Direct reactions at low energies: Part III – Transfer Spectroscopy

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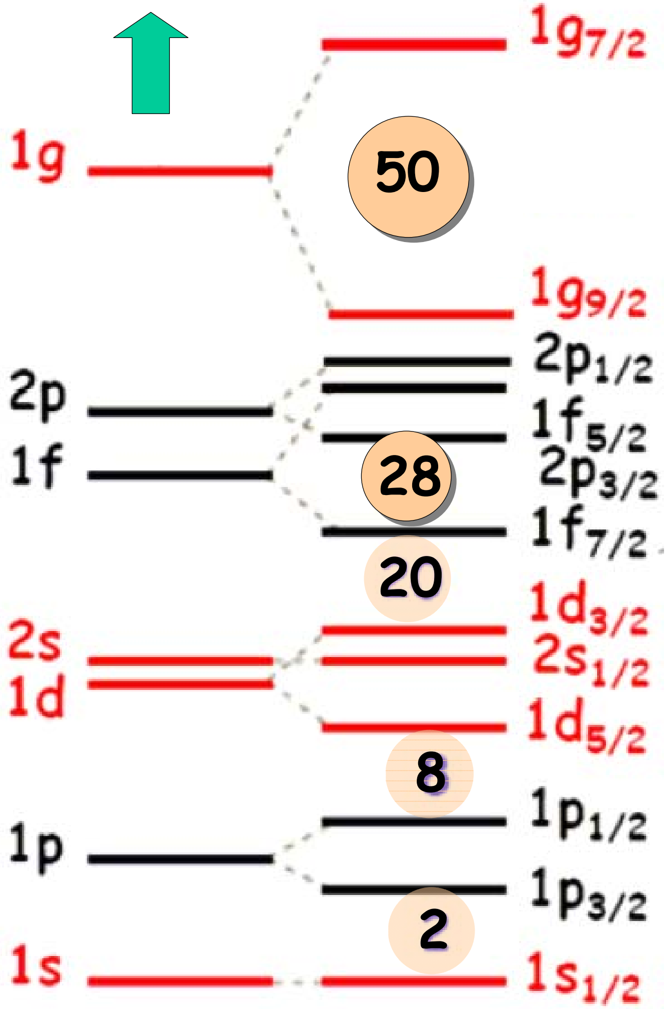
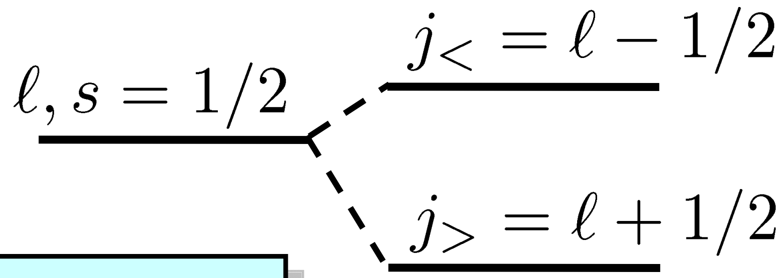
What is involved in realistic reaction calculations?

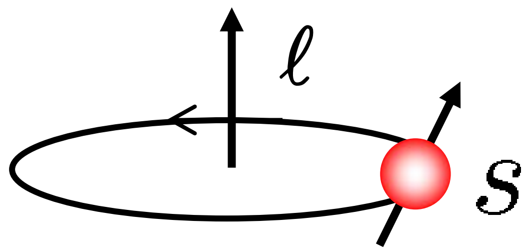




$^{23}O(p,d)$

Z=8

N=15

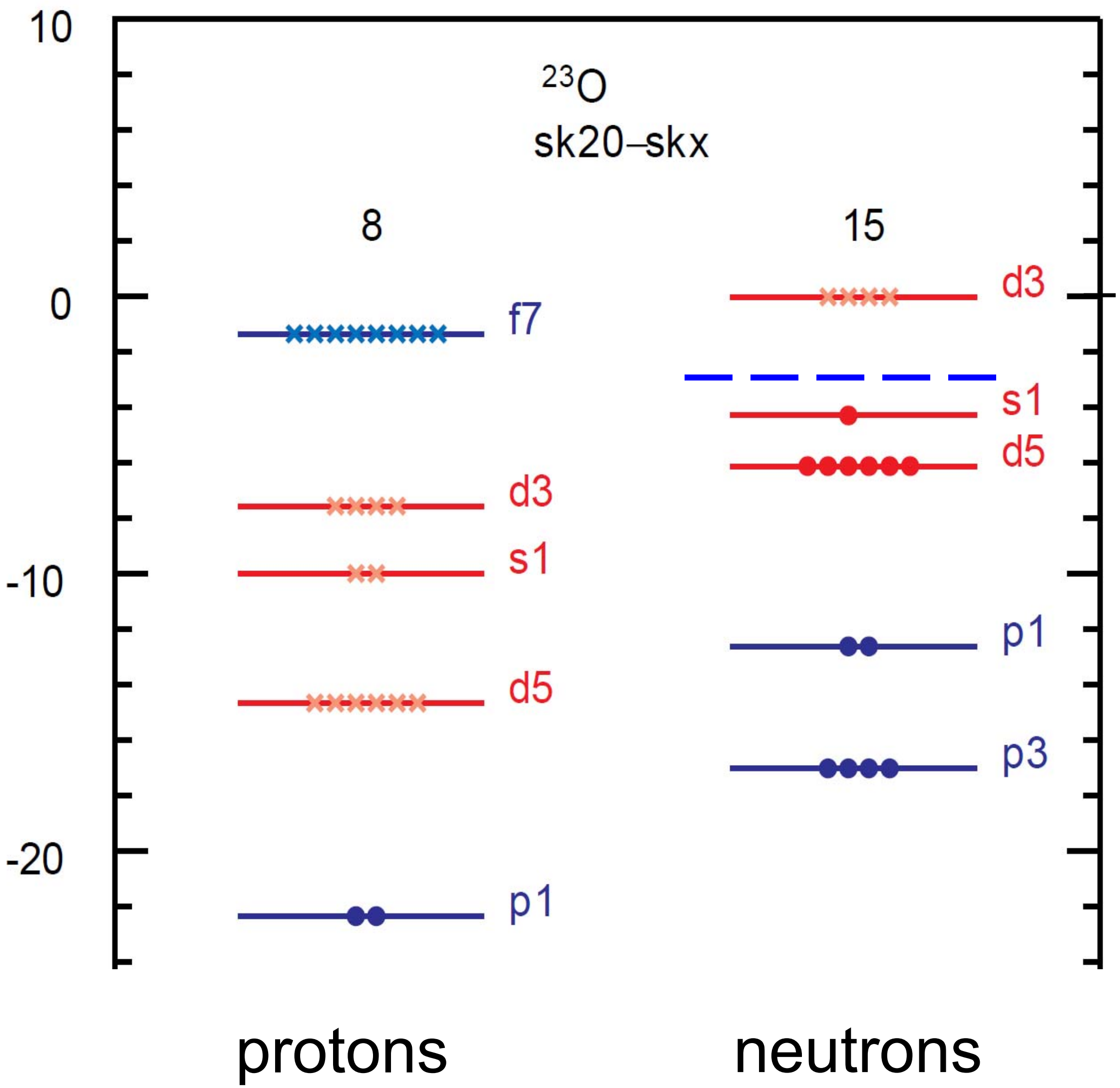


$$V_{\ell s}(r)\vec{\ell}\cdot\vec{s}$$

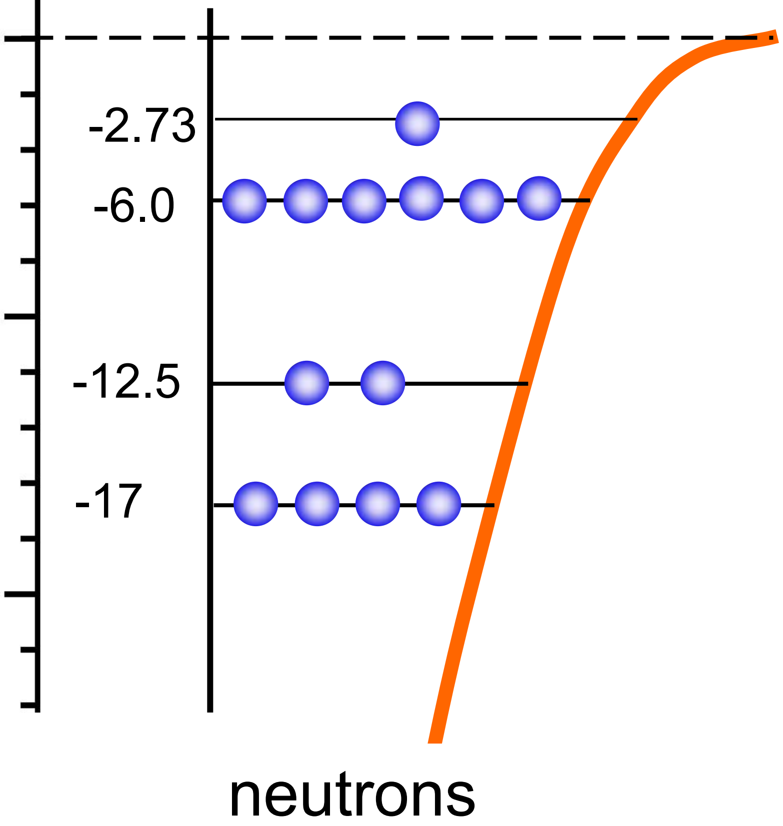
$$V(r) + V_{so}(r)\vec{\ell}\cdot\vec{s}$$

$$V_{so}(r) < 0$$

Example: What is involved – take neutron from ^{23}O



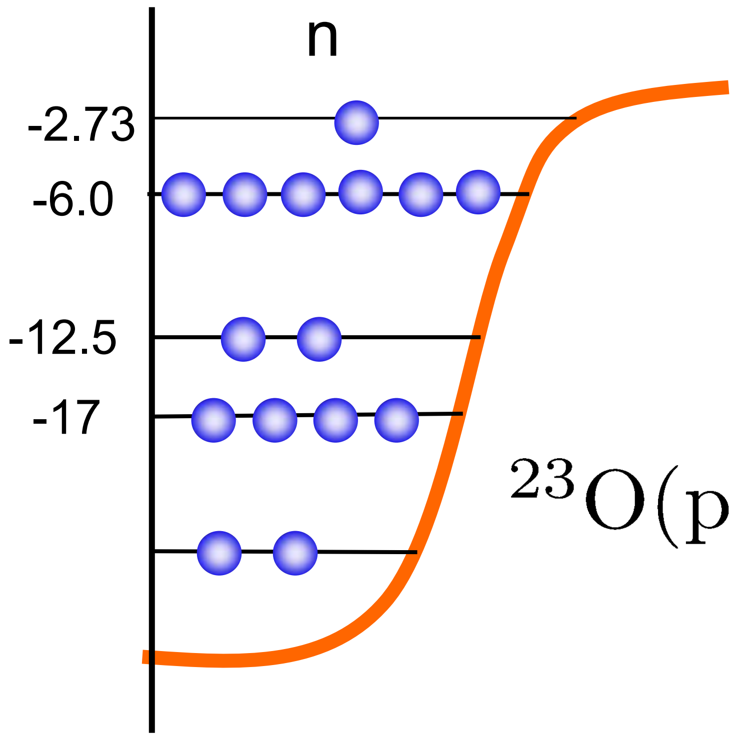
Experimental separation energy known



Hartree-Fock mean field calculation

Independent particle – (p,d) reaction

Single neutron removal from $^{23}O \equiv [1d_{5/2}]^6\,[2s_{1/2}]$



$2s_{1/2}$ S_n=2.73 MeV

$1d_{5/2}$ S_n=6.0 MeV

SF are?

$$^{23}\mathrm{O(p,d)}^{22}\mathrm{O}(J_f^\pi)$$

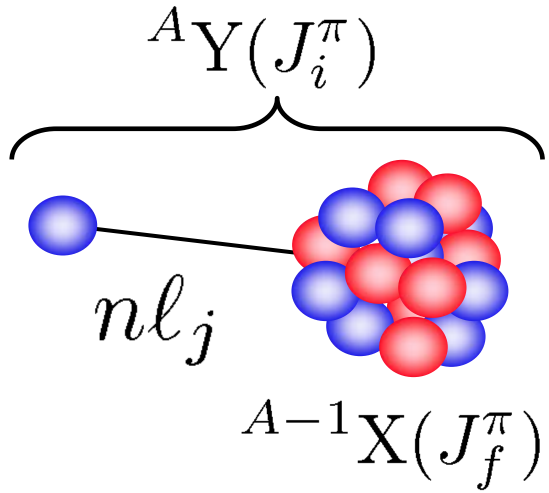
$J_f^\pi = 0^+$, g.s.
S_n=2.73 MeV

$J_f^\pi = 2^+$, 3.2 MeV
S_n=6.0 MeV

transfer reaction code(s) available at:
http://www.nucleartheory.net/NPG/code.htm

Bound states – spectroscopic factors

In a potential model it is natural to define normalised bound state wave functions.



$$\phi^{m}_{n\ell j}(\vec{r}) = \sum_{\lambda\sigma}(\ell\lambda s\sigma|jm)\frac{u_{n\ell j}(r)}{r}Y^{\lambda}_{\ell}(\hat{r})\chi^{\sigma}_{s},$$

$$\int_0^{\infty}[u_{n\ell j}(r)]^2 dr = 1$$

The potential model wave function approximates the overlap function of the A and A–1 body wave functions (A and A–n in the case of an n-body cluster) i.e. the overlap

$$\langle \ell j, \vec{r}, {}^{A-1}\mathrm{X}(J_f^{\pi})|{}^{A}\mathrm{Y}(J_i^{\pi})\rangle \rightarrow I_{\ell j}(r), \quad \int_0^{\infty}[I_{\ell j}(r)]^2 dr = S(J_i, J_f \ell j)$$

S(…) is a spectroscopic factor, that scales the normalised single-particle wave function/overlap/form-factor

Connection to many-body structure calculations (1)

$$\langle \alpha, \vec{r}, {}^{A-1}\mathrm{X}(J_f^\pi) | {}^{A}\mathrm{Y}(J_i^\pi) \rangle$$

If we describe many body states by single Slater determinants, since these must be antisymmetric

$$\langle 1 \ldots A | {}^{A}\mathrm{Y} \rangle \equiv \frac{1}{\sqrt{A!}} \begin{vmatrix} \phi_1(1) & \phi_2(1) & \ldots & \phi_A(1) \\ \phi_1(2) & \phi_2(2) & \ldots & \phi_A(2) \\ \ldots & \ldots & \ldots & \ldots \\ \phi_1(A) & \phi_2(A) & \ldots & \phi_A(A) \end{vmatrix}$$

then, for A identical particles (isospin) [or if (n,p), then N or Z]

$$\langle \alpha, \vec{r}, {}^{A-1}\mathrm{X}(J_f^\pi) | {}^{A}\mathrm{Y}(J_i^\pi) \rangle = \frac{1}{\sqrt{A}} \phi_\alpha(\vec{r})$$

The *A* factor is not usually carried: it cancels in cross sections that have an *A* multiplier to account for each identical particle.

Connection to many-body structure calculations (2)

$$\langle \alpha, \vec{r}, {}^{A-1}\mathrm{X}(J_f^\pi) | {}^A\mathrm{Y}(J_i^\pi) \rangle = \frac{1}{\sqrt{A}} \phi_\alpha(\vec{r})$$

Here the radial wave function (form factor) is normalised. In a reaction that removes a nucleon from a given orbital then, if a sub-shell is filled in the initial nucleus there are (2j+1) nucleons available with a given (j,ℓ) to contribute.

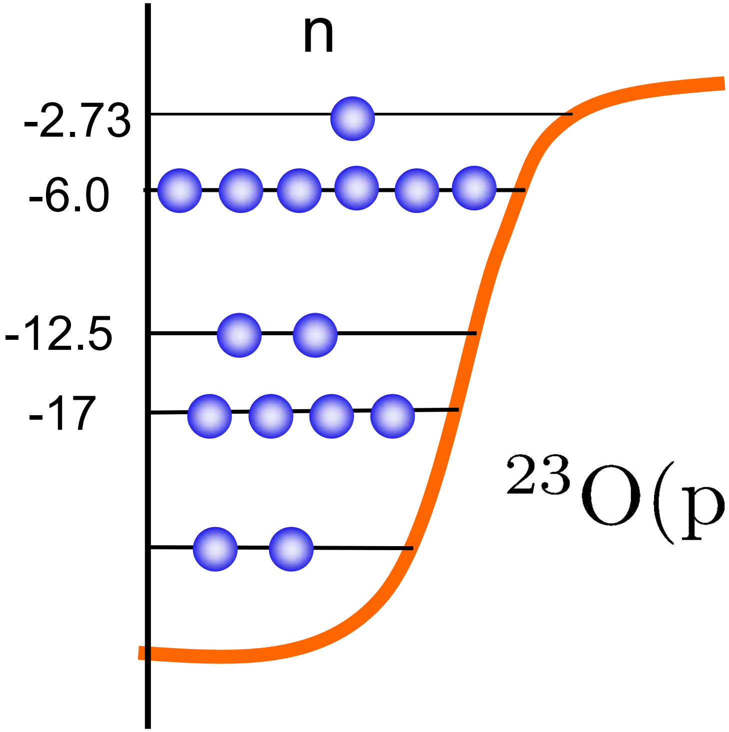
So, more generally (non-single Slater determinant) many-body structure models calculate and provided overlaps as:

$$\langle j\ell, \vec{r}, {}^{A-1}\mathrm{X}(J_f^\pi) | {}^A\mathrm{Y}(J_i^\pi) \rangle = \frac{\sqrt{S(J_i, J_f j\ell)}}{\sqrt{A}} \phi_{j\ell m}(\vec{r})$$

So, *S* multiplies the cross section calculated with a normalised form-factor. The *S* are defined so that (for given n j,ℓ quantum numbers) their sum over final states is the mean number of nucleons occupying the given sub-shell (sum-rule).

Independent particle – (p,d) reaction

Single neutron removal from $^{23}O \equiv [1d_{5/2}]^6\,[2s_{1/2}]$



$2s_{1/2}$ S_n=2.73 MeV

$1d_{5/2}$ S_n=6.0 MeV

SF are?

$$^{23}\mathrm{O(p,d)}^{22}\mathrm{O}(J_f^\pi)$$

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transfer reaction code(s) available at:
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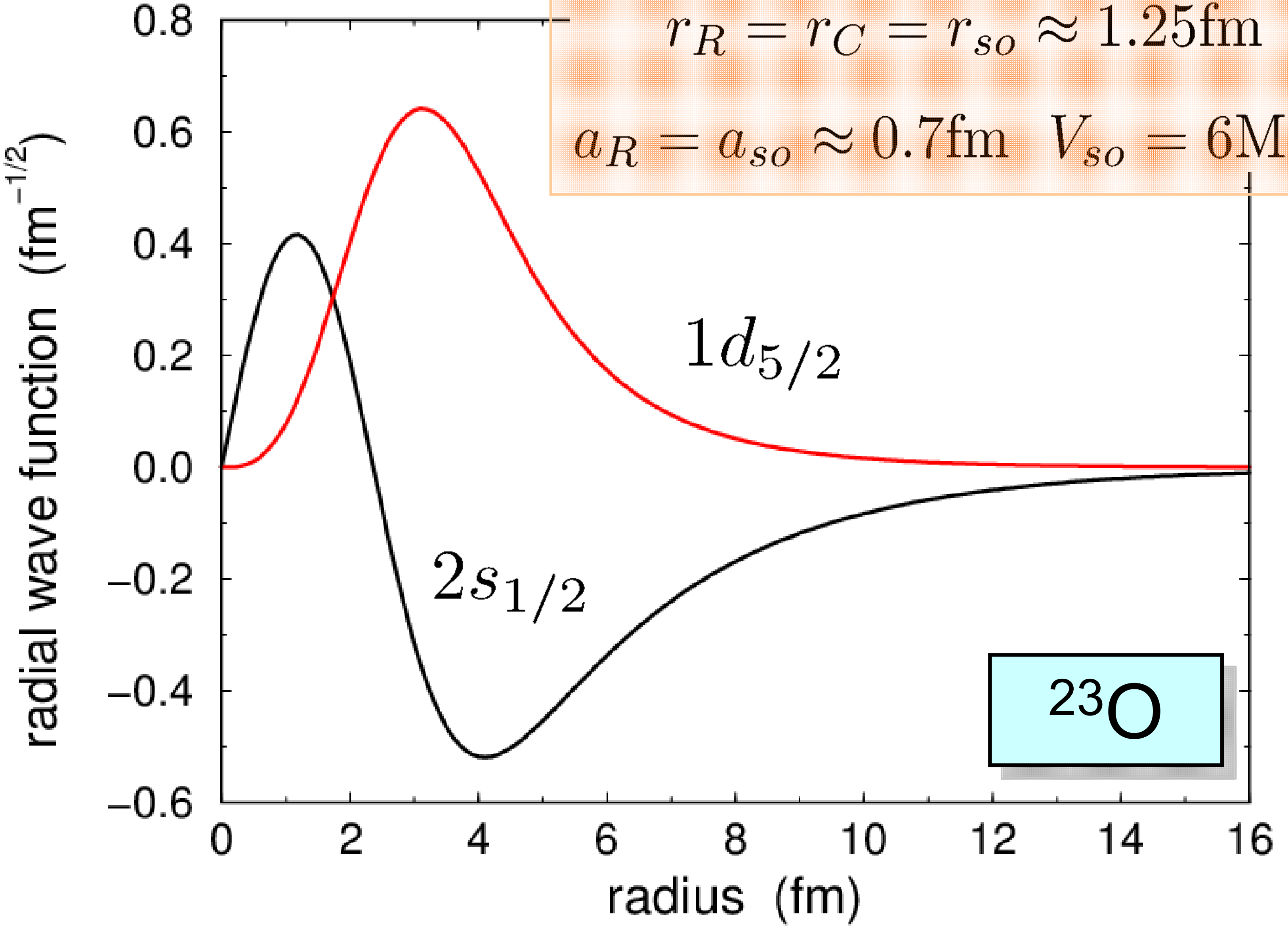
Neutron bound state wave functions

$$r_R = r_C = r_{so} \approx 1.25\text{fm}$$

$$a_R = a_{so} \approx 0.7\text{fm} \quad V_{so} = 6\text{MeV}$$



Transfer reactions e.g. (p,d) – coordinate systems

$$\vec{R} = [\vec{r}_n + \vec{r}_p]2$$

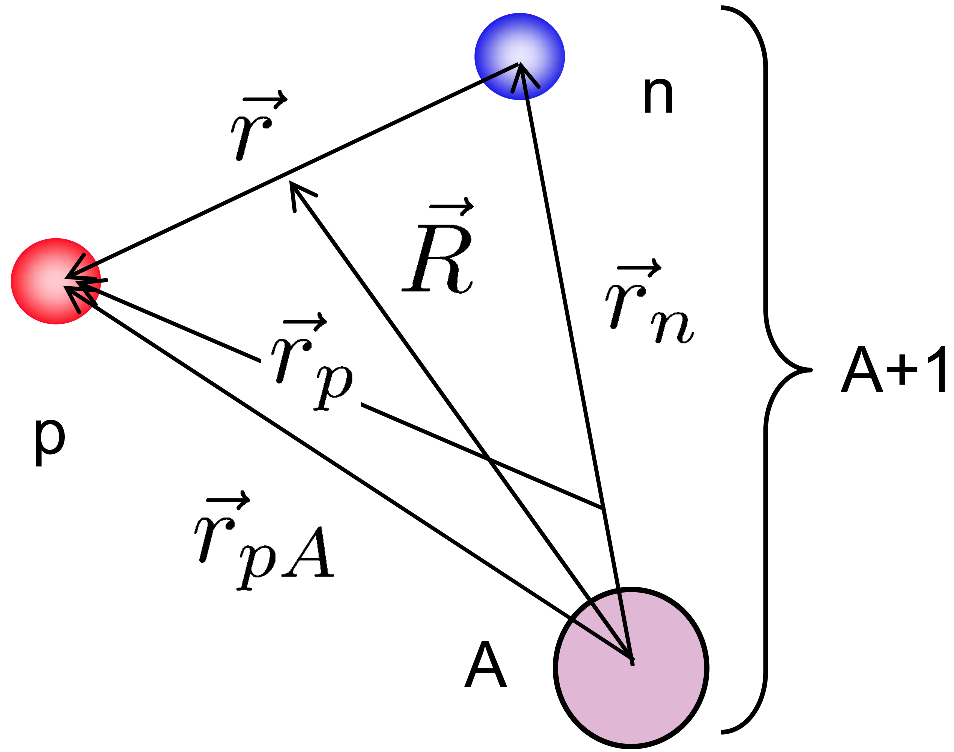
$$\vec{r}_{pA} = \vec{R} + \vec{r}/2$$

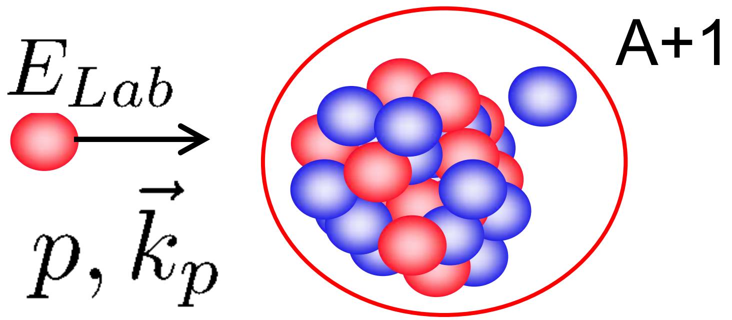
$$\vec{r}_n = \vec{R} - \vec{r}/2$$

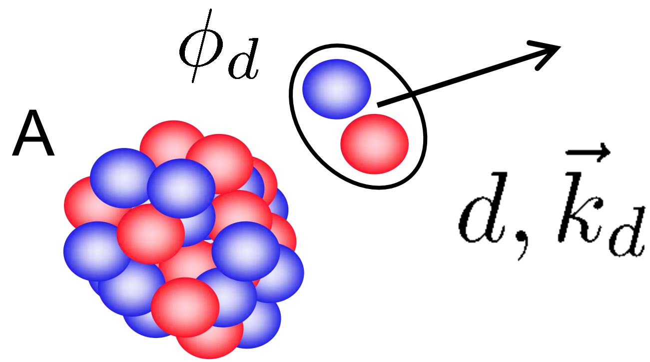
$$V_p(\vec{r}_{pA}) = V_p(\vec{R} + \vec{r}/2)$$

$$V_n(\vec{r}_n) = V_n(\vec{R} - \vec{r}/2)$$

$$V_{np}(\vec{r})$$



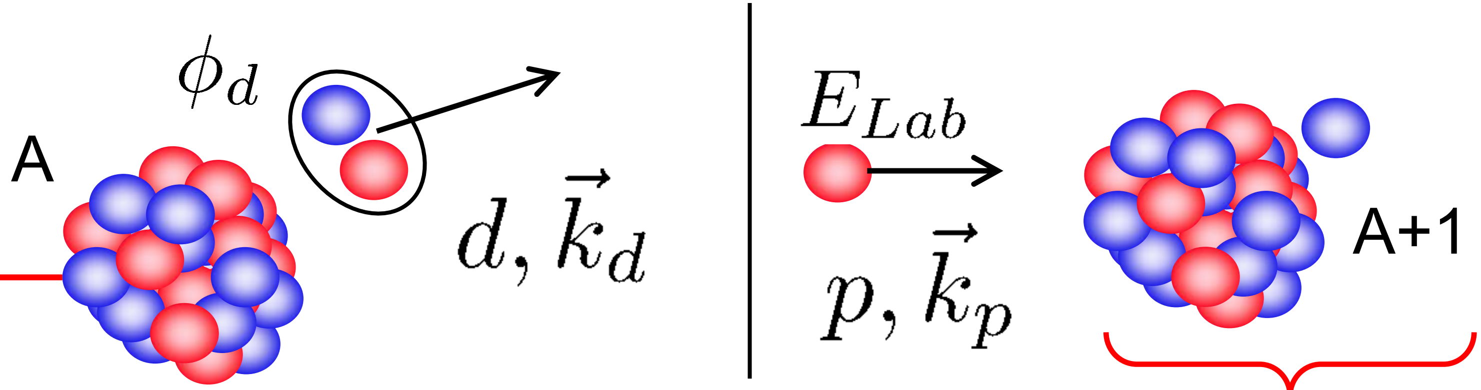




Transfer reaction transition amplitudes - DWBA

$$T(p,d) = \langle\, \chi^{(-)}_{d,\vec{k}_d}\,\phi_d\;\Phi(A,J_f)|V_{np}|\chi^{(+)}_{p,\vec{k}_p}\,\Phi(A+1,J_i)\rangle$$

exit channel — entrance channel



$V_{np}\phi_d(\vec{r})$ - vertex function – of short but finite range

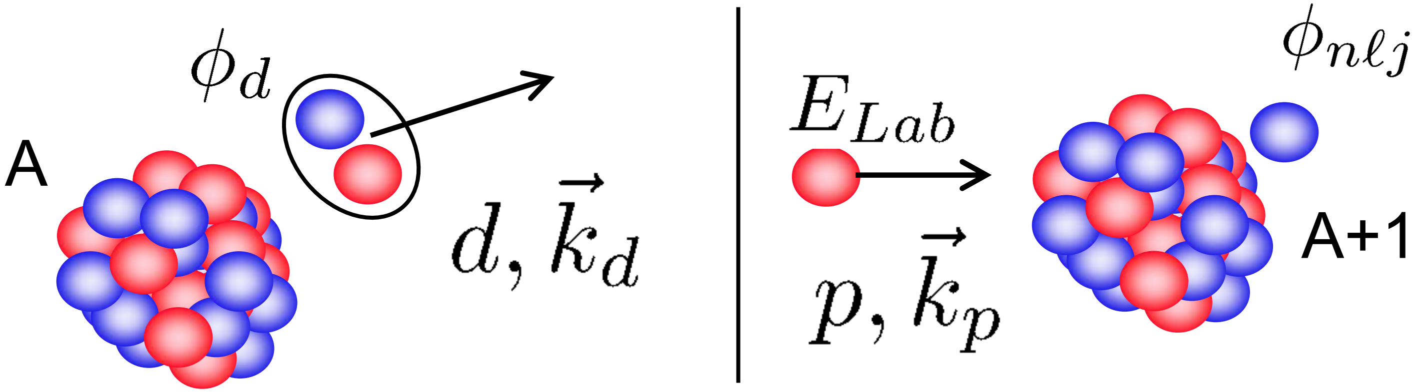
$$\phi_{n\ell j}(\vec{r}_n) = \langle\Phi(A,J_f)|\Phi(A+1,J_i)\rangle$$

Transfer reaction – involve structure via overlaps

$$T(p,d) = \langle \chi^{(-)}_{d,\vec{k}_d} \underbrace{\Phi(A,J_f)}\phi_d | V_{np} | \chi^{(+)}_{p,\vec{k}_p} \underbrace{\Phi(A+1,J_i)} \rangle$$

$$\phi_{n\ell j}(\vec{r}_n) = \langle \Phi(A,J_f) | \Phi(A+1,J_i) \rangle$$

$$T(p,d) = \langle \chi^{(-)}_{d,\vec{k}_d}(\vec{R})\phi_d(r) | V_{np} | \chi^{(+)}_{p,\vec{k}_p}(\vec{r}_p)\phi_{n\ell j}(\vec{r}_n) \rangle$$

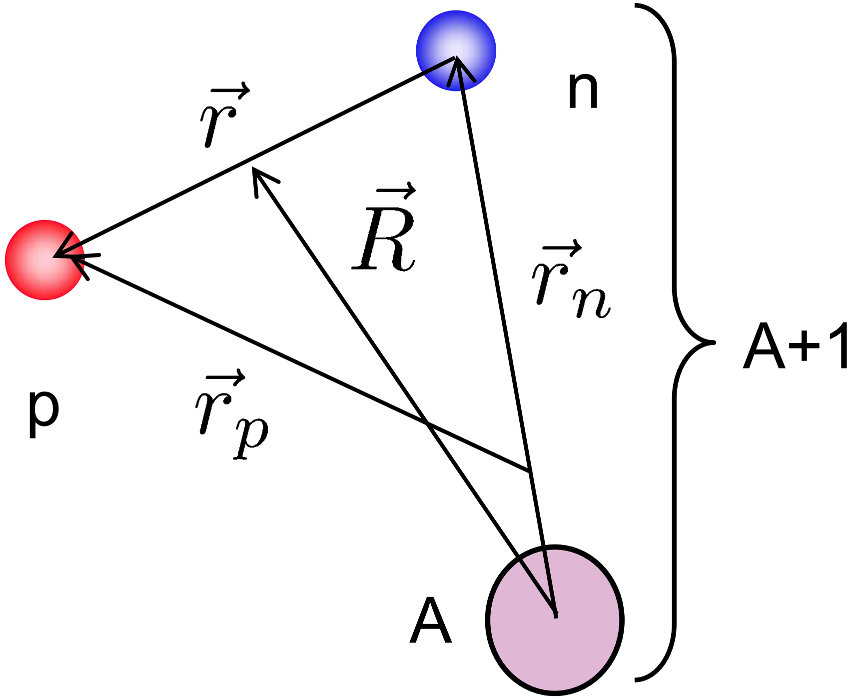


Transfer reaction – plane waves for insight (1)

$$T(p,d) = \langle \chi^{(-)}_{d,\vec{k}_d}(\vec{R})\phi_d(r)|V_{np}|\chi^{(+)}_{p,\vec{k}_p}(\vec{r}_p)\phi_{n\ell j}(\vec{r}_n)\rangle$$

when using plane waves for p and d – i.e. 'weak' distortions

$$T_{pw} \approx \int d\vec{r}_n \int d\vec{r}\, e^{-i\vec{k}_d\cdot\vec{R}} V_{np}\phi_d(r) e^{i\vec{k}_p\cdot\vec{r}_p}\phi_{n\ell j}(\vec{r}_n)$$



$$\vec{r}_p = \gamma\vec{r}_n + \vec{r}$$

$$\gamma = A/(A+1) \approx 1$$

$$\vec{R} = \vec{r}_n + \vec{r}/2$$

$$\vec{k}_p\cdot\vec{r}_p - \vec{k}_d\cdot\vec{R} =$$

$$[\gamma\vec{k}_p - \vec{k}_d]\cdot\vec{r}_n +$$

$$[\vec{k}_p - \vec{k}_d/2]\cdot\vec{r}$$

Transfer reaction – plane waves for insight (2)

$$T_{pw} \approx \int d\vec{r}_n \int d\vec{r}\, e^{-i\vec{k}_d\cdot\vec{R}} V_{np}\phi_d(r) e^{i\vec{k}_p\cdot\vec{r}_p}\phi_{n\ell j}(\vec{r}_n)$$

$$\begin{aligned}\vec{k}_p\cdot\vec{r}_p - \vec{k}_d\cdot\vec{R} &= [\gamma\vec{k}_p - \vec{k}_d]\cdot\vec{r}_n + [\vec{k}_p - \vec{k}_d/2]\cdot\vec{r} \\ &= \vec{q}_n\cdot\vec{r}_n + \vec{q}\cdot\vec{r}\end{aligned}$$

$$T_{pw} \approx \int d\vec{r}_n e^{i\vec{q}_n\cdot\vec{r}_n}\phi_{n\ell j}(\vec{r}_n) \times \int d\vec{r}\, e^{i\vec{q}\cdot\vec{r}} V_{np}\phi_d(r)$$

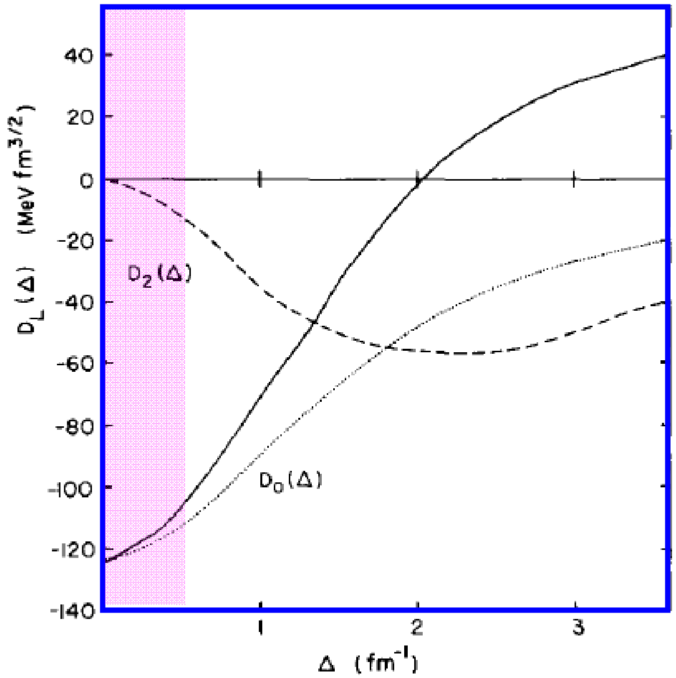
$$\sigma_{pw} \propto |F(\vec{q}_n)|^2 D^2(q)$$

and expanding $e^{i\vec{q}\cdot\vec{r}}$ for small q

$$D(q) = D_0[1 - \beta^2 q^2 + \ldots]$$

$$D_0 = -122.5 \text{ MeV fm}^{3/2}$$

$$\beta \approx 0.75 \text{ fm}$$



Transfer reactions – “matching” considerations

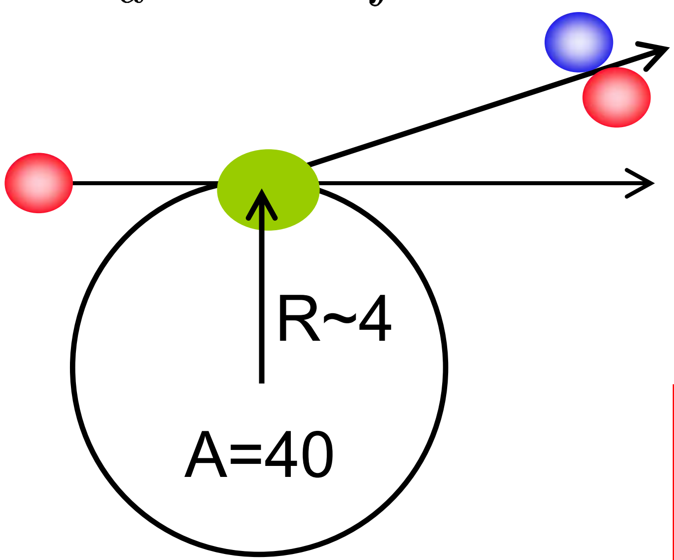
$$\vec{q}_n = [\gamma \vec{k}_p - \vec{k}_d] \qquad \vec{q} = [\vec{k}_p - \vec{k}_d/2] \cdot \vec{r}$$

$$T_{pw} \approx \int d\vec{r}_n e^{i\vec{q}_n \cdot \vec{r}_n} \phi_{n\ell j}(\vec{r}_n) \times \int d\vec{r} e^{i\vec{q} \cdot \vec{r}} V_{np} \phi_d(r)$$

e.g. (p,d) on A=40 at E_p=10 MeV, say S_n=4 MeV, R_{40}~4 fm

$$k_p = 0.68 fm^{-1} \qquad \Delta L = |L_d - L_p| \approx 0.7$$

$$k_d = 0.86 fm^{-1}$$



$$\vec{k}_d$$

$$L_d \approx k_d R$$

$$\vec{k}_p$$

$$L_p \approx k_p R$$

$$L_p = 2.8$$

$$L_d = 3.5$$

with E_p=20 MeV

$$k_p = 0.96 fm^{-1}$$

$$k_d = 1.27 fm^{-1}$$

$$L_p = 3.9$$

$$L_d = 5.2$$

$$\Delta L = |L_d - L_p| \approx 1.3$$

Phenomenological optical potentials – where?

C.M. Perey and F.G. Perey, At. Data Nucl. Data Tables 17, 1 (1976) Compilation for many systems

J.J.H. Menet, E.E. Gross, J.J. Malanify, and A. Zucker, Phys. Rev. C 4, 1114 (1971) – for nucleons

R.L. Varner, W.J. Thompson, T.L. McAbee, E.J. Ludwig, and T.B. Clegg, Phys. Rep. 201, 57 (1991) – Chapel Hill 89 potential – for nucleons

F.D. Becchetti, Jr. and G.W. Greenlees, Phys. Rev. 182, 1190 (1969) – 'old faithful' parameterisation – for nucleons

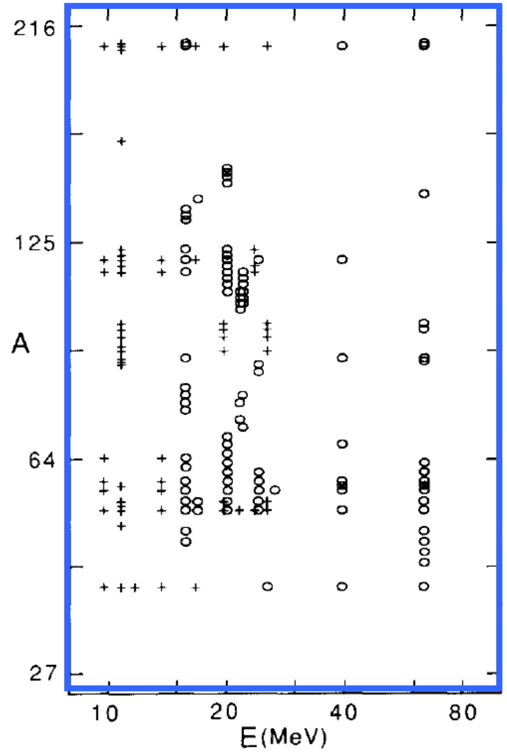
W.W. Daehnick, J.D. Childs, and Z. Vrcelj, Phys. Rev. C 21, 2253 (1980) – good parameter set – for deuterons

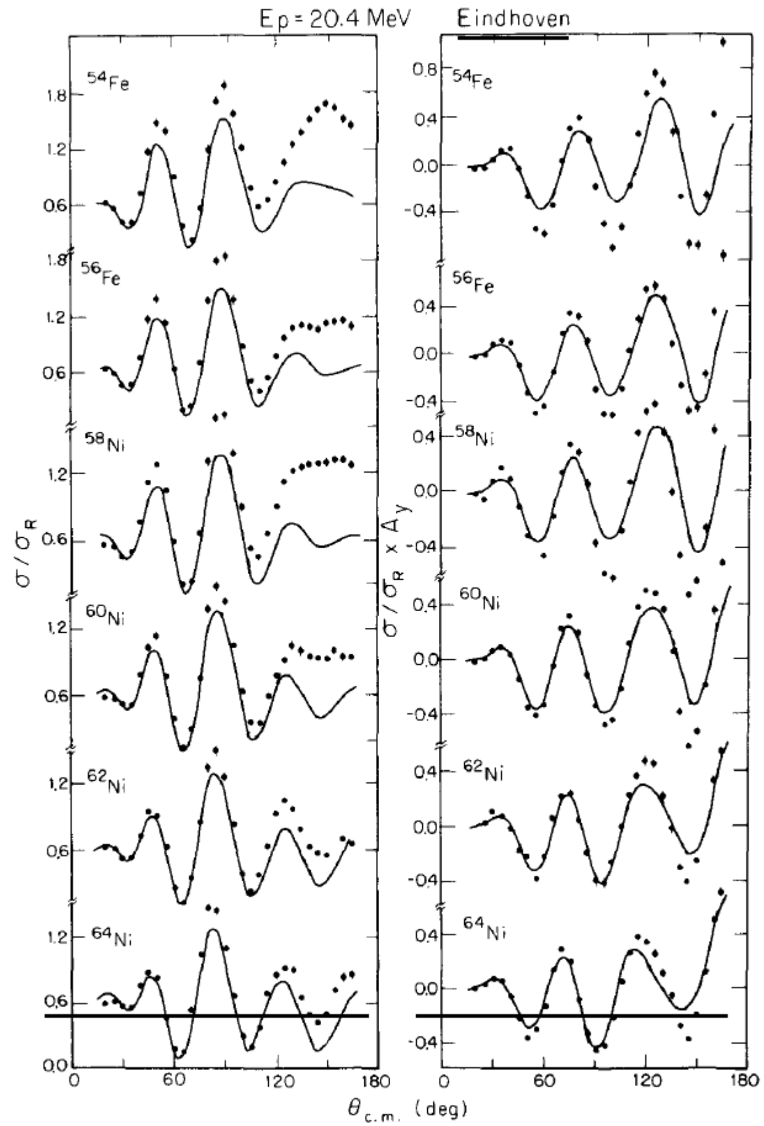
J.M. Lohr and W. Haeberli, Nucl. Phys. A232, 381 (1974) – for low energy deuterons

..... and many many more ... but many many gaps

http://www-nds.iaea.org/RIPL-2/optical.html

Global optical potentials – e.g. CH91 for nucleons





A GLOBAL NUCLEON OPTICAL MODEL POTENTIAL*

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and

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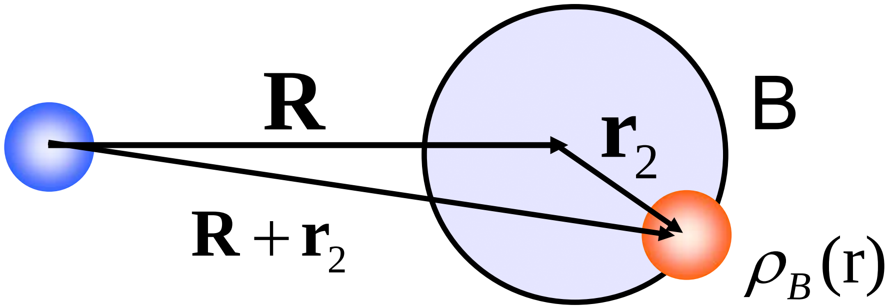
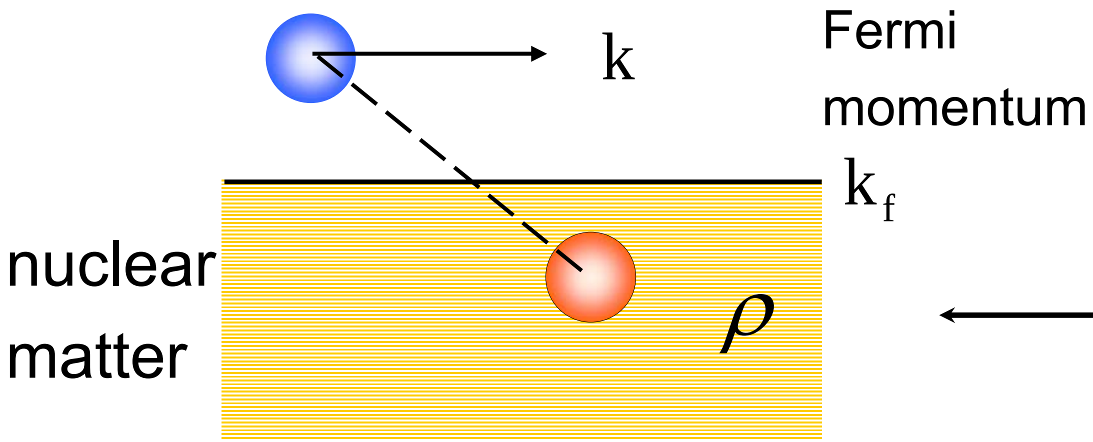
PHYSICS REPORTS (Review Section of Physics Letters) 201, No. 2 (1991) 57–119. North-Holland

Theoretical nucleon potential – based on density

$$V_{NB}(\mathrm{R}) = \int d\mathbf{r}_2 \; \rho_B(\mathrm{r}_2)\, \mathrm{v}_{\mathrm{NN}}(\mathbf{R}+\mathbf{r}_2)$$





include the effect of NN interaction in the “nuclear medium” – Pauli blocking of pair scattering into occupied states

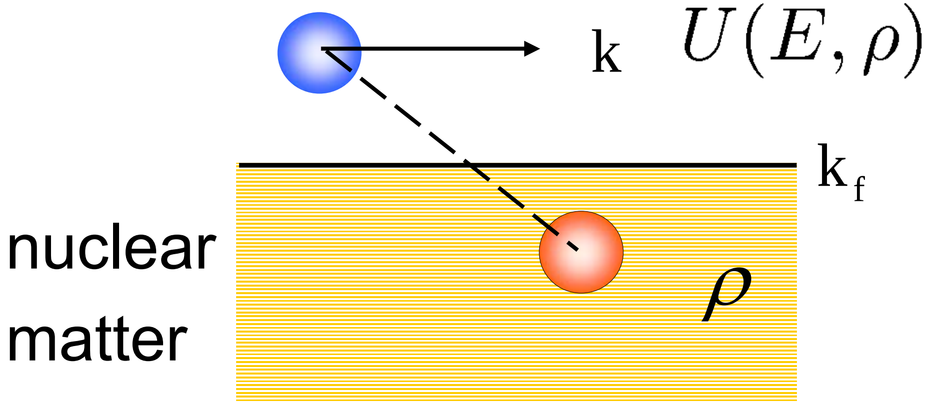
$\rightarrow \mathrm{v}_{\mathrm{NN}}(\rho, \mathbf{r})$

(e.g. JLM)

But as E → high

$\mathrm{v}_{\mathrm{NN}} \rightarrow \mathrm{v}_{\mathrm{NN}}^{\mathrm{free}}$

JLM interaction – local density approximation

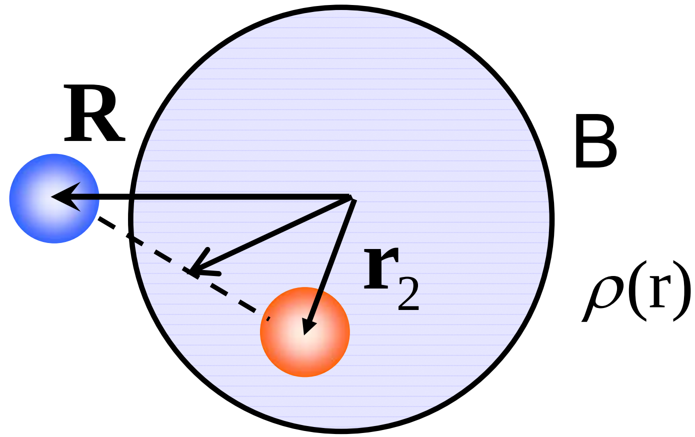


complex and density dependent interaction

$$v_{NN}(r) = \frac{U(E,\rho)}{\rho} f(r)$$

$$f(r) = (\sqrt{\pi}t)^{-3} \exp(-r^2/t^2)$$

For finite nuclei, what value of density should be used in calculation of nucleon-nucleus potential? Usually the local density at the mid-point of the two nucleon positions $\mathbf{r}_x$



$$U_B(R) = V_B(R) + iW_B(R) = \int d\vec{r}_2\, \rho_B(r_2) \frac{U(E,\rho(r_x))}{\rho(r_x)} f(r)$$

JLM interaction – fine tuning

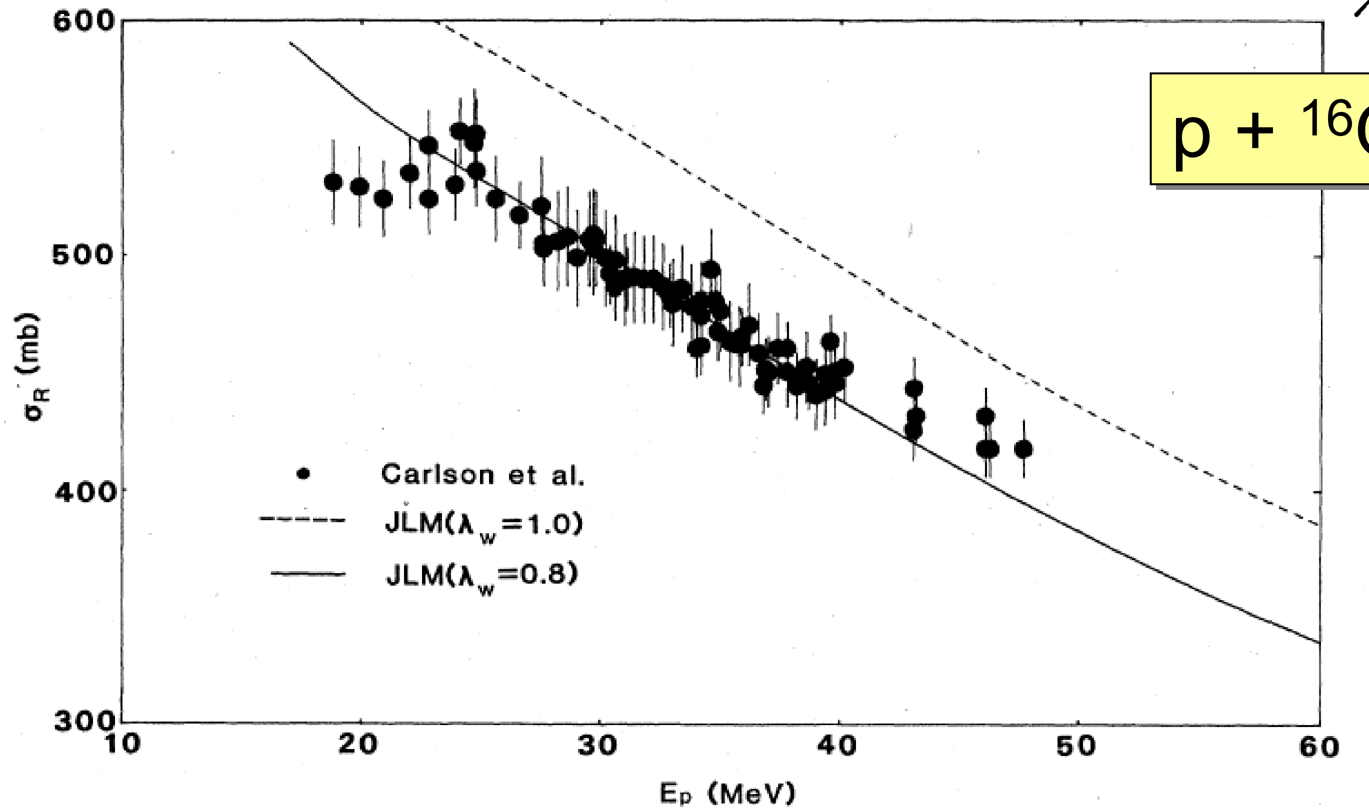
Strengths of the real and imaginary parts of the potential can be adjusted based on experience of fitting data.

$$U_B(R) = \lambda_v V_B(R) + i\lambda_w W_B(R)$$

$$\lambda_v \approx 1.0$$

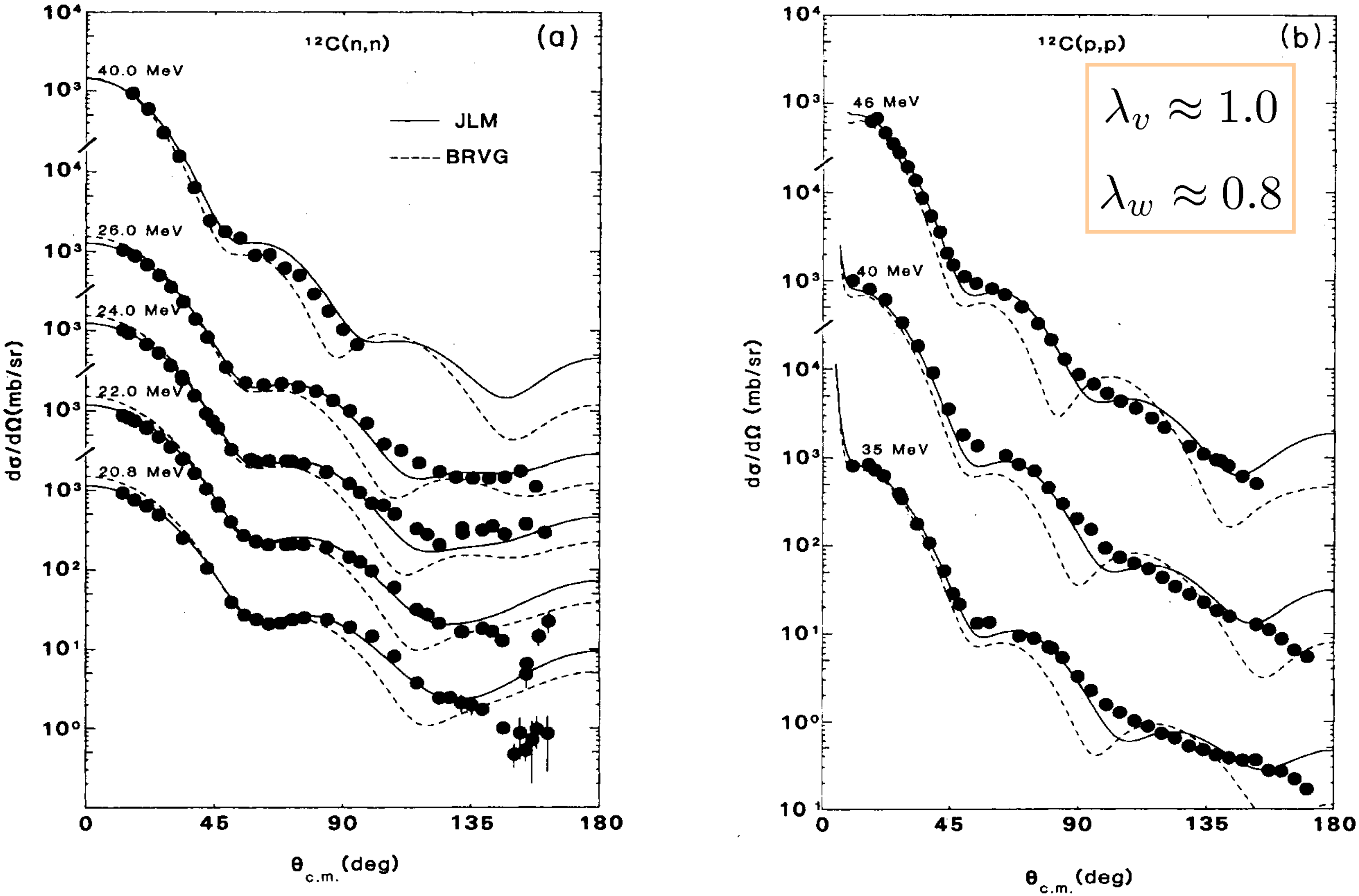
$$\lambda_w \approx 0.8$$

p + ^{16}O



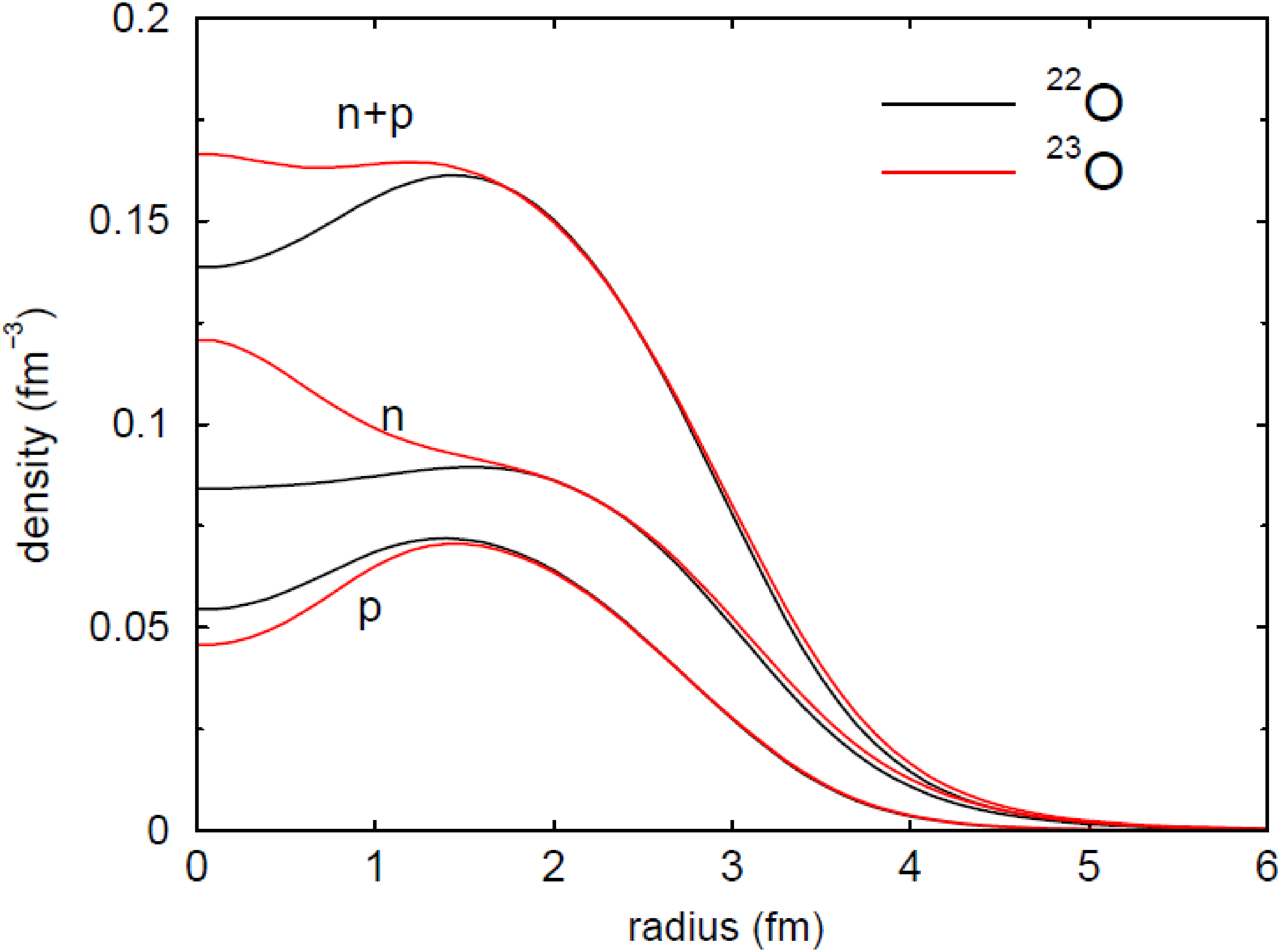
J.S. Petler et al. Phys. Rev. C **32** (1985), 673

JLM folded nucleon-nucleus optical potentials



J.S. Petler et al. Phys. Rev. C **32** (1985), 673

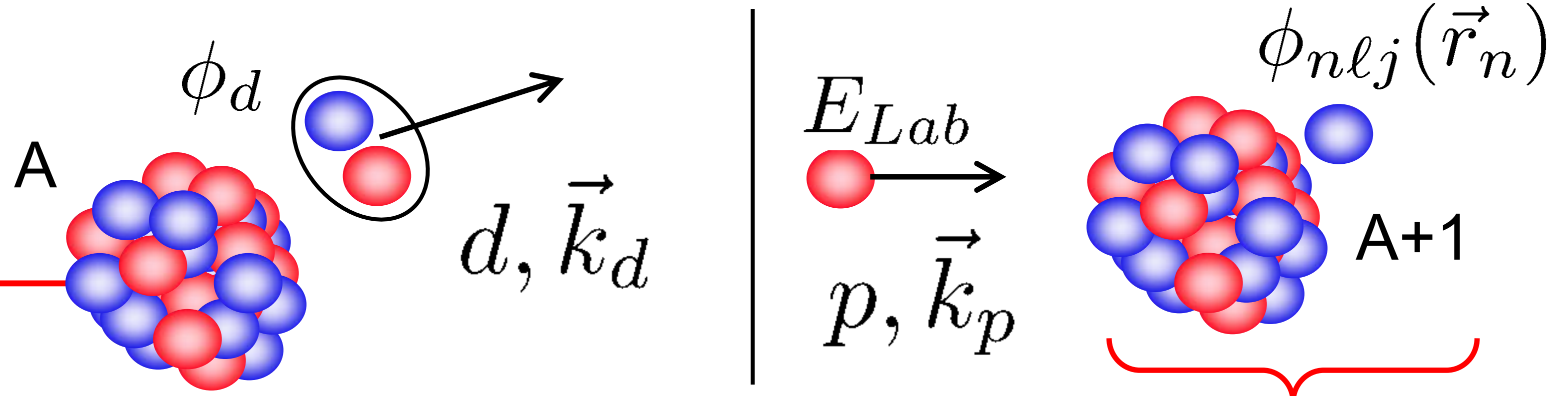
Neutron: proton: nucleon radial densities (HF)



Transfer reaction transition amplitudes - DWBA

$$T(p,d) = \langle \chi^{(-)}_{d,\vec{k}_d}(\vec{R})\phi_d(r)|V_{np}|\chi^{(+)}_{p,\vec{k}_p}(\vec{r}_p)\phi_{n\ell j}(\vec{r}_n)\rangle$$

exit channel — entrance channel



$$V_{np}\phi_d(\vec{r}) \approx D_0\delta(\vec{r})$$ - short range

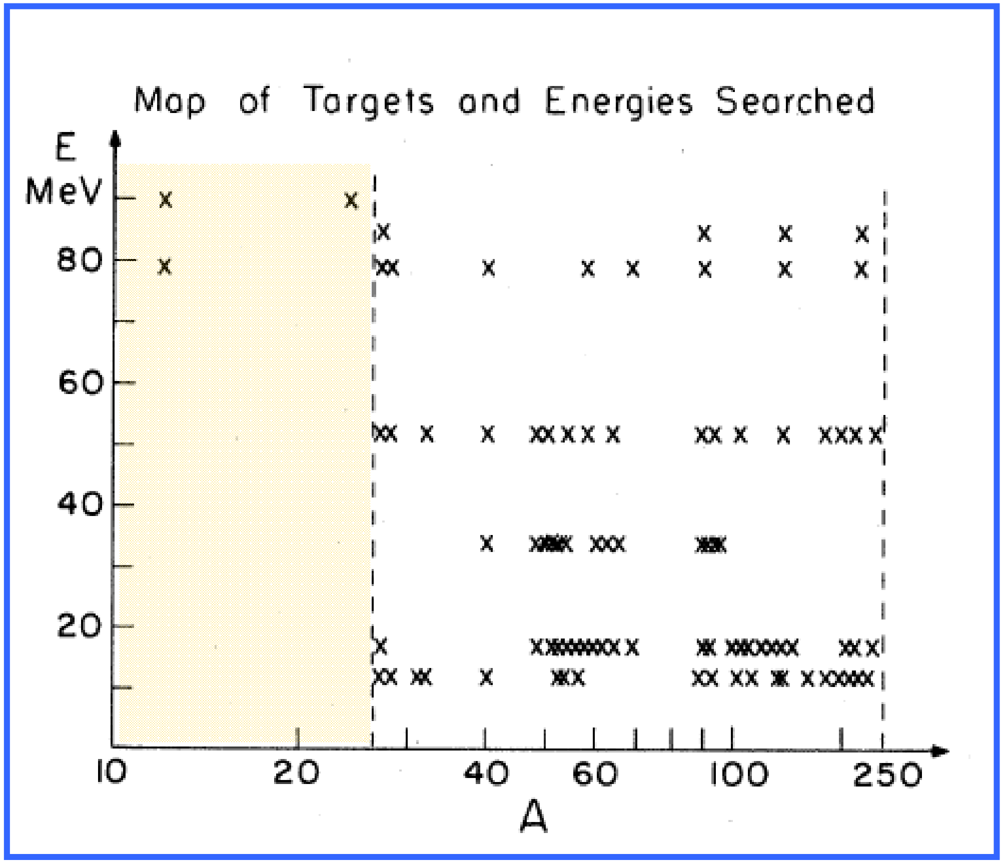
$$\phi_{n\ell j}(\vec{r}_n) = \langle \Phi(A, J_f)|\Phi(A+1, J_i)\rangle$$

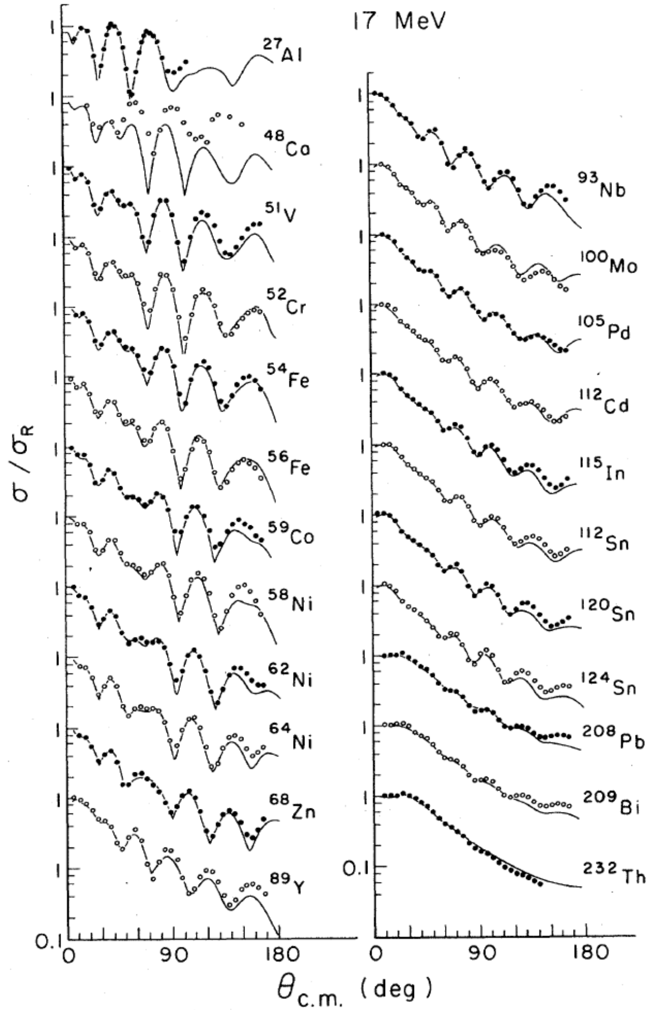
Global optical potentials – e.g. for deuterons

PHYSICAL REVIEW C VOLUME 21, NUMBER 6 JUNE 1980

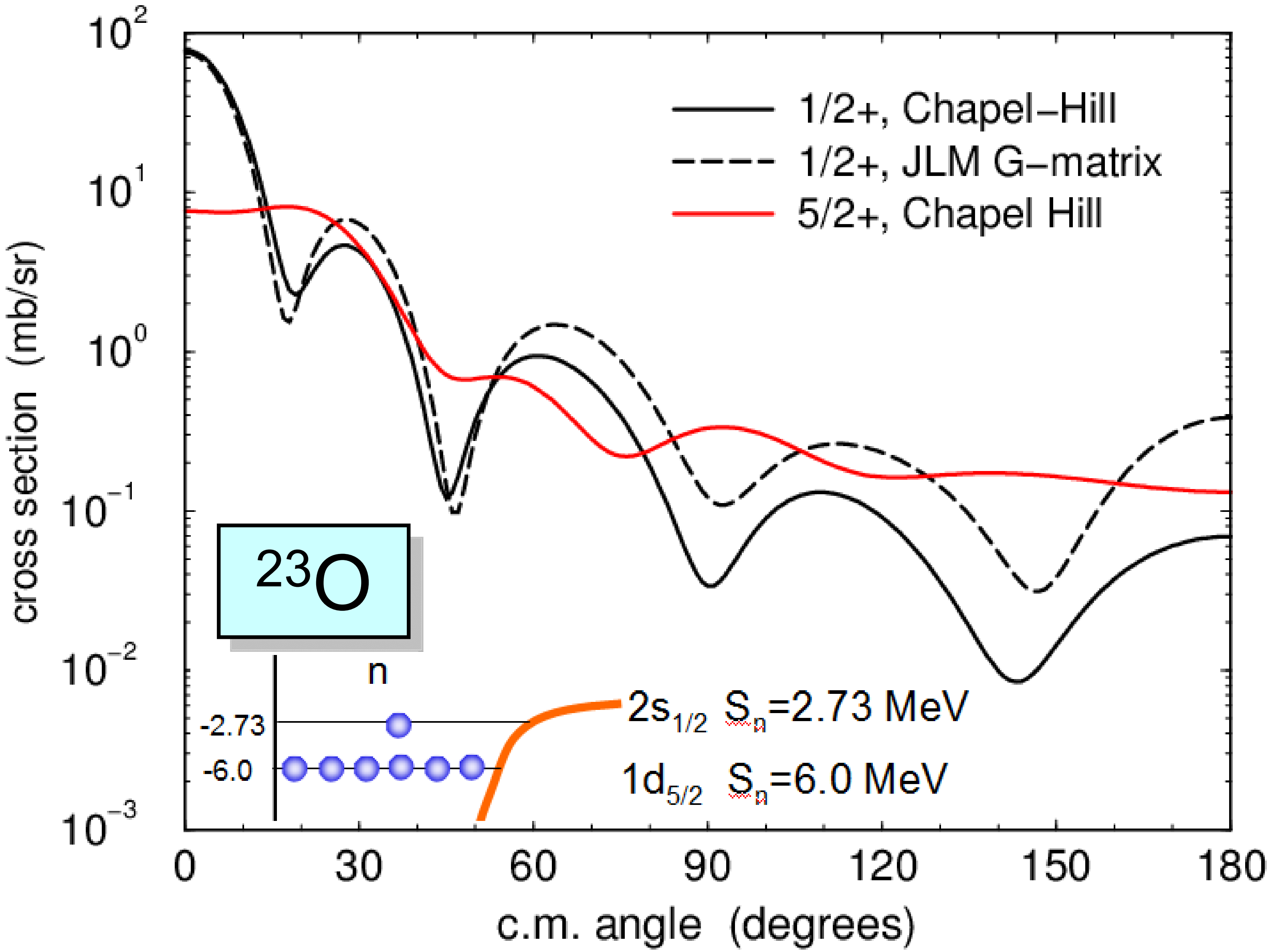
Global optical model potential for elastic deuteron scattering from 12 to 90 MeV

W. W. Daehnick, J. D. Childs,* and Z. Vrcelj

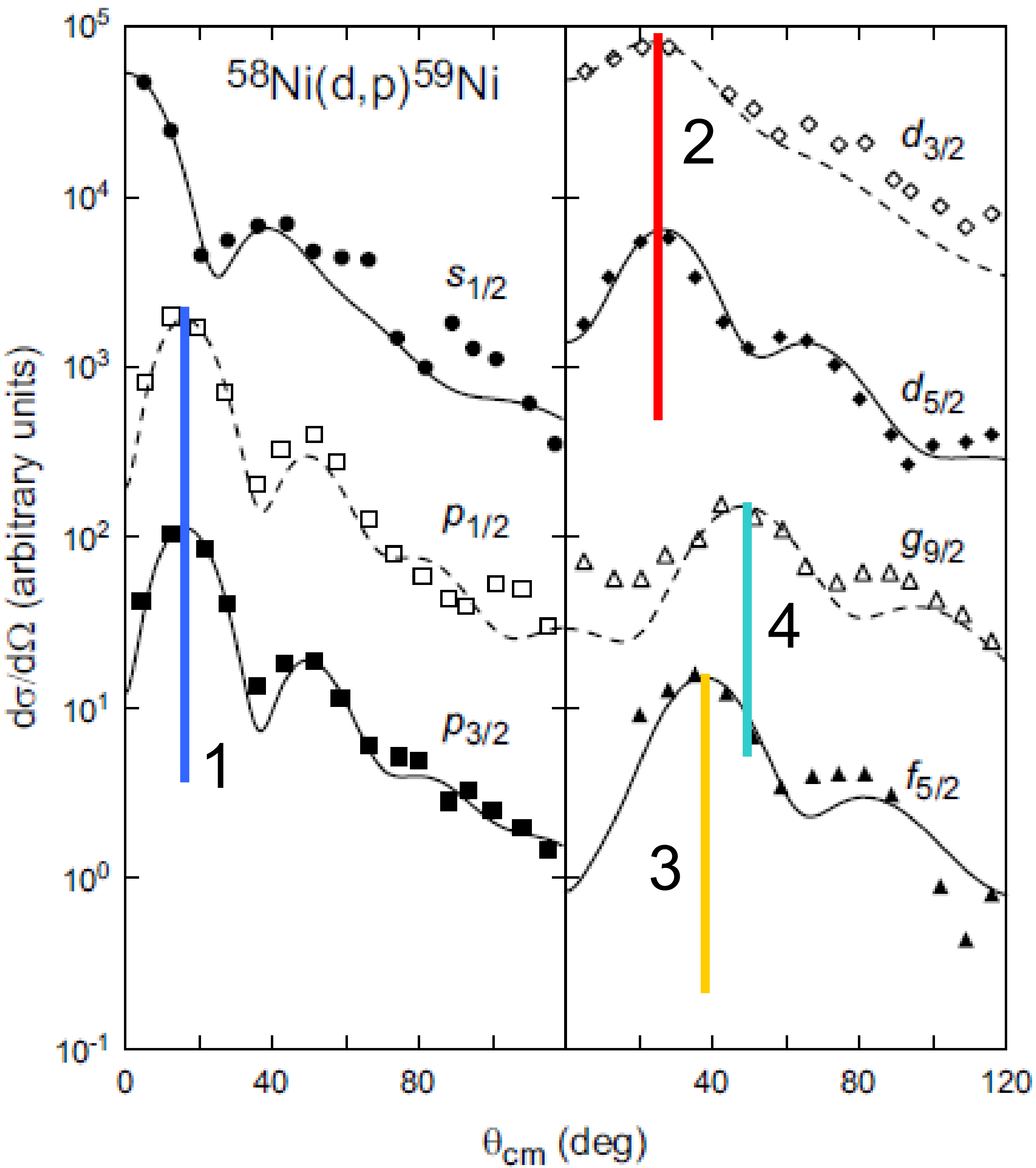




Calculated (p,d) transfer (pick-up) cross sections



Single-particle spectroscopy – angular distributions

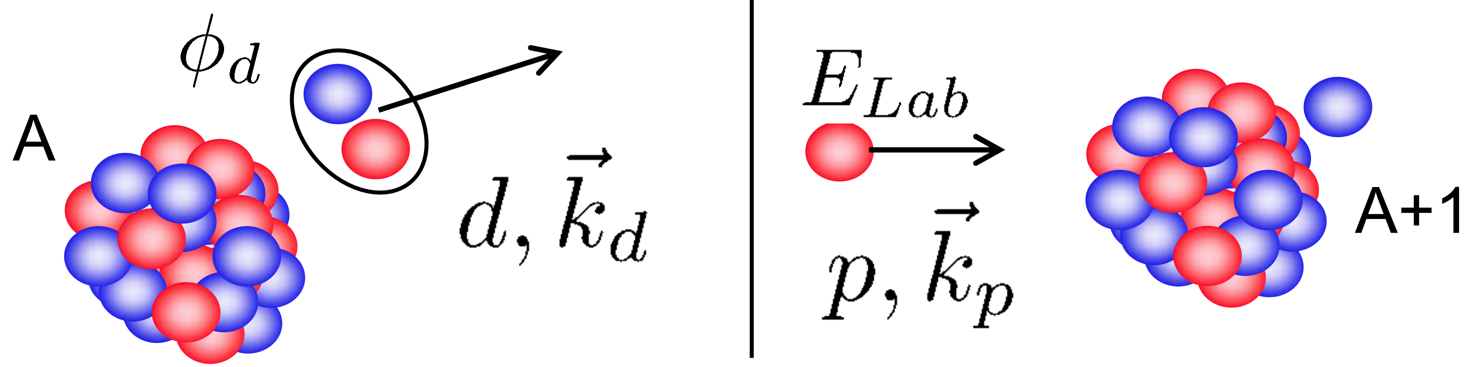


Data: M.S. Chowdhury and H.M. Sen Gupta Nucl. Phys. **A205**, 454 (2005)

Figure: Isotope Science Facility (ISF) White Paper, NSCL (2007)

Transfer reaction – beyond DWBA - breakup

$$T(p,d) = \underbrace{\langle \psi^{(-)}_{d,\vec{k}_d}\, \Phi(A, J_f)}_{\text{exit channel}} | V_{np} | \underbrace{\chi^{(+)}_{p,\vec{k}_p}\, \Phi(A+1, J_i)\rangle}_{\text{entrance channel}}$$



$$[T_R + \mathcal{H}_{np} + V_p(\vec{r}_p) + V_n(\vec{r}_n) - E]\psi^{(+)}_{d,\vec{k}_d} = 0$$

$$\psi^{(+)}_{d,\vec{k}_d} = \exp(i\vec{k}_d \cdot \vec{R})\phi_d(r) + \text{outgoing waves}$$

$$\mathcal{H}_{np}\phi_d = \varepsilon_0 \phi_d, \quad \mathcal{H}_{np}\hat{\phi}_i = \hat{\varepsilon}_i \hat{\phi}_i$$

$$\psi^{(+)}_{d,\vec{k}_d}(\vec{r}, \vec{R}) = \chi_{d,\vec{k}_d}(\vec{R})\phi_d(r) + \sum_i \chi_i(\vec{R})\hat{\phi}_i(\vec{r})$$

Transfer reaction – three-body models - breakup

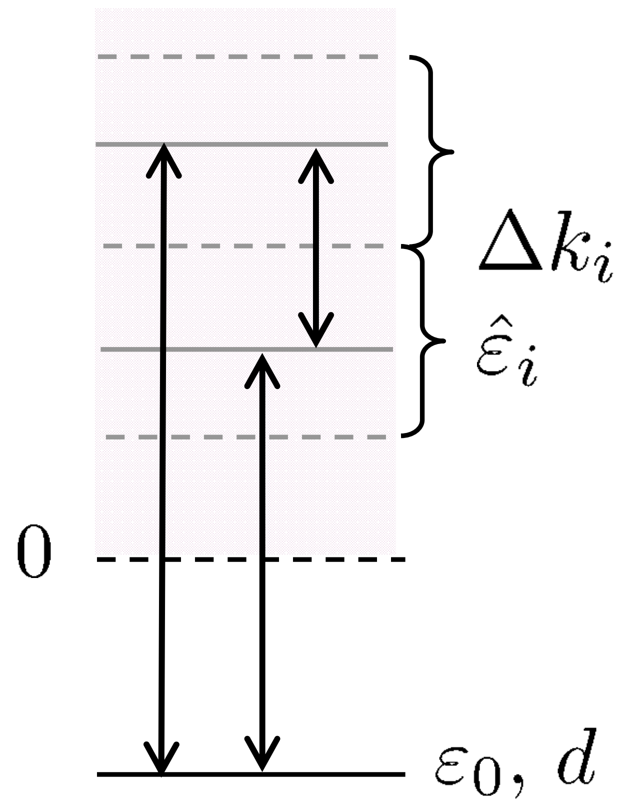
$$T(p,d) = \langle \psi^{(-)}_{d,\vec{k}_d} \Phi(A, J_f) | V_{np} | \chi^{(+)}_{p,\vec{k}_p} \Phi(A+1, J_i) \rangle$$

$$\mathcal{H}_{np}\phi_d = \varepsilon_0 \phi_d, \quad \mathcal{H}_{np}\hat{\phi}_i = \hat{\varepsilon}_i \hat{\phi}_i$$

neutron is also transferred to unbound states (d*) of the n-p system – represented by continuum bins – that are coupled to the deuteron g.s. for as long as the two nucleons remain within the range of

$$V_p(\vec{r}_{pA}), \quad V_n(\vec{r}_n)$$

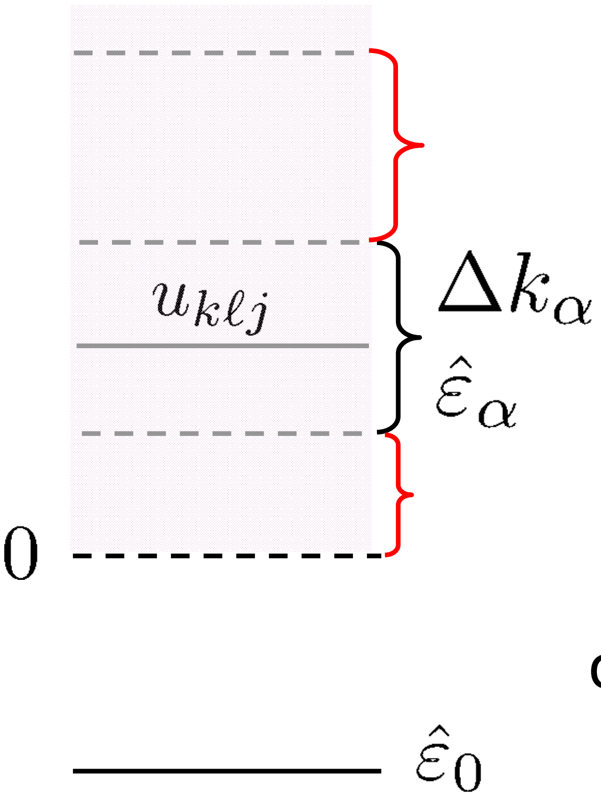
These <u>higher-order effects</u> can be important in slower (lower-energy) reactions



Treating breakup effects with continuum bins

Scattering states

$$u_{k\ell j}(r) \quad \rightarrow \quad e^{i\delta_{\ell j}}\left[\cos\delta_{\ell j} F_\ell(\eta, kr) + \sin\delta_{\ell j} G_\ell(\eta, kr)\right]$$



$$\int_0^\infty dr\, u_{k\ell j}(r)\, u^*_{k'\ell j}(r) = \frac{\pi}{2}\delta(k - k')$$

$$\hat{u}_{\alpha\ell j}(r) = \sqrt{\frac{2}{\pi N_\alpha}} \int_{\Delta k_\alpha} dk\, g(k)\, u_{k\ell j}(r)$$

$$N_\alpha = \int_{\Delta k_\alpha} dk\, [g(k)]^2$$

weight function

orthonormal set

$$\int_0^\infty dr\, \hat{u}^*_{\alpha\ell j}(r)\, \hat{u}_{\beta\ell j}(r) = \delta_{\alpha\beta}$$

$$g(k) = 1 \qquad g(k) = \sin\delta_{\ell j}$$

Adiabatic three-body model – breakup made simpler

$$T(p,d) = \langle \psi^{(-)}_{d,\vec{k}_d} \Phi(A, J_f)|V_{np}|\chi^{(+)}_{p,\vec{k}_p} \Phi(A+1, J_i)\rangle$$

$$[T_R + \mathcal{H}_{np} + V_p(\vec{r}_{pA}) + V_n(\vec{r}_n) - E]\psi^{(+)}_{d,\vec{k}_d}(\vec{r}, \vec{R}) = 0$$

Since to calculate the transfer amplitude we need the three body wave function only in regions where $V_{np} \neq 0$, $r \approx 0$

$$\mathcal{H}_{np} \to \varepsilon_0,\ V_p(\vec{r}_{pA}) \to V_p(\vec{R}), \quad V_n(\vec{r}_n) \to V_n(\vec{R})$$

$$[T_R + \varepsilon_0 + V_p(\vec{R}) + V_n(\vec{R}) - E]\psi^{(+)}_{d,\vec{k}_d}(\vec{r} \approx 0, \vec{R}) = 0$$

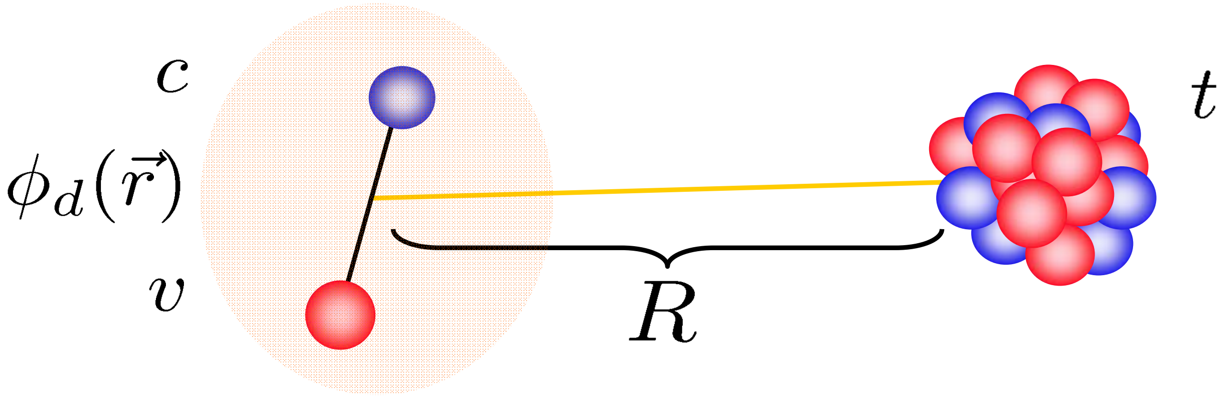
So, with $E_0 = E - \varepsilon_0$

$$\psi^{(+)}_{d,\vec{k}_d}(\vec{r} \approx 0, \vec{R}) \approx \chi^{Ad}_{d,\vec{k}_d}(\vec{R})\phi_d(r),$$

$$[T_R + V_p(\vec{R}) + V_n(\vec{R}) - E_0]\chi^{Ad}_{d,\vec{k}_d}(\vec{R}) = 0$$

"ADWA"

The adiabatic deuteron distorting potential



$$V_{Ad}(\vec{R}) = \int d\vec{r}\,[V_n(\vec{r}_n) + V_p(\vec{r}_p)]|\phi_d(\vec{r})|^2$$

$$[T_R + \underbrace{V_p(\vec{R}) + V_n(\vec{R})} - E_0]\chi^{Ad}_{d,\vec{k}_d}(\vec{R}) = 0$$

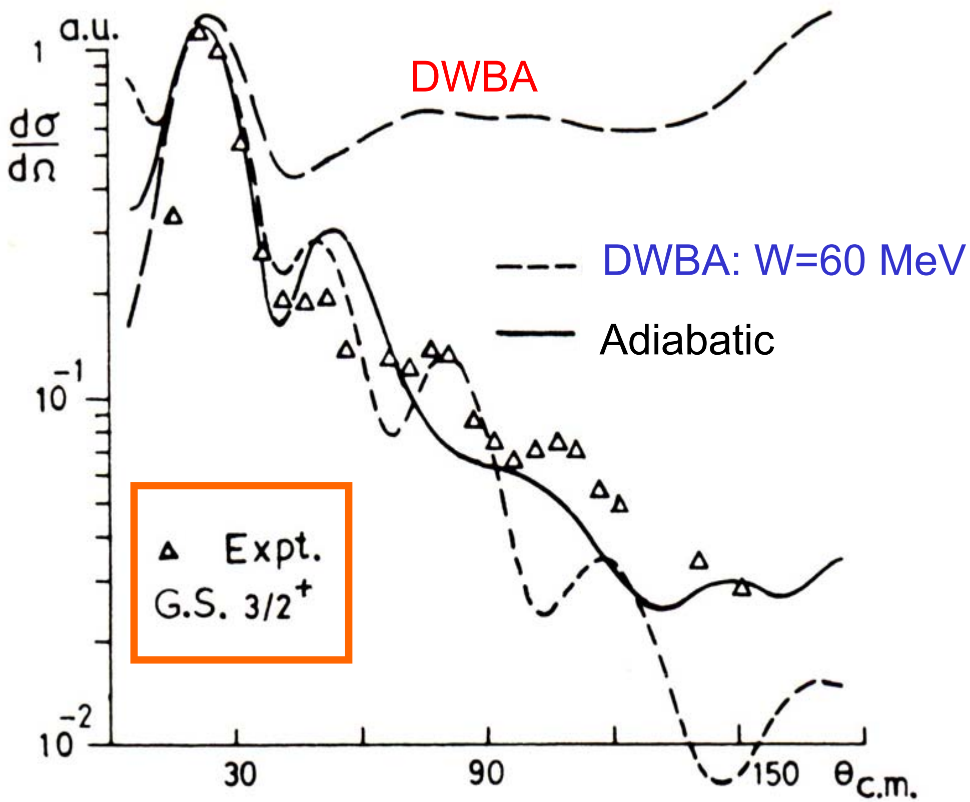
$$V_{Ad}(\vec{R}) = V_n(\vec{R}) + V_p(\vec{R})$$

$$V_{Ad}(\vec{R}) = \int d\vec{r}\,[V_n(\vec{r}_n) + V_p(\vec{r}_{pA})]\,\delta(\vec{r})$$

this is NOT an optical potential and is not meant to and DOES NOT describe deuteron elastic scattering

Key features for transfer reactions - spectroscopy

$^{40}Ca(p,d)^{39}Ca$, 30.5 MeV



Increased reflection at nuclear surface - less diffuse deuteron channel potential

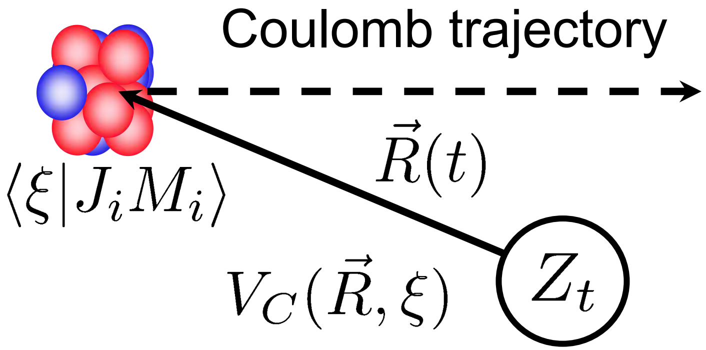
Greater surface localisation - L-space localisation

Less nuclear volume contribution and less sensitivity to optical model parameters

More consistent sets of deduced spectroscopic factors

J.D. Harvey and R.C. Johnson, Phys. Rev.C **3** (1971) 636

Coulomb interaction – electromagnetic probe



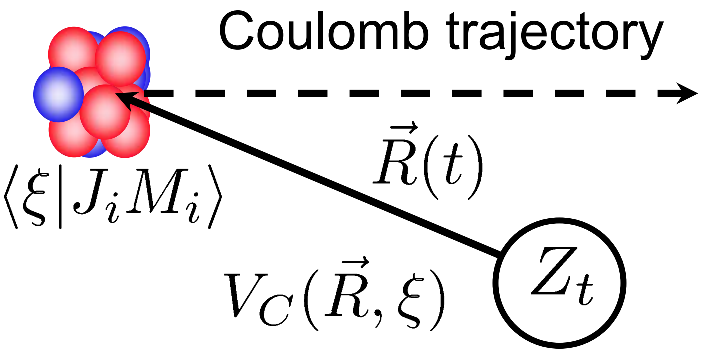
$$\xi \equiv \{\vec{r}_i | i = 1, 2, \ldots A\}$$

$$V_C(\vec{R},\xi) = \sum_{\text{protons}} \frac{Z_t e^2}{|\vec{R}+\vec{r}_i|}\ , \quad (R > r_i),$$

$$= \sum_{LM,i}^{Z} \frac{4\pi\, Z_t e^2}{2L+1} \frac{(-1)^L}{R^{L+1}}\, r_i^L Y_{LM}(\hat{r}_i) Y^*_{LM}(\hat{R})$$

$$Q_{LM} = \sum_{\text{protons}}^{Z} e\, r_i^L Y_{LM}(\hat{r}_i) = \sum_{i=1}^{Z} Q_{LM}(i)$$

Coulomb excitation - transition strengths



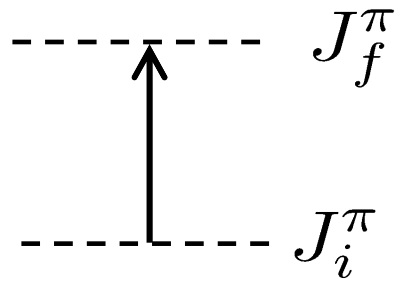
$$\xi \equiv \{\vec{r}_i | i = 1, 2, \ldots A\}$$

$$Q_{LM} = \sum_{\text{protons}}^{Z} e r_i^L Y_{LM}(\hat{r}_i) = \sum_{i=1}^{Z} Q_{LM}(i)$$

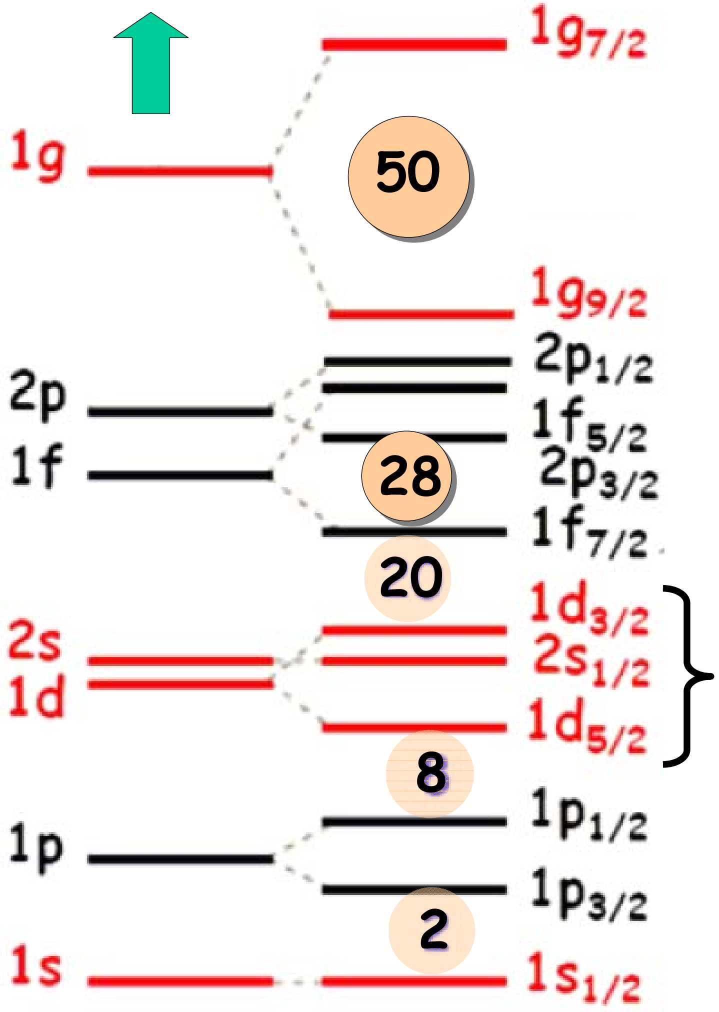
$$B(EL; J_i \to J_f) = \frac{1}{2J_i + 1} \sum_{M_i M_f} |\langle J_f M_f | Q_{LM} | J_i M_i \rangle|^2$$

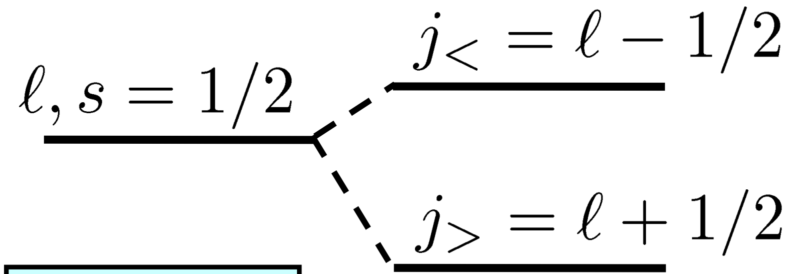
Weisskopf units – single proton expectation

$$B(EL)_{Wu} = \frac{2L+1}{4\pi} \left(\frac{3\mathcal{R}^L}{L+3} \right)^2 e^2 \ \mathrm{fm}^{2L}$$



Halo configurations – use of Coulomb dissociation

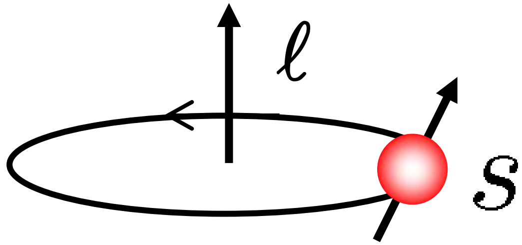




^{19}C

Z=6

N=13



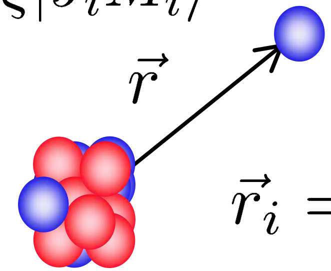
$$V_{\ell s}(r)\vec{\ell}\cdot\vec{s}$$

$$V(r) + V_{so}(r)\vec{\ell}\cdot\vec{s}$$

$$V_{so}(r) < 0$$

Coulomb breakup – n-halo systems: weak binding

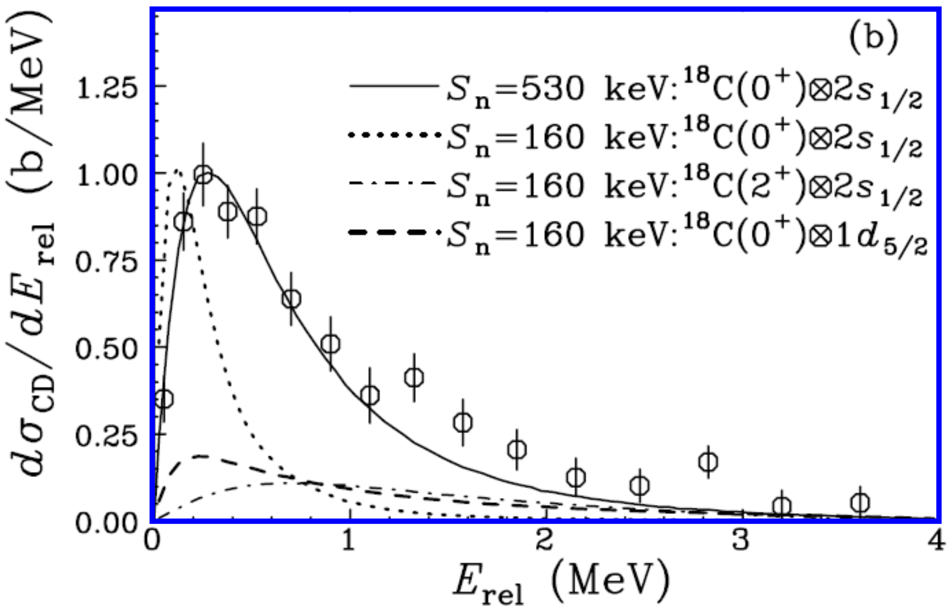
$\langle \xi | J_i M_i \rangle$

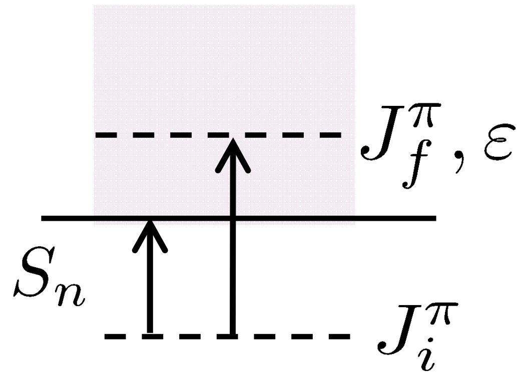


$$Q_{1M} = \sum_{\text{protons}} e\, r_i Y_{LM}(\hat{r}_i)$$

$$\vec{r}_i = \vec{x}_i - \frac{\vec{r}}{(A_c+1)} \qquad = Q^c_{1M} - \frac{Z_c}{A_c+1} e\, r Y_{1M}(\hat{r})$$

$$B(E1; J_i \to J_f, \varepsilon) = \frac{1}{2J_i+1} \sum_{M_i M_f} |\langle J_f M_f, \varepsilon | Q_{1M} | J_i M_i \rangle|^2$$





T. Nakamura et al., Phys. Rev. Lett. **83**, 1112–1115 (1999)