DIRECT REACTIONS
With EXOTIC NUCLEI

References, Collaborators
Recent Developments in Electromagnetic Excitation
With Fast Heavy Ions
G.Baur, K.Hencken, D.Trautmann, S.Typel
nucl-th/0402012, Hirschegg2004
Theory of the Trojan Horse Method
G.Baur, S.Typel nucl-th/0401054,Fusion03

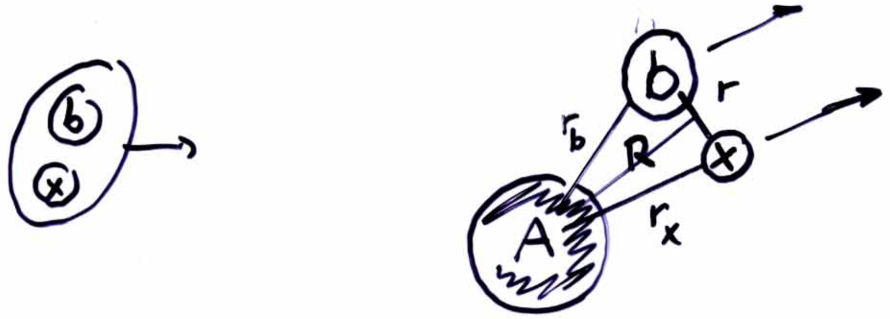
Trento March 9, 2004

General

Direct reactions have been studied for decades
low energies: DWBA, coupled channels
simplification for high energies: Glauber(Eikonal) Methods

Reaction theories for elastic scattering, inelastic scattering , transfer reactions
breakup: inelastic scattering? or transfer reaction?

$A + (b + x) \longrightarrow A + b + x$



Ψ_{final} : more like $\sim \chi_b(r_b)\,\chi_x(r_x)$

or

$\sim \chi_{(bx)}(R)\,\varphi(r)$?

Content

1. Transfer Reactions

Trojan Horse Method

Transfer reaction into the continuum (resonant states) just above threshold

"Surface Approximation": phase shifts(or ANC) are measured

2. Electromagnetic excitation and dissociation

electromagnetic matrix elements are measured

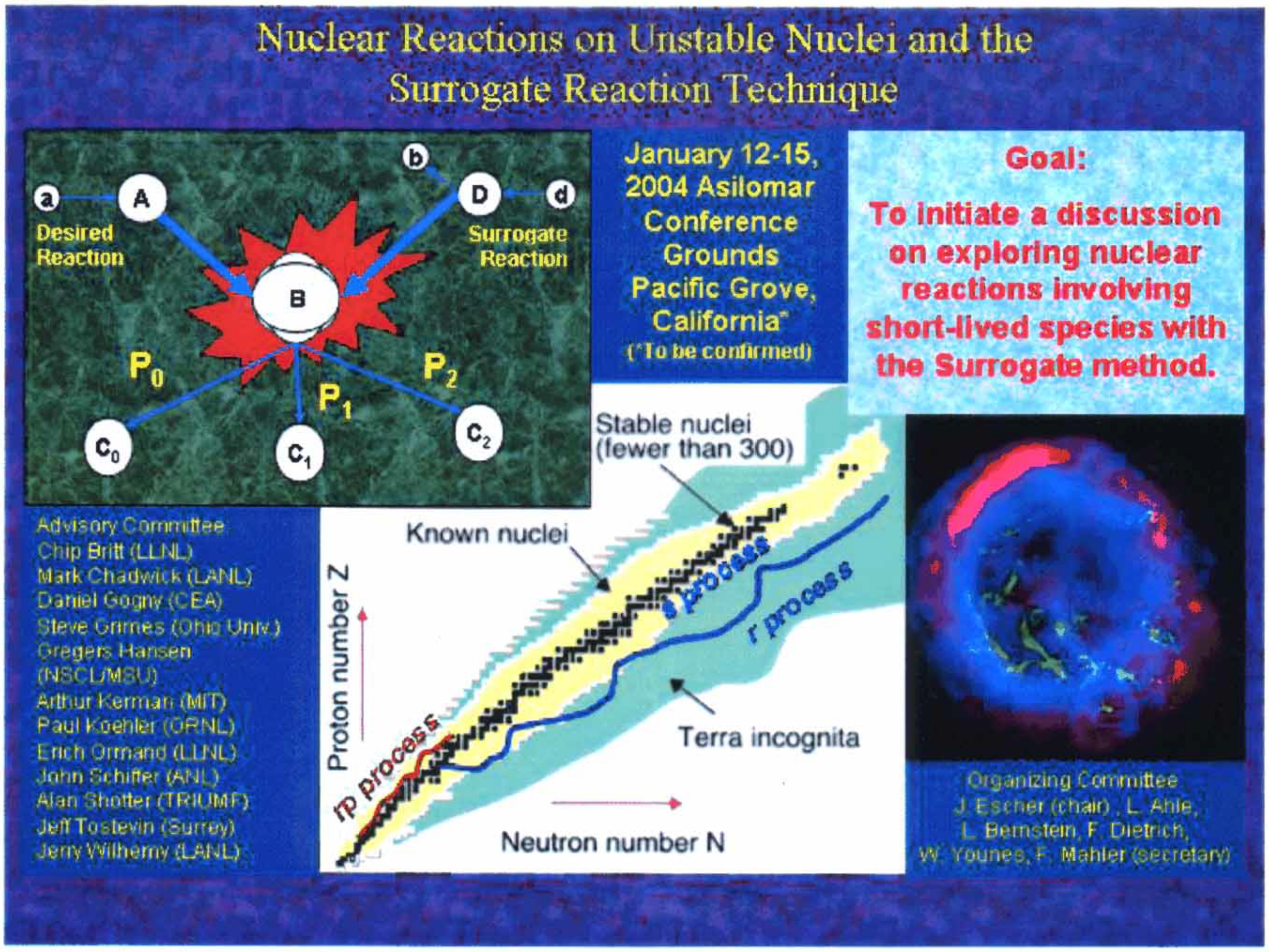
not spectroscopic factors

relation to spectroscopic factors in special situations

important parameters

A Toy Model for Coulomb Dissociation of Halo Nuclei

Effective range theory of Halo Nuclei



desired reaction

surrogate reaction

THM: $x + A \rightarrow c + C$

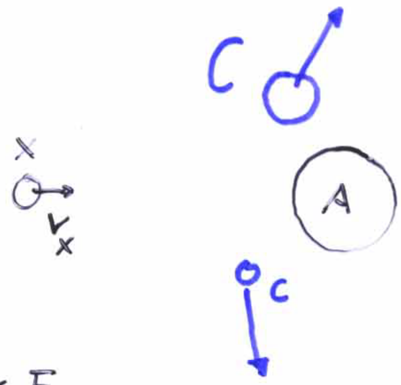
$(b+x) + A \rightarrow b + c + C$

EMD: $x + b \rightarrow a + \gamma$

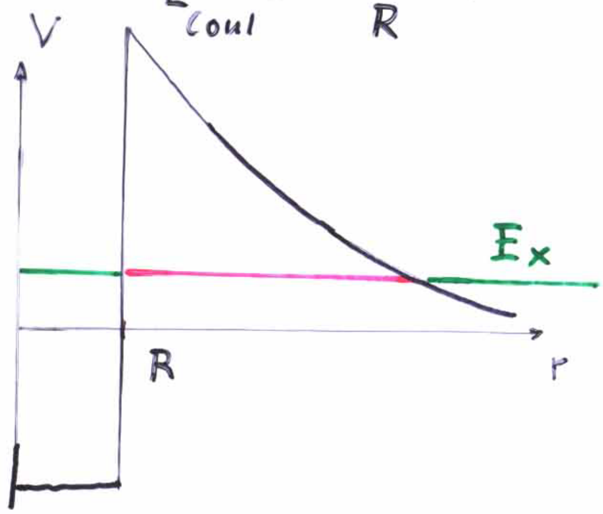
$\underbrace{(x+b)}_{a} + Z \rightarrow x + b + Z$

Trojan Horse Method

charged particle reaction $\underline{A + x \to c + C}$

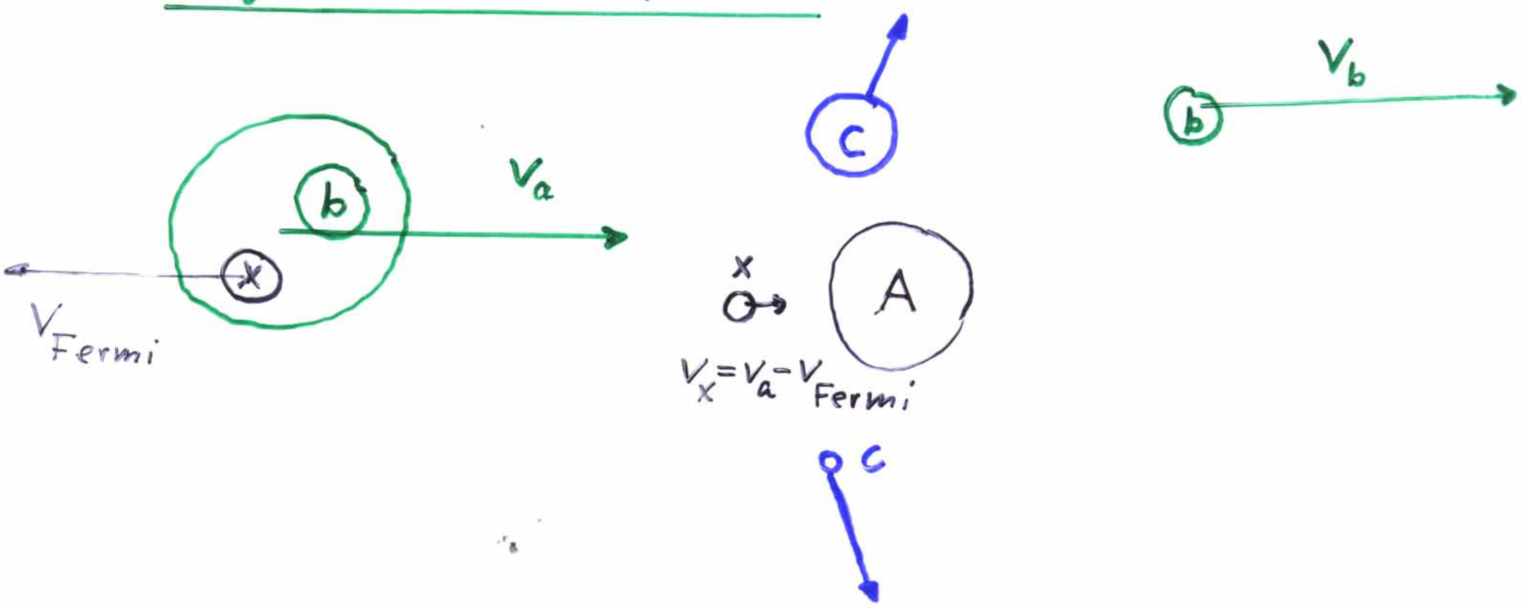


$$E_{Coul} = \frac{Z_A Z_x e^2}{R}$$



$$E_x = \frac{1}{2} m_x v_x^2 \ll E_{Coul}$$

trojan horse $a = (b + x)$

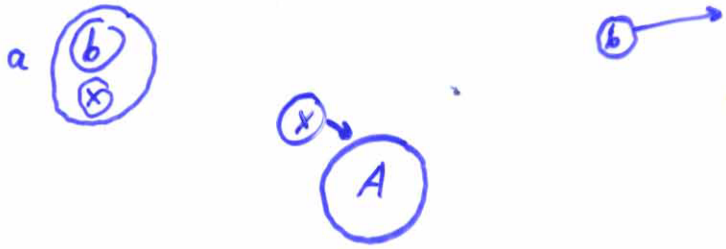


Mechanisms for Breakup Reactions

sequential

projectile a is excited as a whole

spectator quasifree



subsystem b is spectator

reactions of A+x subsystem:

$x + A \to x + A$ elastic breakup

$x + A \to c + C$ inelastic breakup

for THM to work, the spectator (or quasifree) mechanism must be dominant

ensure by choosing kinematical conditions

various models (semiclassical, DWBA, eikonal, ...)

Bonaccorso, Brink:

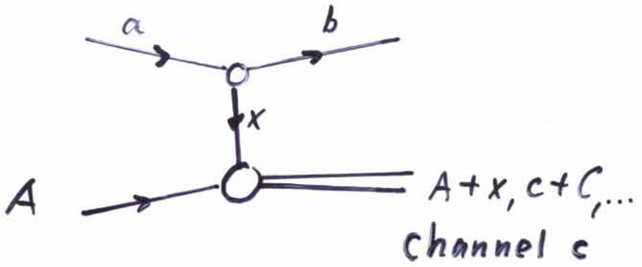
breakup probability $\frac{dP}{dq_n} \sim \sum_j \left(|1 - S_j|^2 + (1 - |S_j|^2) B_j \right)$

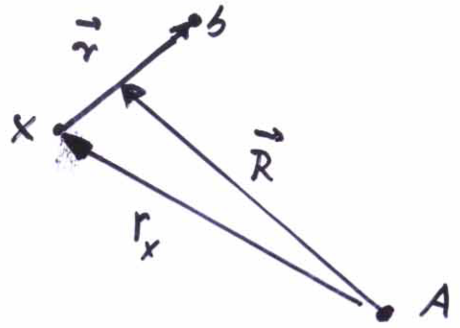
S-matrix for x-A interaction

see also C.A. Bertulani, G. Baur, M.S. Hussein NPA 526 (1991) 751

M.S. Hussein, K. McVoy NPA 445 (1985) 124

Post-form DWBA





elastic breakup

$$T \sim \int d^3R\, d^3r\, \chi_b^{(-)*}\, \chi_x^{(-)*}\, V_{bx}(r)\, \varphi_{bx}(r)\, \chi_a^{(+)}(\vec{R})$$

for numerical calculations $V_{bx} \sim \delta(\vec{r})$ $\quad D_0 \equiv \int d^3r\, V_{bx}(r)\varphi_{bx}(r)$

"zero range"

inelastic breakup

$$T \sim D_0 \int d\xi_A\, \Phi_{B,c}^{(-)*}(\xi_A, r_x)\, \Phi_A(\xi_A) \ldots$$

"wave function of transferred particle"

internal coordinates of A

"surface approximation" $\sim \delta_{\ell_x c}\, j_{\ell_x} + (S_{\ell_x c} - \delta_{\ell_x c})\, h^+_{\ell_x}$

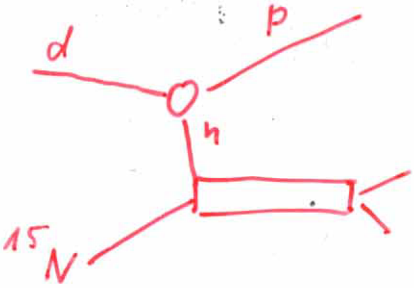
Inclusive cross section $A + a \to b + X$

use $\sum_{c \neq \ell_x} |S_{\ell_x c}|^2 = 1 - |S_{\ell_x \ell_x}|^2$

M. Ichimura PR C41 (1990) 834 relation among theories of inclusive breakup reactions

H. Fuchs, H. Homeyer, Th. Lorenz, H. Oeschler
PLB 37B '71 285

Trojan Horse Method



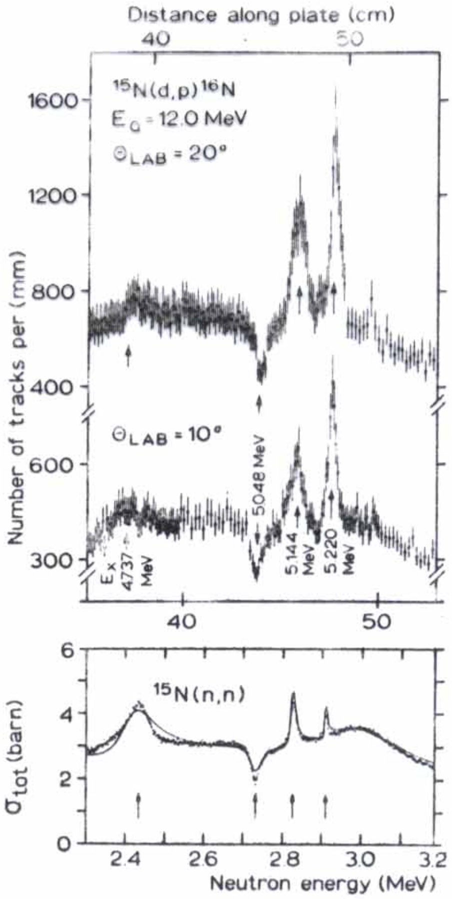
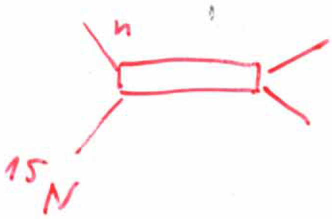


Fig. 1 Details of proton spectra from $^{15}N(d,p)\,^{16}N$ (upper part) in comparison with the $^{15}N(n,n)$ total cross section of Zeitnitz et al. [4] (lower part). Resonance energies E_x in ^{16}N are from the neutron data. Their positions expected in the proton spectra are indicated by arrows. (solid line: R-matrix fit).



compare also the method to extract n-n scattering

from $n + d \rightarrow n' + n + p$

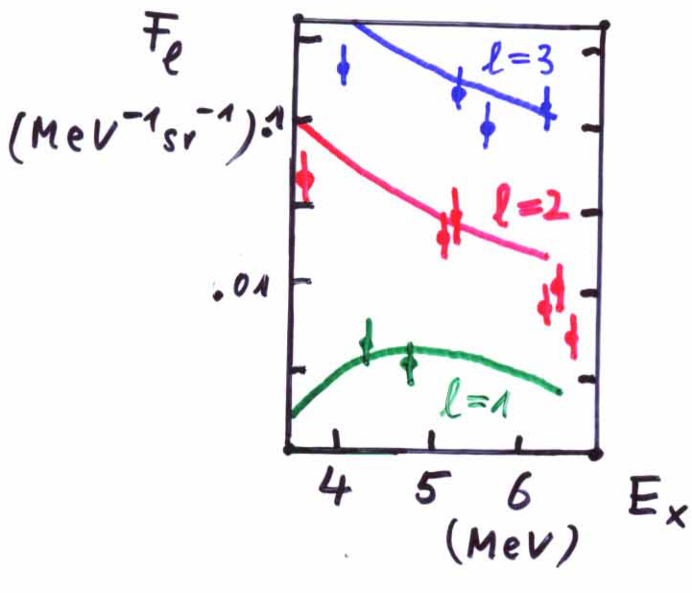
Parallelism

G. Baur, D. Trautmann Phys. Rep. 25C (1976) 293

$$\frac{d^2\sigma}{d\Omega_p\, dE_p}(d,p) = F_\ell(q_n, q_d, q_p)\cdot \sigma_\ell(n,n)$$

"stripping enhancement factor"
depends on a cut-off radius R

results for $^{15}N(d,p)^{16}N^* / ^{15}N(n,n)^{15}N$



similar results for $^{24}Mg(d,p)^{25}Mg^* / ^{24}Mg(n,n)^{24}Mg$

investigate unbound nuclei:
e.g. $^{10}Li = (n + {}^9Li)$ $\quad$ $^9Li(d,p)^{10}Li$
$\qquad n + {}^9Li^* + \ldots$

P. Santi et al. at MSU
G. Blanchon, A. Bonaccorso and N. Vinh Mau nucl-th/0402050

$E_x \to 0$ Threshold behaviour

x = neutral particle

$$\frac{d^2\sigma(\text{inelastic})}{d\Omega\, dE} \sim q_n \left(\frac{1}{q_n^{\ell_n+1}}\right)^2 \underbrace{\left(1 - |S_{\ell_n \ell_n}|^2\right)}_{\sim q_n^{2\ell_n+1}} \sim \text{finite} \quad (\neq 0)$$

from DWBA integral

$\sim q_n^{2\ell_n+1}$ ($\ell_n = 0$: Fermi's $\frac{1}{v}$-law in n-A scattering)

$$\frac{d^2\sigma(\text{elastic})}{d\Omega\, dE} \underset{q_n \to 0}{\longrightarrow} 0$$

x = charged particle

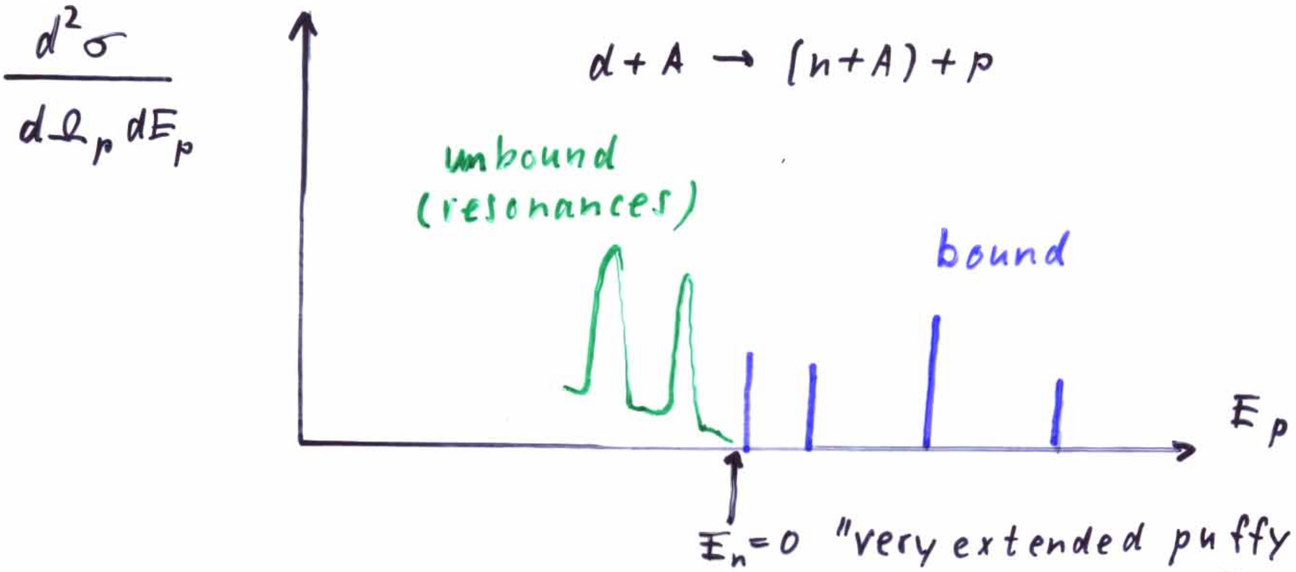
$$\sigma(A + x \to c + C) \sim \frac{e^{-2\pi\eta}}{q_x^2}$$

$$\frac{d^3\sigma(\text{inelastic})}{d\Omega_c\, d\Omega_b\, dE_b} \sim q_x \left| S_{\ell_x c}\; T^{(+)}_{\ell_x m_x} \right|^2 \to \text{finite } (\neq 0)$$

$S_{\ell_x c} \sim e^{-\pi\eta}$, $\quad T^{(+)}_{\ell_x m_x} \sim \frac{e^{+\pi\eta}}{\sqrt{q_x}}$

- DWBA-integral $T^{(+)}_{\ell_x m_x}$ must be known theoretically
- extraction of inelastic S-matrixelement $S_{\ell_x c}$ relies on surface approximation

Stripping to bound and unbound states: continuous transition



"very extended puffy states"
P.v. Brentano et al. PL B46 (1973) 177

bound states $\quad E_b = \frac{\hbar^2 \alpha^2}{2m}$

$$\varphi_n(r) = \underbrace{\sqrt{S} \cdot N}_{ANC} \cdot h_\ell(i\alpha r) \qquad r > R$$

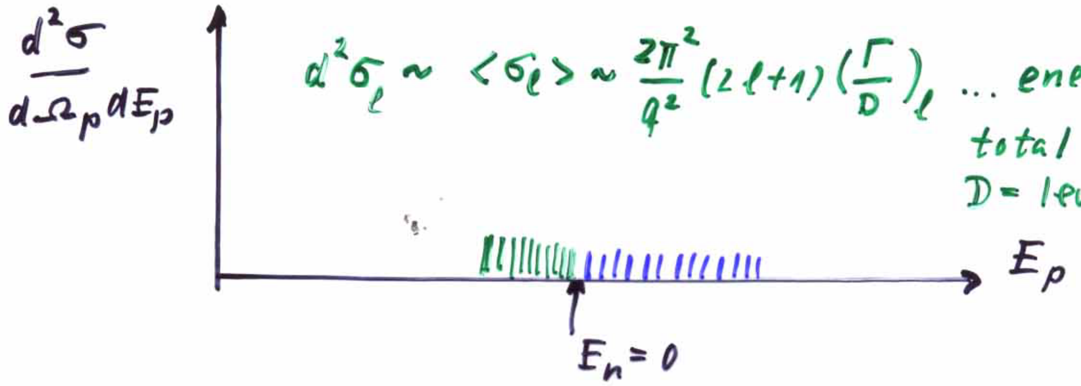
unbound states (continuum) $\quad E_n = \frac{\hbar^2 q^2}{2m}$

natural definition of spectroscopic factor: $\Gamma = \Gamma_{s.p.} \cdot S$

with $\quad \Gamma_{s.p.} = \frac{\hbar^2}{mq} \cdot N^2$

for densely spaced levels:

$$d^2\sigma_\ell \sim \langle \sigma_\ell \rangle \sim \frac{2\pi^2}{q^2}(2\ell+1)\left(\frac{\Gamma}{D}\right)_\ell$$ ... energy averaged total $n+A$ cross-sect.
D = level spacing



see G. Baur, F. Rösel, D. Trautmann, R. Shyam Phys. Rep. 111 (1984) 333

— Kasano, Ichimura Phys. Lett. 115B (1982) 81

Pampus, Bisplinghoff, Ernst, Mayer-Kuckuk, Rama Rao, Baur, Rösel, Trautmann

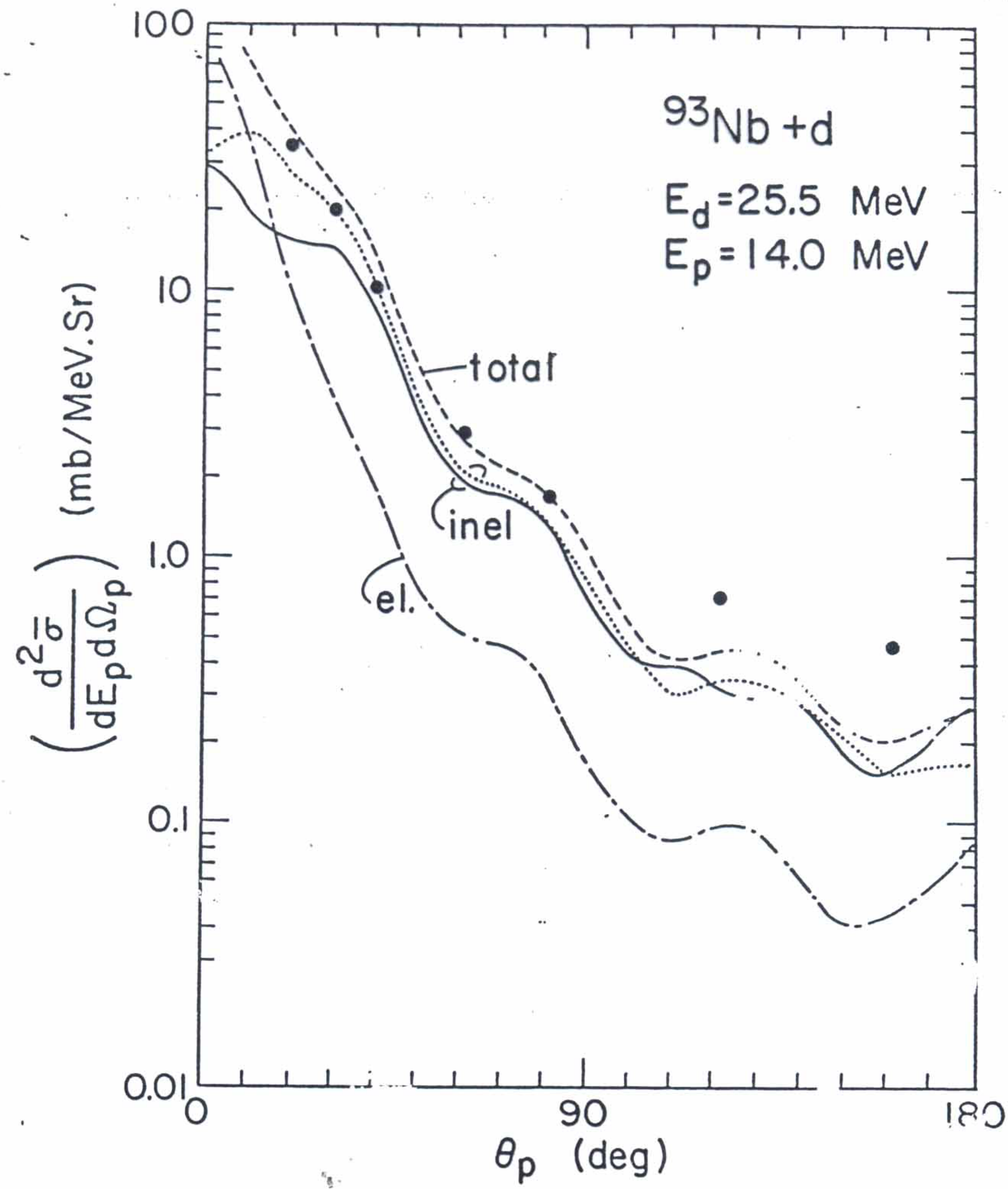


FIG. 1

Formalism for breakup reactions without use of surface approximation:

A. Kasano, M. Ichimura Phys. Lett. B 115 (1982) 81

⇒ a numerical check of the accuracy of the surface approximation

Inelastic breakup mechanism clarified in a series of papers ("IAV")

see M. Ichimura, N. Austern and C. M. Vincent Phys. Rev. C37 (1988) 2264 · to trace back this story

Conclusion

- Trojan-horse method is indirect, needs theoretical analysis
  S. Typel, G. Baur Ann. Phys. 305 (2003) 228
- assumes simple reaction mechanism
- DWBA, or modified PWBA-methods
  at higher energies: eikonal approach
- electron screening can be neglected

Experiments

- Catania group C. Spitaleri et al.

- $^{12}C(^{7}Li, t\gamma)^{16}O$ Heidelberg Heusler, Reiter et al.
  not (yet) successful
- populate resonant states

$^{22}Na(^{3}He, d)^{23}Mg \rightarrow {}^{22}Na(p,\gamma)^{23}Mg$ C. Rolfs et al. 1995

$^{17}O(^{3}He, d)^{18}F \rightarrow {}^{17}O(p,\gamma)^{18}F$ V. Landre et al. 1989

$^{15}N(^{7}Li, t)^{19}F \rightarrow {}^{15}N(\alpha,\gamma)^{19}F$ F. de Oliveira et al. 1996

- application to radioactive beams EXL
  a wide choice of targets and projectiles

  cf. K.E. Rehm et al $d(^{56}Ni, p)^{57}Ni$ 1998
  study of transitions to bound states
  extend to unbound states

Coulomb Dissociation Method

a "nuclear physics Primakoff effect"

- nuclear structure

  GDR in unstable nuclei

  low lying E1 strength

- nuclear astrophysics

  indirect method to study radiative capture

  e.g. $^{8}B + {}^{208}Pb \rightarrow {}^{7}Be + p + {}^{208}Pb$

  $\Rightarrow S_{17}(E)$ for $^{7}Be(p,\gamma)^{8}B$

  solar neutrinos

complementary to direct studies:

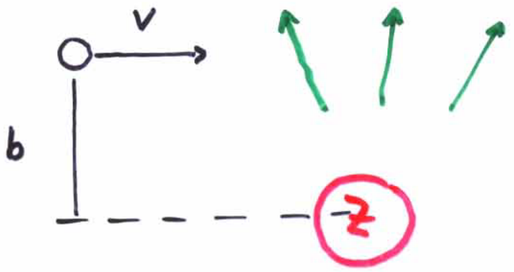
a few selected examples

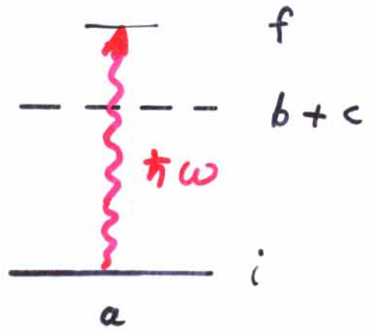
unstable nuclei become accessible

e.g. r- and rp-process nuclei

2p-capture

Basic Parameters





collision time $\tau_{coll} = \dfrac{b}{\gamma v}$ $\qquad$ $\gamma \equiv (1 - v^2)^{-\frac{1}{2}}$

excitation time $\tau_{exc} = \dfrac{1}{\omega}$

adiabaticity parameter $\xi \equiv \dfrac{\tau_{coll}}{\tau_{exc}} = \dfrac{\omega b}{\gamma v}$

$\xi \ll 1$ excitation happens

$\xi \gg 1$ excitation is only virtual

strength parameter χ

$$V_{int} \sim \frac{\gamma}{b^{\lambda+1}} \langle f | \mathcal{M}(\pi\lambda) | i \rangle \cdot Ze$$

electromagnetic matrix-el.
$\pi\lambda$ = multipolarity

$$\chi = \frac{V_{int} \cdot \tau_{coll}}{\hbar} = Z \frac{\langle f | \mathcal{M}(\pi\lambda) | i \rangle e}{b^{\lambda} \hbar v}$$

$\chi \sim$ number of exchanged photons

($\eta_{Sommerfeld} = \dfrac{Z Z_a e^2}{\hbar v}$ "monopole-monopole interaction") lowest order: factorization

$$\sigma_c = \sum_{\pi\lambda} \frac{d\omega}{\omega}\, n_{\pi\lambda}(\omega)\, \sigma_\gamma^{\pi\lambda}(\omega)$$

multipolarity

equivalent photon spectra $n_{\pi\lambda}$

- $n_{E1} \sim \frac{1}{v^2} Z^2 \log \frac{\gamma v}{\omega R_{min}}$
- $n_{M1} \sim \left(\frac{v}{c}\right)^2 n_{E1}$

$\omega_{max} \cong \frac{\gamma v}{R_{min}}$

b-dependent equivalent photon spectra

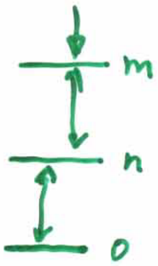
$N_{E1}(\omega, b) \sim \frac{1}{b^2}$ for $b_{min} < b \lesssim \frac{\gamma v}{\omega}$

"adiabatic radius"

$N_{E2}(\omega, b) \sim \frac{1}{b^4} \sim \frac{N_{E1}}{(k_\gamma b)^2}$ $\quad (k_\gamma = \frac{\omega}{c})$

i.e. $N_{E2} \gg N_{E1}$ in many cases

Higher order effects



$$\Psi_n(t) = \sum_n a_n(t)\, e^{-i\omega_n t}\, \phi_n$$

with nuclear eigenstates $H_0 \phi_n = \hbar\omega_n \phi_n$

$\Rightarrow$ Coupled equations

$$i\hbar\, \dot{a}_n(t) = \sum_m \langle n | V(t) | m \rangle\, e^{i(\omega_n - \omega_m)\cdot t}\, a_m(t)$$

solve numerically

or S-matrix-formalism

$$\tilde{V}(t) = e^{iH_0 t}\, V(t)\, e^{-iH_0 t}$$

$$a_n(\infty) = \langle n | T\left(\exp\left\{-i\int_{-\infty}^{\infty} \tilde{V}(t)\,dt\right\}\right) | 0 \rangle$$

time ordering operator $T(A(t_1)\ldots A(t_n)) = A(t_{p_1})A(t_{p_2})\ldots$

$t_{p_1} \geq t_{p_2} \geq \ldots$

limits:

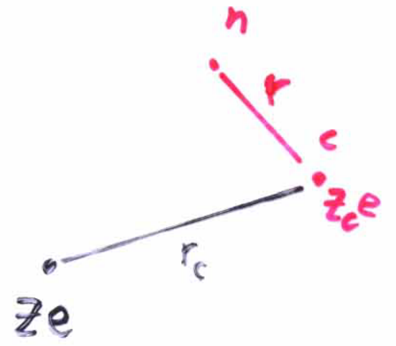
- weak coupling : 1st order, see above
- $\xi = \dfrac{\tau_{coll}}{\tau_{nucl}} \ll 1$ sudden limit

neglect T-operator all orders are included

Coulomb Dissociation of Neutron Halo Nuclei

A simple model

G. Baur, K. Hencken, D. Trautmann
Prog. Part. Nucl. Phys. 51 (2003) 487



$$H = T + \frac{Z Z_c e^2}{r_c} + V_{nc}(r)$$

short range

$$\Phi_0 = \sqrt{\frac{\varkappa}{2\pi}} \; \frac{e^{-\varkappa r}}{r}$$ ground-state halo wave fction.

$$\Phi_{\vec{q}} = e^{i \vec{q} \cdot \vec{r}} - \frac{i}{\varkappa + iq} \, \frac{e^{iqr}}{r}$$ continuum states

a theoretical laboratory to study

- higher order effects
  "post-acceleration"
- quantal and semiclassical methods

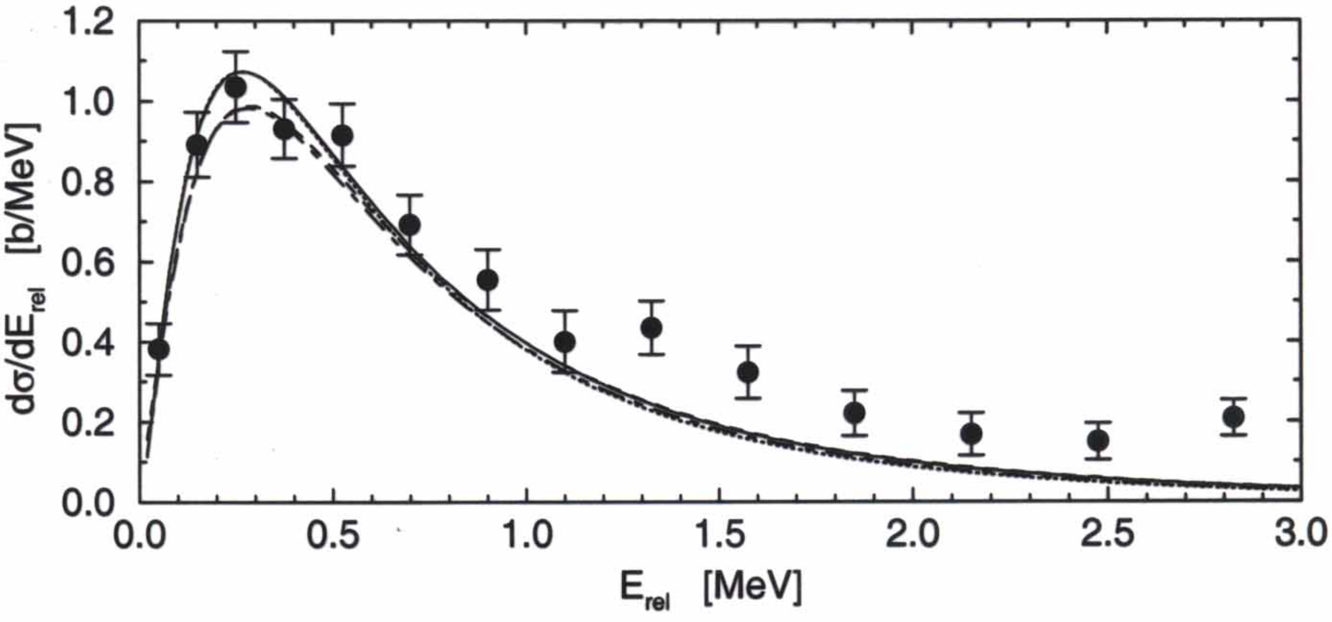
Comparison with experiment

halo nucleus $^{19}C \rightarrow {}^{18}C + n$

{ ———— LO (with finite range correction)
-------- 1^{st} order semiclassical calculation (with finite range w.f.) }

{ — — — LO + NLO
-·—·— time-dependent Schrödinger eq. }

S. Typel, G. Baur (2001) PRC



T. Nakamura et.al. ^{19}C on ^{208}Pb $E/A = 67\,MeV/A$

$0 < \theta < 3^\circ$ angle integrated

Scaling laws

S. Typel, G. Baur PRC 64 (2001)

$$\underbrace{(c+n)}_{\equiv a} + Z \to c + n + Z \qquad \vec{q}_a - \vec{q}_c - \vec{q}_n \equiv \vec{q}_{coul}$$

$$x \equiv \frac{q_{rel}}{\varkappa}$$ ... shape parameter $$E_{rel} = \frac{\hbar^2 q_{rel}^2}{2\mu}$$

$$y = \frac{2 Z Z_c e^2 m_n}{\hbar v (m_n + m_c) b \varkappa}$$ strength parameter

excitation amplitude $a(q_{rel}) = a^{(1)} + a^{(2)} + a^{(3)} + \ldots$

breakup probability (integrated over $\Omega_{q_{rel}}$)

$\sim |a^{(1)}|^2$:

$$\frac{dP_{LO}}{dq_{rel}} = \text{const.}\, y^2 \frac{x^4}{(1+x^2)^4}$$

$\sim |a^{(2)}|^2 + 2\,\mathrm{Re}\left(a^{(1)} a^{(3)*}\right)$:

$$\frac{dP_{NLO}}{dq_{rel}} = \text{const.}\, y^4 \frac{x^2(5 - 55x^2 + 28x^4)}{15(1+x^2)^6}$$

$$\text{const.} \equiv \frac{16}{3\pi\varkappa}$$

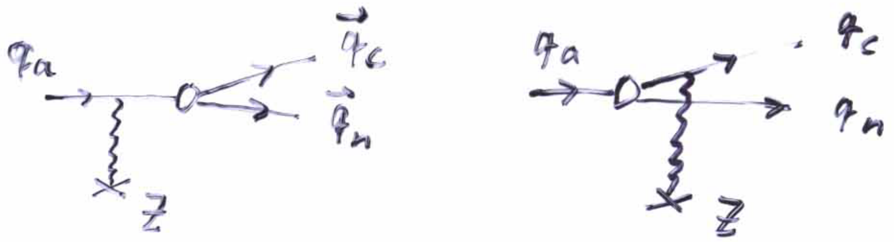
CWBA (Coulomb Wave Born Approximation)

$$T_{\vec{q}_a \to \vec{q}_c \vec{q}_n} = D_0 \int d^3R \, \chi^{(-)}_{\vec{q}_c}(\vec{R}) \, e^{-i \vec{q}_n \cdot \vec{R}} \, \chi^{(+)}_{\vec{q}_a}(\vec{R})$$

$$D_0 = \frac{\hbar^2}{2\mu} \sqrt{8\pi\varkappa} \qquad \mu = \frac{m_n m_c}{(m_n + m_c)}$$

For $\eta_a \gg 1, \; \eta_c \gg 1 \quad \xi \equiv \eta_c - \eta_a \ll 1 \qquad \eta_{a,c} = \frac{Z Z_c e^2}{\hbar v_{a,c}}$

$$T \cong T_{Born} \sim \frac{1}{q_{rel}^2 + \varkappa^2} - \frac{1}{(\vec{q}_{rel} - \Delta\vec{p})^2 + \varkappa^2}$$



$$\Delta\vec{p} = \frac{m_n}{m_a} \vec{q}_{coul} \qquad \vec{q}_{coul} = \vec{q}_a - \vec{q}_c - \vec{q}_n \qquad b = \frac{2\eta_a}{q_{coul}}$$

b: impact parameter

For fast projectiles: $\eta_a \gg 1, \; \eta_c \gg 1, \; \xi \ll 1$

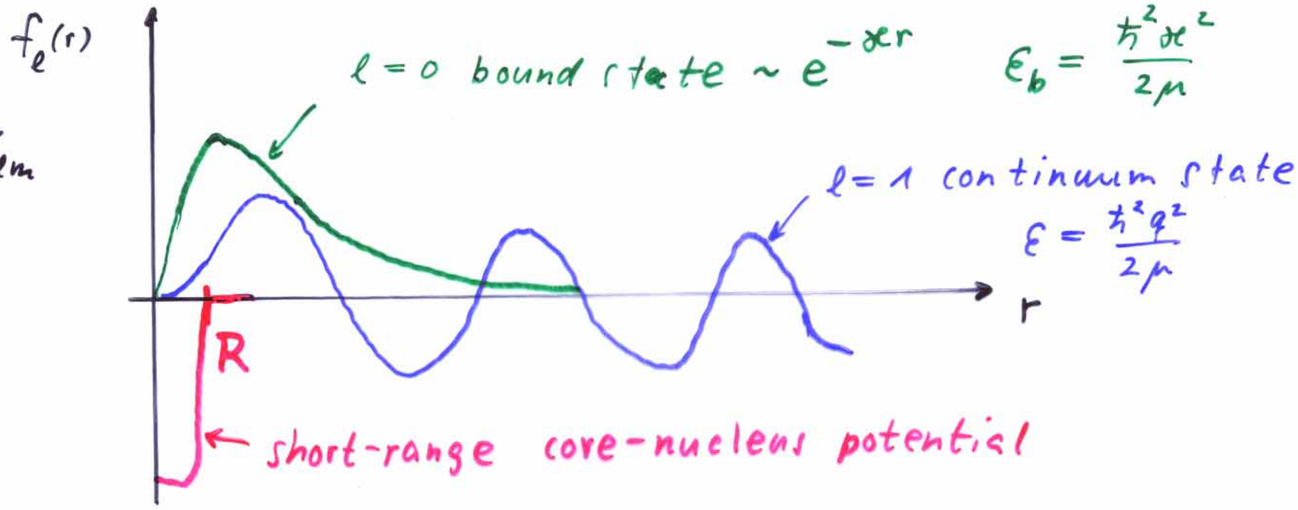
$\Longrightarrow$ no post-acceleration

(cf. Bush et al. PRL 1998: $^{11}Be \to {}^{10}Be + n$:

... no evidence for previously suggested velocity difference

Effective range theory of Halo Nuclei

$\psi = \frac{f_\ell(r)}{r} Y_{\ell m}$



$\varepsilon_b = \frac{\hbar^2 \varkappa^2}{2\mu}$

$\varepsilon = \frac{\hbar^2 q^2}{2\mu}$

$\frac{1}{\varkappa} \gg R$ halo nucleus

$q \sim \varkappa \quad \rightarrow \quad q \cdot R \ll 1$

radial dipole matrix-element

$$R^1_{\ell_i \ell_f} \equiv \int_0^\infty dr\, e^{-\varkappa r} \cdot r^2 j_1(qr) = \frac{2q}{(\varkappa^2 + q^2)^2}$$

shape of B(E1)-distribution determined by a few low energy constants

$R \rightarrow 0$: $\underline{\varkappa}$

$x = \frac{q}{\varkappa}$ $\qquad$ $\underline{B(E1) \sim \frac{x^2}{(1+x^2)^4}}$

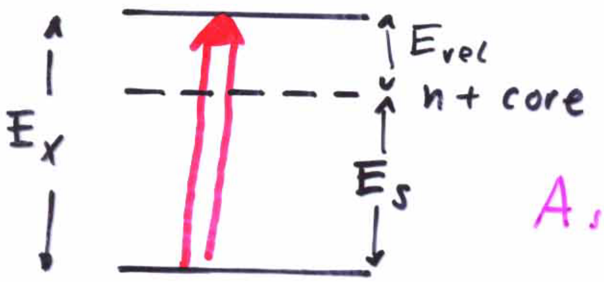
examples: d, ${}^{11}Be$, ${}^{19}C$, ${}^{15}C = ({}^{14}C + n)$

spectroscopic factor $S = 0.75$ (T. Aumann et al.)

calculation of lowlying E1-strength in

simple model : bound state (s-wave) in short range pot.

→ plane wave continuum state



• determine from experiment:

Asymptotic Normalization Constant

$$\frac{dB(\mathrm{E1})}{dE_x} = S\left|\left\langle q \middle| e\frac{Z}{A} r Y^1_m \middle| N_0 \sqrt{\frac{\kappa}{2\pi}}\exp(-\kappa r)/r \right\rangle\right|^2$$

$$= S\frac{\exp(2\kappa r_0)}{1+\kappa r_0}\frac{3\hbar^2}{\pi^2\mu}e^2\left(\frac{Z}{A}\right)^2\frac{\sqrt{E_s}(E_x-E_s)^{3/2}}{E_x^4} , \qquad (5.1)$$

Bauer, Bertulani 1986
or Blatt-Weisskopf 1952
deuteron photo-disintegration

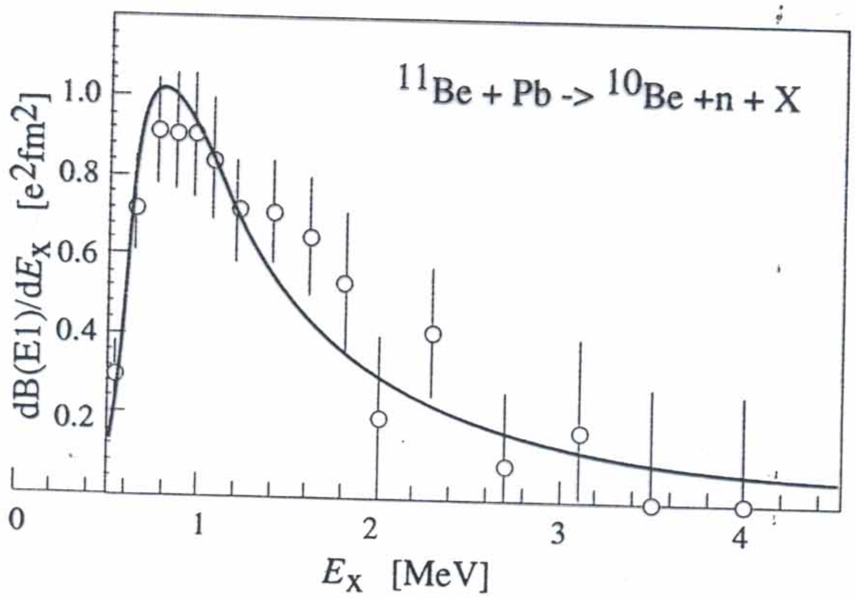


Fig. 5.4 E1 strength distribution deduced from the EMD cross section of ^{11}Be.

T. Nakamura et al.

(from Tanihata '95)

$$\underline{E_X = E_s + E_{rel}}$$

• determine E_s (separation energy) from shape:

$$\sim \frac{E_{rel}^{3/2}}{(E_s+E_{rel})^4}$$

Chapter 2a: Applications to nuclear structure, transparency 21

Prototype of Halo Nucleus: Deuteron

B = 2.23 MeV

see Blatt and Weisskopf (1952)

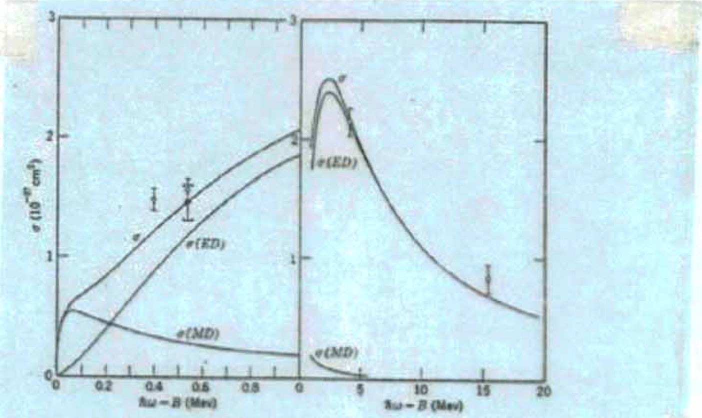


FIG. 4.1. Photodisintegration cross section of the deuteron. *ED* means electric dipole absorption, *MD* means magnetic dipole absorption.

low lying M1 strength

$^3S \longrightarrow {}^1S$ threshold behaviour: $\sigma_\gamma^{M1} \sim (\mu_n - \mu_p)^2 \dfrac{q_{rel}}{(q_{rel}^2 + \eta_{bind}^2)}$

$\left(\sigma_{capt.} \sim \dfrac{1}{q_{rel}} \right)$

other cases?

$\underbrace{n +}_{\ell=0} \text{core} \longrightarrow (\underbrace{n+\text{core}}_{\ell=0}) + \gamma$ → odd-odd halo nuclei?

no angular momentum or Coulomb barrier

anyway, probably too difficult to see in Coulomb dissociation

e.g. $n + {}^{17}F \rightarrow {}^{18}F + \gamma$
(not a halo nucleus, $E_n = 9.15$ MeV)

systematic corrections for finite range R

normalization of (single particle) bound state wave function

$$\sqrt{2\varkappa}\;\frac{e^{-\varkappa r}}{r} \to \sqrt{\frac{2\varkappa}{1-\varkappa r_0}}\;\frac{e^{-\varkappa r}}{r}$$

$$q^{2\ell+1}\cot\delta_\ell = -\frac{1}{a_\ell} + \frac{r_\ell}{2}q^2 + \dots$$ effective range expansion

$d = (p+n)$: $\frac{1}{\varkappa} = 4.3\,\mathrm{fm}$ $\quad r_0 = 1.6\,\mathrm{fm}$

continuum wave function

free wave $\quad j_\ell(qr) \xrightarrow[r>R]{} \cos\delta_\ell\, j_\ell + \sin\delta_\ell\, n_\ell$

neglect contribution to radial integral from $r<R$:

$s \to p$ excitation

$$B(E1) \sim \left(\cos\delta_1 \frac{x}{(1+x^2)^2} + \sin\delta_1 \frac{1+3x^2}{2x^2(1+x^2)^3}\right)^2$$

$$\cos\delta_1 \simeq 1 \qquad \sin\delta_1 \simeq -a_1 q^3 = -x^3(\underbrace{\varkappa^3 a_1}_{\text{small}})$$

Kalassa, Baur (1994, 1996), Mengoni et al. (1995), Typel

$p \to s$ excitation:

$$\delta_0 = -a_0 \cdot q$$

halo nature less pronounced due to centrifugal barrier

Proton Halo Nuclei

e.g. $^8B = (^7Be + p)$

$$R^1_{l_i l_f} \cong \int_R^\infty dr \; f_{l_i}(r) \cdot r \cdot \left(F_{l_f}(\eta, qr) + \tan\delta_{l_f} \, G_{l_f} \right)$$

$$\equiv R^F_{l_i l_f} + \tan\delta_{l_f} \, R^G_{l_i l_f}$$

ANC - method $\quad \delta_{l_f} = 0$

$$C_0^2 \, k \cot\delta_0 = -\frac{1}{a} - \frac{1}{a_{Bohr}} h(\eta) \qquad C_0^2 = \frac{2\pi\eta}{e^{2\pi\eta} - 1} \qquad \delta_0 \sim e^{-2\pi\eta}$$

behaviour of Coulomb functions

$r \sim 0 \qquad F_0 \sim C_0 \qquad G_0 \sim \frac{1}{C_0}$

$r \to \infty \qquad F \to \sin(\dots) \qquad G \to \cos(\dots)$

$R^F_{l_i l_f}$ ~ independent of R

$\tan\delta_{l_f} \, R^G_{l_i l_f}$ ... strongly dependent on R, small for halo nuclei (S. Typel)

2-neutron-halo nuclei

example: Migdal (1973)

two interacting neutrons in a potential well

R. Morlock et al.

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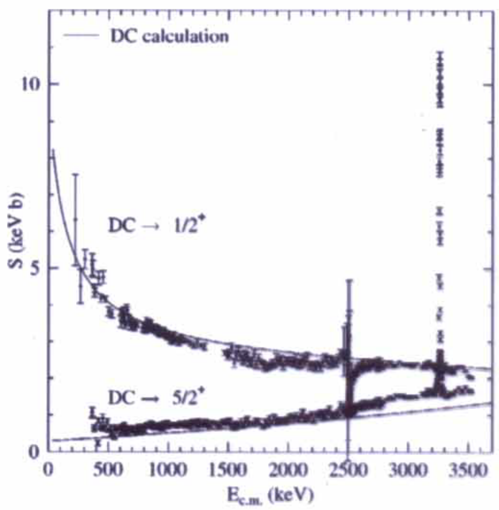


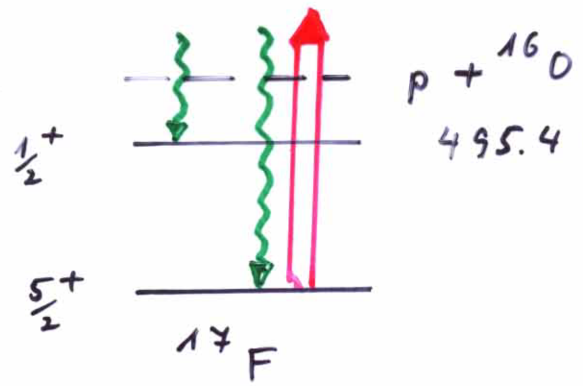
FIG. 3. Experimental capture cross section of the reactions $^{16}O(p,\gamma_0)^{17}F$ and $^{16}O(p,\gamma_1)^{17}F$ compared to a DC calculation. Note the strikingly different branching ratio between DC → $5/2^+$ and DC → $1/2^+$.

Radiatie capture

$$p + {}^{16}O \rightarrow {}^{17}F + \gamma$$

$$\sigma = \frac{1}{E} e^{-2\pi\eta} \cdot S$$

astrophysikalischer S-Faktor



Coulomb dissociation

$$^{17}F + Z \rightarrow {}^{16}O + p + Z$$

- only ground state branch
- would be a test of the method

Conclusion Outlook

Coulomb Excitation and Dissociation:

a powerful tool for nuclear structure

- E1, E2, M1, ... strength in unstable (light and heavy) nuclei
- applications to nuclear astrophysics
- model investigation of halo nucleus Coulomb breakup: 1st order theories are OK for high projectile energies

- effective range methods for halo nuclei

- applications to UPC (ultra-peripheral collisions) at RHIC and LHC