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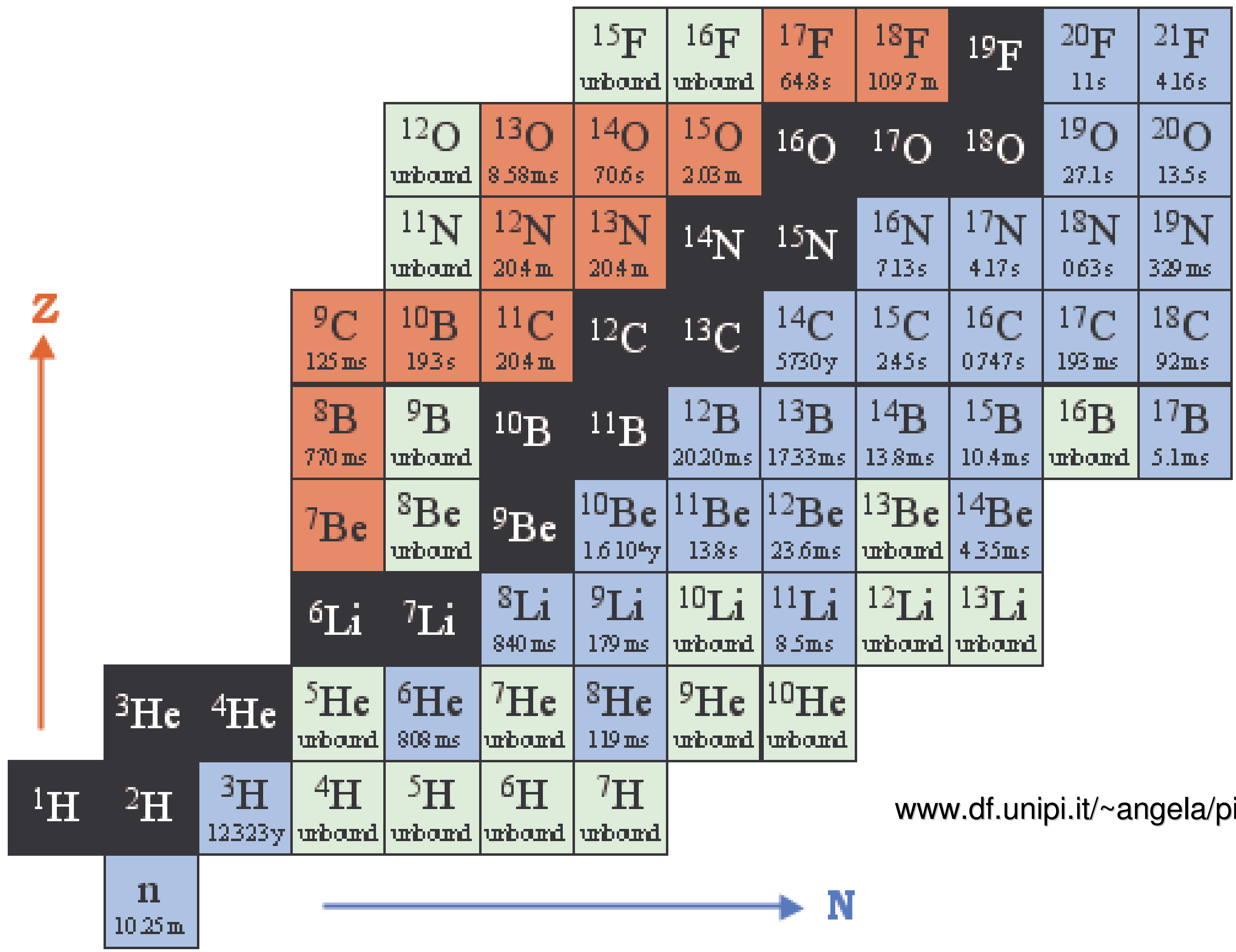
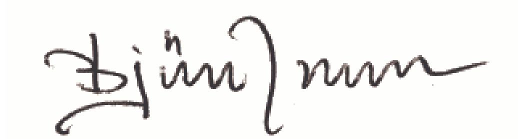
Angela Bonaccorso

G. Blanchon (CEA, Saclay), D.M. Brink, N. Vinh Mau



www.df.unipi.it/~angela/pisa08

Beyond the dripline: an outlook



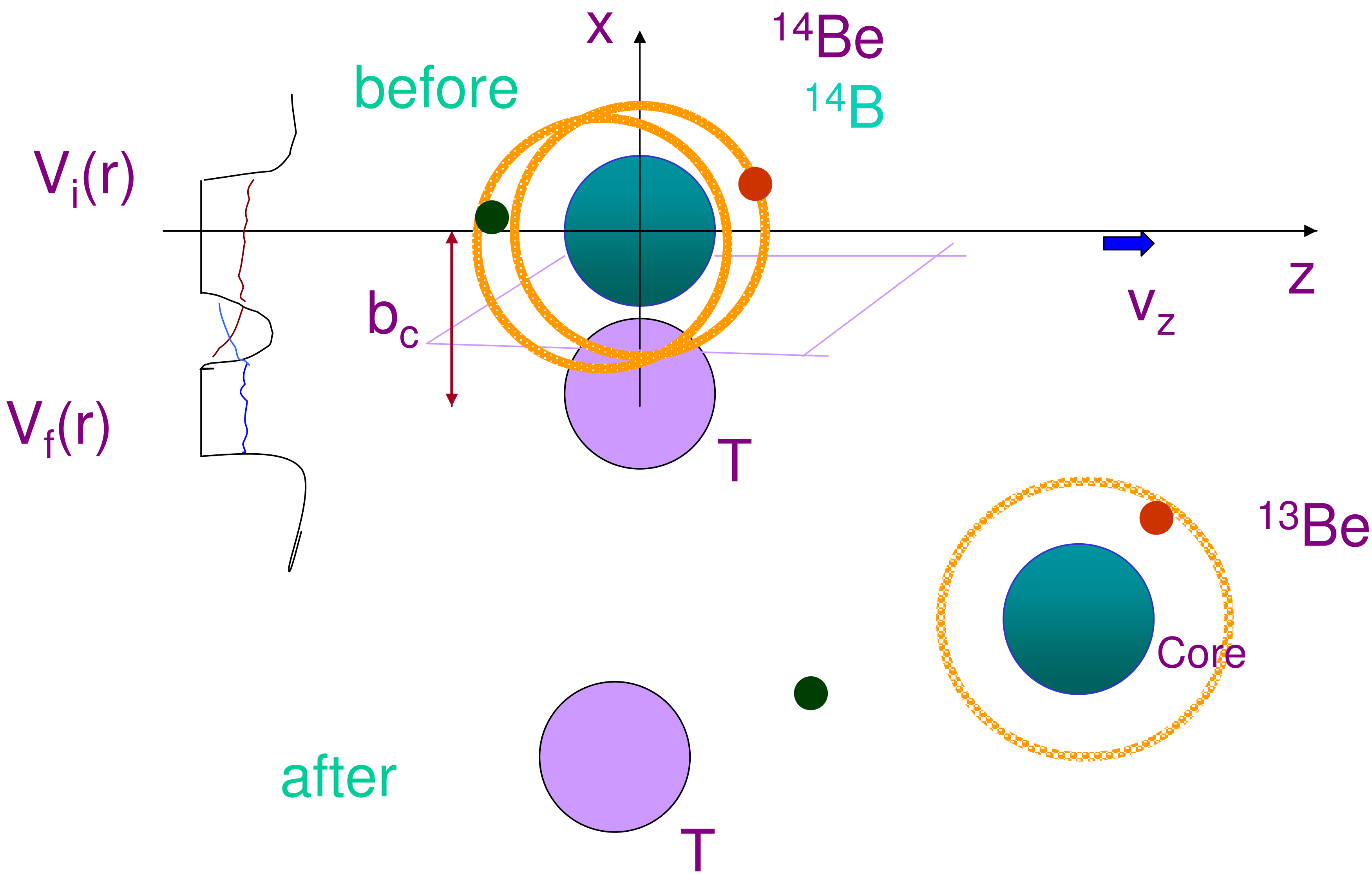
Experimental Studies of Unbound Nuclei

- **Experimental filter**
  - Acceptance, resolution, efficiency
- **Structure of projectile and target**
  - Clusterisation, spin
- **Reaction Mechanism and projectile energy**
  - Knockout, transfer, inelastic scattering, models
- **Final State Interactions in the Continuum**

Cross sections, scattering length, angular distributions, resonance energies and widths, energy and angular correlations

2. Projectile fragmentation

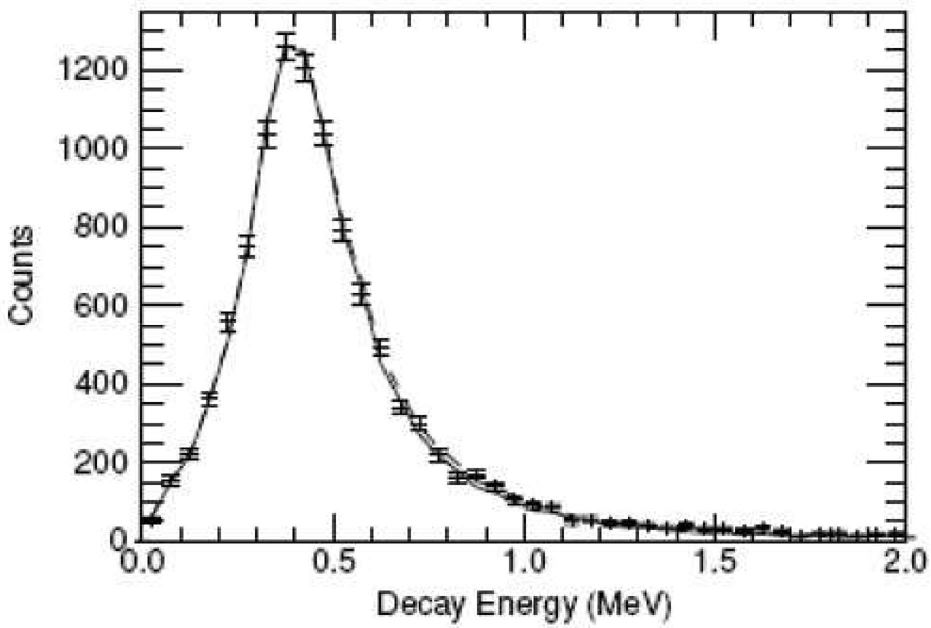
n-core final state interaction



Ground state energy and width of ^{7}He from ^{8}Li proton knockout

D. H. Denby,[1] P. A. DeYoung,[1] T. Baumann,[2] D. Bazin,[2] E. Breitbach,[3] J. Brown,[4] N. Frank,[2,5,*] A. Gade,[2,5] C. C. Hall,[1] J. Hinnefeld,[6] C. R. Hoffman,[7] R. Howes,[3] R. A. Jenson,[8] B. Luther,[8] S. M. Mosby,[2,5] C. W. Olson,[8] W. A. Peters,[2,5] A. Schiller,[9] A. Spyrou,[2] and M. Thoennessen[2,5]

PHYSICAL REVIEW C **78**, 044303 (2008)



A1900, MSU
^{8}Li @ 41 MeV/u

$$E = 400(10)\ \text{keV}$$

$$\Gamma = 125^{+40}_{-15}\ \text{keV}$$

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^{11}**Be**: a test case for the projectile fragmentation model

^{11}Be+^{12}C @ 67A.MeV

from bound s-state to d-resonance: inelastic excitation to the continuum?

CAPEL, GOLDSTEIN, AND BAYE PHYSICAL REVIEW C 70, 064605 (2004)

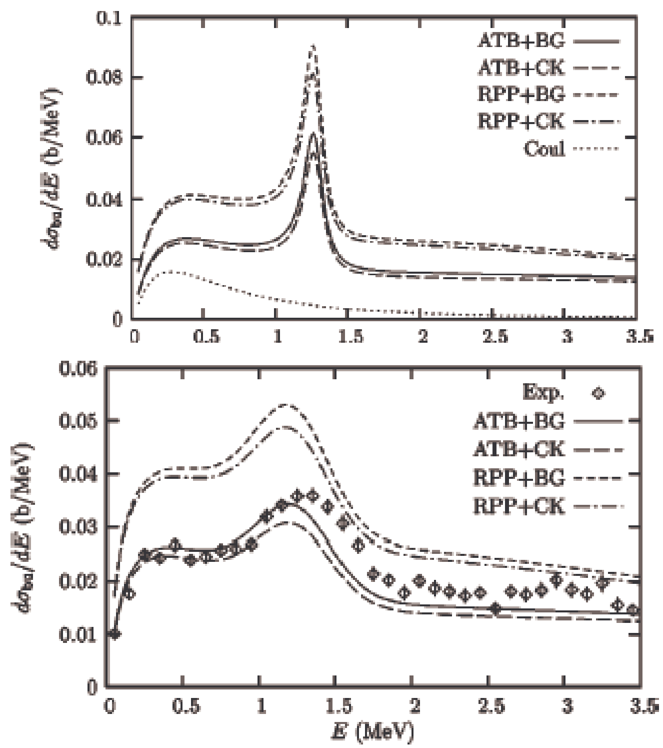


FIG. 4. Theoretical and experimental breakup cross sections as a function of the energy. The four curves correspond to the calculations performed with various combinations of the potentials of Table III convoluted with energy resolution. Experimental data are from Ref. [39].

60 G. Blanchon et al. / Nuclear Physics A 784 (2007) 49–78

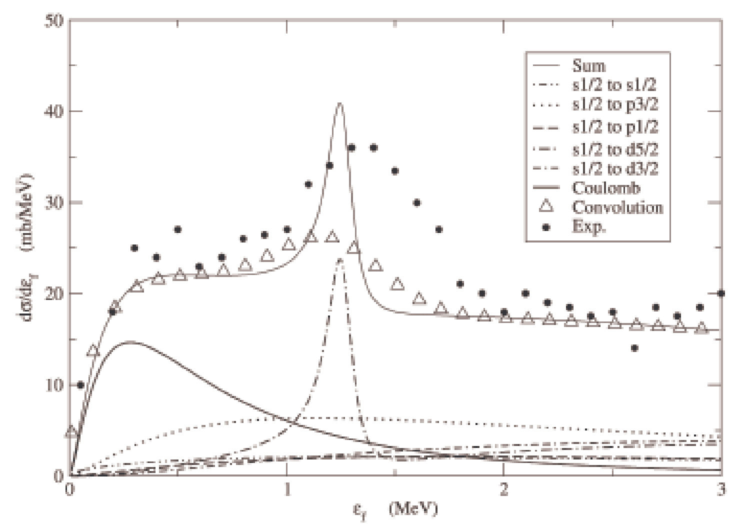


Fig. 3. n–^{10}Be relative energy spectrum, including Coulomb and nuclear breakup for the reac ^{11}Be + ^{12}C $\to n$ + ^{10}Be+X at 67A MeV. Only the contributions from an s initial state with spectroscopic : tor $C^2S = 0.84$ are calculated. The triangles are the total calculated result after convolution with the experime resolution function. The dots are the experimental points from [1].

[39] N. Fukuda *et al.*, Phys. Rev. C 70, 054606 (2004).

ELSEVIER Nuclear Physics A 791 (2007) 303–312

^{10}Li spectrum from ^{11}Li fragmentation

G. Blanchon [a], A. Bonaccorso [a,*], D.M. Brink [b], N. Vinh Mau [c]

^{10}Li:

1) virtual state: sudden approach OK;
2) evidence for a $d_{5/2}$ resonance

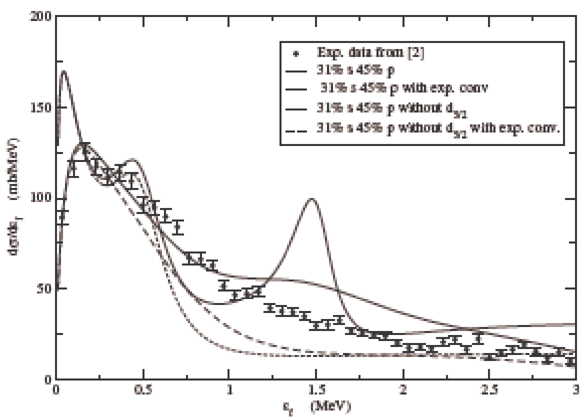
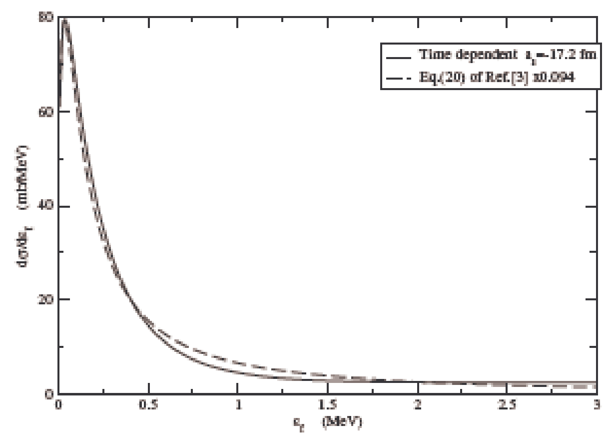


Figure 2: n-^{9}Li relative energy spectrum, for the reaction ^{11}Li+^{12}C → n+^{9}Li+X at 264 A.MeV. Only the contributions from an s and p initial state with experimental spectroscopic factors [4] C^2S= 0.31 and 0.45 respectively are included. The thin solid curve is the total calculated result. The thick solid curve curve is after convolution with the experimental resolution function. The thin dashed curve is the calculation without the d-resonance while the thick dashed curve is the same calculation after convolution. The symbols with error bars are the experimental points from [2]. Calculations are normalised to the data.



re 4: Comparison for the s to s transition of our calculation (solid curve) with that ling to the sudden formula Eq. (20) of [3]. Both calculations use the *exact* phase

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^{7}Be	^{8}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be	^{13}Be	^{14}Be
	unbound		1.6 10^{6} y	13.8 s	23.6 ms	unbound	4.35 ms

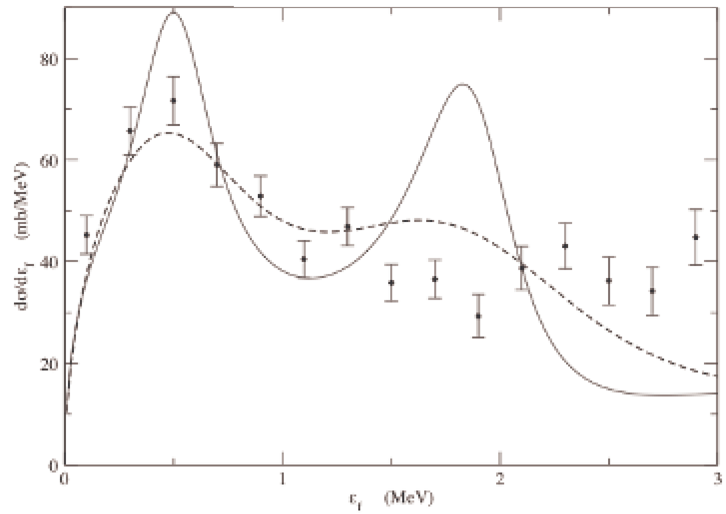


Figure 12: Sum of all transitions from the s initial state with ε_f=-1.85 MeV (solic line). Experimental points from L. Chulkov et al. [56]. Dashed line is the folding of the calculated spectrum with the experimental resolution curve.

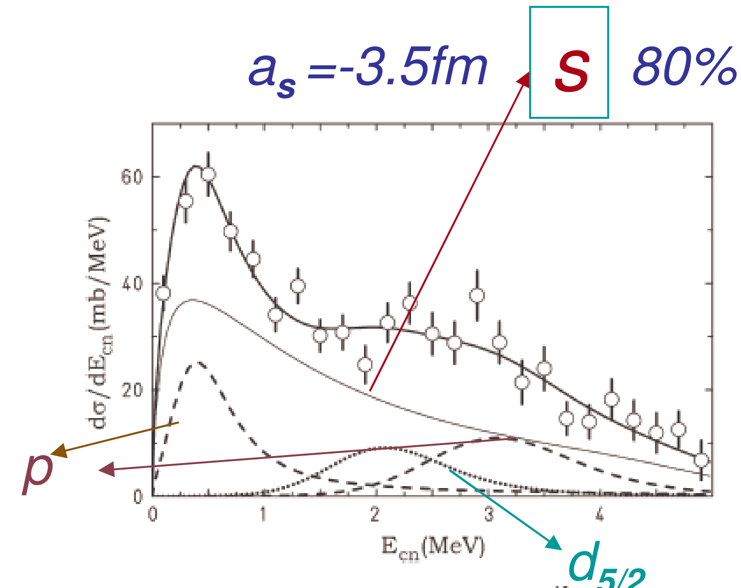


Fig. 10. Differential cross section as a function of the relative energy between ^{12}Be and a neutron. The data points are the same as those in Fig. 4, panel 3. The thin-solid line corresponds to the $1/2^{+}$ virtual state, the dotted line is the contribution from the $5/2^{+}$ state. Dashed lines display the $1/2^{-}$ state and its satellite at low energy. The thick-solid line is the sum of the reaction branches.

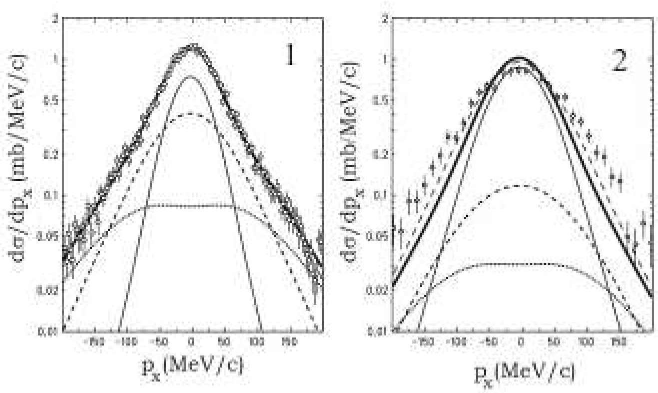


Fig. 5. Transverse momentum distributions of the $(A-1)$ fragments, reconstructed from the momenta of the $(A-2)$ fragment and the neutron measured in coincidence after neutron knockout from ^{11}Li (Panel 1) and ^{14}Be (Panel 2). Experimental data are shown as open circles with statistical uncertainties. The thin solid, dashed and dotted lines represent l=0, l=1 and l=2 single particle momentum distributions calculated for one of the halo neutrons, including core shadowing and the experimental resolution. The thick solid lines represent the sum of these distributions. The wide distribution shown by the thin hatched line in Panel 2 corresponds to the case when the separation energy for the $s-$wave neutron was increased by 2 MeV.

^{14}Be $T_{1/2}$=4.35ms±0.17

Systematic investigation of the drip-line nuclei ^{11}Li and ^{14}Be and their unbound subsystems ^{10}Li and ^{13}Be.

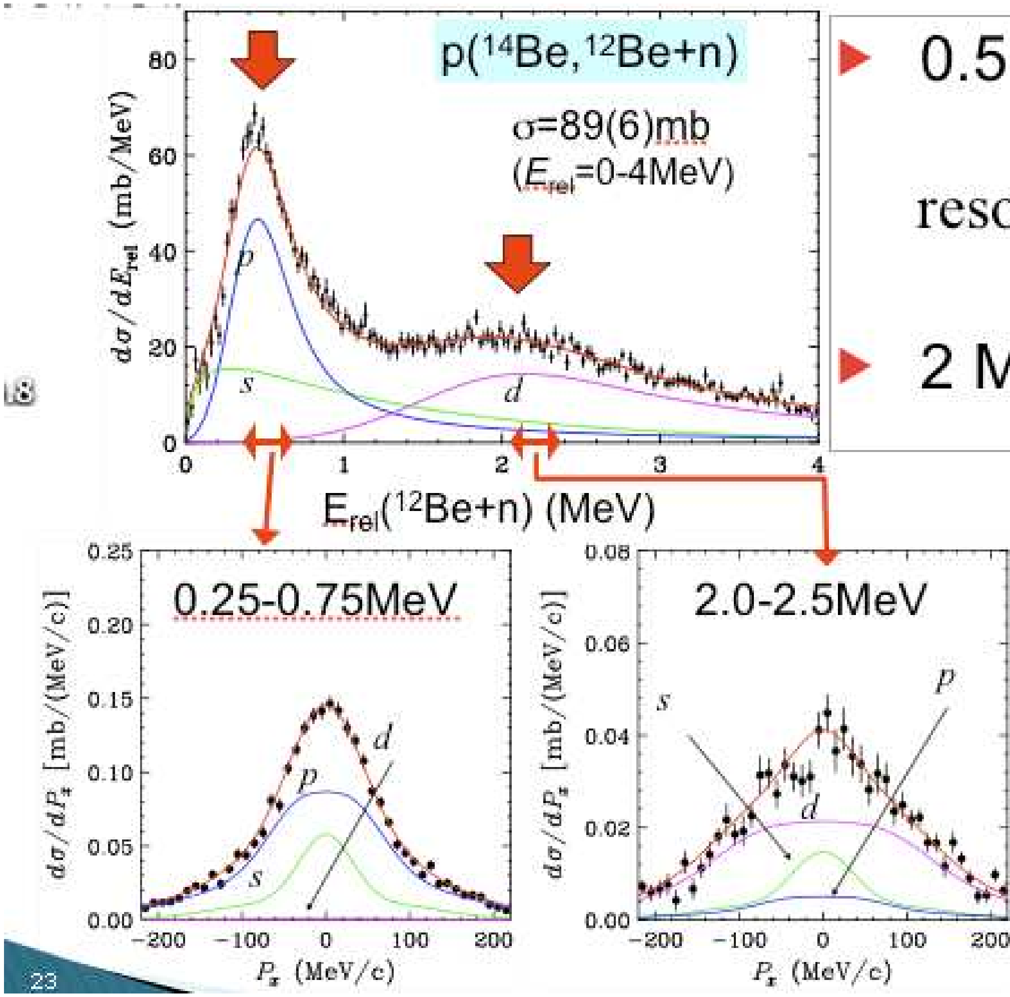
Nucl. Phys. A791 (2007) 267.

H. Simon [a,b], M. Meister [a,c], T. Aumann [b,d], M.J.G. Borge [e], L.V. Chulkov [b,f], Th. W. Elze [g], H. Emling [b], C. Forseén [h,c], H. Geissel [b], M. Hellström [b], B. Jonson [c], J. V. Kratz [d], R. Kulessa [i], Y. Leifels [b], K. Markenroth [c], G. Münzenberg [b], F. Nickel [b], T. Nilsson [a,c], G. Nyman [c], A. Richter [a], K. Riisager [j], C. Scheidenberger [b], G. Schrieder [a], O. Tengblad [e] and M. V. Zhukov [c]

Problems to be solved

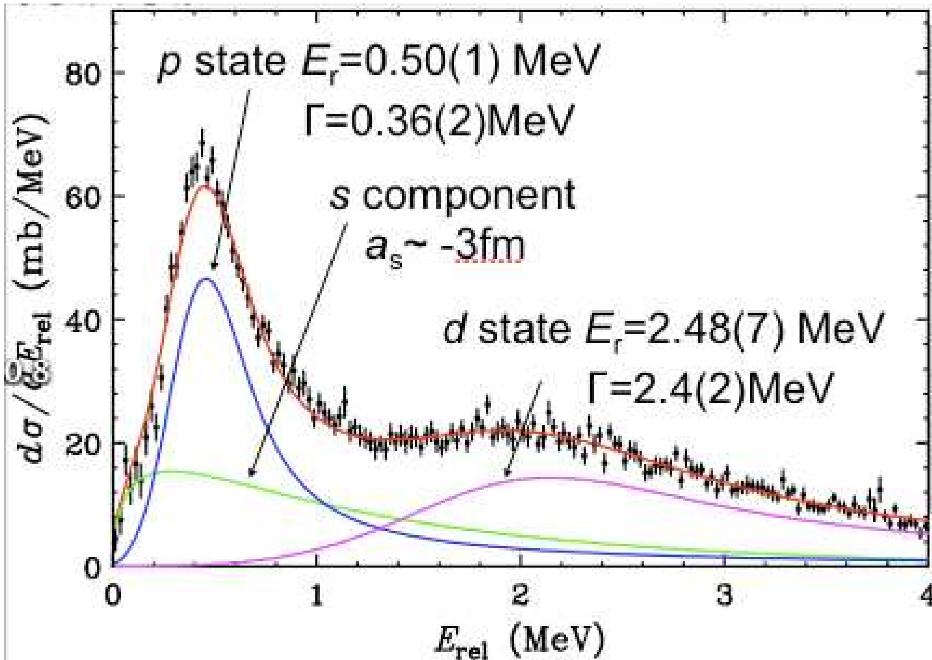
Reaction Mechanism : *Sudden vs final state interaction*

Structure : *nature of state of given* ℓ*,*
state of core, coupling,
ordering of single particle states



- 0.5 MeV peak →*p*-wave resonance
- 2 MeV peak

*** Kondo, Nakamura et al. in preparation**

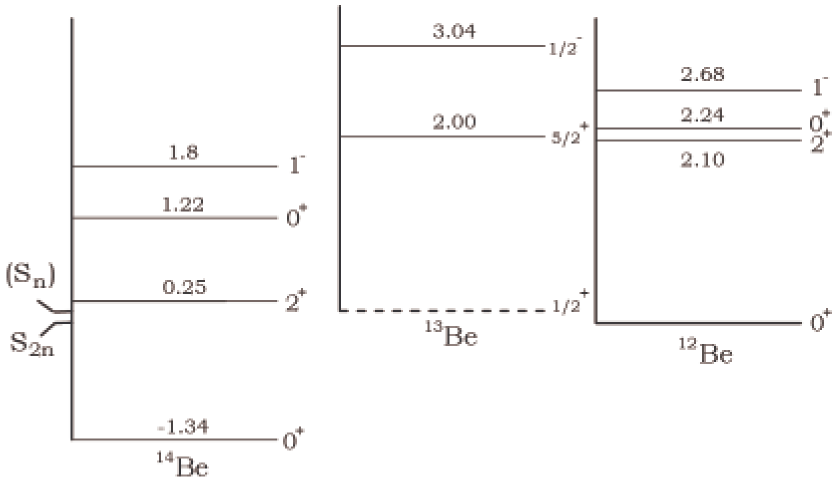


- **p-wave component**
  - E_r=0.50(1) MeV
  - Γ=0.36(2) MeV
    - consistent with Γ_{sp} (l=1)
  - J^{π}=1/2-
- **d-wave component**
  - E_r=2.48(7) MeV
  - Γ=2.4(2) MeV
    - larger than Γ_{sp} (l=2)

single particle width

p-wave @0.50MeV
Γ_{sp}~0.5MeV

d-wave @2.48MeV
Γ_{sp}~1.4MeV

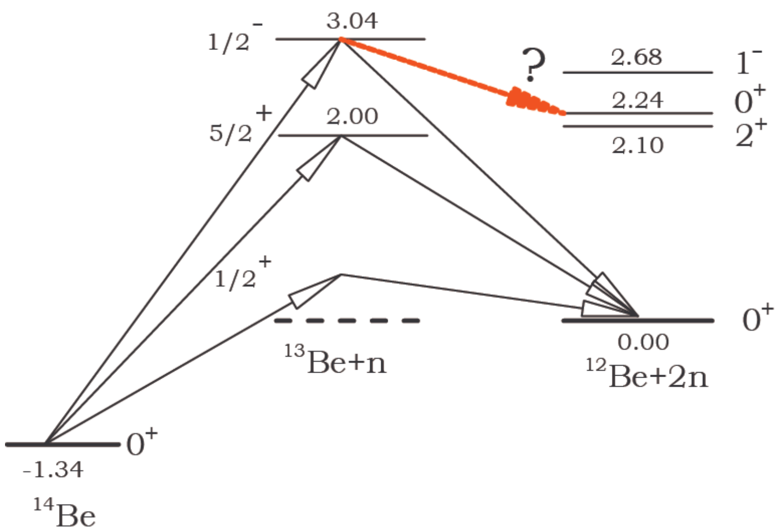


QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

*

* **Kondo, Nakamura et al. in preparation**

H. Simon et al. Nucl. Phys. A791 (2007) 267.



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are needed to see this picture.

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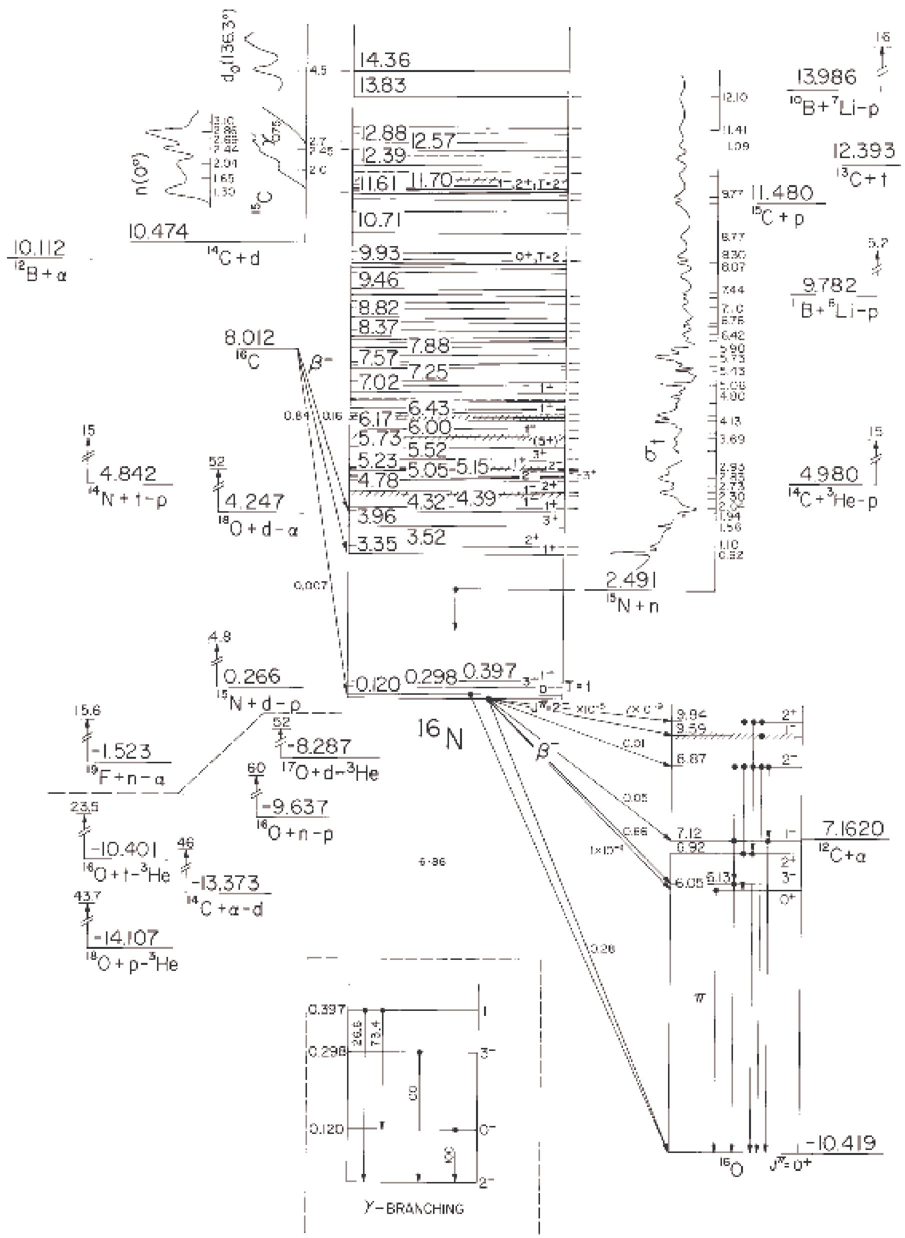
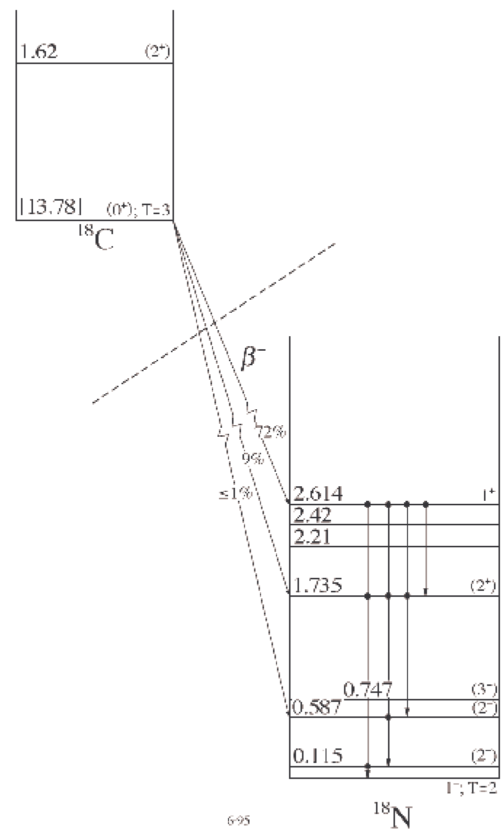
Z=7 N=9





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Analytical methods for transfer and breakup

$$\sigma = \int d^2 b_c \underbrace{P_{el}(b_c)}_{|S_{ct}|^2} P_{tr}(b_c); \; P_{tr} = |A|^2 \longrightarrow A = \frac{1}{i\hbar}\int dt \left\langle \psi_f(r,t) \middle| V_2 \middle| \psi_i(r - R(t), t) \right\rangle$$

Seaking a clear physical interpretation of DWBA (Brink et al. since 1978).

similar to Alder& Winther for Coulomb excitations.

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Transfer to the continuum vs. Projectile fragmentation: a model for diffractive breakup in which the observable studied is the n-core relative energy spectrum and its resonances

$$A_{fi} = \frac{1}{i\hbar}\int_{-\infty}^{\infty} dt \langle \psi_f(\mathbf{r},t)|V_2(\mathbf{r}-\mathbf{R}(t))|\psi_i(\mathbf{r},t)\rangle,$$

$$\begin{aligned}\frac{dP_t(b_c)}{d\varepsilon_f} &= \frac{1}{8\pi^3}\frac{mk_f}{\hbar^2}\frac{1}{2l_i+1}\Sigma_{m_i}|A_{fi}|^2 \\ &\approx \frac{4\pi}{2k_f^2}\Sigma_{j_f}(\underbrace{|1-S_{j_f}|^2}_{\text{diffraction}}+\underbrace{1-|S_{j_f}|^2}_{\text{stripping}})(2j_f+1)(1+F_{l_f,l_i,j_f,j_i})B_{l_f,l_i} \\ &= \sigma_{nN}(\varepsilon_f)\mathcal{F},\end{aligned}$$

$$\frac{dP_{in}}{d\varepsilon_f} = \frac{2}{\pi}\frac{v_2^2}{\hbar^2 v^2}C_i^2\frac{m}{\hbar^2 k}\frac{1}{2l_i+1}\Sigma_{m_i,m_f}|1-\bar{S}_{m_i,m_f}|^2|I_{m_i,m_f}|^2,$$

$$B_{l_f,l_i} \approx \frac{e^{-2\eta b_c}}{b_c}$$ **Knockout**

$$\bar{S} = Se^{2i\nu} = e^{2i(\delta+\nu)}$$

$\overline{S}$ *off-shell*

S *on shell*

$$I_{l_f,l_i} \approx \frac{e^{-2\gamma b_c}}{b_c^3}$$ **Fragmentation**

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Initial states chosen to fit known separation energy,
s & p components for ^{11}Li with known spectroscopic factors.
For ^{14}Be s-p-d components with unit C^2S.
Final states determined by S-matrix via n-core interaction

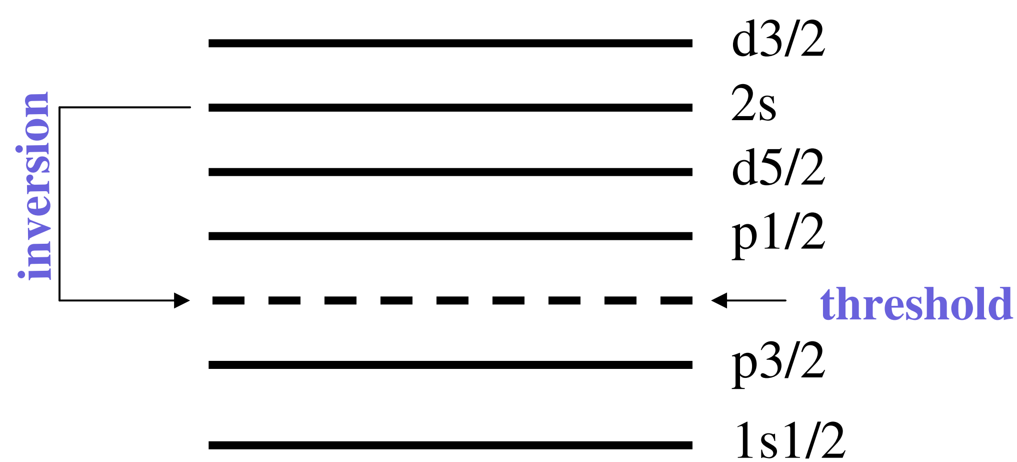
Potential corrections due to the particle-vibration coupling
(N. Vinh Mau and J. C. Pacheco, NPA607 (1996) 163.
also T. Tarutina, I.J. Thompson, J.A. Tostevin NPA733 (2004) 53)
…can be modeled as:

$$U(r) = V_{WS} + V_{so} + \delta V$$

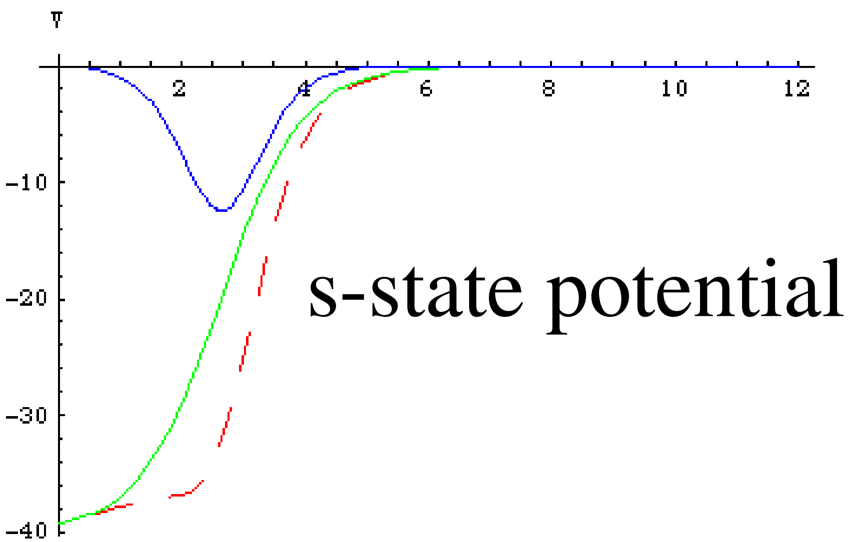
$$\delta V(r) = 16\,\alpha\, e^{2(r-R)/a} / (1+e^{(r-R)/a})^4$$

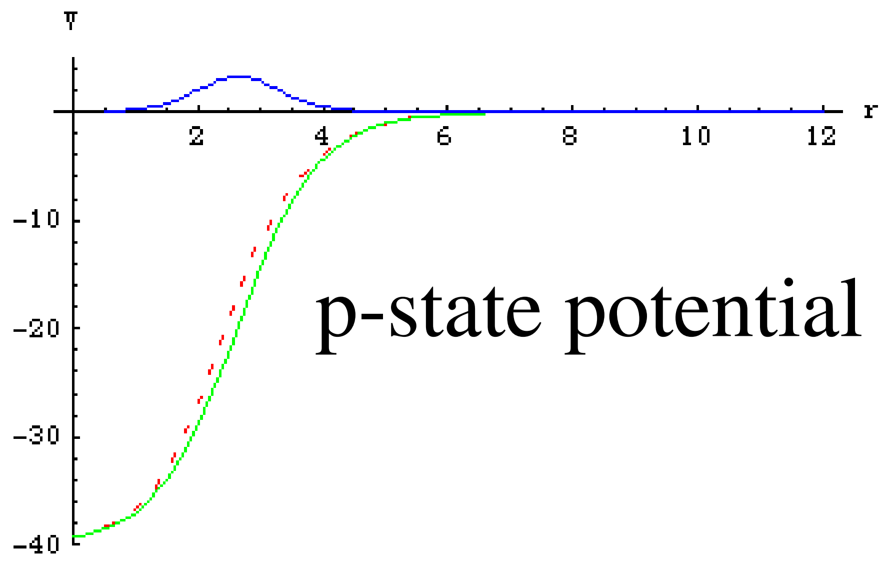
n+^{12}Be:

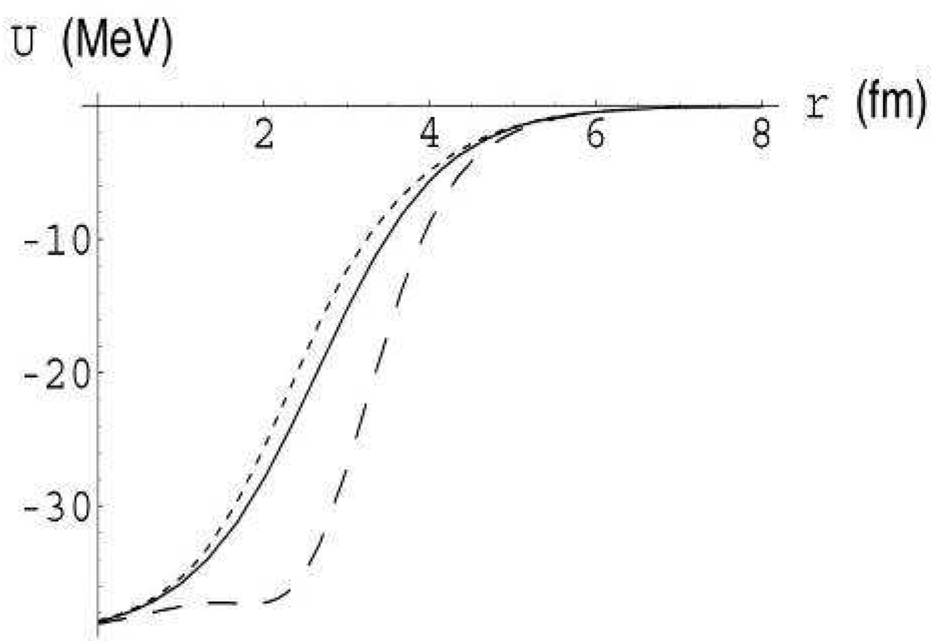
	ε_{res} (MeV)	Γ (MeV)	α (MeV)
$1p_{1/2}$	0.67	0.28	8.34
$1d_{5/2}$	2.0	0.40	-2.36



$$U(r) = V_{WS} + \delta V$$







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^{13}Be and ^{14}Be structure

G. Blanchon , N. Vinh Mau

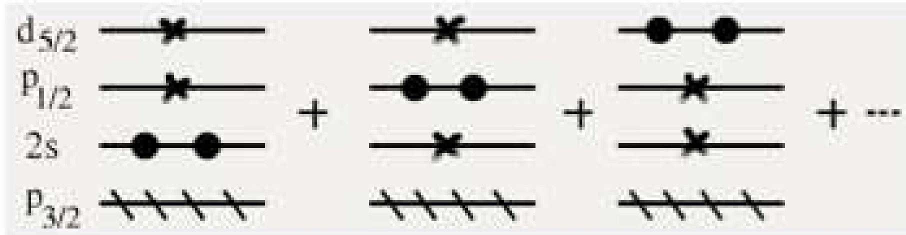

Figure 3.5: Formation of ^{13}Be with one neutron (crosses) added to an open shell ^{12}Be. Only one neutron is added in each configuration, but the cross indicates states which can be populated.

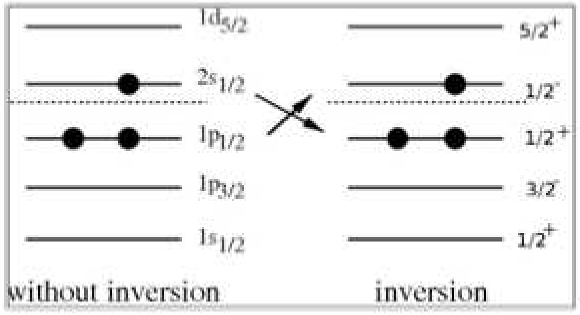

Table 3.3: ^{13}Be neutron spectrum with and without inversion with the corresponding α_l from Eq.(3.102). The continuum is discretized in a 20 fm box.

Inversion				Without Inversion			
Core							
l	j	ε (MeV)	α_l	l	j	ε (MeV)	α_l
0	1	-28.00	0	0	1	-28.00	0
1	3	-6.58	0	1	3	-6.58	0
0	1	-3.15	-23.3	1	1	-3.03	0
Continuum							
l	j	ε (MeV)	α_l	l	j	ε (MeV)	α_l (MeV)
1	1	0.67	8.9	0	1	0.09	-4.4
1	3	1.20	0	1	3	1.20	0
1	1	1.27	0	1	1	1.27	0
2	3	1.83	0	2	3	1.83	0
0	1	1.97	0	0	1	1.97	0
2	5	2.00	-2.4	2	5	2.00	-2.4

G. Blanchon, Ph.D. Thesis, Pisa July 2008, http://www.infn.it/thesis/

Table 3.2: Theoretical results vs. experimental data. E and S_{2n} are respectively the energy of the excited states and the two-neutron separation energy in MeV. rms, $\sqrt{\langle\rho^2\rangle}$ and $\sqrt{\langle\lambda^2\rangle}$ are respectively the root mean squared radius, the average distance between the two halo neutrons and the average distance between the c.m. of the core and the c.m. of the two neutrons out of the core (see Fig. 3.2) in fm. B(E1) is the total dipole strength. The sum rule is calculated with Eq.(3.101) in e.fm^2. B(E2) is the total quadrupole strength in e^2.fm^4.

		RPA ^{10}Be core	Experiment	RPA ^{12}Be core Inversion	RPA ^{12}Be core Without Inversion
^{8}Be	E_{2+}	3.1	3.04		
^{10}Be	S_{2n}	8.29	8.5		
	E_{0+}		6.18	5.4	7.2
	E_{1-}		5.96	4.8	
^{12}Be	S_{2n}	3.63	3.67±0.015	3.83	1.16
	rms	2.76	2.59±0.06		
	E_{0+}	2.47	2.25		
	E_{1-} (1)	2.57	2.71		
	E_{1-} (2)	4.25			
	E_{1-} (3)	4.47			
	E_{2+} (1)		2.10		
	E_{2+} (2)	3.72	3.37		
^{14}Be	S_{2n}		1.34±0.11	1.33	0.54
	rms		3.1±0.4	2.90	3.51
	$\sqrt{\langle\rho^2\rangle}$		5.4±1.0	4.6	8.7
	$\sqrt{\langle\lambda^2\rangle}$		4.5±1.0	4.0	5.6
	E_{0+} (1)		2.56	2.74	1.71
	E_{0+} (2)			3.11	2.71
	E_{0+} (3)				2.83
	E_{1-} (1)		3.14	2.89	1.79
	E_{1-} (2)			3.38	1.86
	E_{1-} (3)			3.50	3.52
	E_{2+} (1)		1.59		
	E_{2+} (2)			3.16	2.03
	E_{2+} (3)			3.67	2.45

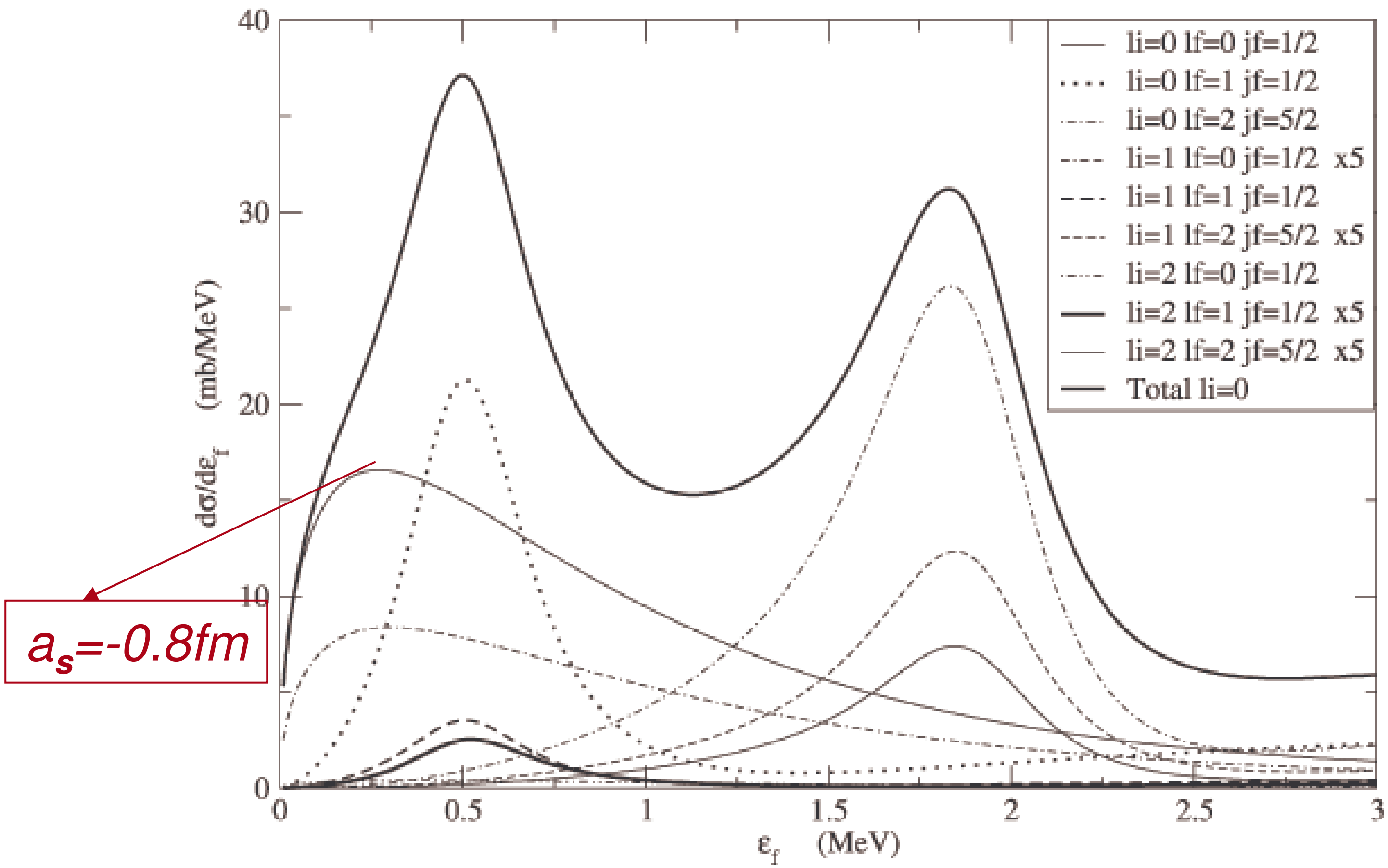

Fig. 8. Results obtained including the s, p and d states. Each curve corresponds to just one transition as indicated. The solid curve is the sum of all transitions from the s-bound state. To make them visible some curves have been multiplied by a factor of five as indicated in the legend.

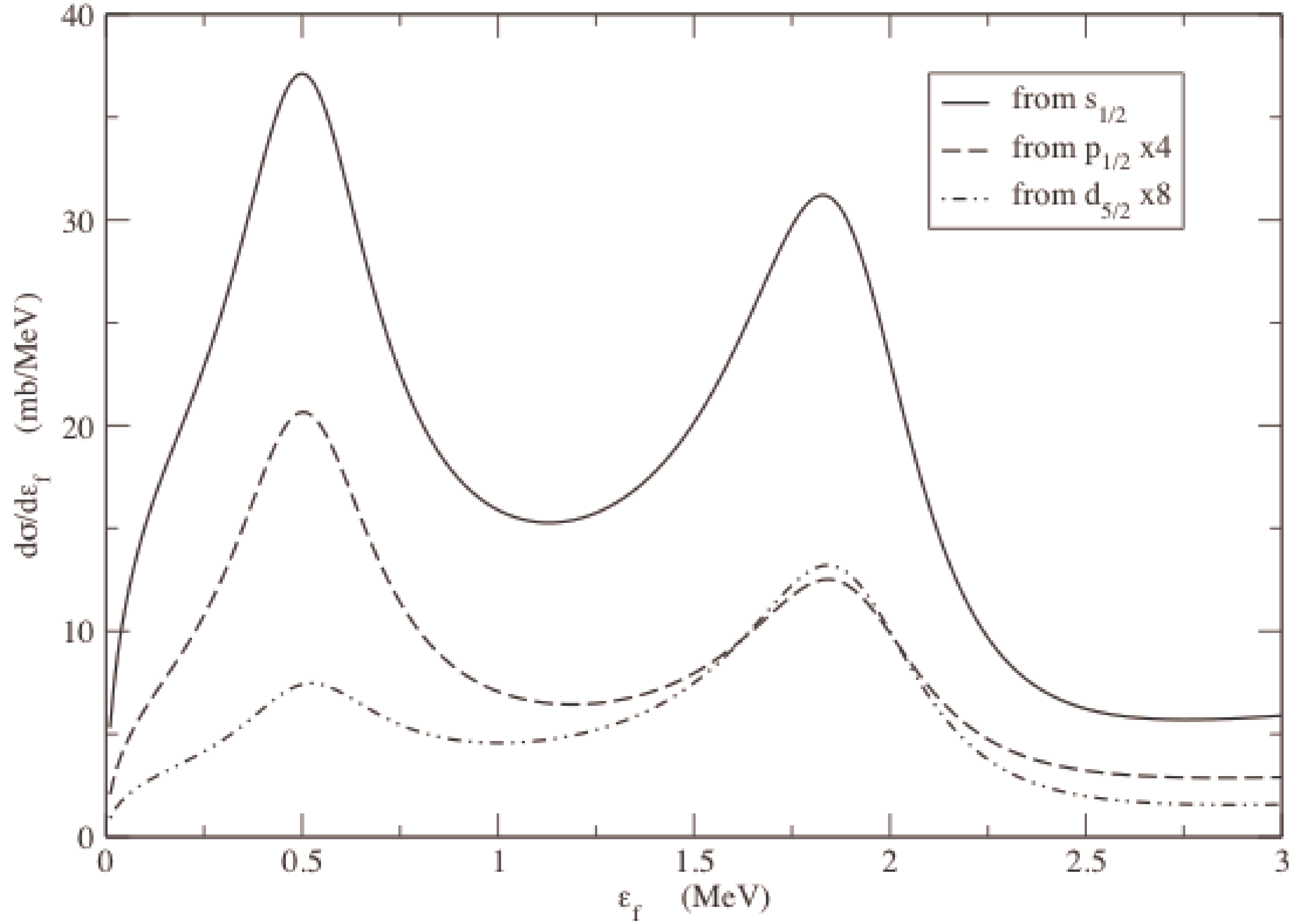

Figure 11: Check of the dependence from the initial state angular momentum. Full curve: sum of transitions from s-initial state. Dashed and dotdashed lines: sum of transitions from p and d-initial states respectively.

Results

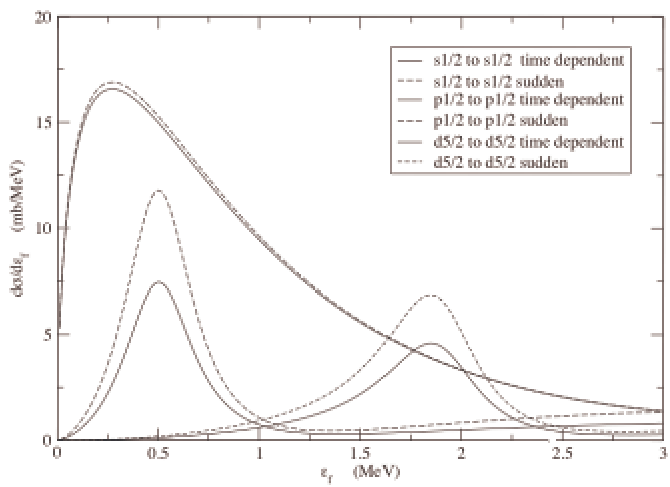

Figure 5: Population of resonances in the n-^{12}Be relative energy spectrum. Comparison of sudden (dashed line) and non-sudden (solid line) results for an s $\rightarrow$ s transition with peak at 0.25 MeV, p$\rightarrow$ p with peak at 0.5 MeV and d$\rightarrow$ d transition with peak around 2 MeV. See text for details.

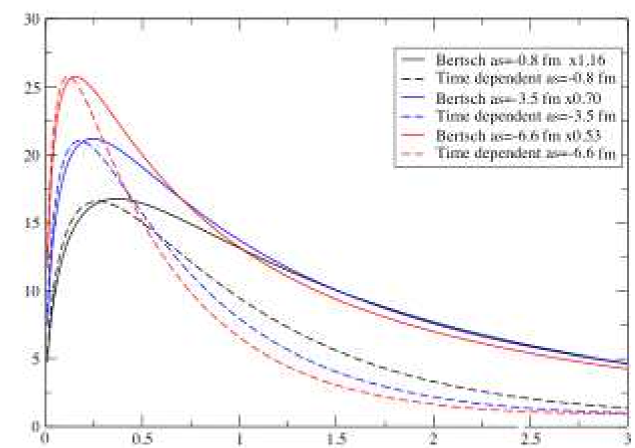

Figure 7: Comparison of time dependent calculation for an s to s transition with results of Eq.(28) using the same optical model phase shifts corresponding to scattering lengths as indicated.

sudden $\longrightarrow$ **q=0**

sudden $\longrightarrow$

$$\frac{d\sigma}{d\varepsilon_f} \approx \frac{1}{k}\left(\frac{k\cos\delta - \gamma\sin\delta}{\gamma^2+k^2}\right)^2$$

$$\approx \frac{1}{k}|\sin(\delta+\beta)|^2$$

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Peak positions of possible continuum s-states in ^{13}Be are not close enough to thereshold to make accurate predictions by the

effective range theory to 1^0 order:
higher orders needed

$$k \cot\delta = -\frac{1}{a_l} + \frac{1}{2} r_l k^2 - P_l r_l^3 k^4 + O(k^6).$$

α (MeV)	a_s (fm)	r_e (fm)	$\lvert\epsilon\rvert$ (MeV)
8.0	-0.8	117.0	
4.0	-3.5	17.9	
2.0	-6.6	11.8	
-1.0	-26.1	7.58	
-5.0	22.4	5.9	0.06
-15.0	7.1	3.8	1.34
-35.0	4.5	2.7	6.49

In Progress

Differences

- **Transfer to the continuum.**
- Long range form factor.
- Overlap of momentum distributions
- On shell n-N S-Matrix

- **Projectile fragmentation.**
- Short range form factor.
- Momentum distribution of overlap
- Off-the-energy-shell n-N S-matrix

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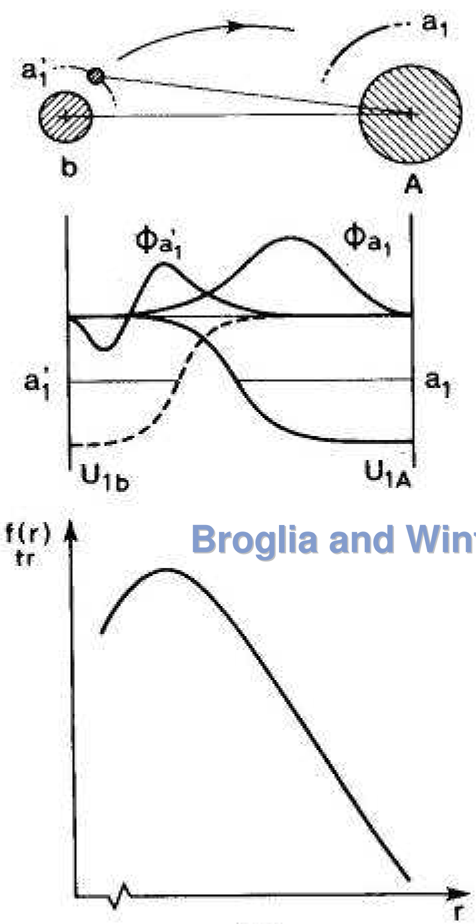
$$A_{bup} = \frac{1}{i\hbar}\int_{-\infty}^{\infty} dt < \psi_2(t)|V_{nt}(r)|\psi_1(t) >$$
$$\approx \int dk_y \sqrt{k_y^2+\eta^2}\,\bar{\psi}_i(d_1,k_y,k_1)\bar{\psi}_f^*(d_2,k_y,k_2)$$

$$A_{fi} = \frac{v_2}{i\hbar v}\int_{-\infty}^{\infty} \mathrm{d}z\ \psi_f^*(b_c,0,z)\psi_i(b_c,0,z)e^{iqz}.$$

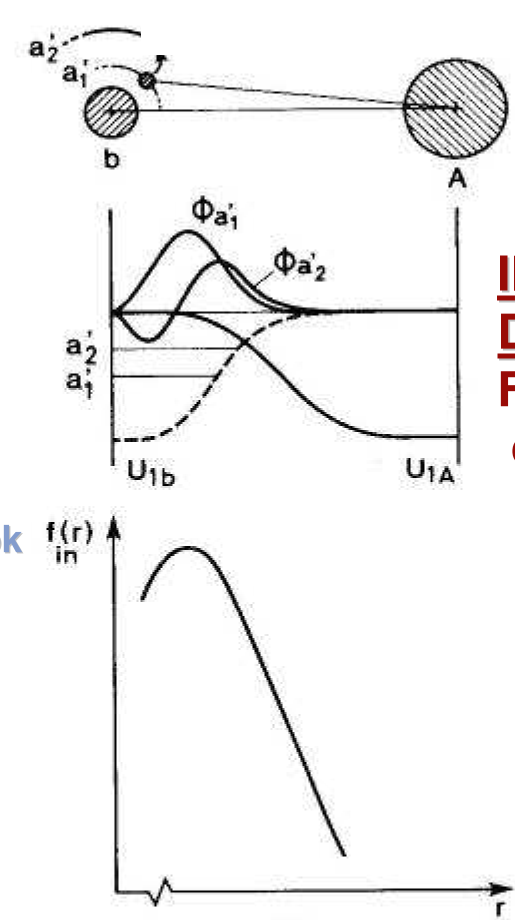
$$A_{fi} = \frac{v_2}{i\hbar v}\int_{-\infty}^{\infty} \mathrm{d}z\ \psi_f^*(b_c,0,z)\psi_i(b_c,0,z)e^{iqz}.$$

TRANSFER
Stripping &
Diffraction
Overlap of momentum distribution (Fourier transforms)



(a)

Broglia and Winther book



(b)

INELASTIC
Diffraction
Fourier transform of the overlap