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Unbound nuclei studied via transfer to the continuum reactions

D. M. Brink, A. Bonaccorso, N.Vinh Mau

- Semi-classical theory of transfer to the continuum
- Example of n+^{9}Li
- Example of n+^{12}Be
- Conclusions

Semiclassical treatment of core-target relative motion, BUT full QM treatment of n-target interaction

AB and DM Brink, PRC38, 1776 (1988), PRC43, 299 (1991),PRC44, 1559 (1991).

$$\frac{d\sigma}{d\varepsilon_f} = C^2 S \int_0^\infty d\mathbf{b_c} \, \frac{dP(b_c)}{d\varepsilon_f} \, P_{el}(b_c), \quad \text{where} \quad P_{el}(b_c) = |S_{cT}|^2$$

$$P_{ct}(b_c) = e^{(-\ln 2 exp[(R_s - b_c)/a])}$$

$$R_s \approx 1.4(A_p^{1/3} + A_t^{1/3})$$

$$A_{if} = \frac{1}{i\hbar} \int dt < \psi_f(t)|V(r)|\psi_i(t) >$$

$$V(r) = U(r) + iW(r)$$

A study of semi-classical approximations for heavy ion transfer reactions, H. Hasan and D.M. Brink, J Phys G4, 1573 (1978).
Perturbation approach to nucleon transfer in heavy ion reactions, L. Lo Monaco and D.M. Brink, J.Phys. G, 935 (1985).

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Understanding the transfer and breakup mechanisms

$$\frac{dP_t(b_c)}{d\varepsilon_f} = \frac{1}{8\pi^3}\frac{mk_f}{\hbar^2}\frac{1}{2l_i+1}\Sigma_{m_i}|A_{fi}|^2$$

$$\approx \frac{4\pi}{2k_f^2}\Sigma_{j_f}(2j_f+1)(|1-\bar{S}_{j_f}|^2 + 1 - |\bar{S}_{j_f}|^2)(1+F_{l\rightarrow j})B_{l_f,l_i}$$

elastic diffraction — absorption stripping

$$= \sigma_{nN}(\varepsilon_f)\mathcal{F}$$

enhancement factor of final state interaction theory

$$B_{l_f,l_i} = \frac{1}{4\pi}\left[\frac{k_f}{mv^2}\right]|C_i|^2\frac{e^{-2\eta b_c}}{2\eta b_c}M_{l_f l_i}.$$

angular parts of $\psi_{i,f}$

$k_f \equiv (i\eta, k_z)$

$|\tilde{\psi}_i|^2$ Fourier transform of initial w. f.

If both initial and final state have I=0

Bound to bound

$$\sigma(\varepsilon_f) = \frac{\pi}{2}|C_i C_f|^2 \left[\frac{\hbar}{mv}\right]^2 \int_0^\infty d\mathbf{b_c} \frac{e^{-2\eta b_c}}{\eta b_c} e^{(-\ln 2 exp[(R_s - b_c)/a])}$$

Bound to continuum

$$\frac{d\sigma}{d\varepsilon_f} = \left(\frac{\sin\delta_0}{k_f}\right)^2 |C_i|^2 \frac{m k_f}{\hbar^2} \left[\frac{\hbar}{mv}\right]^2 \int_0^\infty d\mathbf{b_c} \frac{e^{-2\eta b_c}}{\eta b_c} e^{(-\ln 2 exp[(R_s - b_c)/a])}$$

scattering length

$$a_s = - \lim_{k\rightarrow 0} \frac{tan\delta_0}{k}$$

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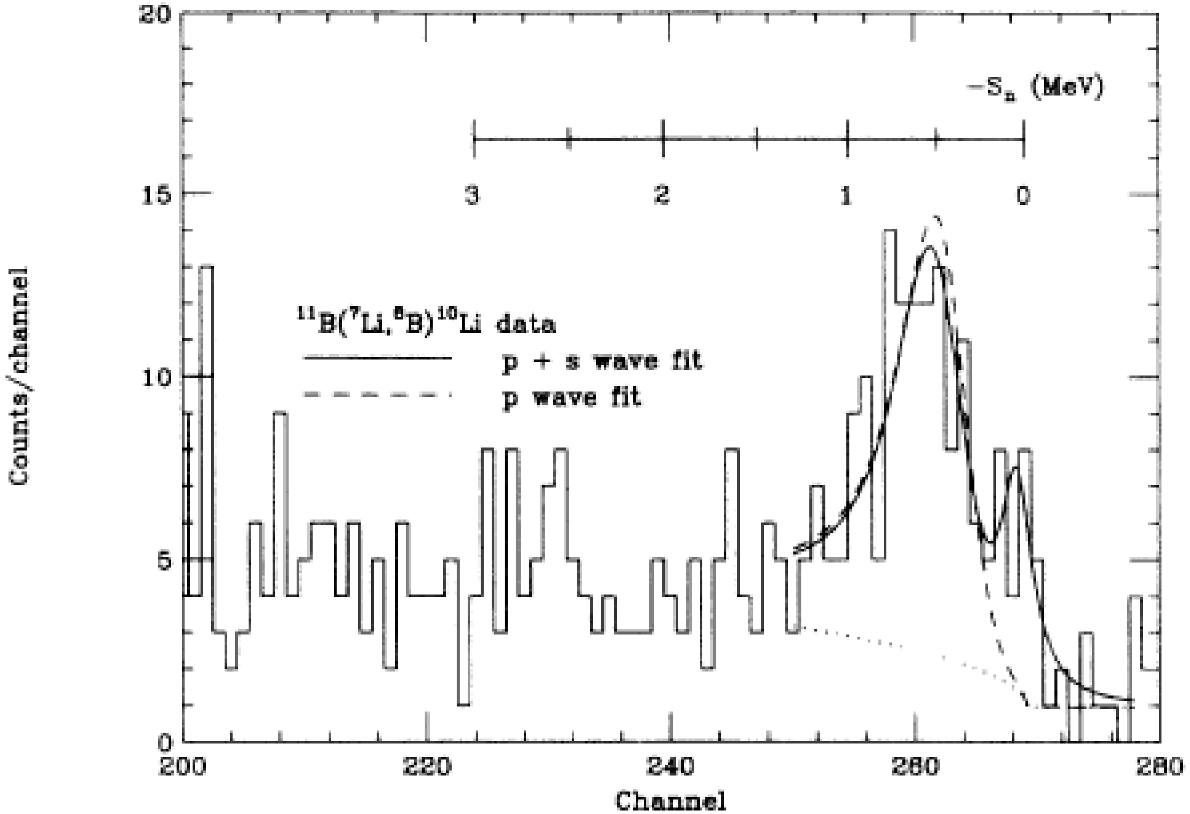
PHYSICAL REVIEW C VOLUME 49, NUMBER 1 JANUARY 1994

Low-lying structure of ^{10}Li in the reaction ^{11}B(^{7}Li,^{8}B)^{10}Li

B. M. Young, W. Benenson, J. H. Kelley, N. A. Orr,* R. Pfaff, B. M. Sherrill, M. Steiner, M. Thoennessen, J. S. Winfield, J. A. Winger,† S. J. Yennello,† and A. Zeller
National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824



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The first excited state of ^{9}Li is at E^*=2.7 MeV

→ $p_{1/2}$ state is at 0.595 MeV

→ s-state is virtual

→ No inelastic channel

→ No use of the stripping part of the transfer cross section

Potential correction which originates from particle-vibration couplings

N. Vinh Mau and J. C. Pacheco, Nucl. Phys. **A607** (1996) 163.

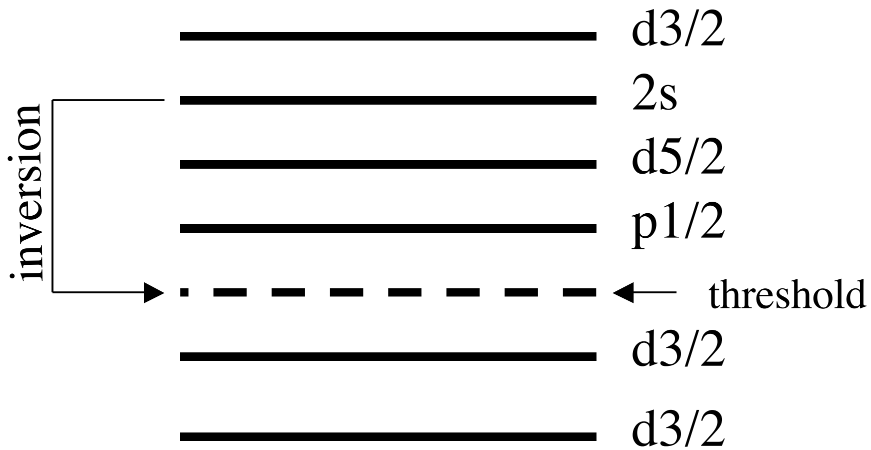
$$U(r) = V_{WS} + \delta V$$

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

with $R \approx r_0 A^{1/3}$

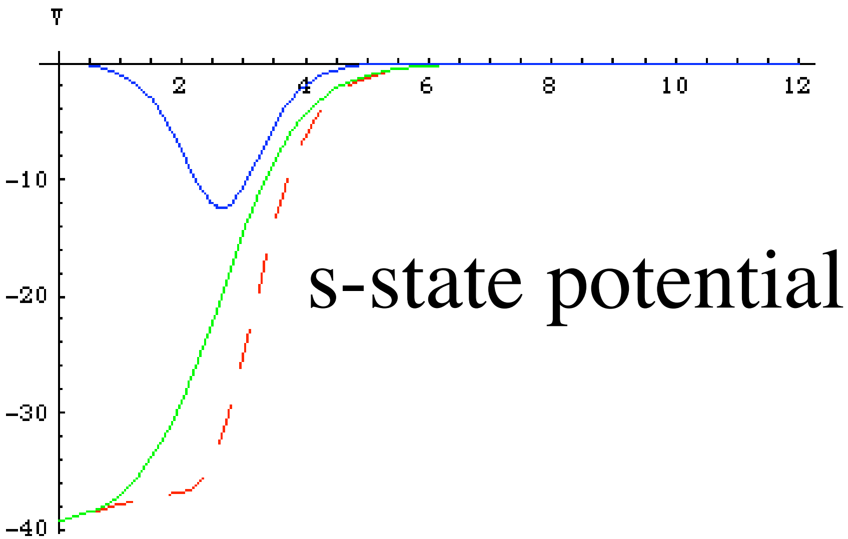
For n+^{9}Li:

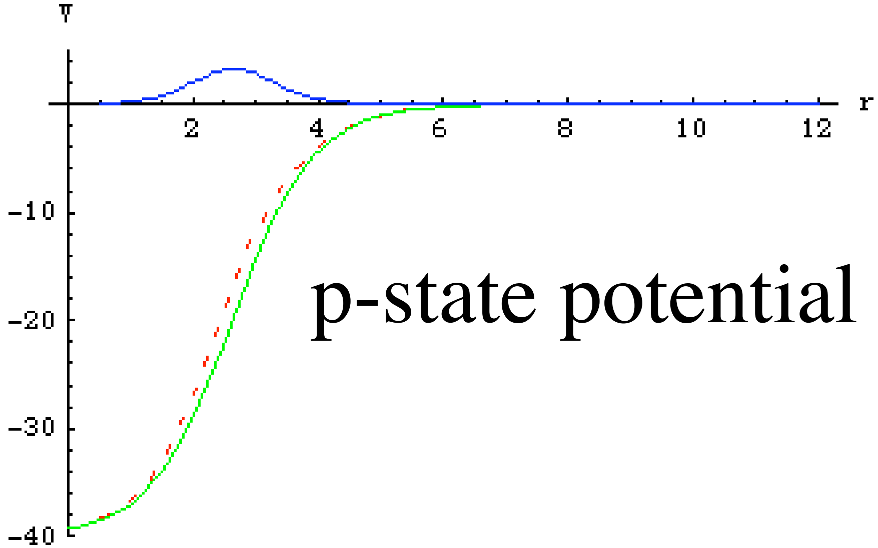
α=-12.5 for the s-state
α=3.33 for the p-state

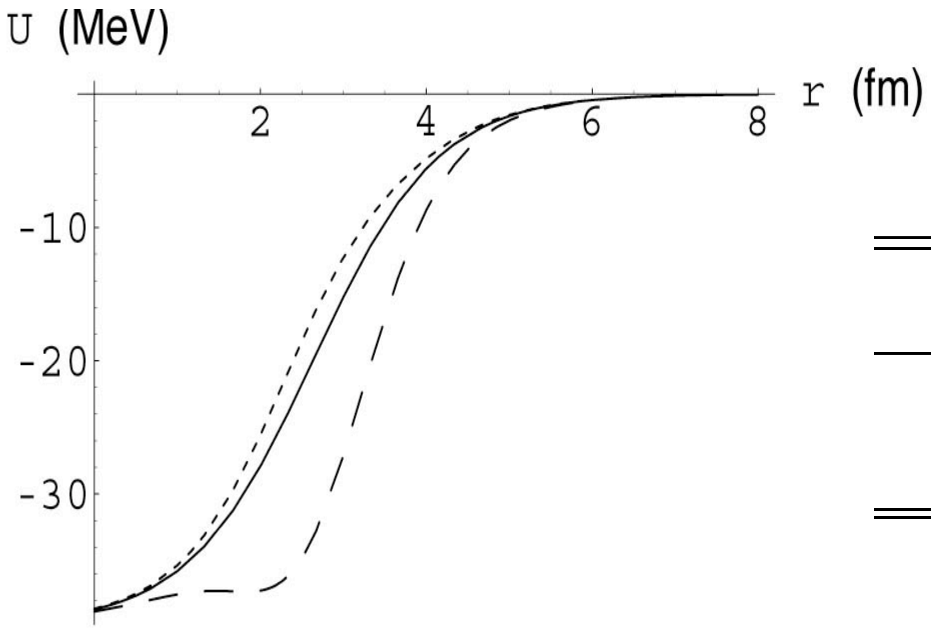


Potential model for n+^{9}Li continuum

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







Resonance states in ^{10}Li

	ε_{res} (MeV)	Γ (MeV)	a_s (fm)	α (MeV)
$2s_{1/2}$			323	-12.5
			-17.20	-10.0
$1p_{1/2}$	0.595	0.48		3.3

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Targets and neutron bound initial state parameters:

Target	d	^{9}Be	^{13}C
$\varepsilon_i(MeV)$	-2.22	-1.66	-4.95
l_i	0	1	1
j_i	1/2	3/2	1/2
$C_i(fm^{-\frac{1}{2}})$	0.95	0.68	1.88

at 2 A.MeV

^{13}C $p_{1/2}$ → $p_{1/2}$ no spin-flip

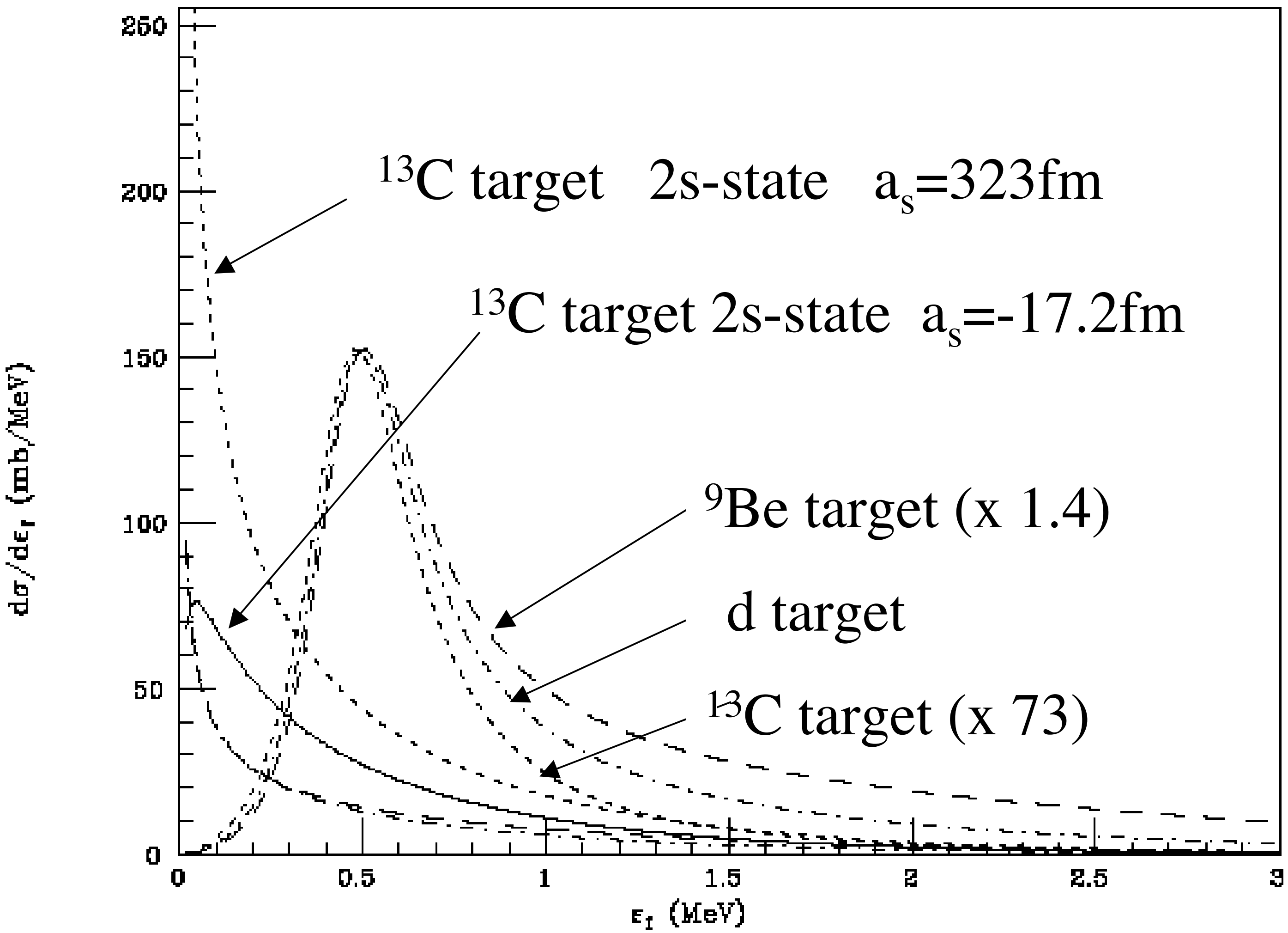
→ $s_{1/2}$ spin-flip

^{9}Be $p_{3/2}$ → $s_{1/2}$ no spin-flip

d $s_{1/2}$ → $p_{1/2}$ spin-flip

enhancement at low energy

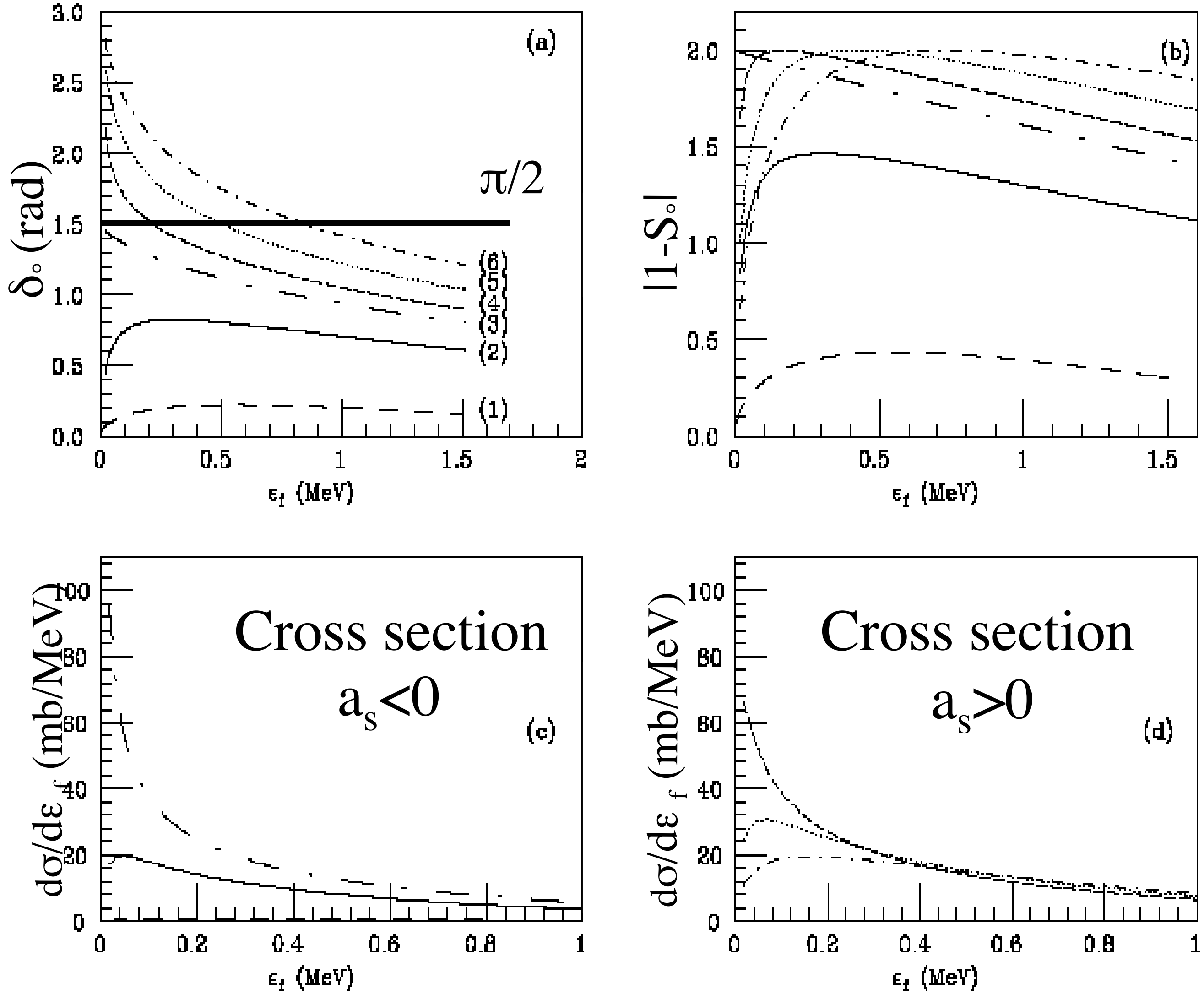
$^{9}Li(X,X-1)\ ^{10}Li$



13C target 2s-state a_s=323fm
13C target 2s-state a_s=-17.2fm
9Be target (x 1.4)
d target
13C target (x 73)
dσ/dε_f (mb/MeV)
ε_f (MeV)
0
50
100
150
200
250
0
0.5
1
1.5
2
2.5
3

$^{9}Be + {}^{9}Li \longrightarrow (n + {}^{9}Li) + {}^{8}Be$

Phase shift　　　　Shape elastic factor



	V_0 (MeV)	α (MeV)	a_s (fm)
(1)	-39.83	-4.0	-2.4
(2)	–	-10.0	-17.2
(3)	–	-12.2	-318
(4)	–	-12.4	955
(-)	–	-13.3	53.9
(5)	–	-15.0	21.4
(6)	-42.80	-13.3	12.9

scattering length

$$a_s = -\lim_{k\to 0} \frac{tan\delta_0}{k}$$

effective range theory (1st order)

$$k \cot\text{an}\, \delta = -\frac{1}{a_s} + \frac{1}{2} r_o k^2$$

α=-10.915 a_s =-26.2 fm r_o=4.3 fm

Nakamura r_o=5.6 fm

^{12}Be-n relative energy spectrum   C(^{14}B,^{12}Be+n)X

(these J.L. Lecouey 2002)

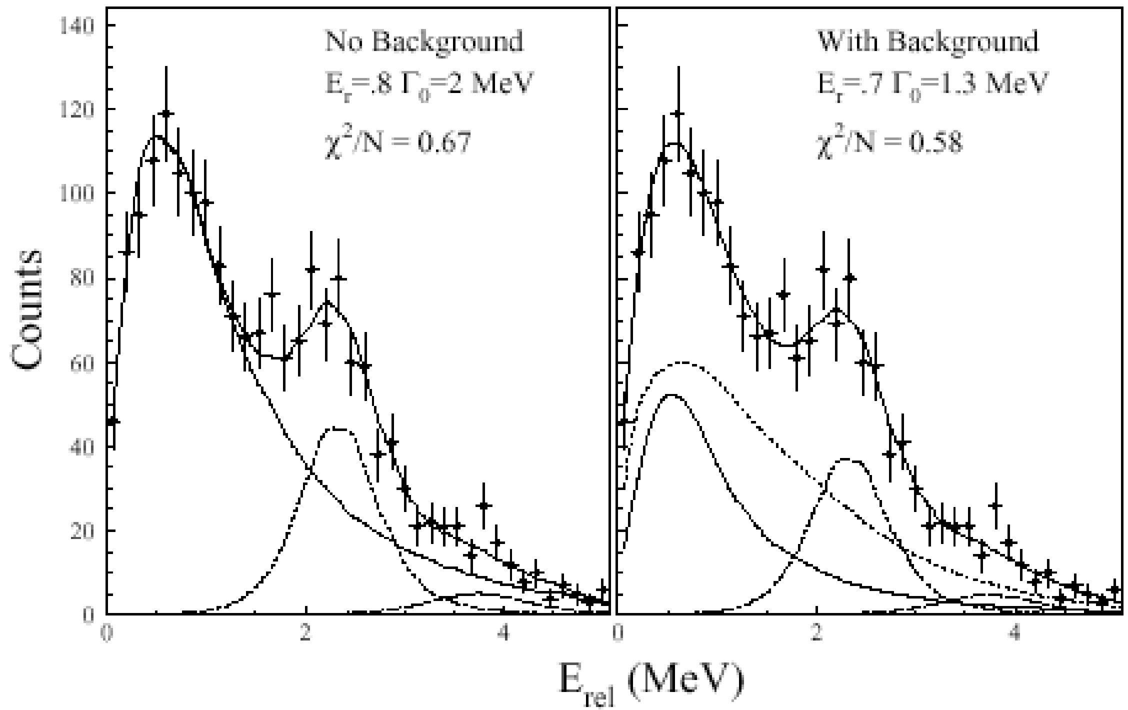
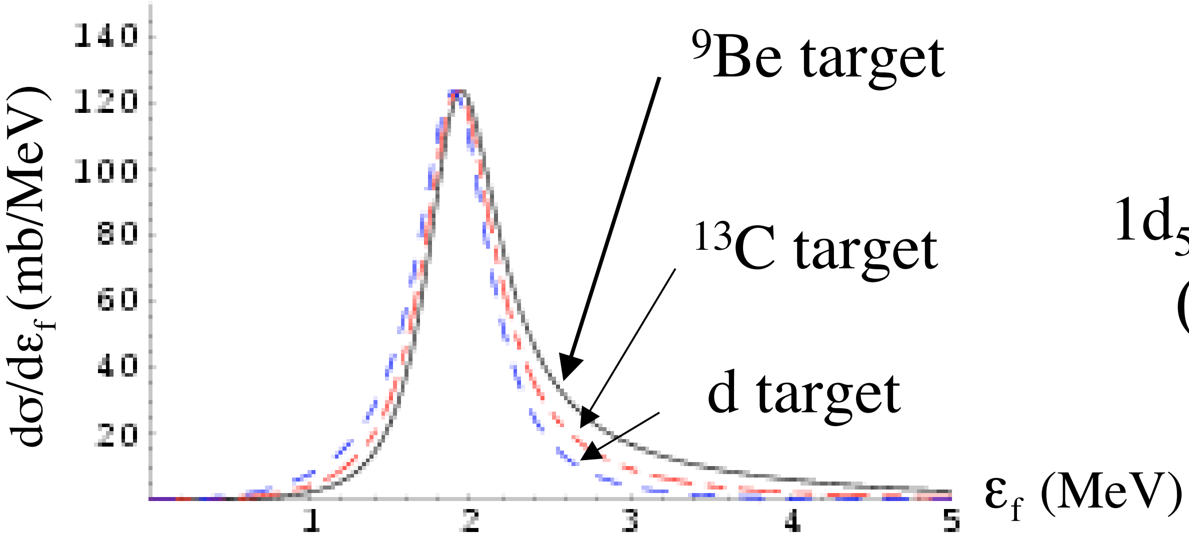
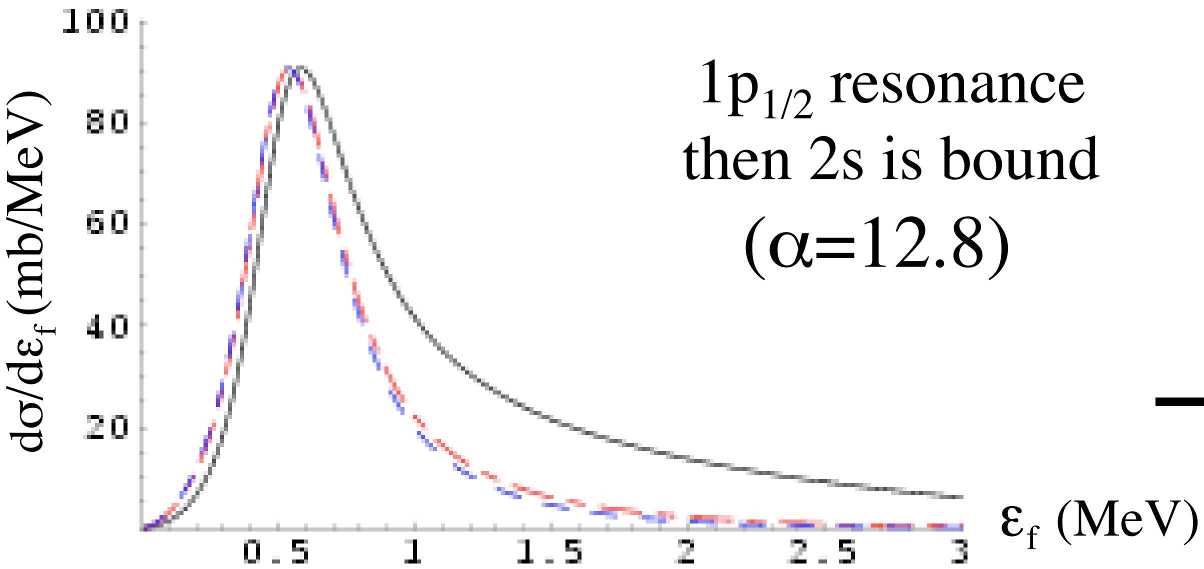


FIG. 3. ^{12}Be-n relative energy spectrum. The points are the data, the thick solid line the result of a fit including an s-wave resonance (thin solid line) and a d-wave resonance (dashed line) and in the right panel, an event-mixing "background" (dotted-dashed line). The parameters shown are those of the s-wave resonance Breit-Wigner lineshape. Note : a third resonance was tentatively introduced near 4 MeV (dotted line) but is not statistically significant. Its presence does not modify the fit in the region of interest.

resonance states in n+^{12}Be

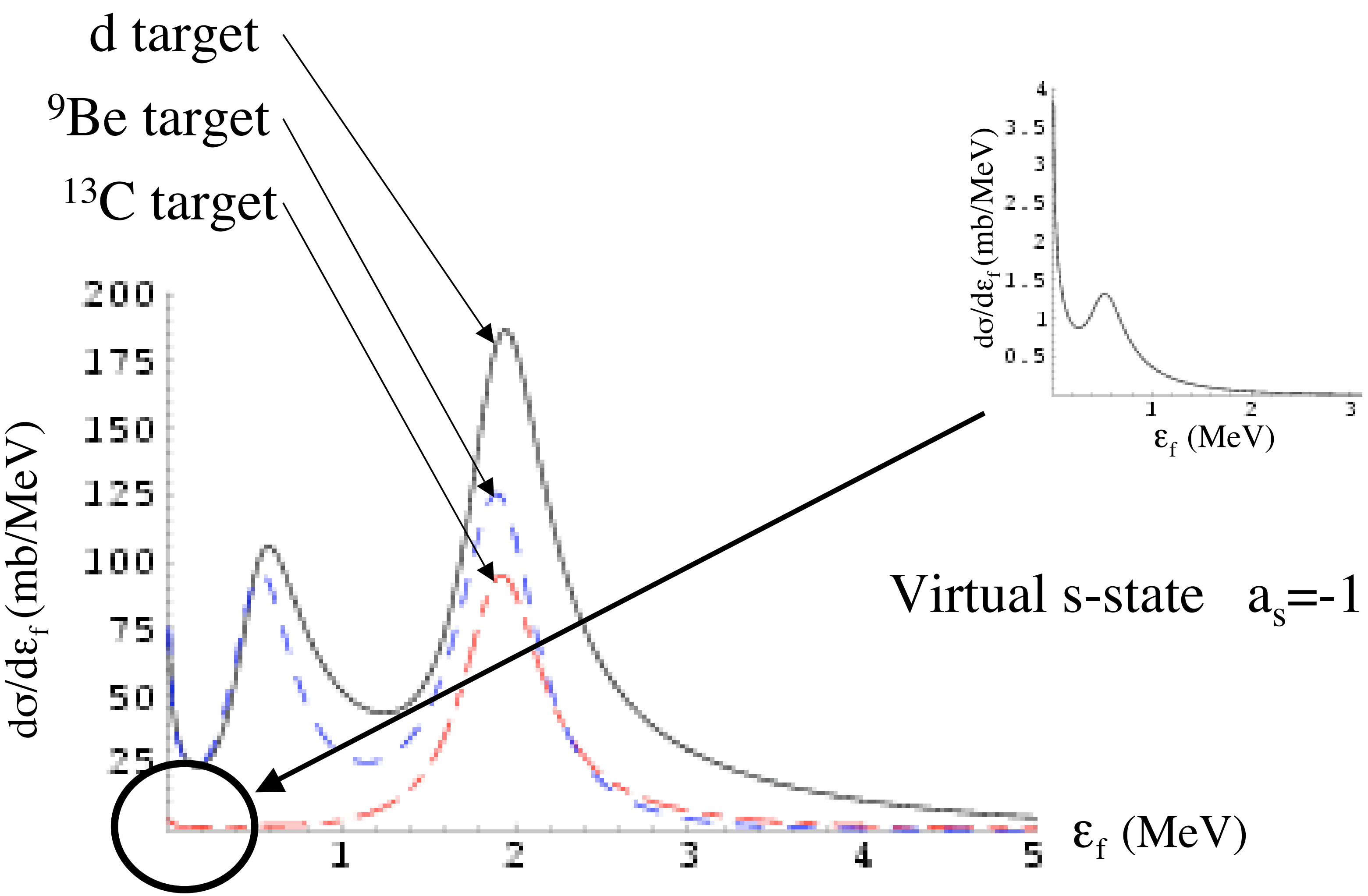


$1d_{5/2}$ resonance
(α=-2.5)



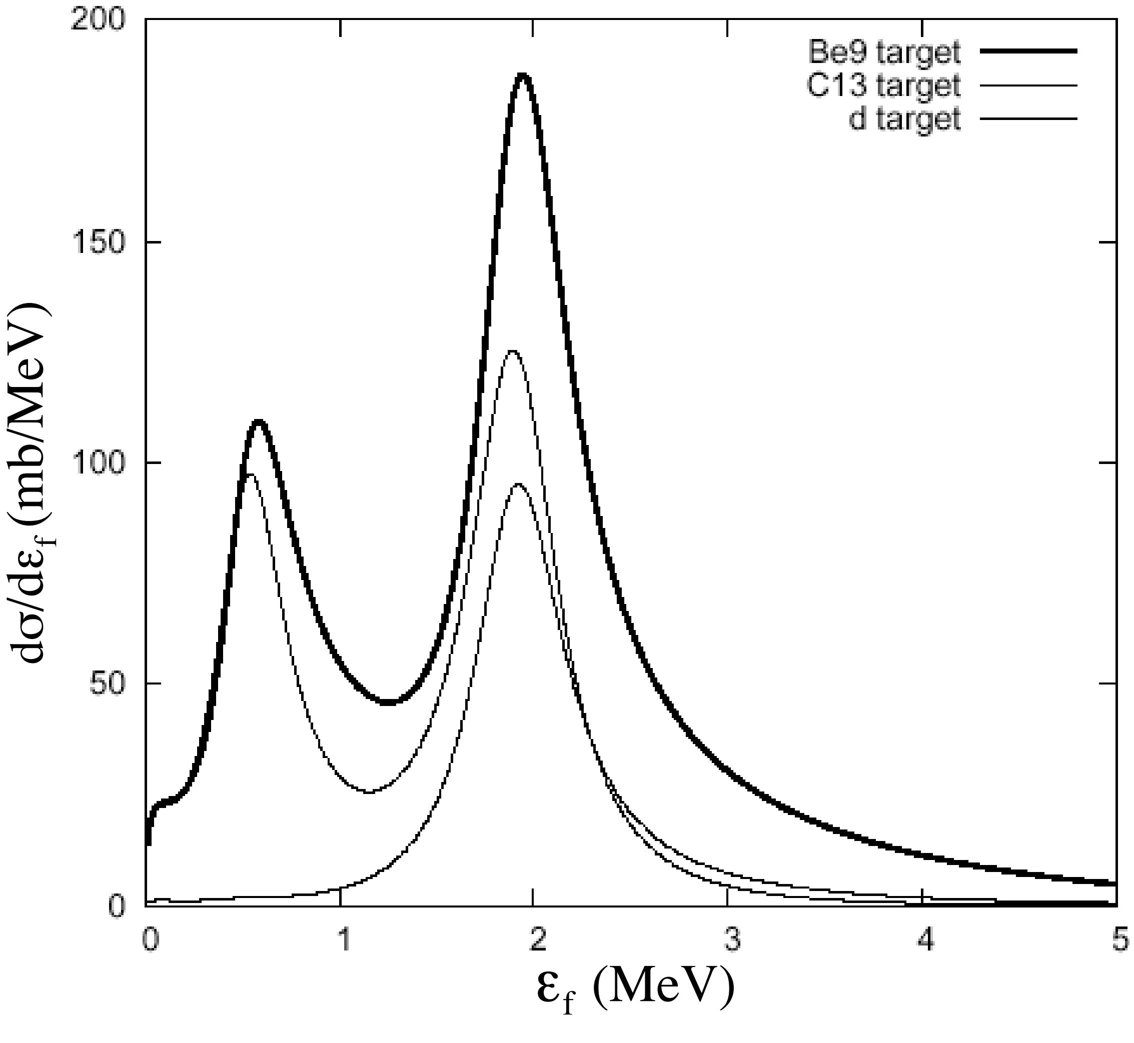
→ No dependence on the target

Overview for n+^{12}Be



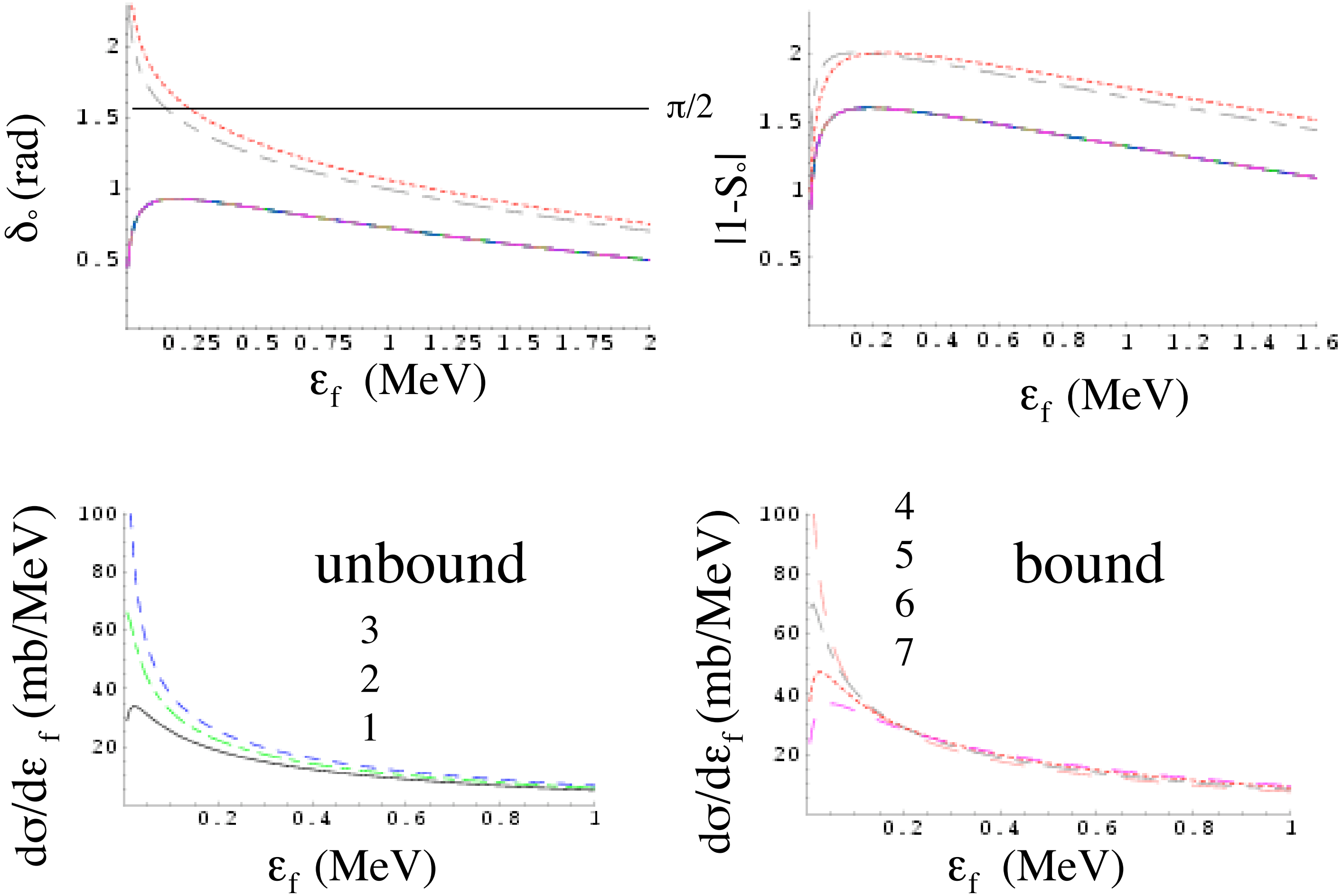
Virtual s-state a_s=-1.66 fm

a_s=11.5



Be9 target
C13 target
d target
200
150
100
50
0
0
1
2
3
4
5
dσ/dε_f (mb/MeV)
ε_f (MeV)

$^9Be + ^{12}Be \longrightarrow (n + ^{12}Be) + ^8Be$



	α	a_s
1	-0.6	-28
2	-1.2	-51
3	-1.9	-206
4	-2.5	118
5	-3.1	48
6	-3.8	31
7	-4.4	23

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Conclusions

- transfer to the continuum method is well suited to study unbound systems such as ^{10}Li which are building blocks of borromean nuclei.

- we are able to determine a_s and the resonance of unbound single particle states