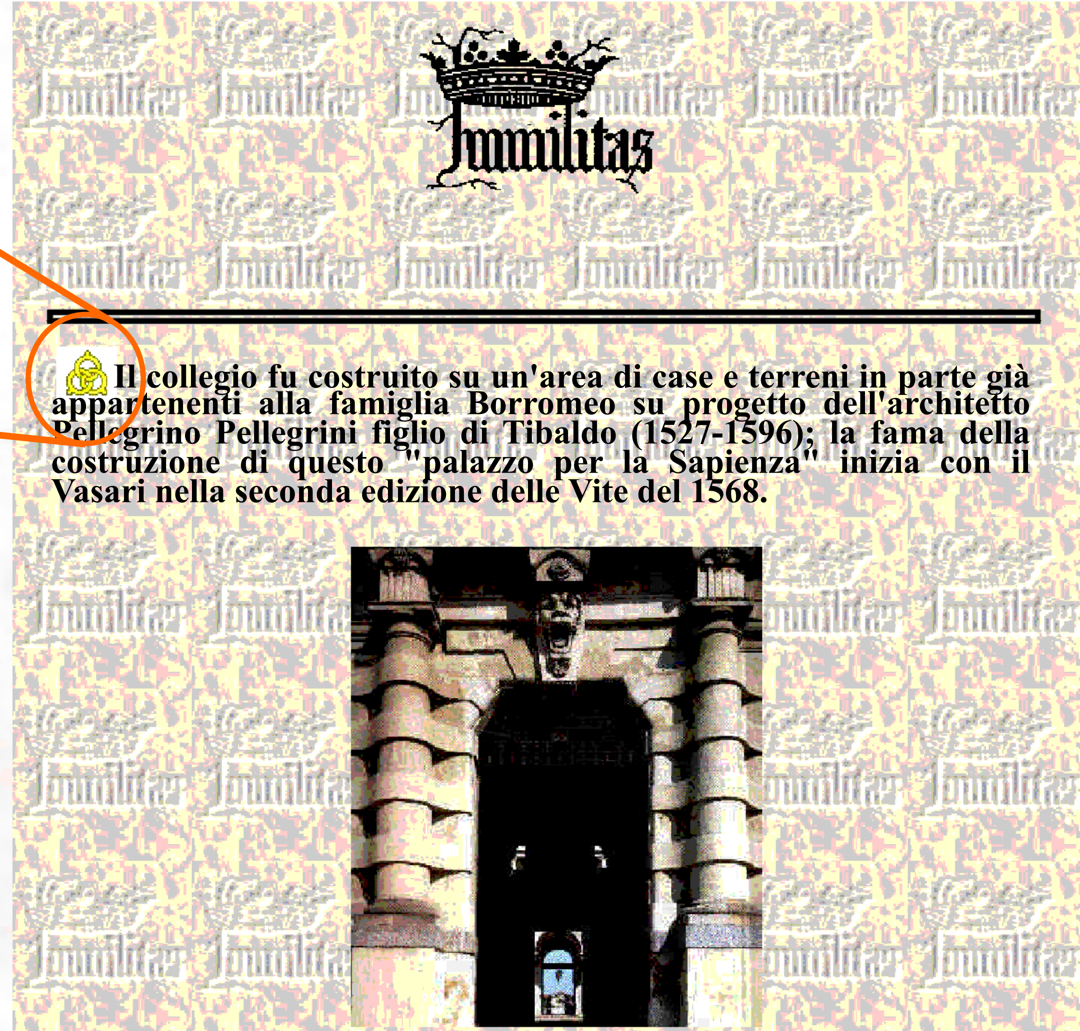
→ large size due to loose binding

Coulomb breakup of ^{11}Li has huge cross sections (1 - 5 barns!):

Baur, Bertulani and Rebel, Nucl. Phys. A458 (1986) 188
Bertulani and Baur, NPA 480 (1988) 615
Hansen and Jonson, Europhys. Lett. 4, 409 (1987) ← "halo" nuclei" nomenclature

3-body calculations → "Borromean nuclei"

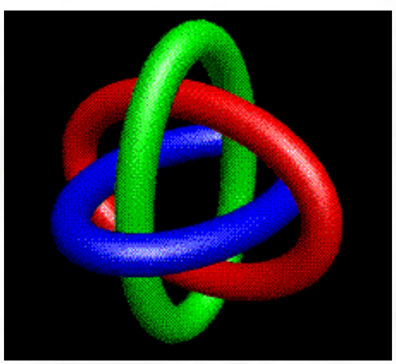
Origin of Borromean rings

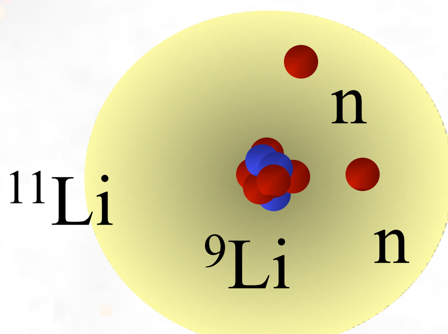

Immilitas

Il collegio fu costruito su un'area di case e terreni in parte già appartenenti alla famiglia Borromeo su progetto dell'architetto Pellegrino Pellegrini figlio di Tibaldo (1527-1596); la fama della costruzione di questo "palazzo per la Sapienza" inizia con il Vasari nella seconda edizione delle Vite del 1568.

Borromean nuclei are a laboratory for 3-body physics. Ex: Efimov effect

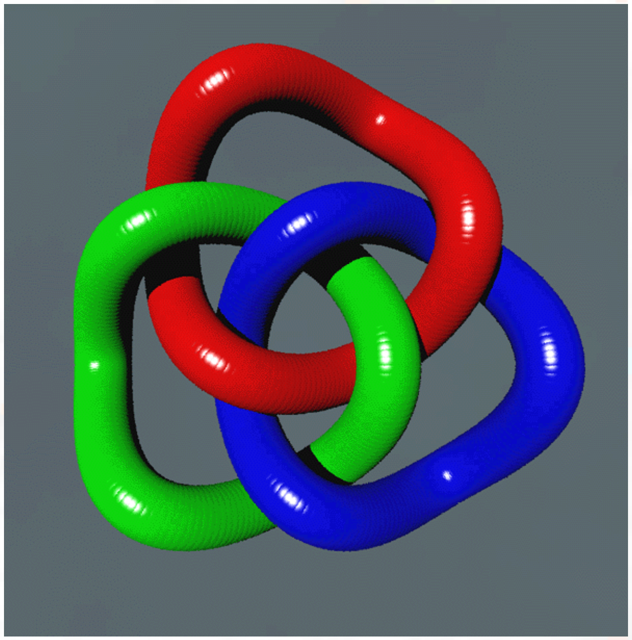
Theoretical description:
- Fadeev equations
- Hyperspherical harmonics
- etc.

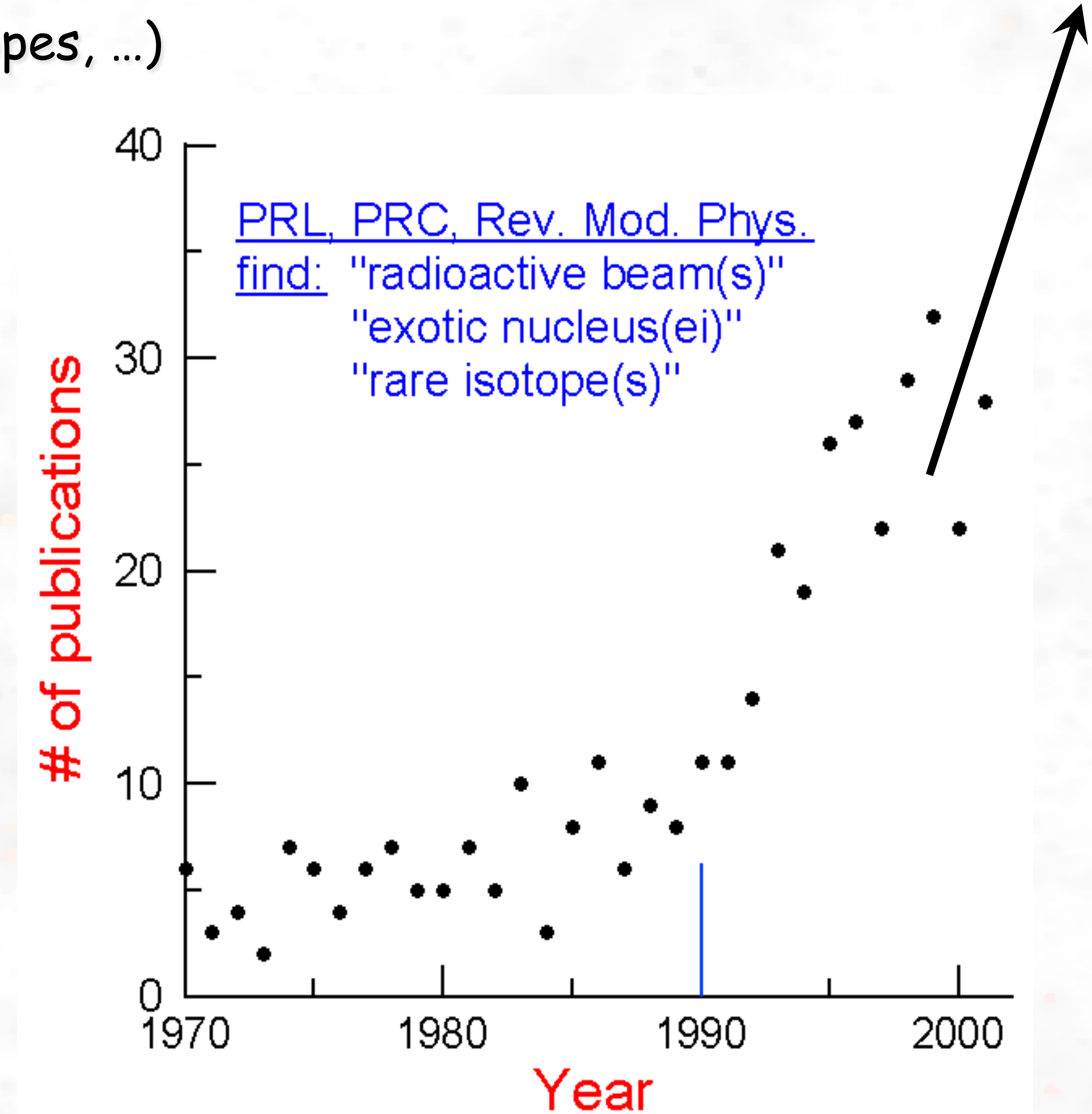




Charismatic names → explosion of publications

(Halo, exotic, borromean, rare isotopes, …)





In the 80's and 90's ^{11}Li became the center of attention

Astrophysics program of rare nuclear isotopes

Future: electron-ion scattering
skins, halos, soft multipole vibrations

Present:

(A) Trojan horse

(B) Asymptotic normalization coefficients

(C) Coulomb dissociation

(D) Charge Exchange $e^- + (Z,A) \rightarrow (Z-1, A) + \nu_e$

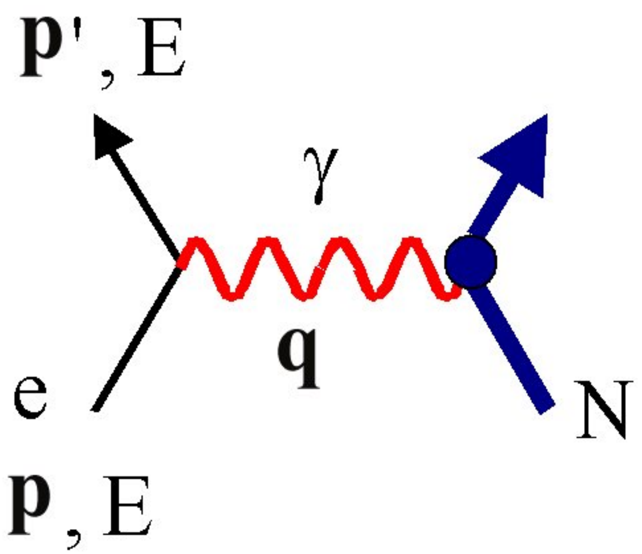
$\left|\langle B \| \sigma\tau \| A \rangle\right|^2$

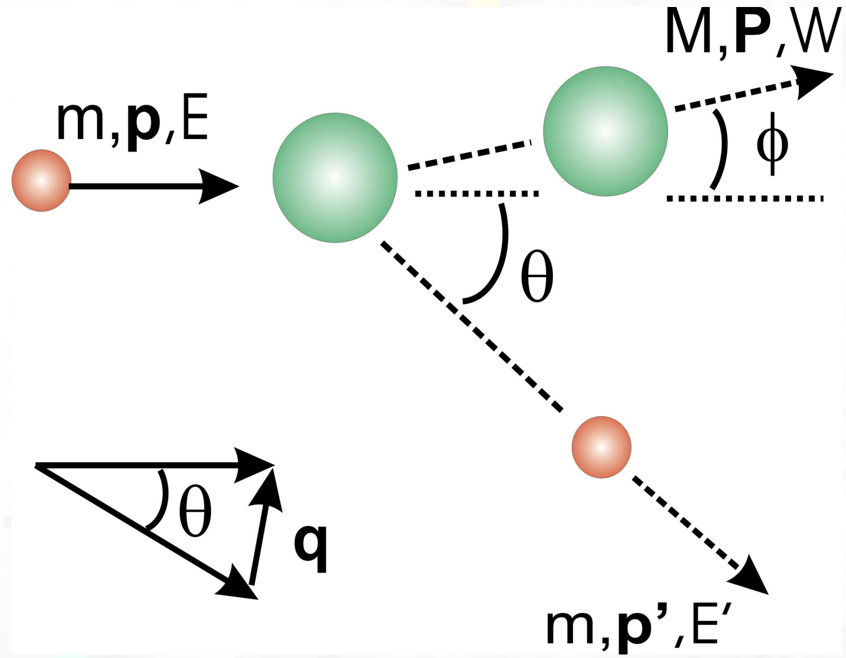
(p,n) (n,p) (d,^{2}He) (Z, Z±1)

(E) Knockout reactions $\left|\Psi(p)\right|^2; \quad C^2 S$

The future: electron scattering

Kinematics of electron scattering





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

electron final momentum

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

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

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

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

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

spin up

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

spin down

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

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

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

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

Mott cross section

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

spherical nuclei

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

Nuclear physics

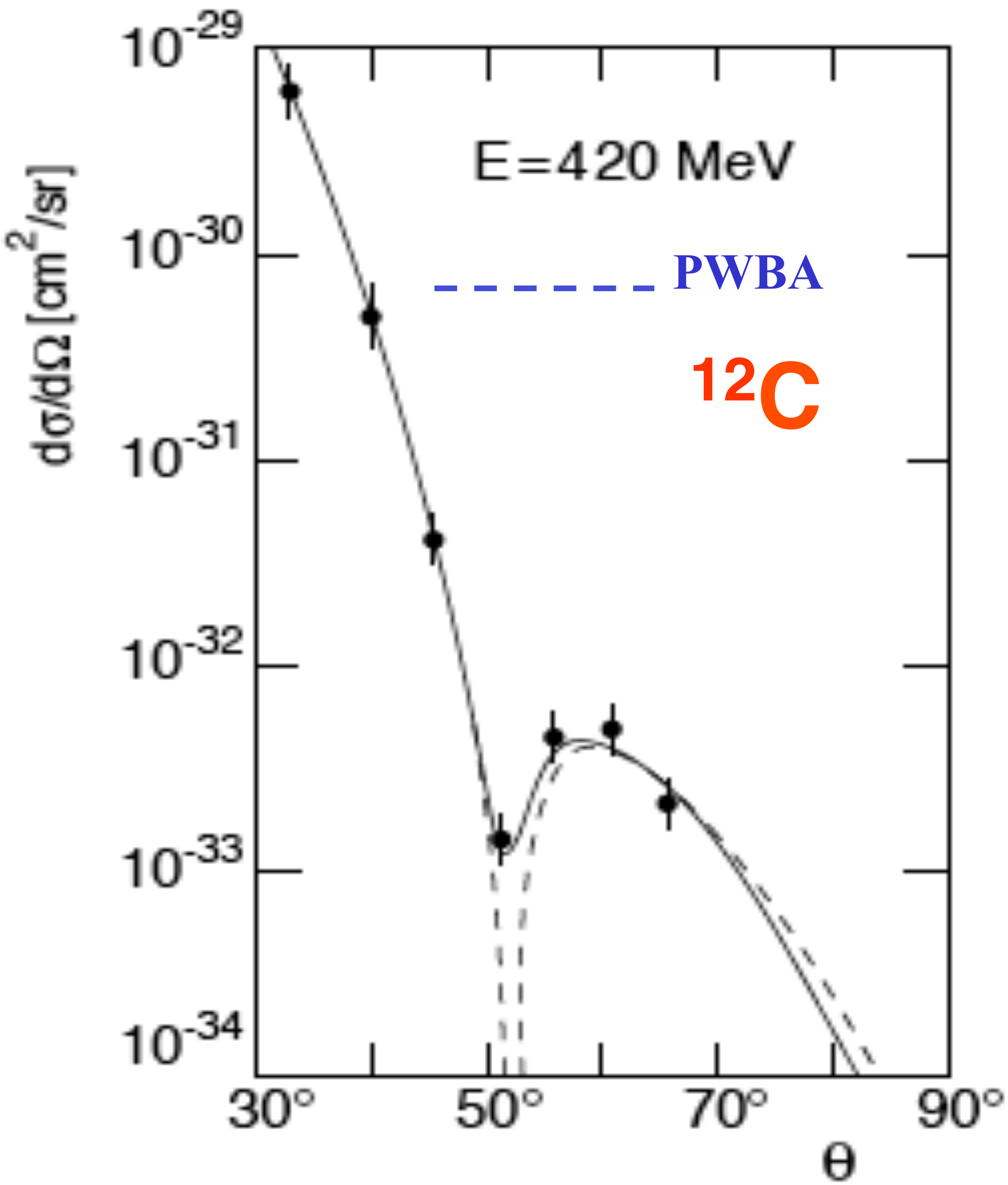
$$\rho_{ch}(r) = \int \rho_p(\mathbf{r}') f_{Ep}(\mathbf{r}-\mathbf{r}')d\mathbf{r}' + \int \rho_n(\mathbf{r}') f_{En}(\mathbf{r}-\mathbf{r}')d\mathbf{r}'$$

f_{Ep} = charge dist. in proton

f_{En} = charge dist. in neutron

< 10% effect, large q’s

DWBA corrections



Hofstadter, 1953

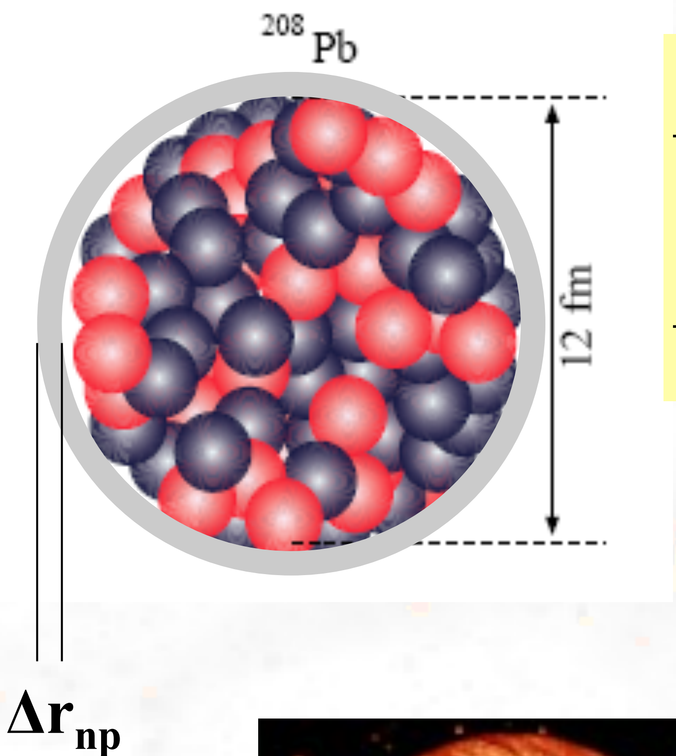
- **electron wavefunction attracted to the nucleus**
- **a measured q probes a larger q = q_{eff} in F(q)**

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

Still valid. But with

$$q_{eff} = q\left(1 - \frac{V(0)}{E}\right) = q\left(1 + 1.5\frac{Ze^2}{ER}\right), \qquad R \cong 1.2A^{1/3}\ \text{fm}$$

Neutron skins & neutron stars



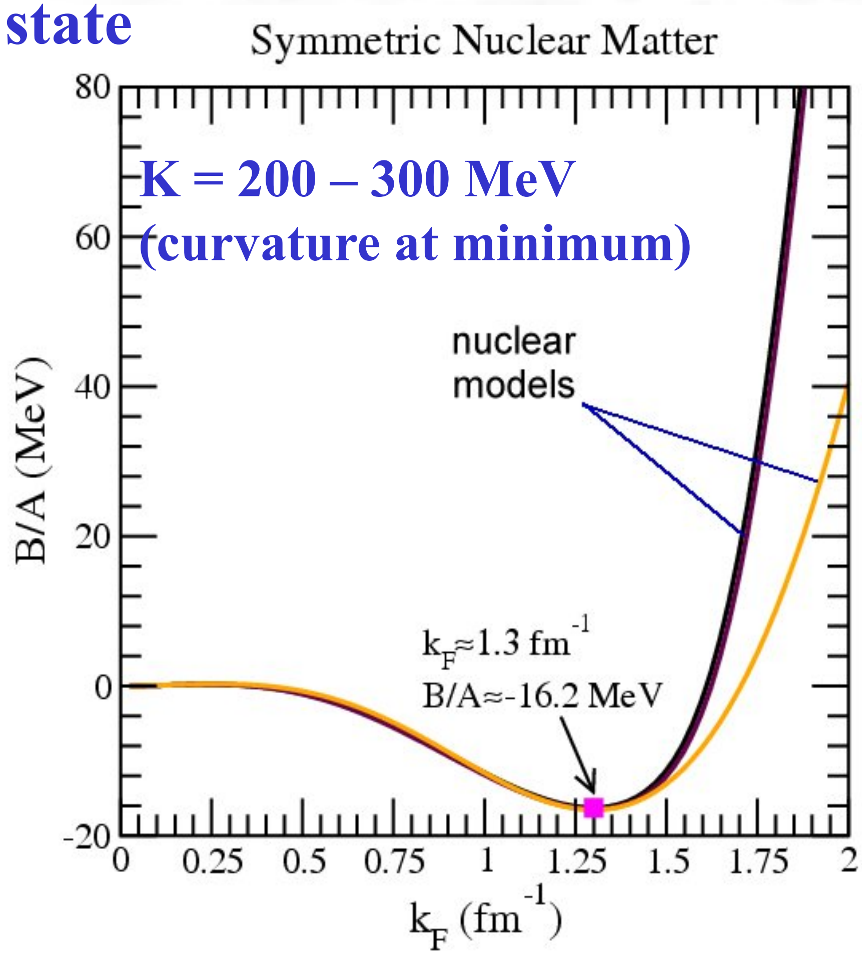
$$\frac{dP}{dr} = -\frac{G\rho(r)M(r)}{r^2}\left[1+\frac{P(r)}{\rho(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

$$\frac{dM}{dr} = 4\pi r^2 \rho(r)$$

Tolman-Oppenheimer-Volkoff

- **need equation of state**

P x ρ



Symmetry energy

$$E = a_v A + a_S A^{2/3} + a_C Z^2 / A^{1/3} + S(N-Z)^2 / A + \ldots$$

Bethe-Weizsaecker formula

$$\rho_0 \approx 0.16\ \mathrm{fm}^{-3}, \quad a_v \approx -16\ \mathrm{MeV}, \quad S \approx 30\ \mathrm{MeV}$$

infinite nuclear matter:

$$E/A = a_v + S\delta^2, \qquad \delta = (N-Z)/A \equiv b$$

$$E(\rho;b)/A = E(\rho=0;b)/A + \cancelto{0}{b\left(\frac{\partial E/A}{\partial b}\right)_{b=0}} + b^2 \frac{1}{2}\left(\frac{\partial^2 E/A}{\partial b^2}\right)_{b=0} + \cdots$$

Symmetric matter

Symmetry energy

Pure neutron matter ≈ symmetric matter + symmetry energy

Finite nuclei:

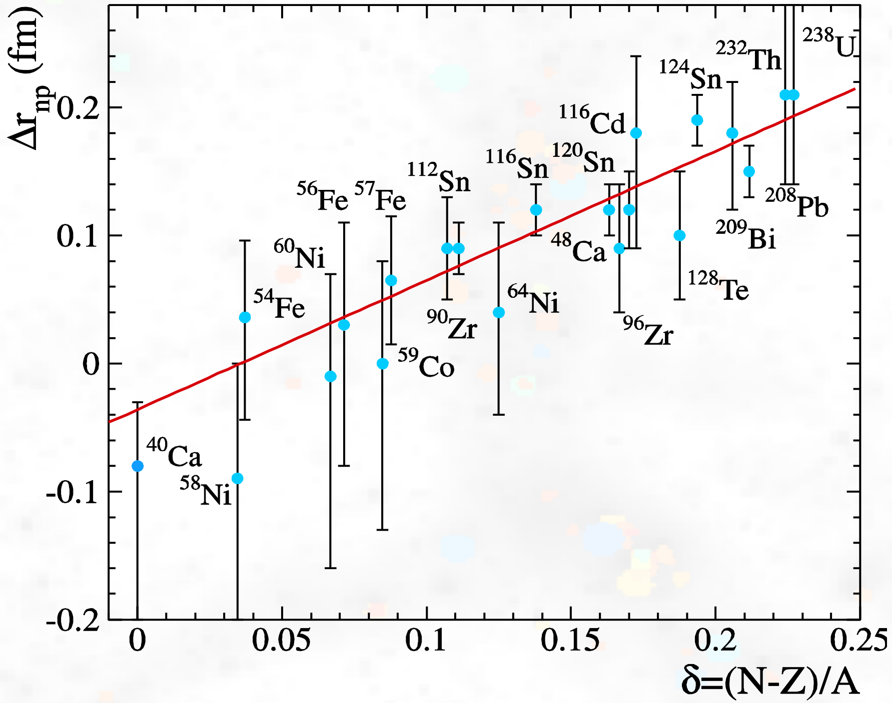
$$S \to S_V \frac{(N_V - Z_V)^2}{A} + S_S \frac{(N_S - Z_S)^2}{A^{2/3}}$$

+ minimization of E/A

neutron skin

$$\boxed{\frac{R_n - R_p}{R} = \frac{A}{6NZ} \frac{N - Z - (a_c/12S_V) Z A^{2/3}}{1 + (S_S/S_V) A^{1/3}}}$$

Neutron skins

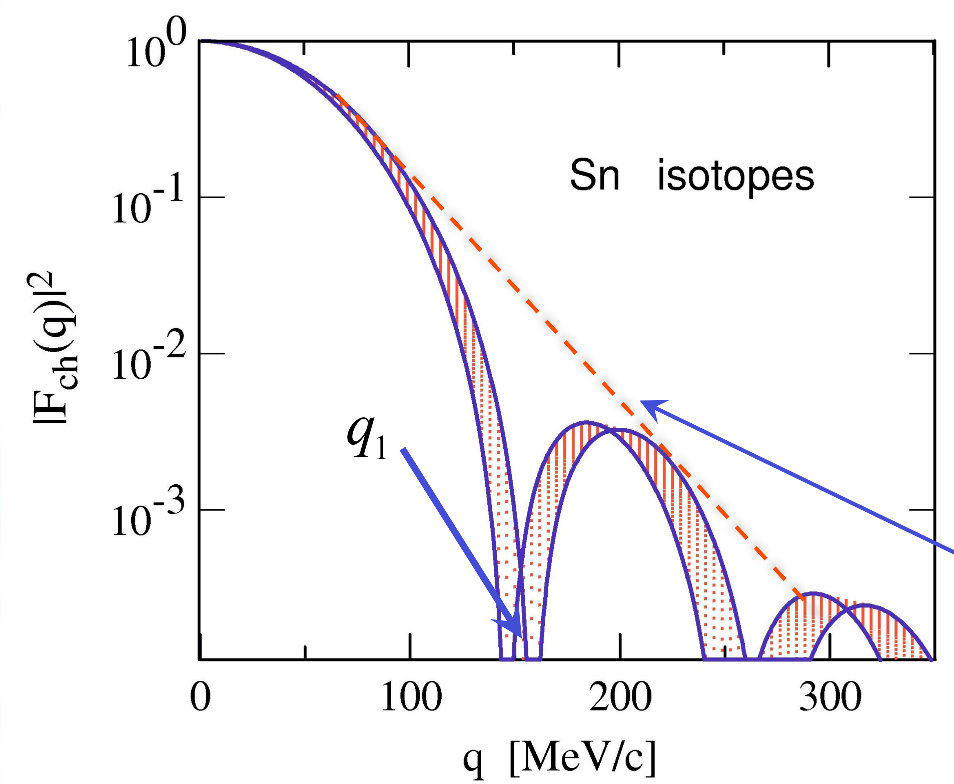


A. Trzcinska, PRL 2001

experimentally:

$$\Delta r_{np} = \left(-0.04 \pm 0.03\right) + (1.01 \pm 0.15)\delta \text{ fm}$$

$$S_V = 28 \text{ MeV}, \qquad S_S = 46.6 \text{ MeV}$$



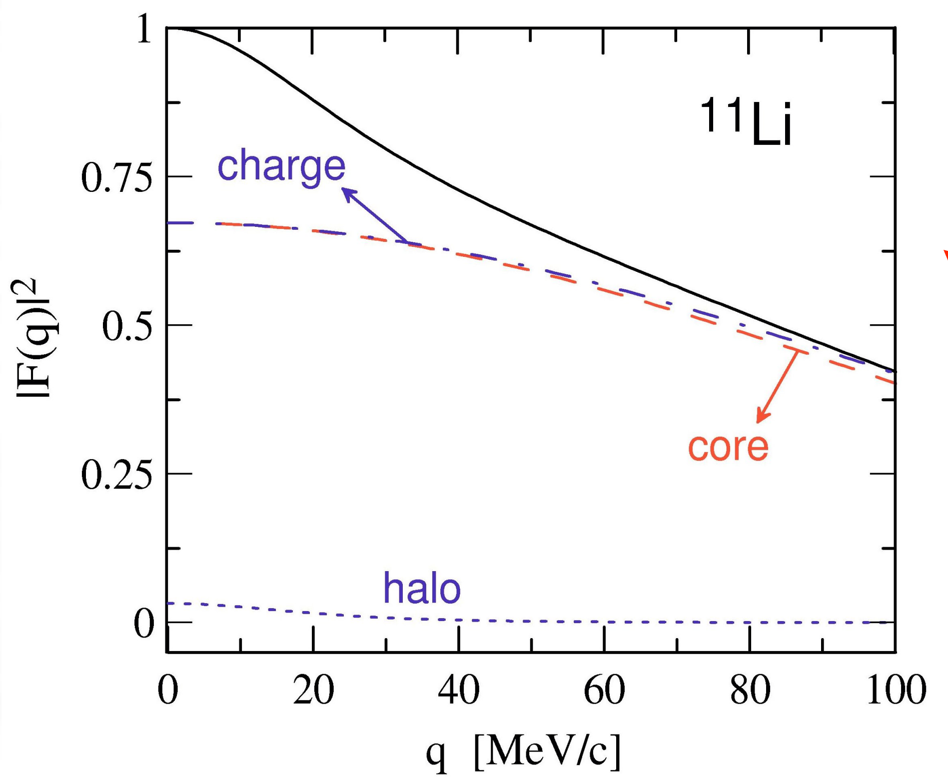
In electron-ion scattering:

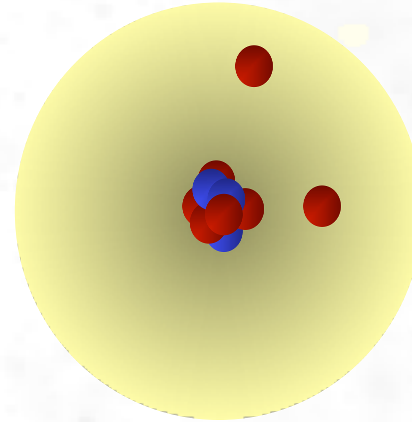
Bertulani, PLB 624, 203 (2005)

$$\boxed{q_1 \cong \frac{3.74}{A^{1/3}}\left[1 - 0.535\frac{\delta}{A^{1/3}}\right] \quad \text{fm}^{-1}}$$

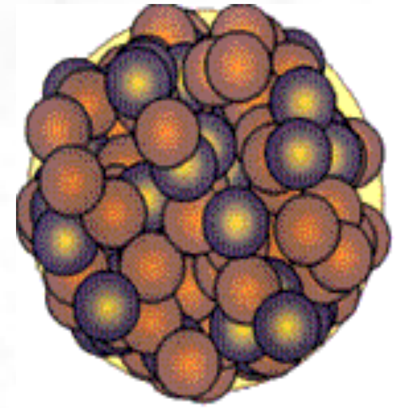
$$\exp(-q^2 a^2)$$

Neutron halos



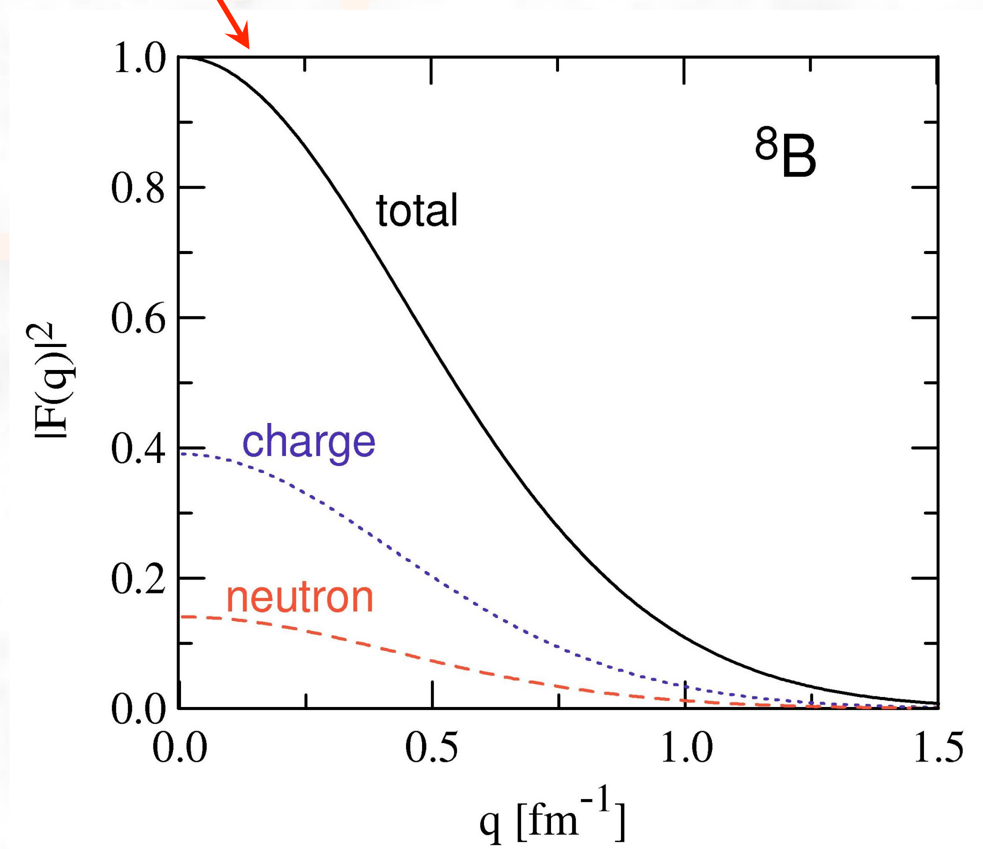


^{11}Li



^{208}Pb

Skyrme
HF + BCS



nuclear halos

Bertulani, JPG 34 (2007) 315

Magnetic interaction

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

averages over initial and sum over final spins

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

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

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

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

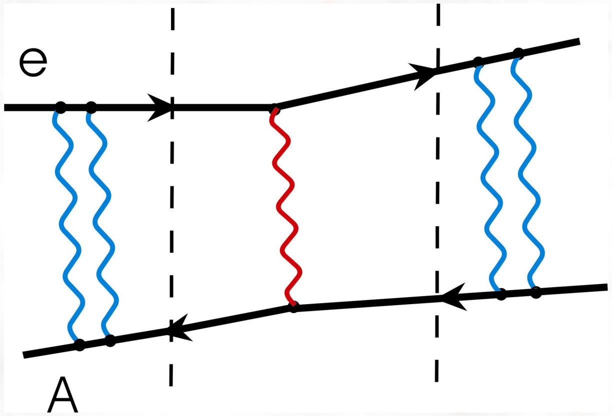
Inelastic electron scattering

$$\langle f,\mathbf{p}'|H|i,\mathbf{p}\rangle = \frac{4\pi e^2}{q^2}\left\langle f\left|\sum_1^Z e^{i\mathbf{q}\cdot\mathbf{r}_k}\left[\left(u_f^* u_i\right)\left(U_f^* U_i\right)-\left(u_f^*\boldsymbol{\alpha}_e u_i\right)\left(U_f^*\boldsymbol{\alpha}_N U_i\right)\right]\right|i\right\rangle$$

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

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

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



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

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

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

Electron-ion collider mode

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

Siegert's theorem

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

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

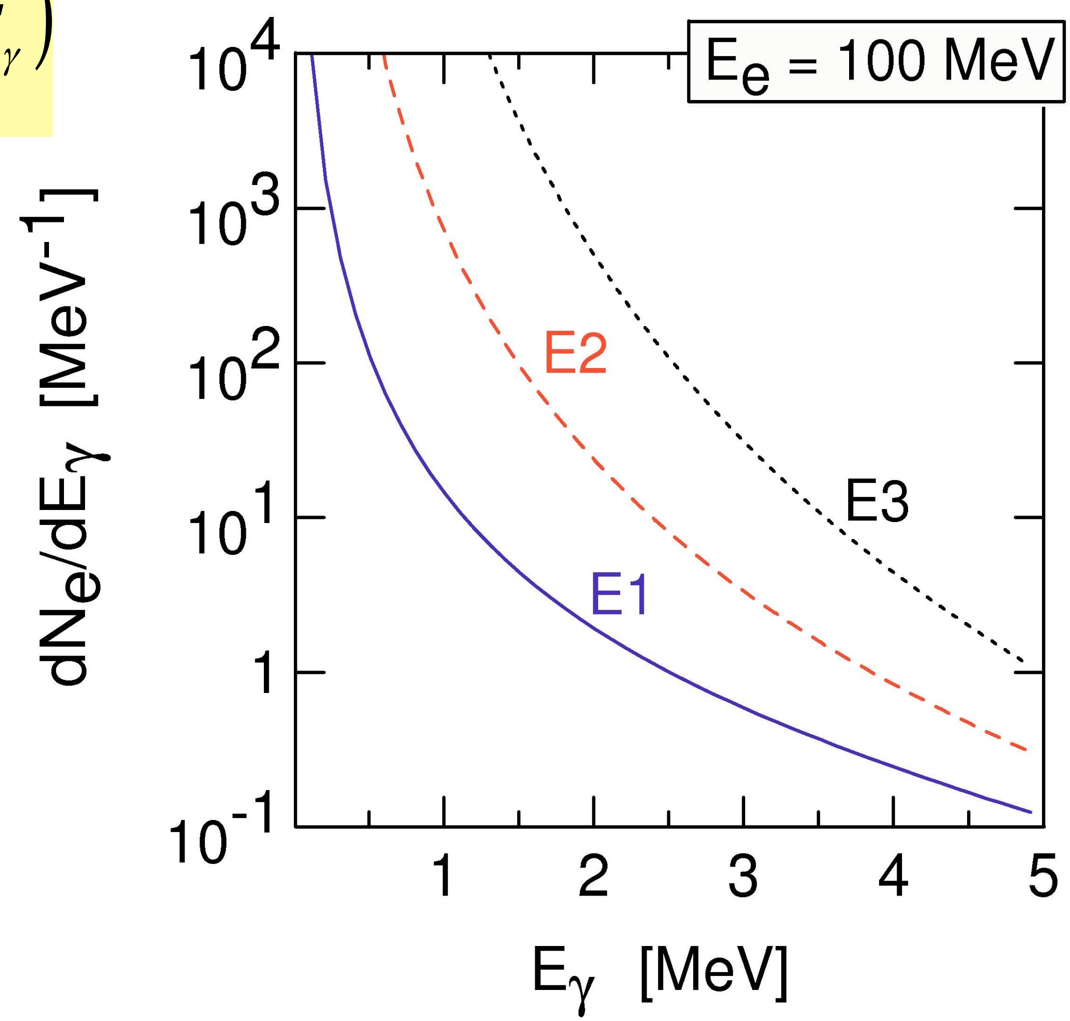
virtual photon spectrum

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

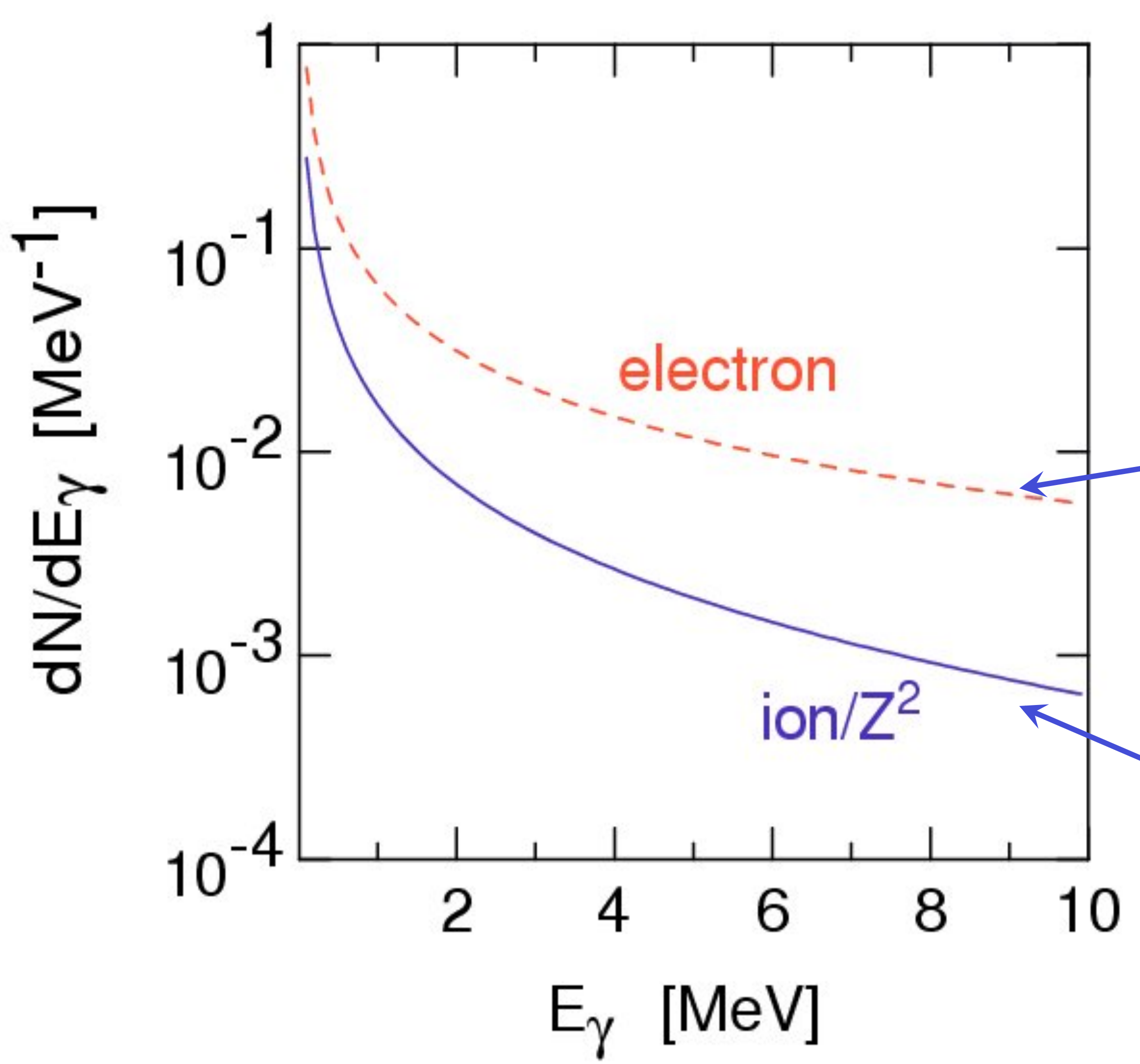
response function

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

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



Electron-ion collider mode



comparison with Coulomb excitation

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

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

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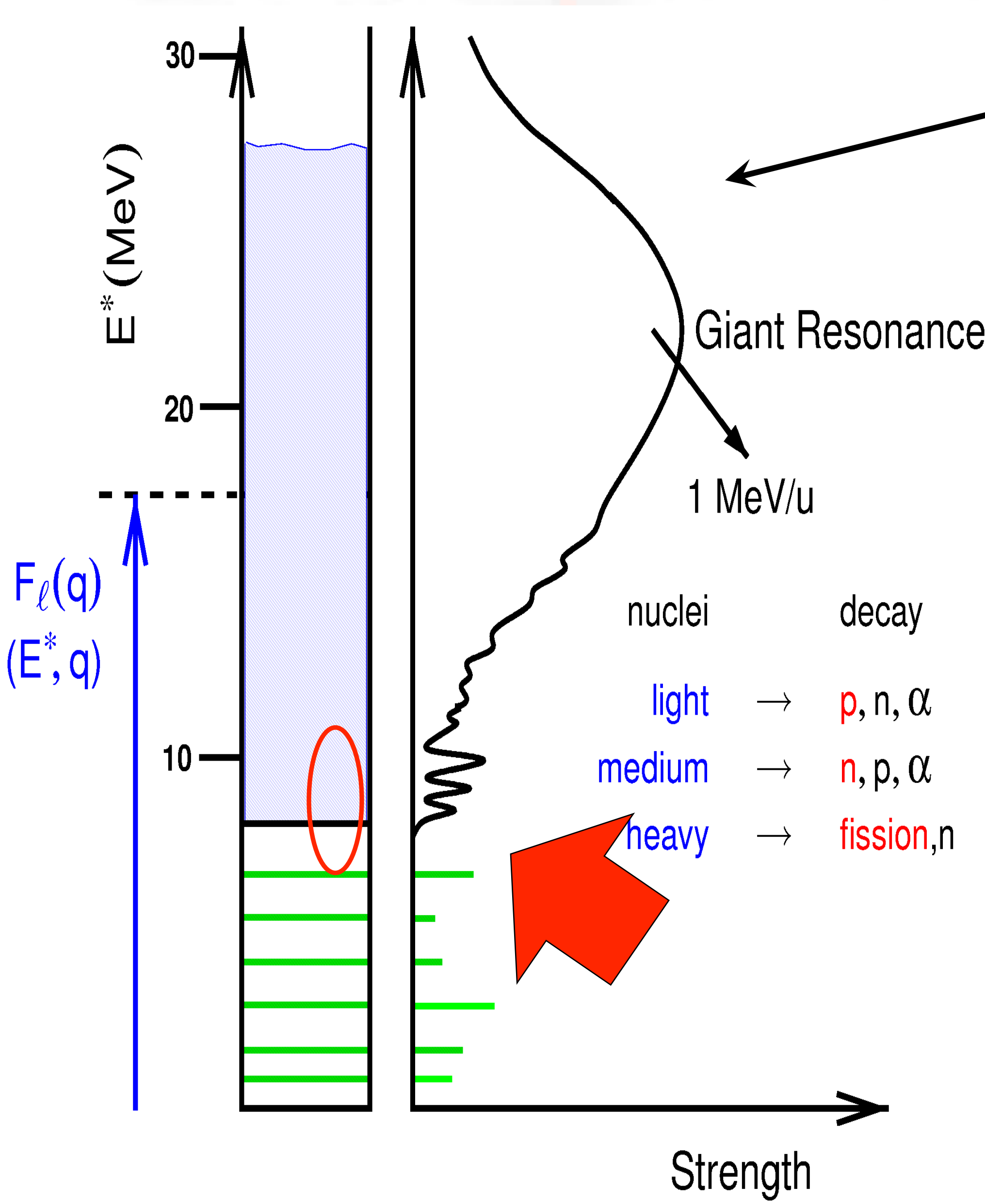
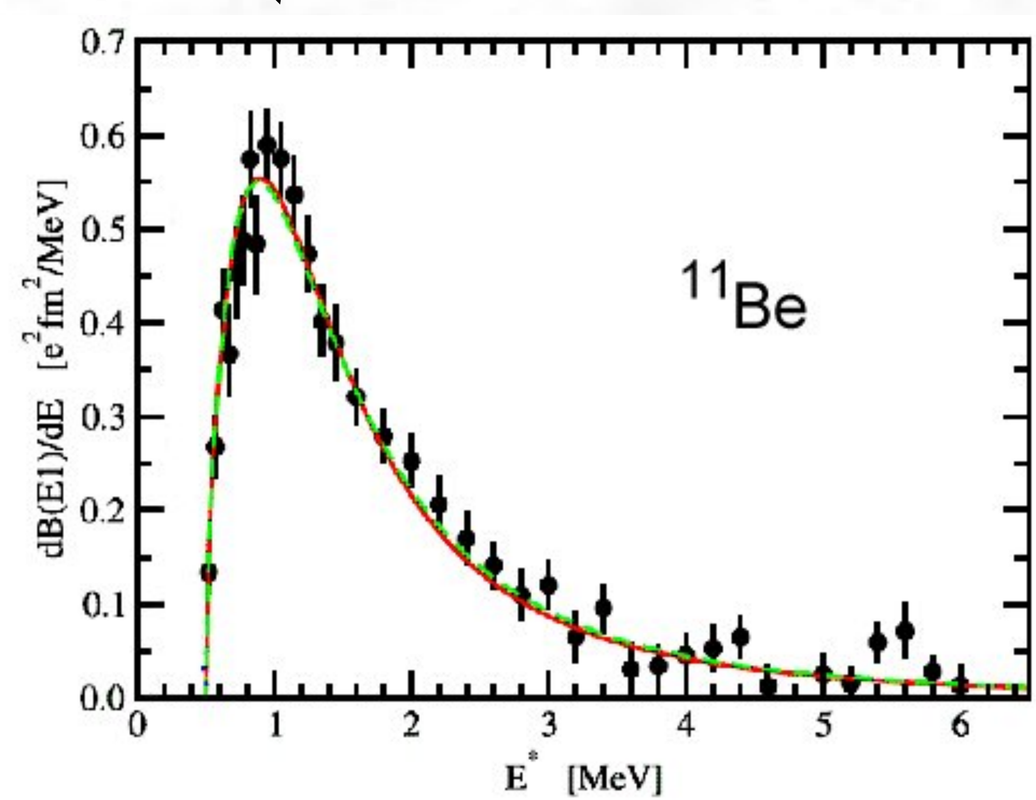
Electron-ion scattering: Response in exotic nuclei

Ex: EM reponse in exotic nuclei

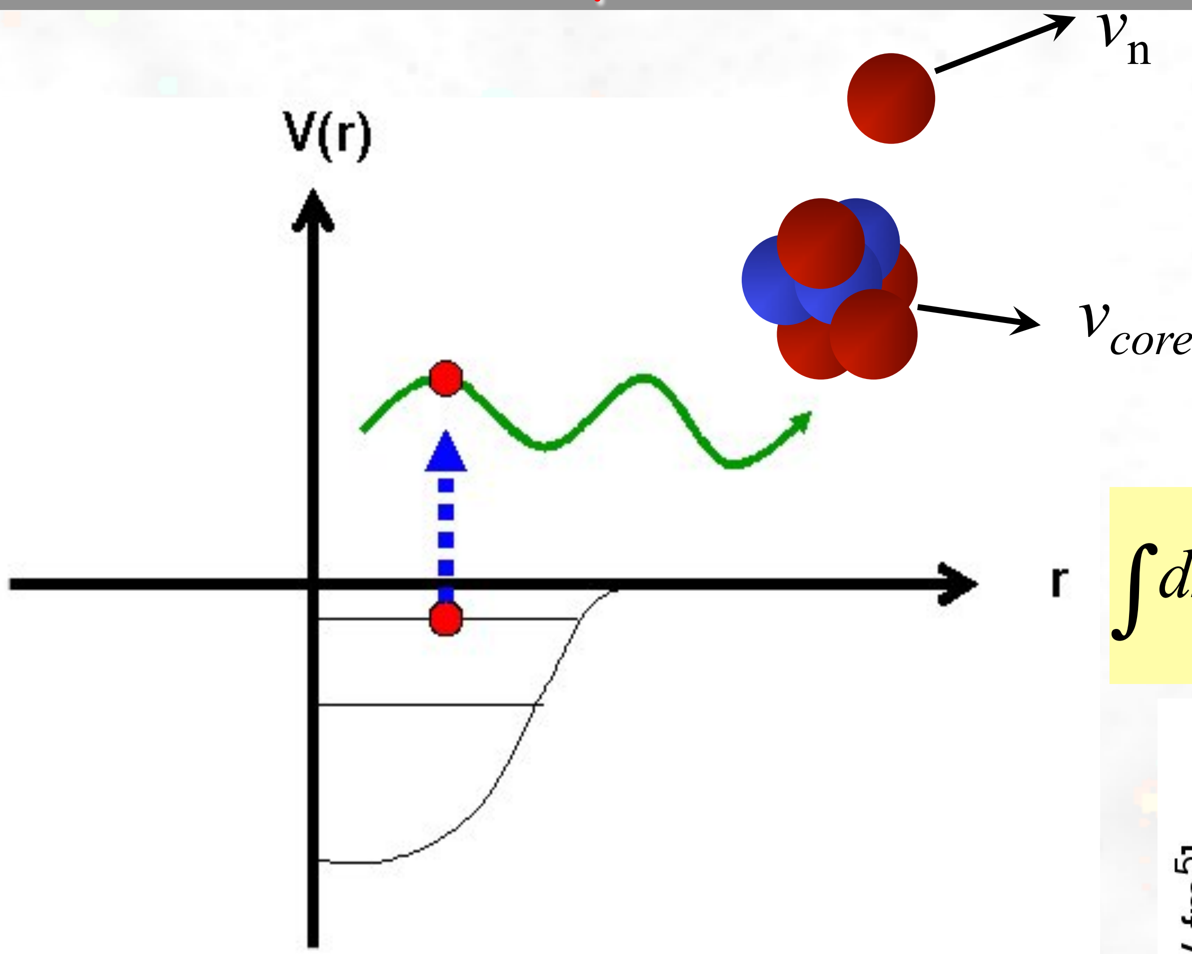
Collective response or

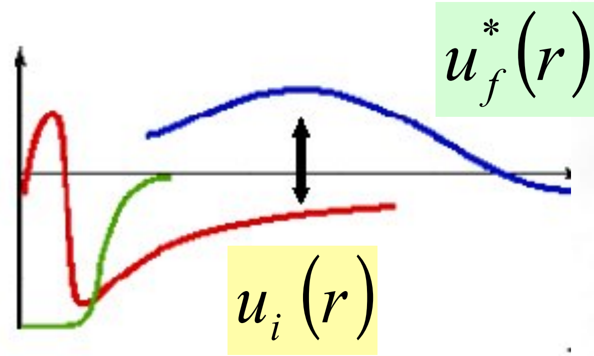
Direct breakup?





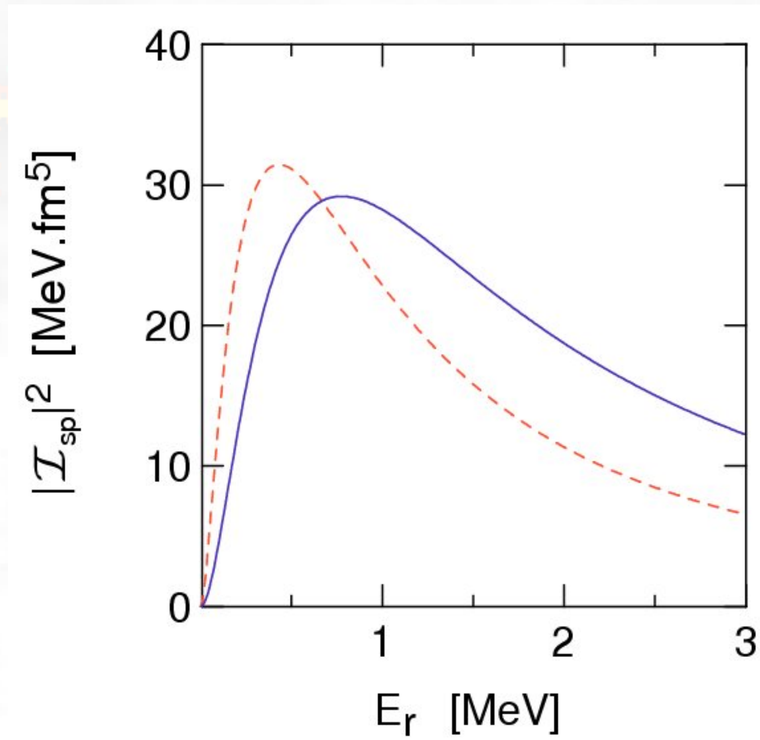
Direct breakup





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

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

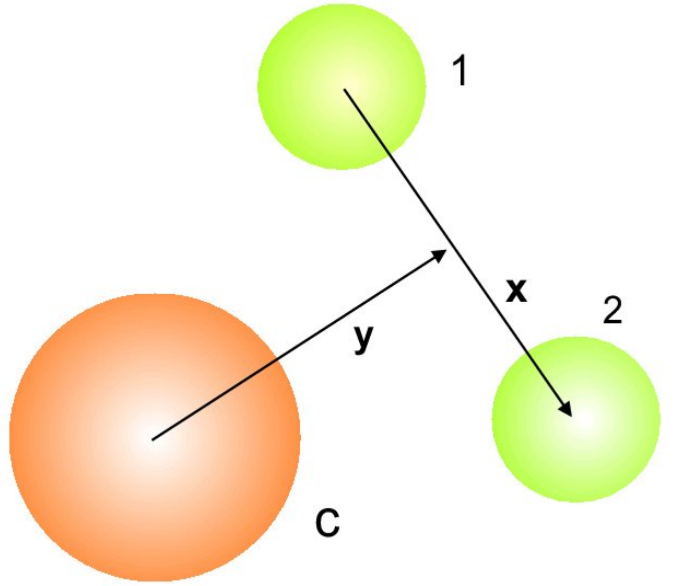


$$\frac{dB(E\lambda)}{dE_r} \propto \frac{E_r^{\lambda+1/2}}{(S_n+E_r)^{2\lambda+2}}(1+FSI)^2$$

Bertulani, Sustich, PRC 46 (1992) 2340

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

Direct breakup in the 3-body model



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

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

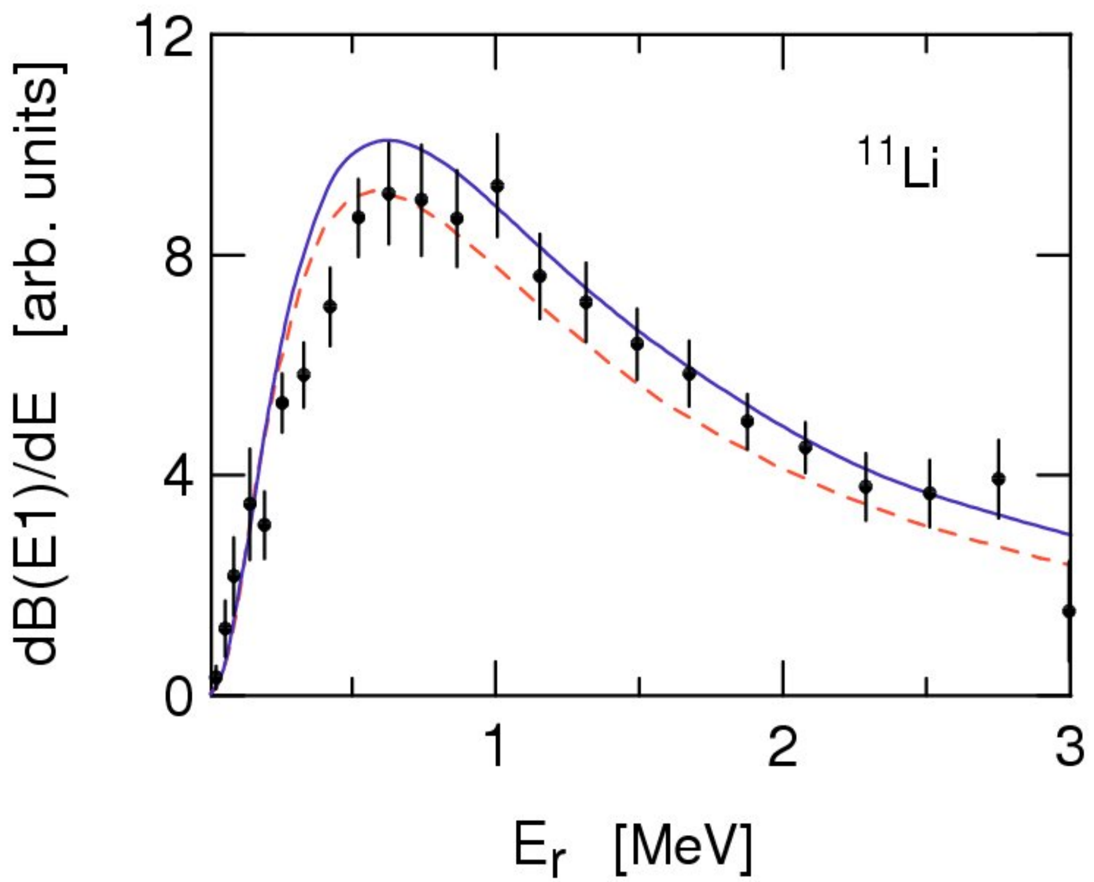
$$y = \rho \sin\theta, \qquad x = \rho \cos\theta$$

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

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

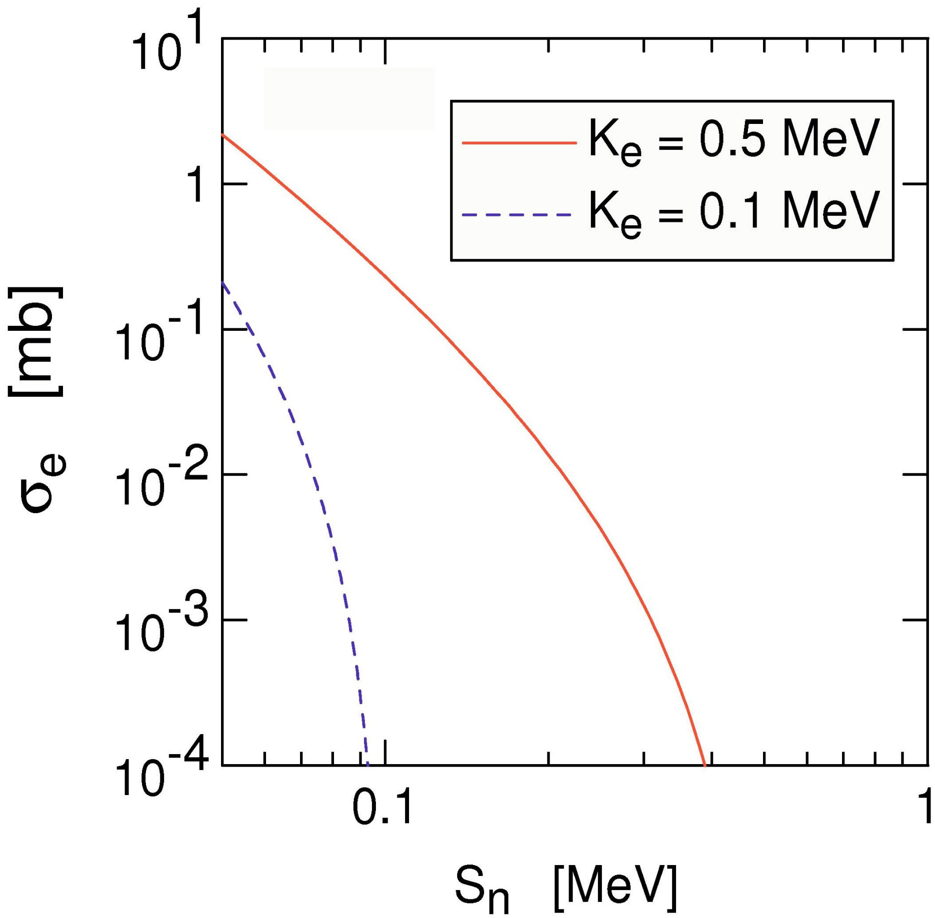
$$\frac{dB(E1)}{dE_r} \propto \frac{E_r^3}{\left(S^{eff}_{2n} + E_r\right)^{11/2}}(1 + FSI)^2$$

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



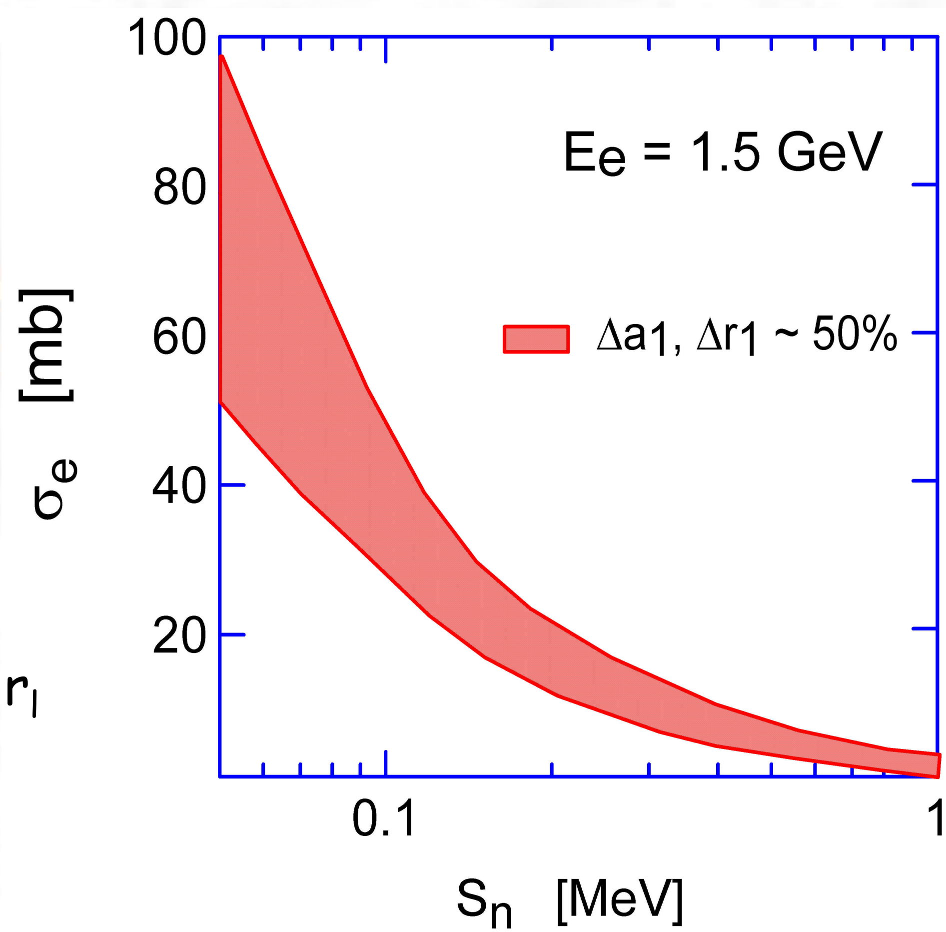
Bertulani, PRC 75, 024606 (2007)

Dependence on bind. energy and FSI



$$\frac{d\sigma}{dE_e d\Omega} \sim |f_l(q)|^2$$

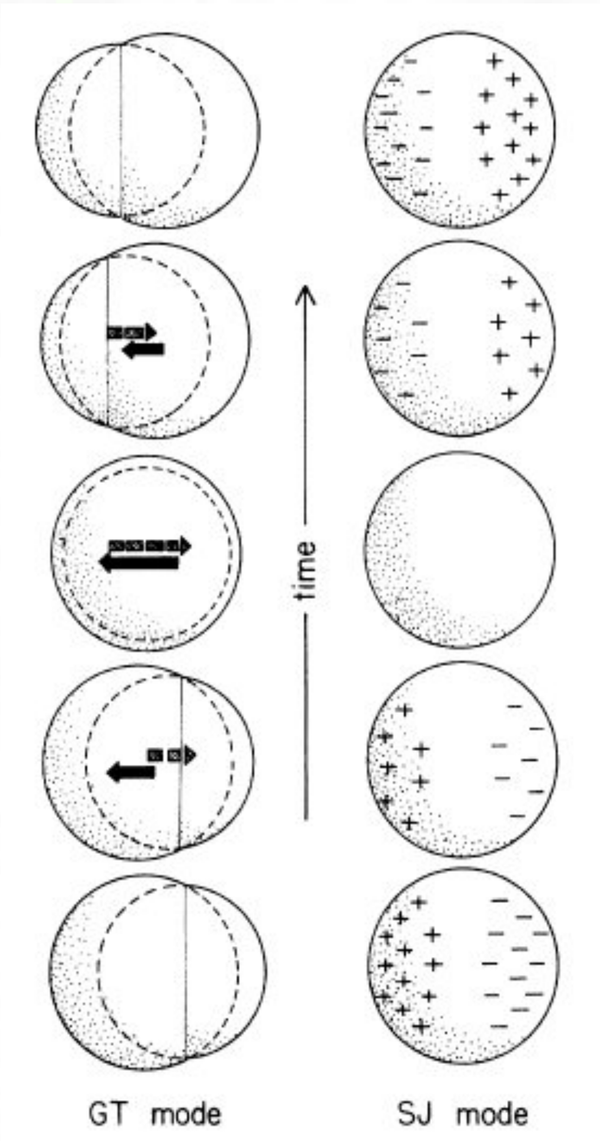
$$f_l \equiv f_l(q, S_n, a_l, r_l)$$



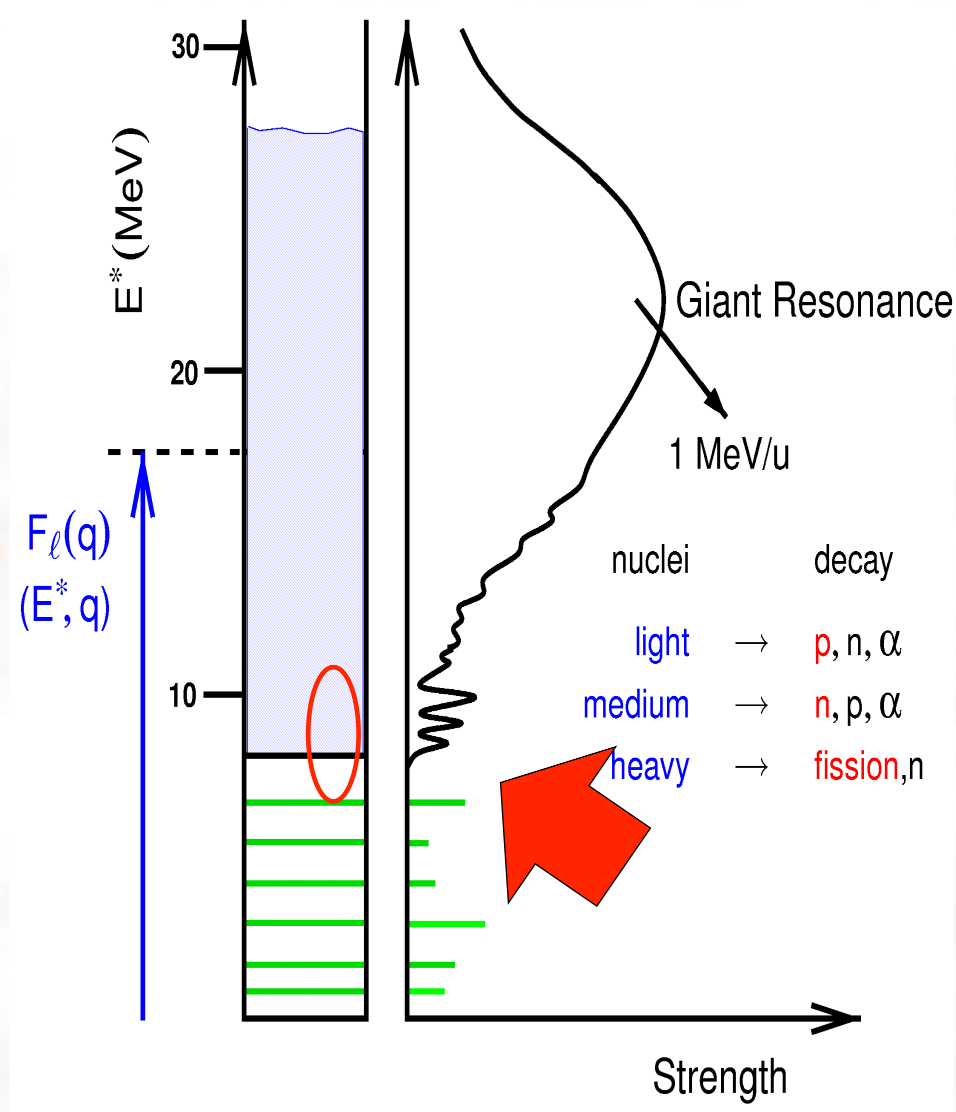
Halo nuclei: very strong dependence on effective range expansion parameters, a_l, r_l

Bertulani, PLB 624, 203 (2005)

Hydrodynamical model for collective vibrations



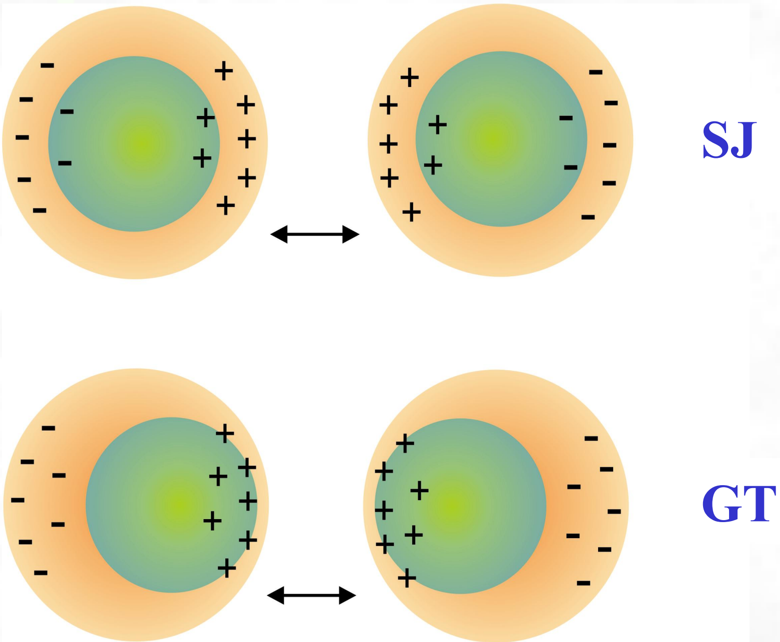
$$T = \frac{1}{2} m^* \int \rho_p \left(\mathbf{v}_{SJ}^{(p)} + \mathbf{v}_{GT}^{(p)} \right)^2 + \rho_n \left(\mathbf{v}_{SJ}^{(n)} + \mathbf{v}_{GT}^{(n)} \right)^2$$



$$V = -\kappa \int d^3 r \frac{\left(\rho_p - \rho_p \right)^2}{\rho_p + \rho_p} + \text{surf. terms}$$

$$\kappa \cong 30 - 40 \text{ MeV}$$

Transition densities for pygmy resonances

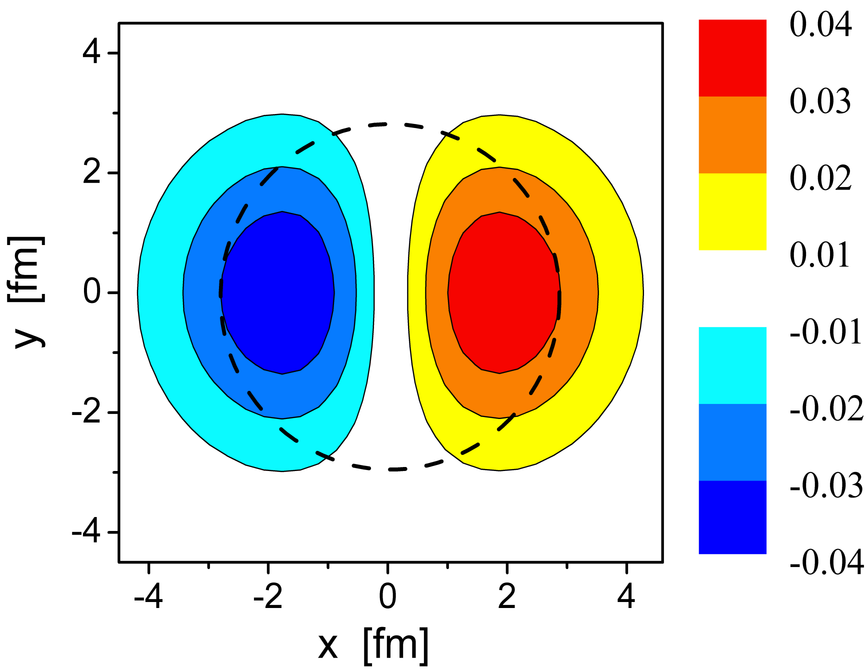


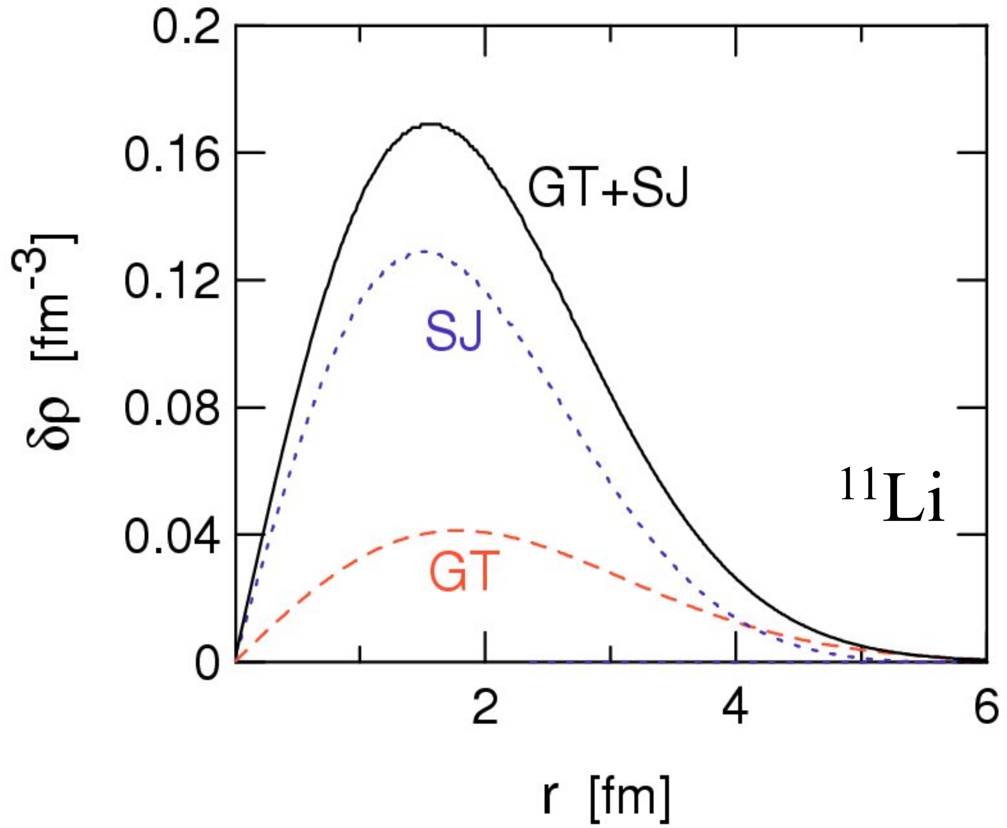
GT SJ

$$\delta\rho = \sqrt{\frac{4\pi}{3}} R \left[Z_{eff}^{(GT)} \alpha_{GT} \frac{d}{dr} + Z_{eff}^{(SJ)} \alpha_{SJ} \frac{K}{R} j_1(kr) \right] \rho_0(r)$$

$$kR = 2.081, \qquad K = 9.93$$

Bertulani, PRC 75, 024606 (2007)

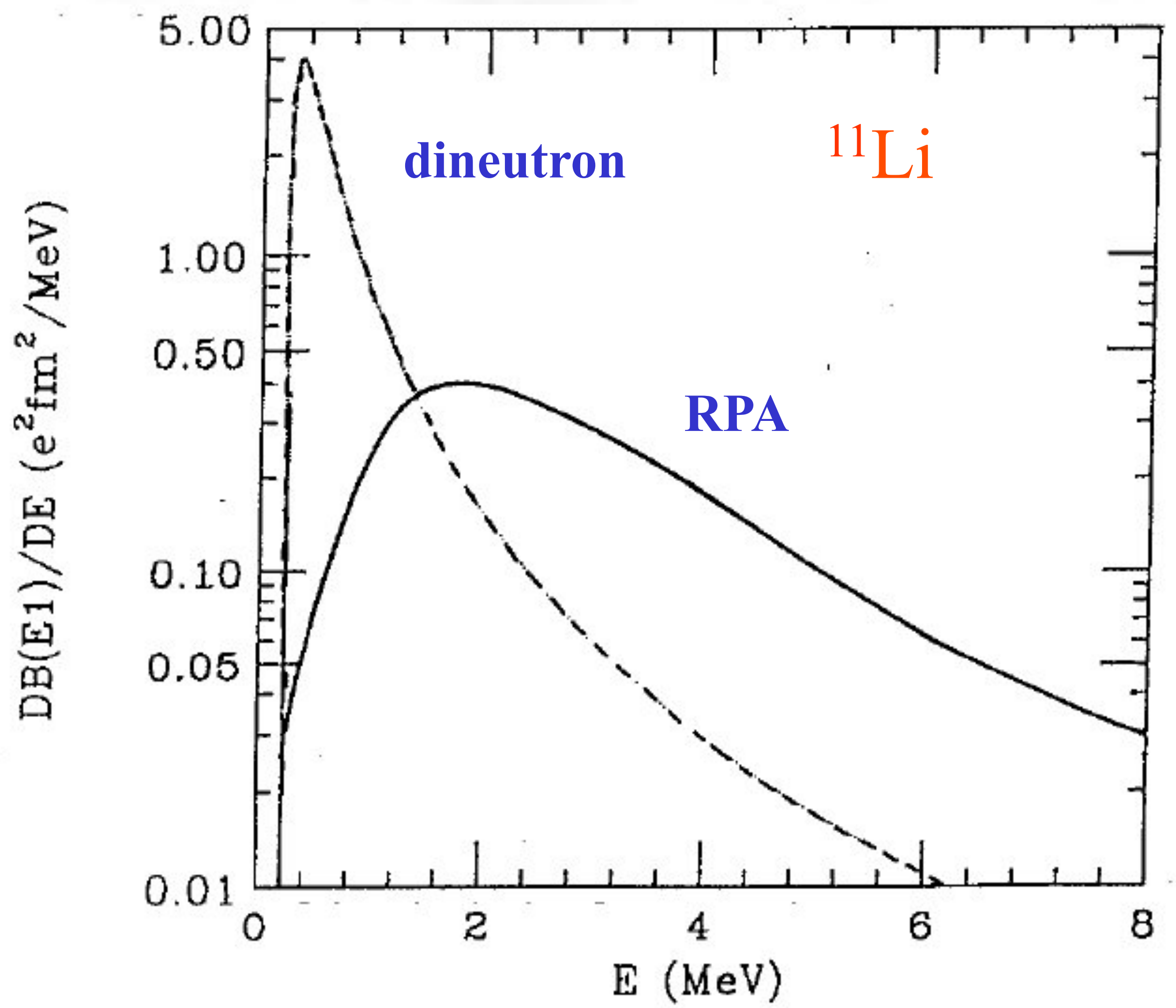




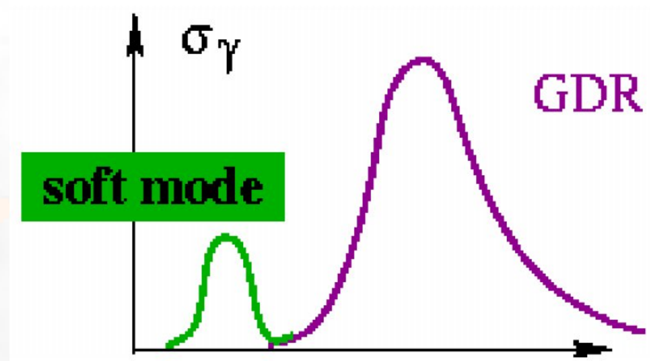
Collective response in light neutron rich nuclei

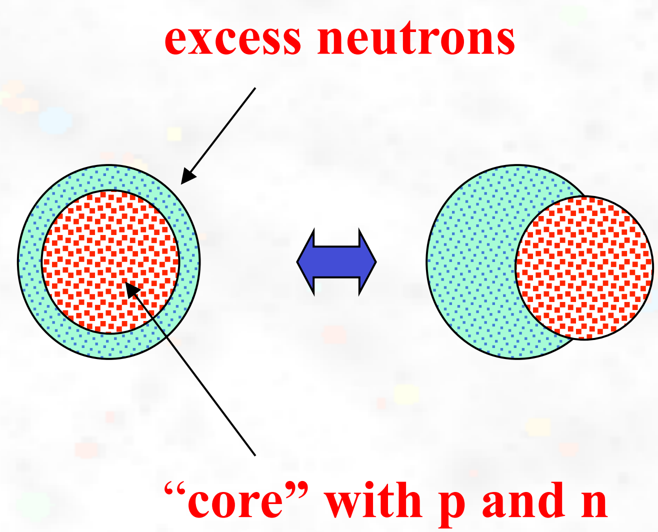
N. Teruya et al,

PRC 43 (1991) 2049 1991



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



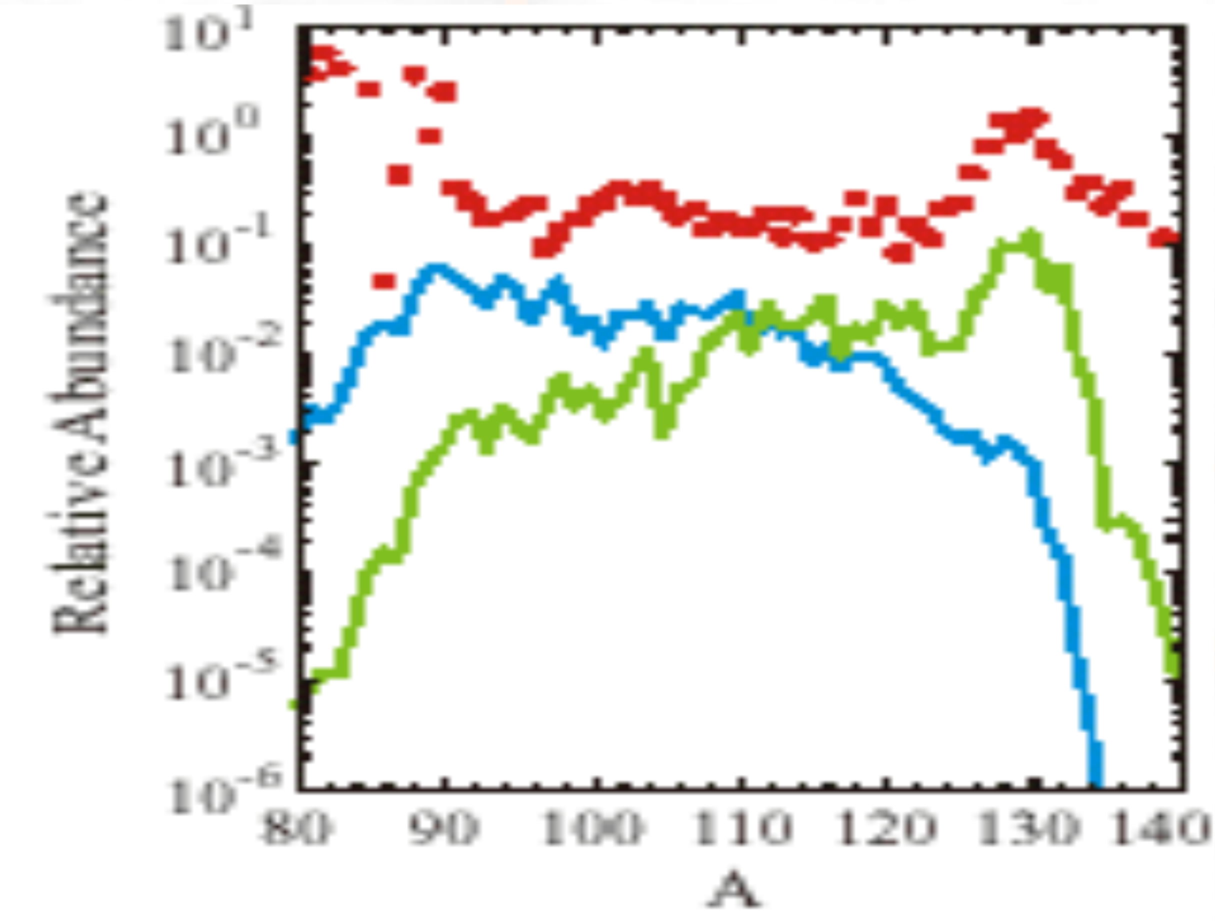


Is there a soft dipole ?

Only in light nuclei ?

Nucleosynthesis: (γ,n) or (n,γ) cross sections in the r-process

Importance of the "pygmy" states



Red: empirical

Blue: no pygmy

Green: with pygmy

S. Goriely, PLB 2000

It is important to have reliable measurements and model predictions

End of part II