The Joint Institute for Nuclear Astrophysics

JINA "Methods of Direct Nuclear Reactions" School

NSCL, East Lansing MI, 9-20th April 2007

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Session (learning) aims:

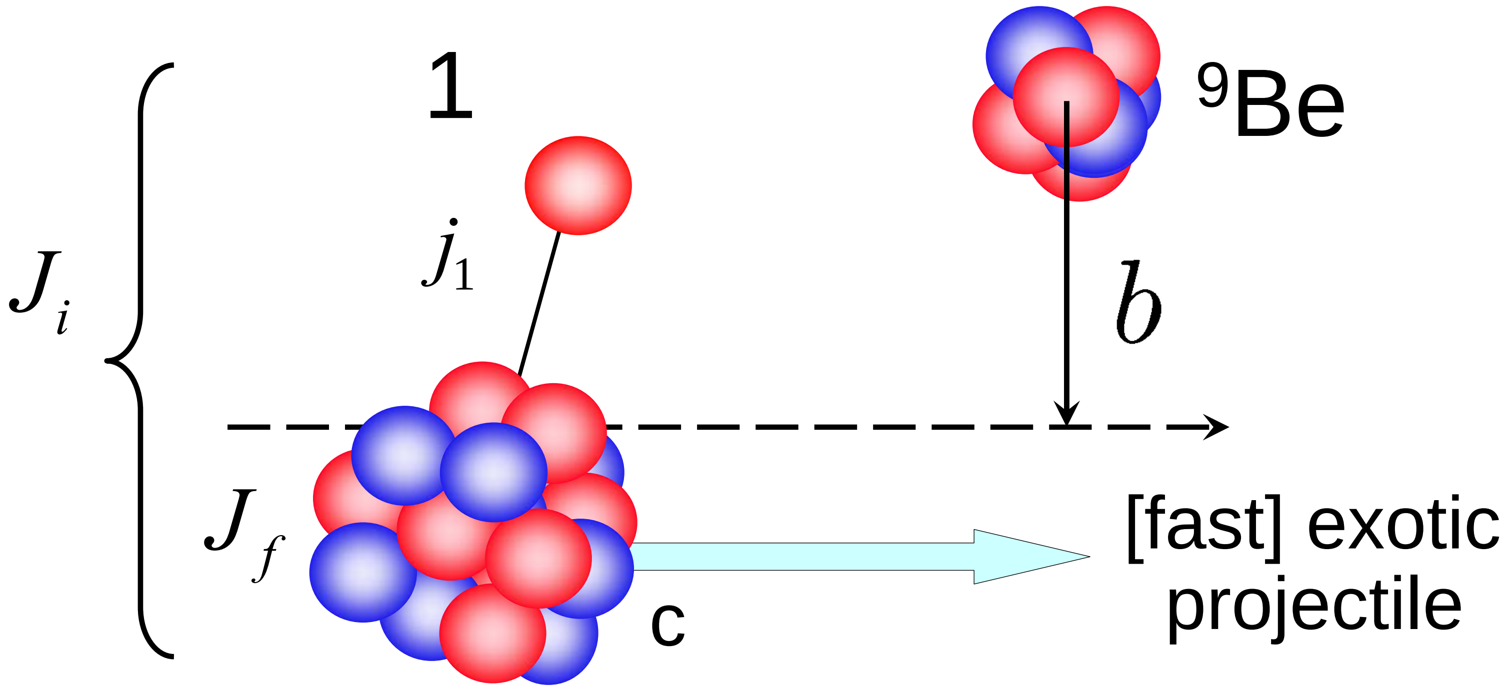
To introduce nucleon knockout reactions and show how these reactions can be calculated from an assumed bound state wave function for the removed nucleon and the eikonal S-matrices of earlier lectures.

To discuss the momentum distributions of the reaction residues (the projectile less one nucleon) and to be able to calculate these for different assumed bound states of the removed nucleon and for reasonable S-matrices.

To calculate realistic S-matrices for the core-target and nucleon-target systems and to compare predictions with neutron knockout data for $^{11}Be \rightarrow {}^{10}Be$(gs) and to different final states in the case of $^{15}C \rightarrow {}^{14}C(J)$.

Probing single particle (shell model) states

One nucleon removal – at ~100 MeV/nucleon

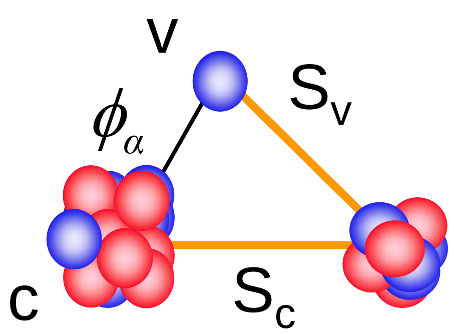


Experiments do not measure target final states. Final state of core c measured (sometimes) – using decay gamma ray coincidences.

P.G. Hansen and J.A. Tostevin, Ann Rev Nucl Part Sci **53** (2003) 219

Eikonal theory - dynamics and structure

Independent scattering information of c and v from target



dynamics

$$S_{\alpha\beta}(b) = \langle \phi_\beta \,|\, \overbrace{S_c(b_c)\, S_v(b_v)}\, |\, \phi_\alpha \rangle$$

structure

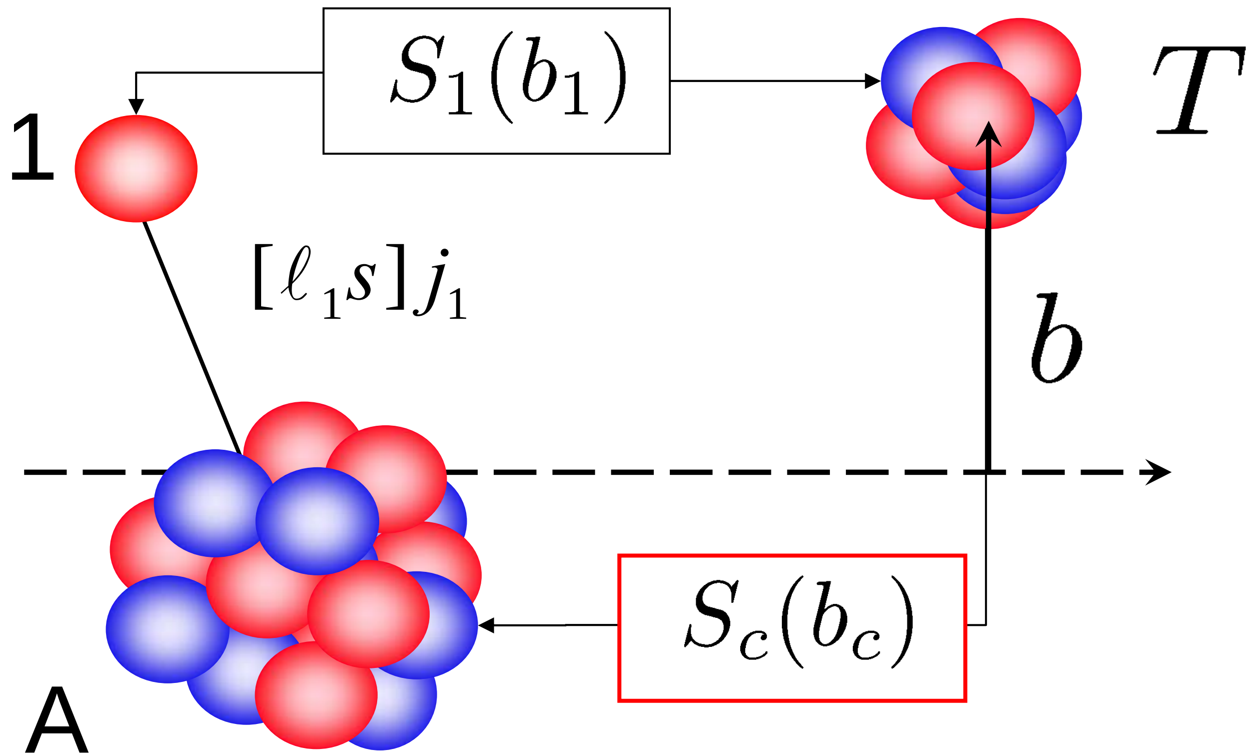
Use the best available few- or many-body wave functions

More generally,

$$S_{\alpha\beta}(b) = \langle \varphi_\beta \,|\, S_1(b_1)\, S_2(b_2) \ldots\ldots S_n(b_n) \,|\, \varphi_\alpha \rangle$$

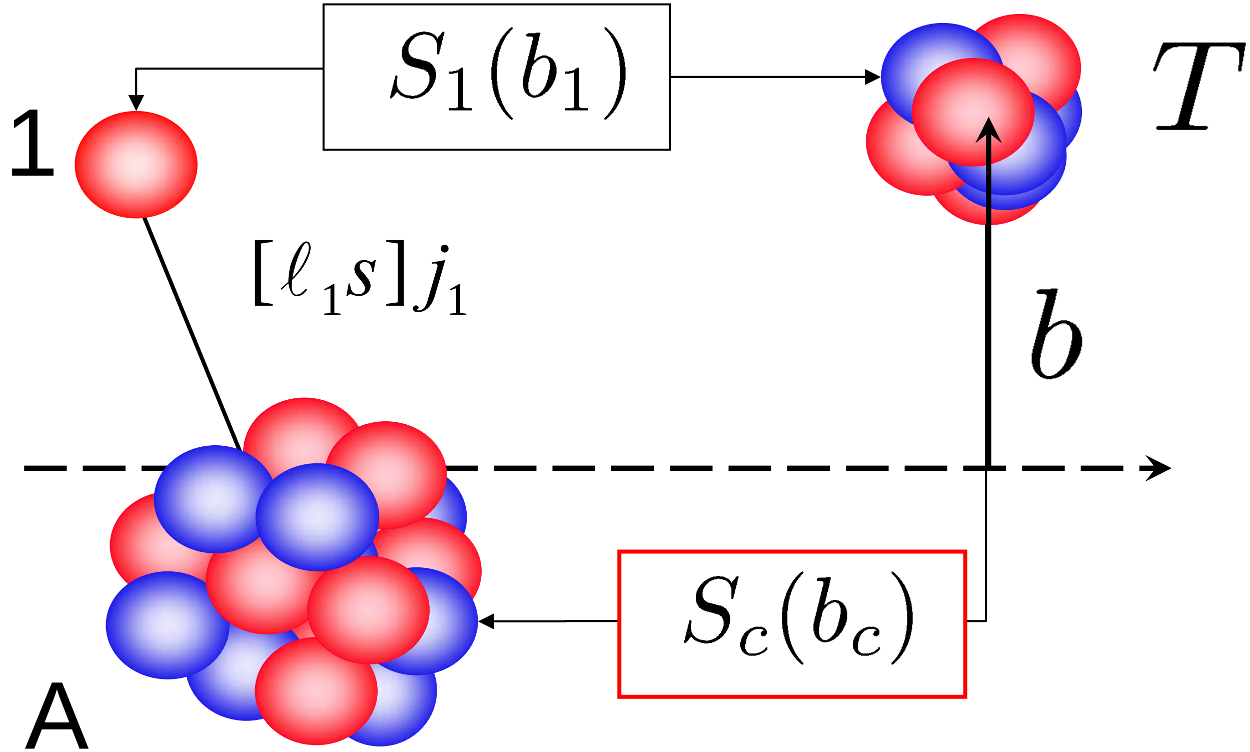
for any choice of 1,2 ,3, ….. n clusters for which a most realistic wave function φ is available

Stripping of a nucleon



$$\sigma_{\text{strip}} = \int d\mathbf{b} \; \langle \phi_0 \,||\, S_C \,|^2 \,(1 - |\, S_1 \,|^2)\,|\, \phi_0 \rangle$$

Diffractive (breakup) removal of a nucleon



$$\sigma_{\text{diff}} = \int d\mathbf{b} \left\{ \langle \phi_0 \,|\, |S_c\, S_v|^2 \,|\, \phi_0 \rangle - |\langle \phi_0 \,|\, S_c\, S_v \,|\, \phi_0 \rangle|^2 \right\}$$

Absorptive cross sections - target excitation

Since our effective interactions are complex all our S(b) include the effects of absorption due to inelastic channels → $|S(b)|^2 \leq 1$

$$\sigma_{abs} = \sigma_R - \sigma_{diff} = \int d\mathbf{b}\ \langle \phi_0 | \underbrace{1 - |S_c S_v|^2} | \phi_0 \rangle$$

$$\left\{ \begin{array}{l} |S_v|^2 (1 - |S_c|^2) + \\ |S_c|^2 (1 - |S_v|^2) + \\ (1 - |S_c|^2)(1 - |S_v|^2) \end{array} \right.$$

- $|S_v|^2 (1 - |S_c|^2)$: v survives, c absorbed
- $|S_c|^2 (1 - |S_v|^2)$: v absorbed, c survives
- $(1 - |S_c|^2)(1 - |S_v|^2)$: v absorbed, c absorbed

$$\sigma_{strip} = \int d\mathbf{b}\ \langle \phi_0 || S_c|^2 (1 - |S_v|^2) | \phi_0 \rangle$$

stripping of v from projectile exciting the target. c scatters at most elastically with the target

Related equations exist for the differential cross sections, etc.

Diffractive dissociation of composite systems

The total cross section for removal of the valence particle from the projectile due to the break-up (or diffractive dissociation) mechanism is the break-up amplitude, summed over all final continuum states

$$\sigma_{\text{diff}} = \int d\mathbf{k} \int d\mathbf{b}\, |\langle \phi_{\mathbf{k}} \,|\, S_c(b_c)\, S_v(b_v)\ |\phi_0\rangle|^2$$

but, using completeness of the break-up states

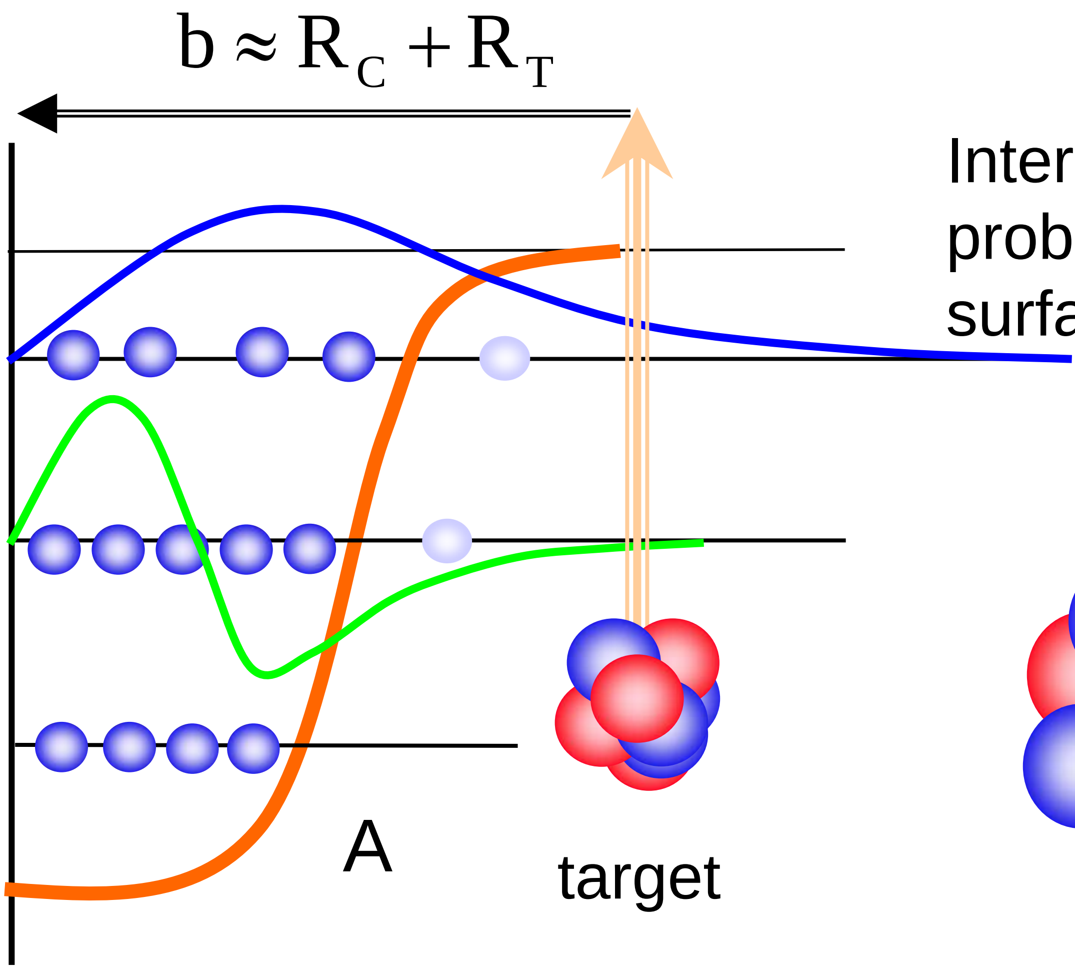
$$\int d\mathbf{k}\, |\phi_{\mathbf{k}}\rangle\langle\phi_{\mathbf{k}}| = 1 - |\phi_0\rangle\langle\phi_0| - |\phi_1\rangle\langle\phi_1| \ \ldots\ldots$$

If > 1 bound state

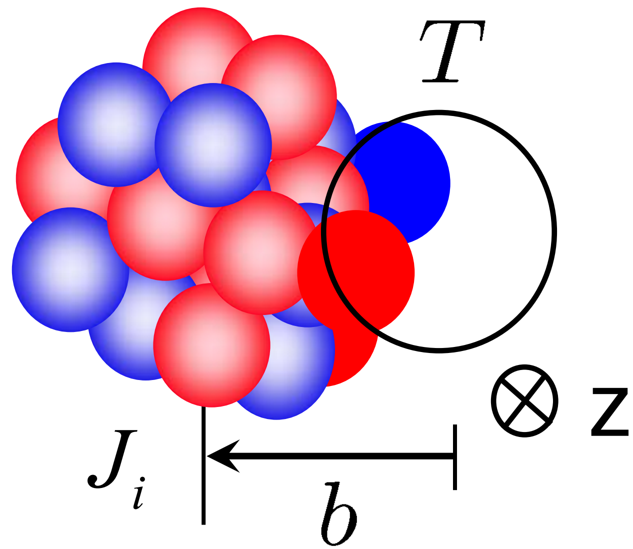
can (for a weakly bound system with a single bound state) be expressed in terms of only the projectile ground state wave function as:

$$\sigma_{\text{diff}} = \int d\mathbf{b} \left\{ \langle\phi_0 \,||S_c\, S_v|^2|\, \phi_0\rangle - |\langle\phi_0\, | S_c\, S_v \,|\phi_0\rangle|^2 \right\}$$

Viewed from the rest frame of the projectile



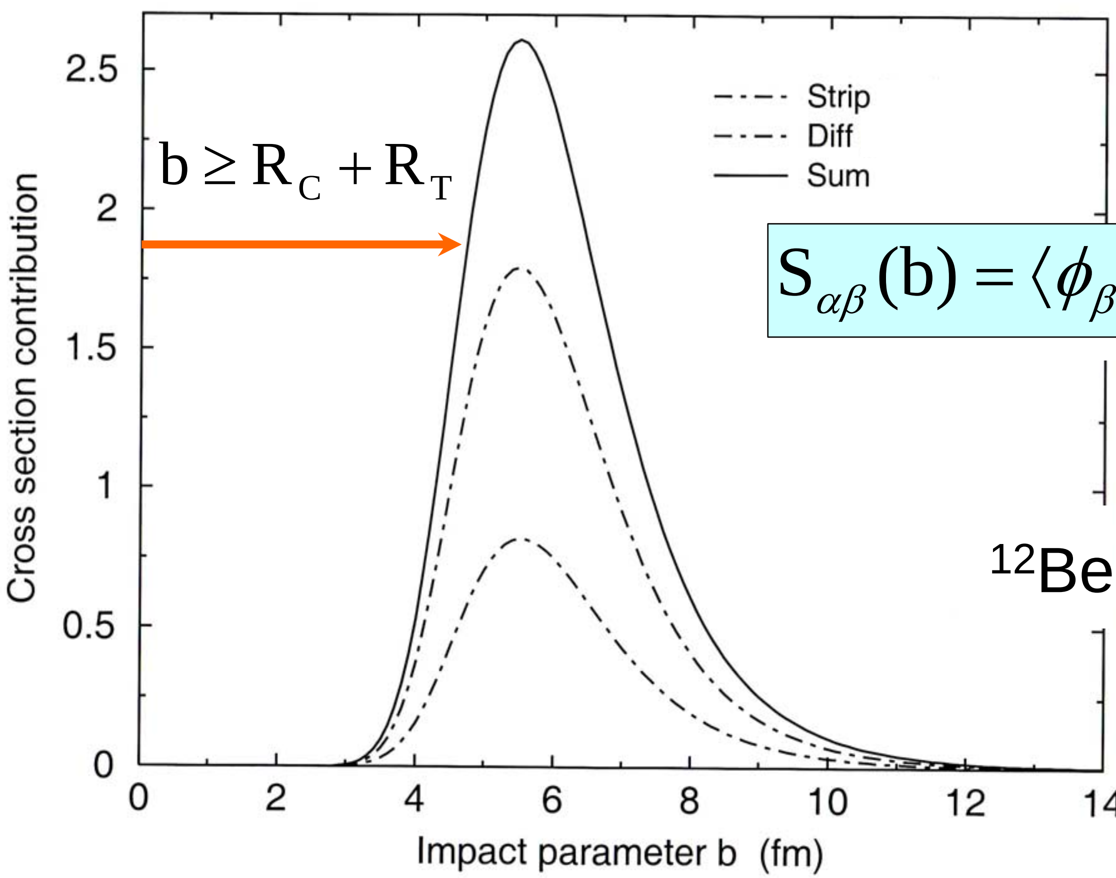
Interaction with the target probes wave functions at surface and beyond



Mass A-1 residue will be left in the ground state or an excited state

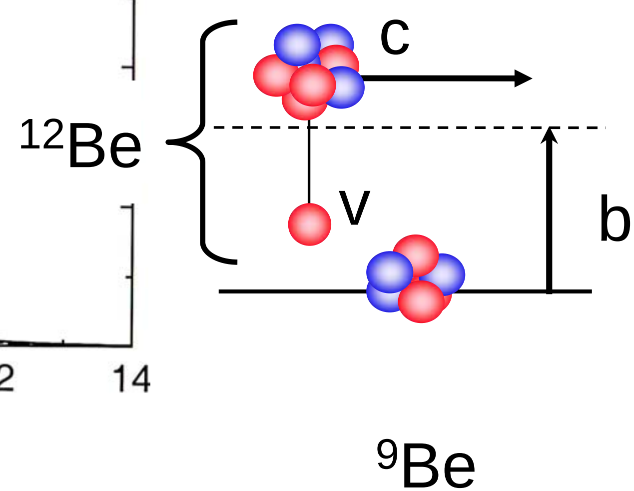
Contributions are from surface and beyond

^{12}Be+^{9}Be $\rightarrow$ ^{11}Be(gs)+X, 80A MeV



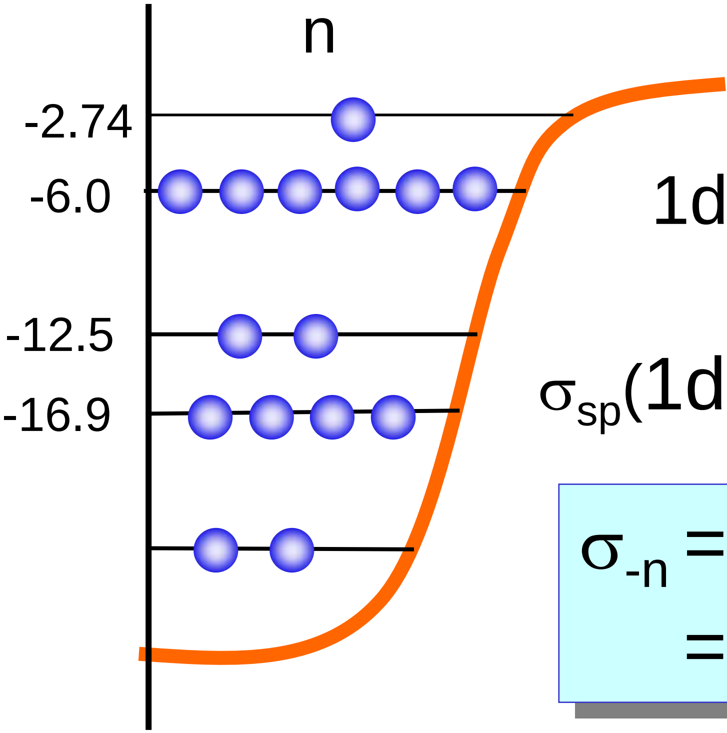
Eikonal reaction theory

$$S_{\alpha\beta}(b) = \langle \phi_\beta \mid S_c(b_c)\, S_v(b_v) \mid \phi_\alpha \rangle$$



Orientation - extreme sp model – inclusive sigma

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



$2s_{1/2}$ S_n=2.74 MeV

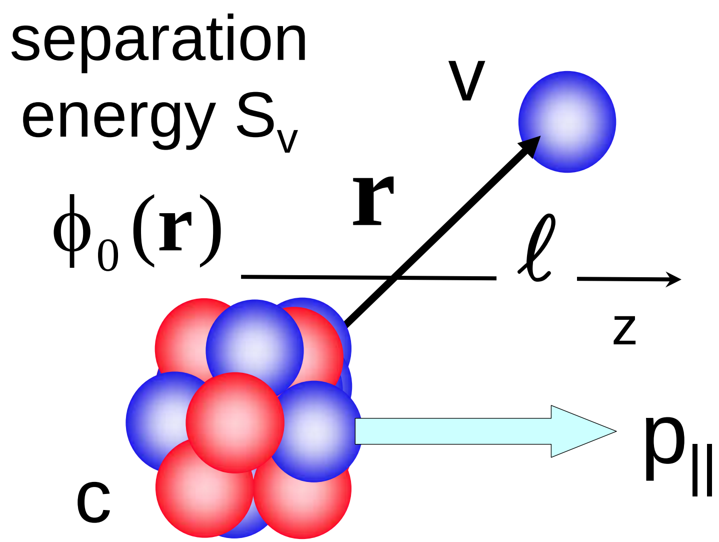
$1d_{5/2}$ S_n=6.0 MeV

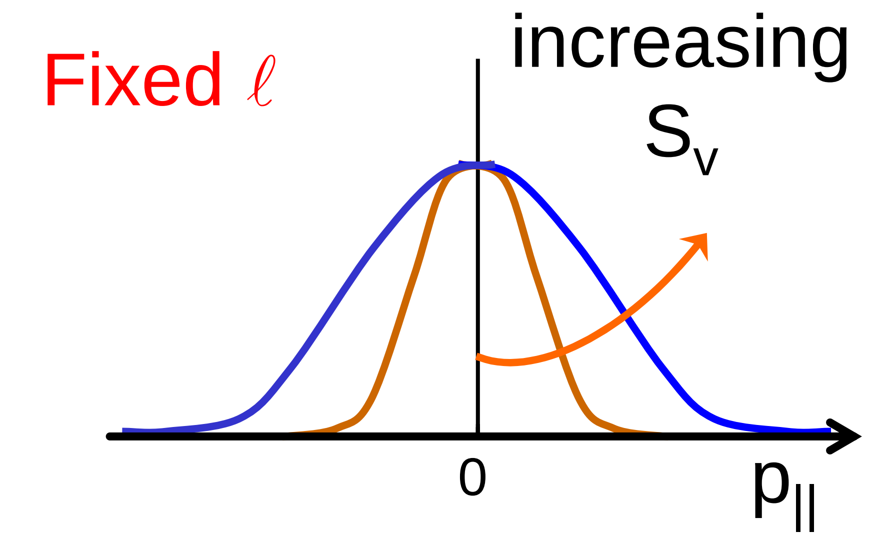
$\sigma_{sp}(1d_{5/2})$=23 mb $\sigma_{sp}(2s_{1/2})$=64 mb

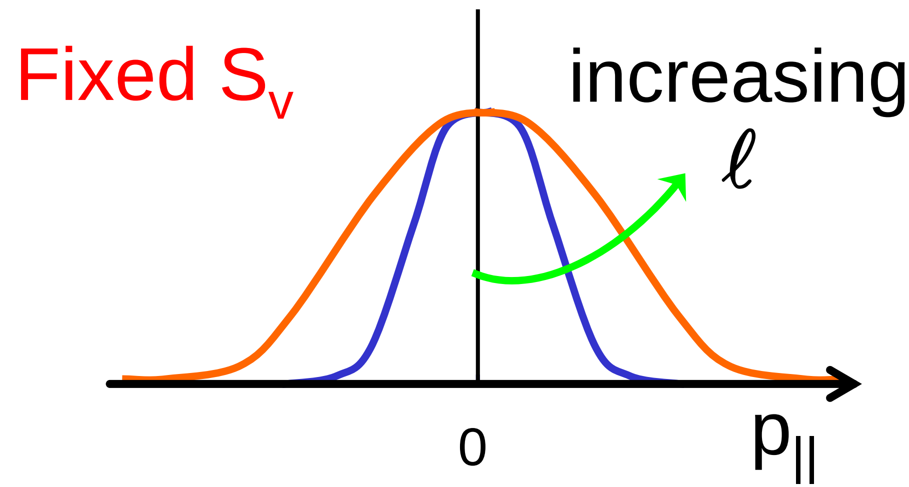
$$\sigma_{-n} = 6\,\sigma_{sp}(1d_{5/2}) + \sigma_{sp}(2s_{1/2})$$
$$= 202 \text{ mb}$$

<u>Measurement at RIKEN</u> [Kanungo *et al.* PRL **88** (‘02) 142502] at 72 MeV/nucleon on a ^{12}C target; σ_{-n} = 233(37)mb

Measurement of the residue's momentum







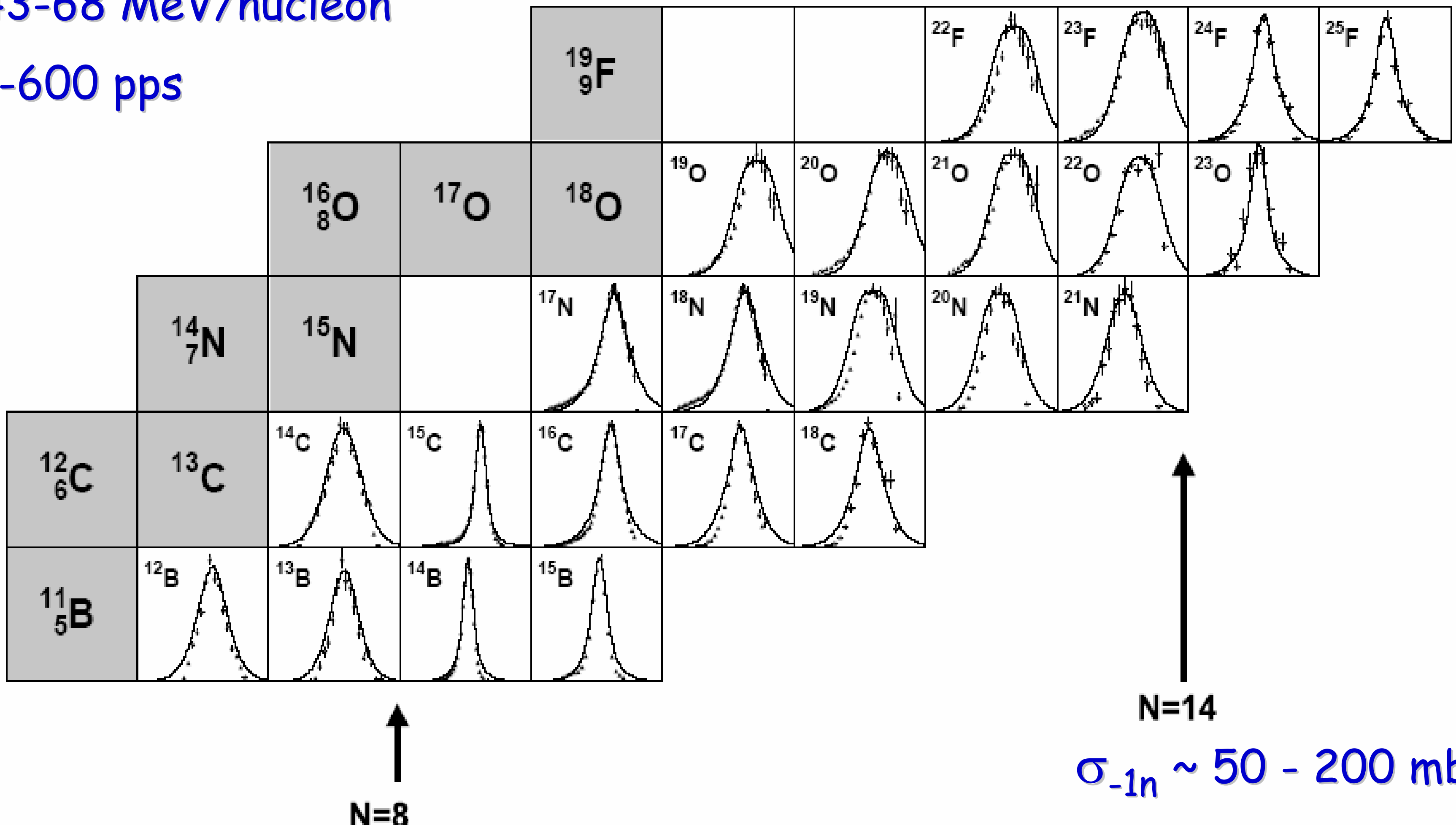
consider momentum components $p_{||}$ of the core parallel to the beam direction, in the projectile rest frame

$$\Delta p \Delta x > \hbar/2$$

Systematics show shell effects

43-68 MeV/nucleon

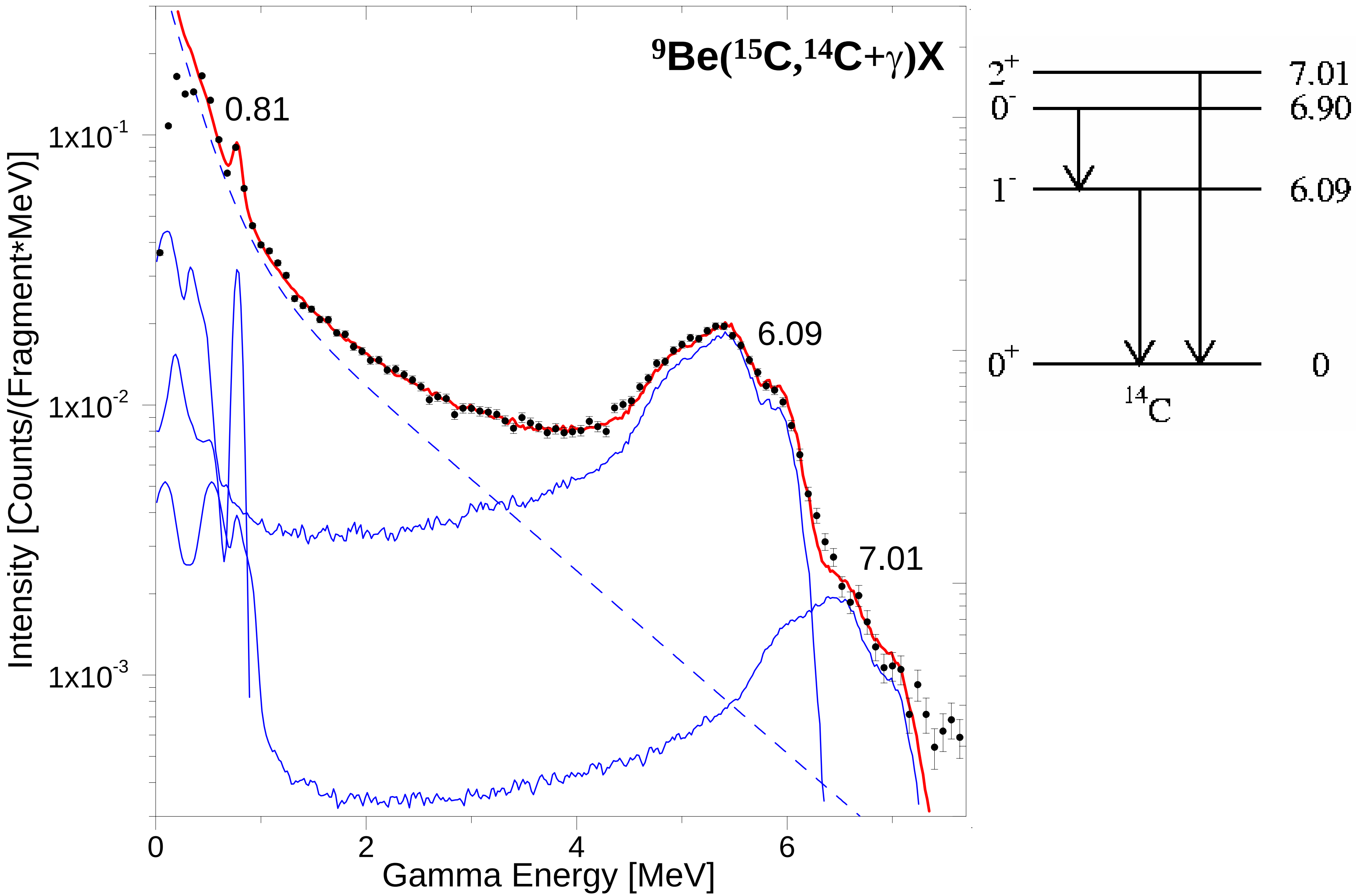
1-600 pps



σ_{-1n} ~ 50 - 200 mb

FWHM ~ 50 - 240 MeV/c

Nucleon knockout with gamma detection

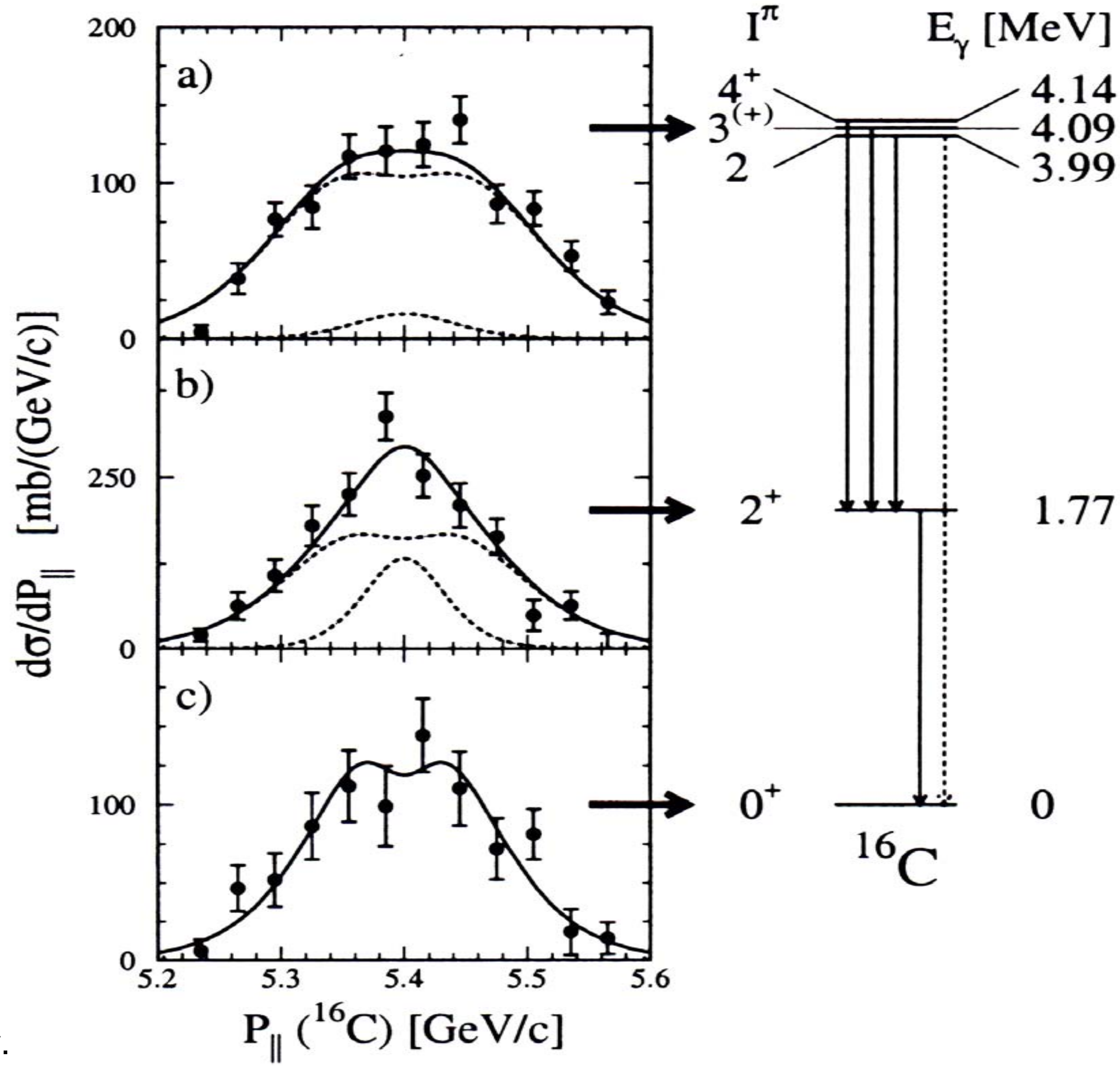


Single-neutron knockout from ^{17}C

ℓ=0,2 admixture

ℓ=0,2 admixture

pure ℓ=2



V. Maddalena et al. Phys. Rev. C **63** (2001) 024613

Residue momentum distributions after knockout

$$\sigma_{str} = \frac{1}{2l+1}\sum_m \int d^2b\,\langle\psi_{lm}||S_c(b_c)|^2(1-|S_n(b_n)|^2)|\psi_{lm}\rangle$$

$$= \frac{1}{2l+1}\sum_m \int d^2b_n\,(1-|S_n(b_n)|^2)\langle\psi_{lm}|\underbrace{S_c^*\,S_c}|\psi_{lm}\rangle$$

$$\frac{1}{(2\pi)^3}\int d\vec{k}_c|\vec{k}_c\rangle\langle\vec{k}_c| = 1$$

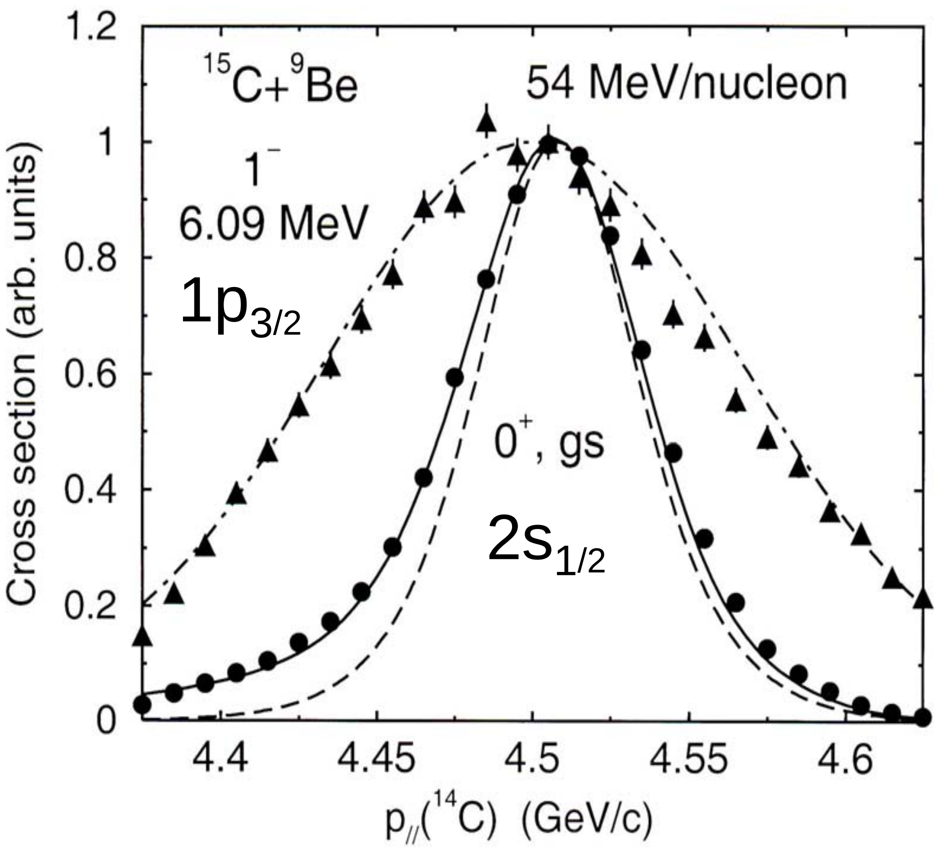
In projectile rest frame:

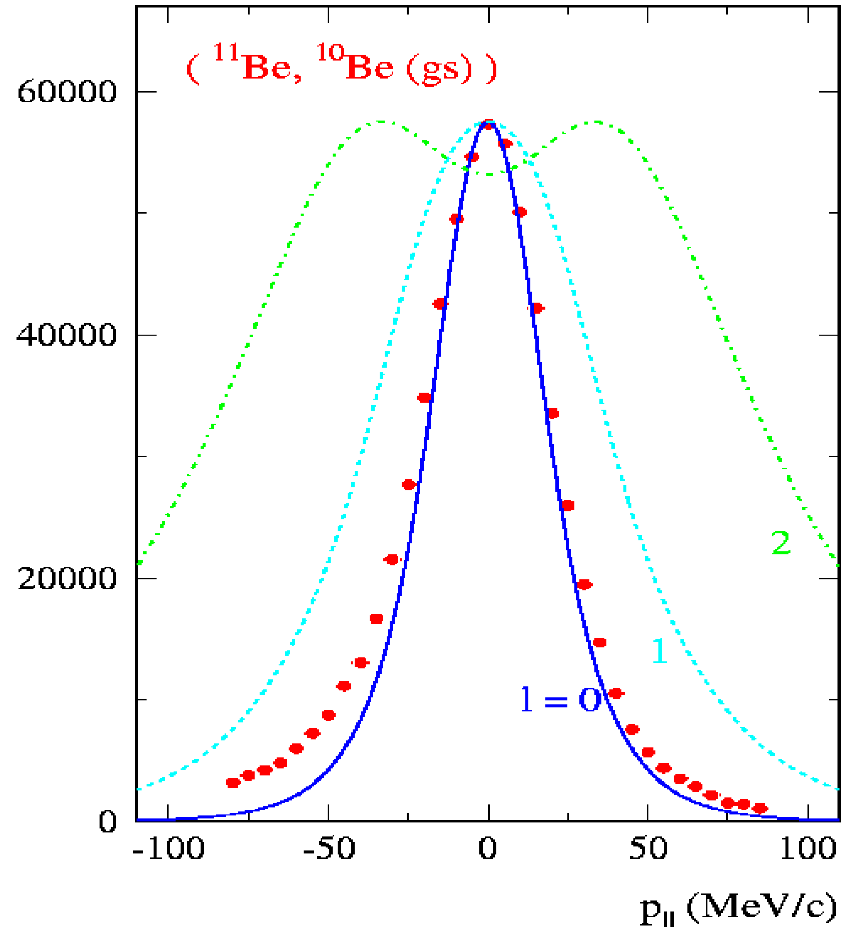
$$\frac{d\sigma_{str}}{d^3k_c} = \frac{1}{(2\pi)^3}\frac{1}{2l+1}\sum_m \int d^2b_n[1-|S_n(b_n)|^2] \times\left|\int d^3r e^{-i\mathbf{k}_c\cdot\mathbf{r}}S_c(b_c)\psi_{lm}(\mathbf{r})\right|^2$$

Residue parallel momentum distribution

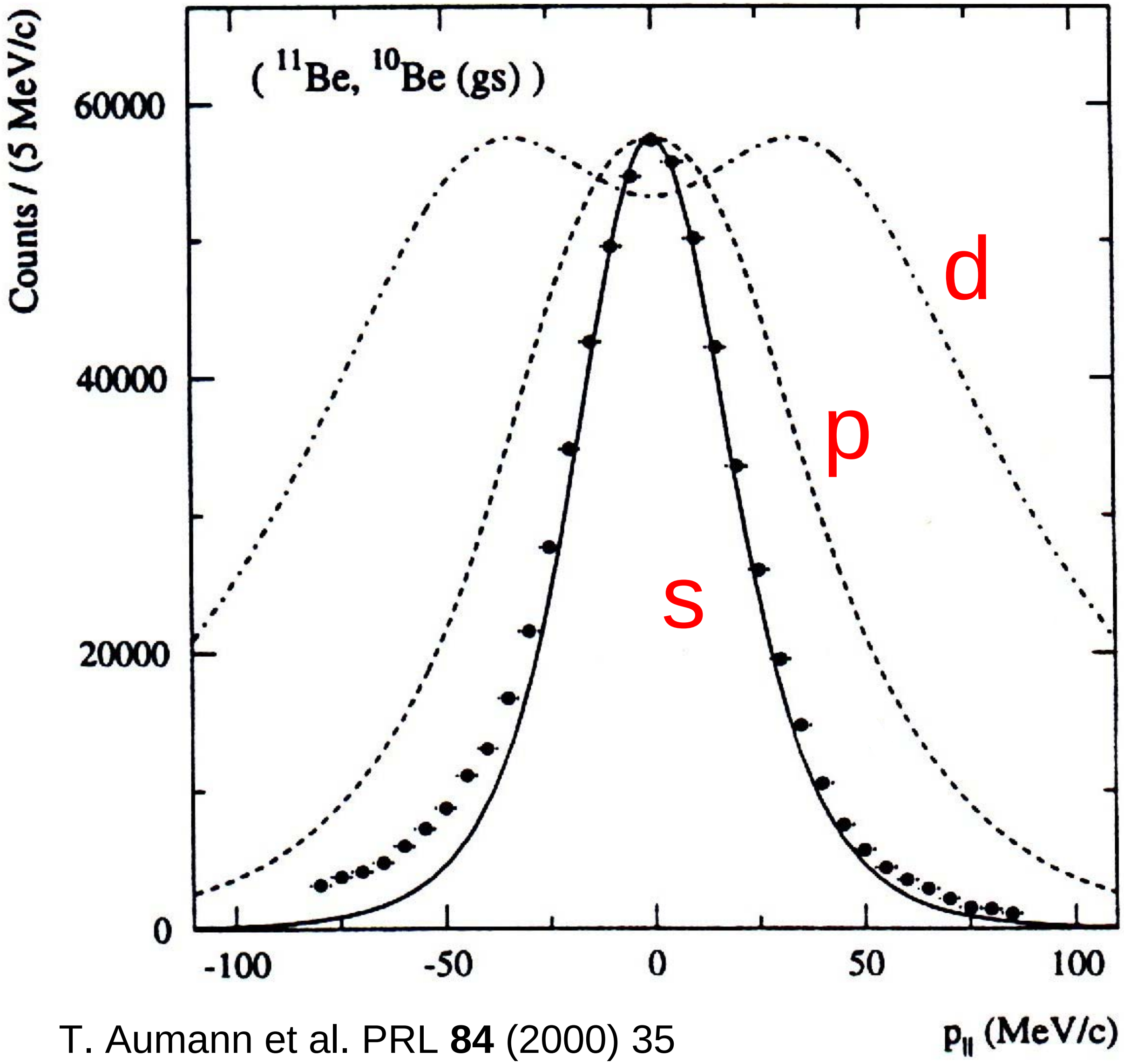
$$\frac{d\sigma_{str}}{dk_z} = \frac{1}{2\pi}\frac{1}{2l+1}\sum_m \int_0^\infty d^2b_n[1-|S_n(b_n)|^2]\int_0^\infty d^2\rho|S_c(b_c)|^2 \times \left|\int_{-\infty}^{\infty} dz\,\exp[-ik_z z]\psi_{lm}(\mathbf{r})\right|^2$$

$$\vec{r} \equiv (\vec{\rho}, z)$$

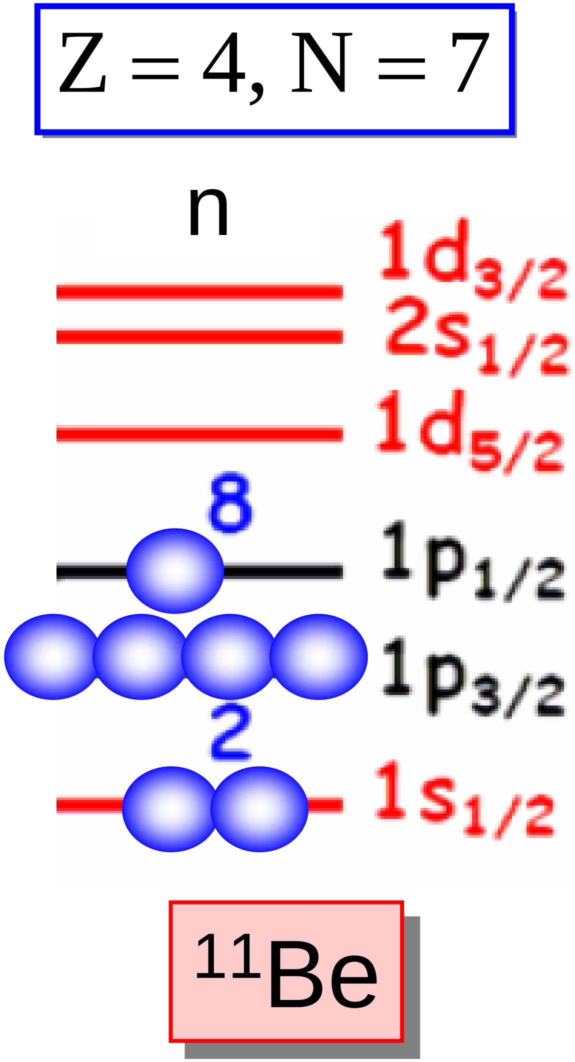




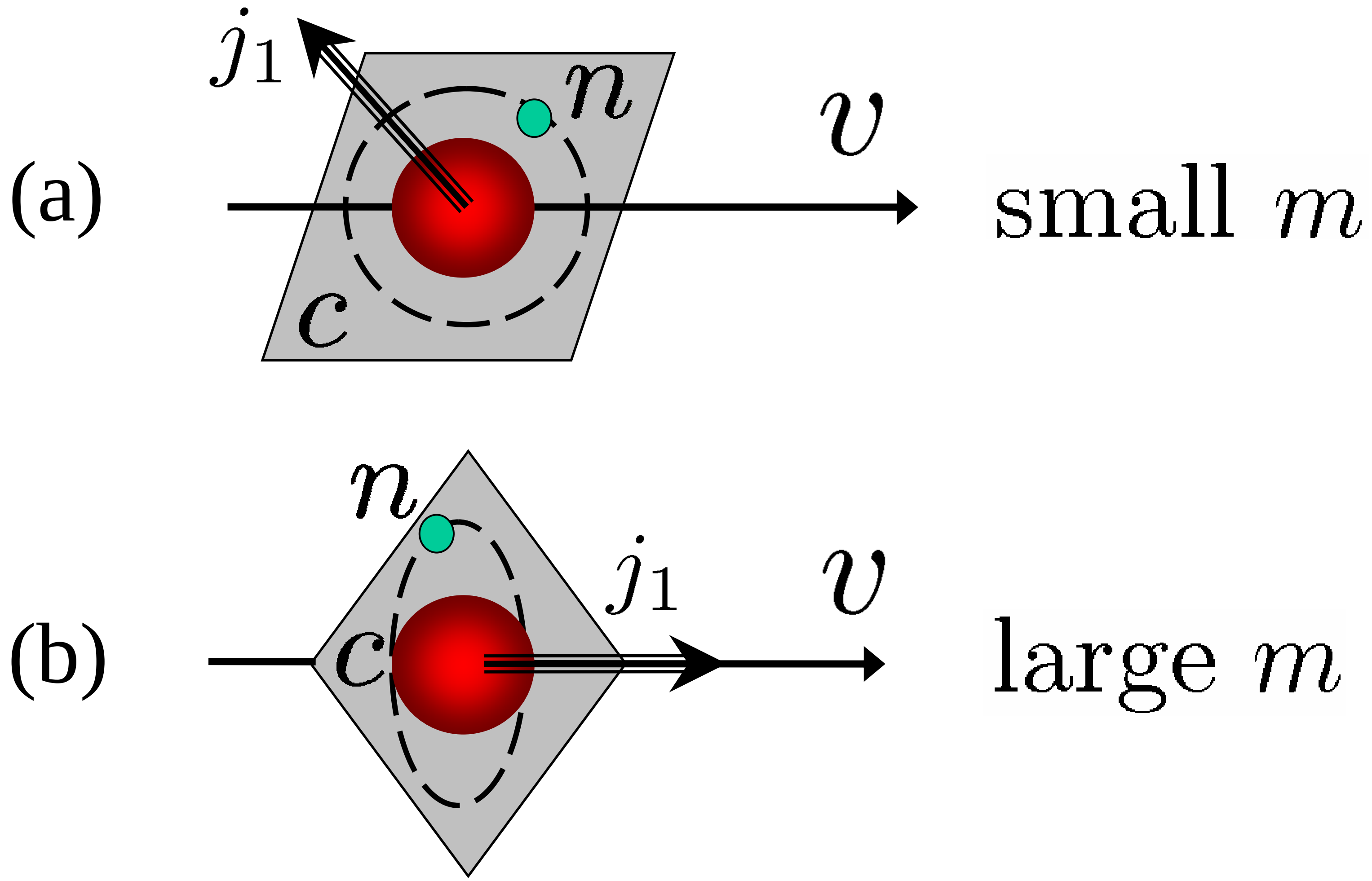
Residue momentum $^{11}Be \rightarrow {}^{10}Be$ – halo case



T. Aumann et al. PRL **84** (2000) 35



projection dependence … what do we expect?



knockout calculates to **`sigl.0,sigl.1,sigl.2 etc`**

One nucleon knockout – ^{28}Mg ($-$p,ℓ=2) 82A MeV