Probing the structures of exotic and halo nuclei

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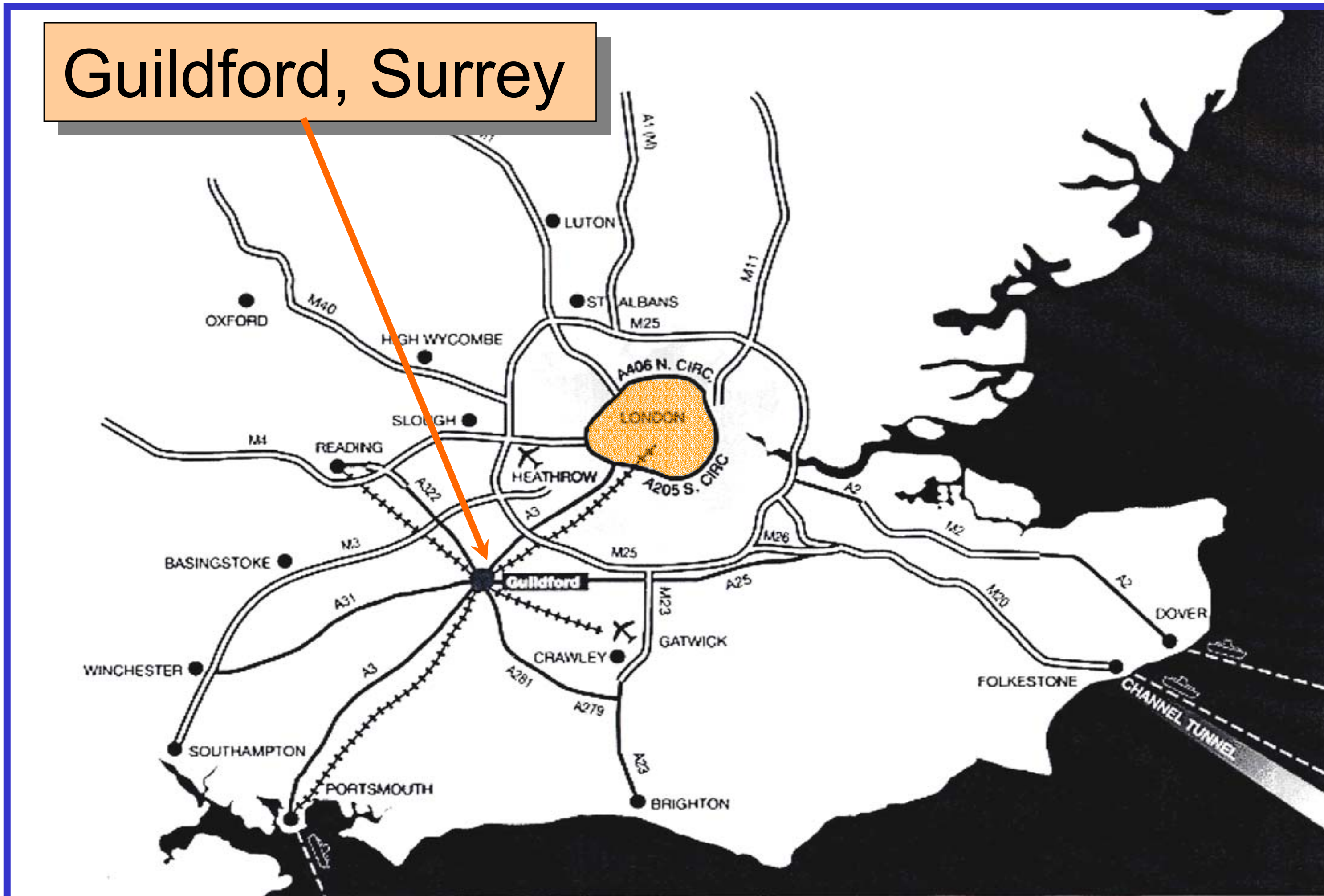
Where is the University of Surrey?



Nuclear physics - old and new

Nucleus is a challenging quantum many-body problem

Nuclear structure theory is well developed for stable and near-stable nuclei - reveals diverse collective, clustering and single-particle phenomena

Macroscopic quantities: mass, size ($\approx r_0 A^{1/3}$), density, well known – allegedly (is textbook stuff!)

Do we understand more extreme states of matter?
- large spin, isospin (abnormal N and/or Z), limits of very weak binding and stability – near the driplines

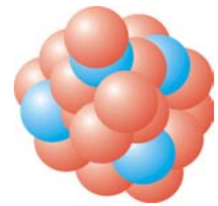
Are the theories in place and correct for such systems?

Rare and exotic nuclei - and their structures?

Normal Nucleus:

^{12}C

Exotic Nucleus:



^{22}C

6 neutrons

6 protons (carbon)

Stable, found in nature

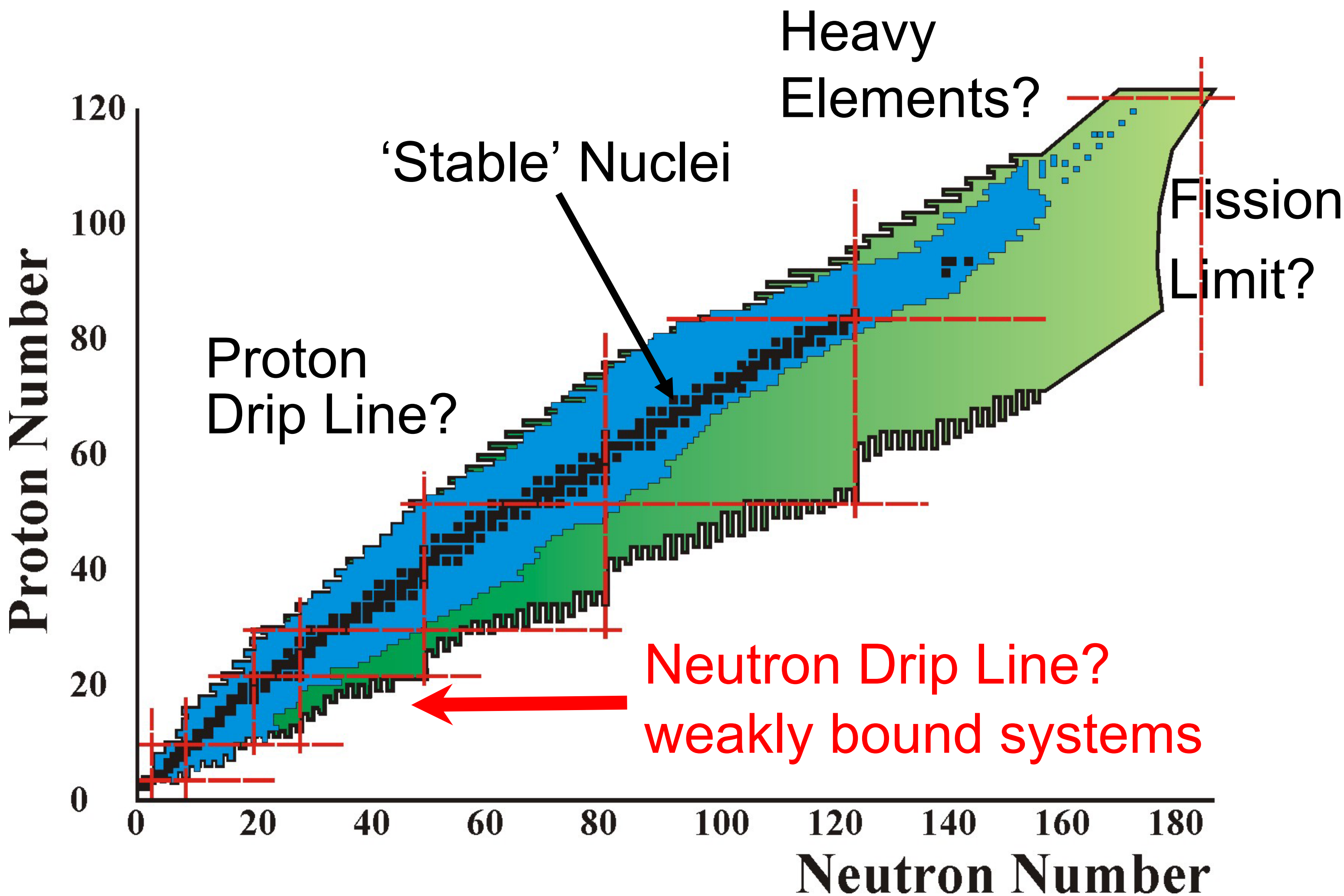
16 neutrons

6 protons (carbon)

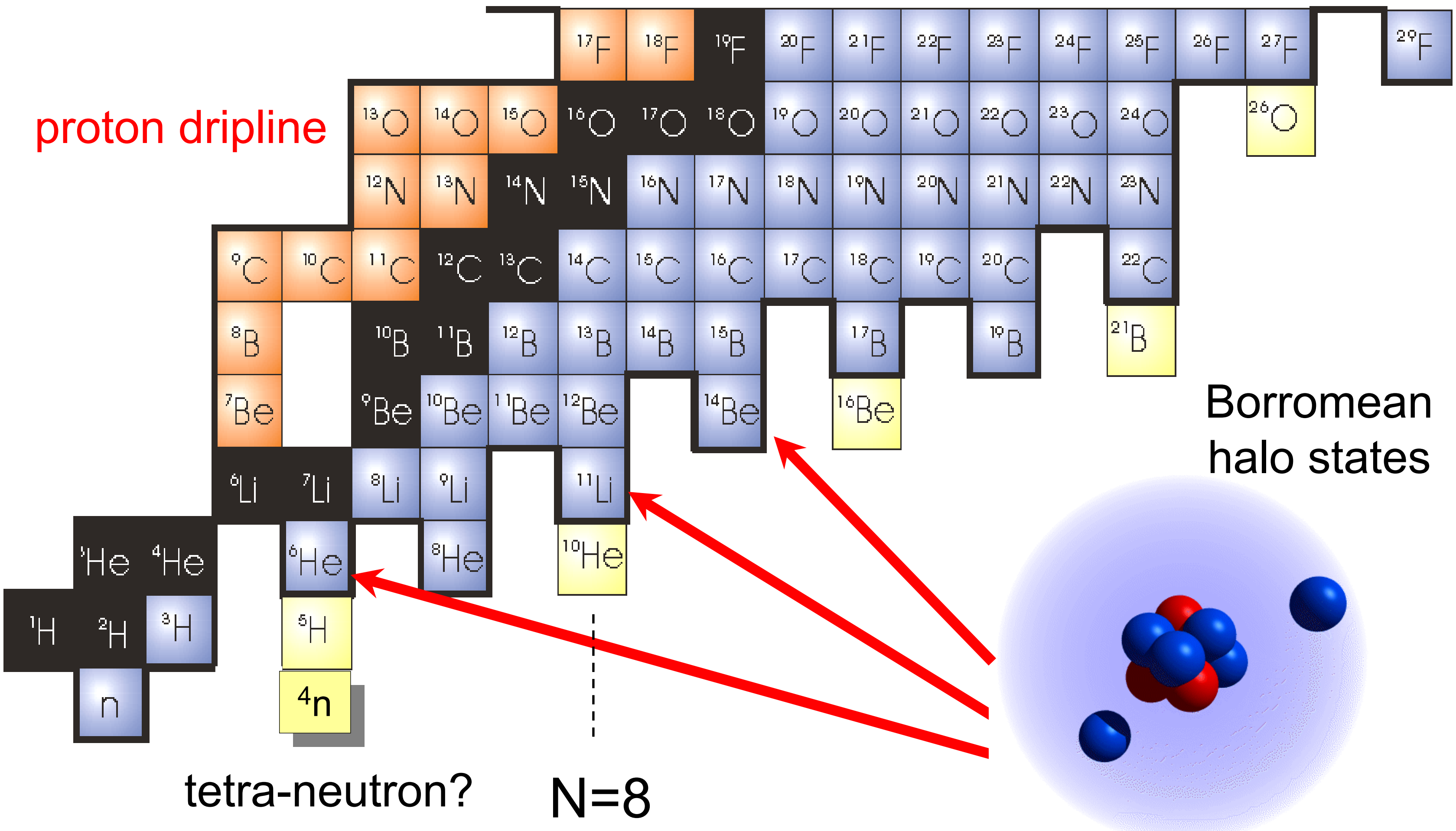
Radioactive, at the limit of nuclear binding

Characteristics of exotic nuclei: Excess of neutrons or protons, short half-life, neutron or proton dominated surface, low binding

Limits of nuclear stability

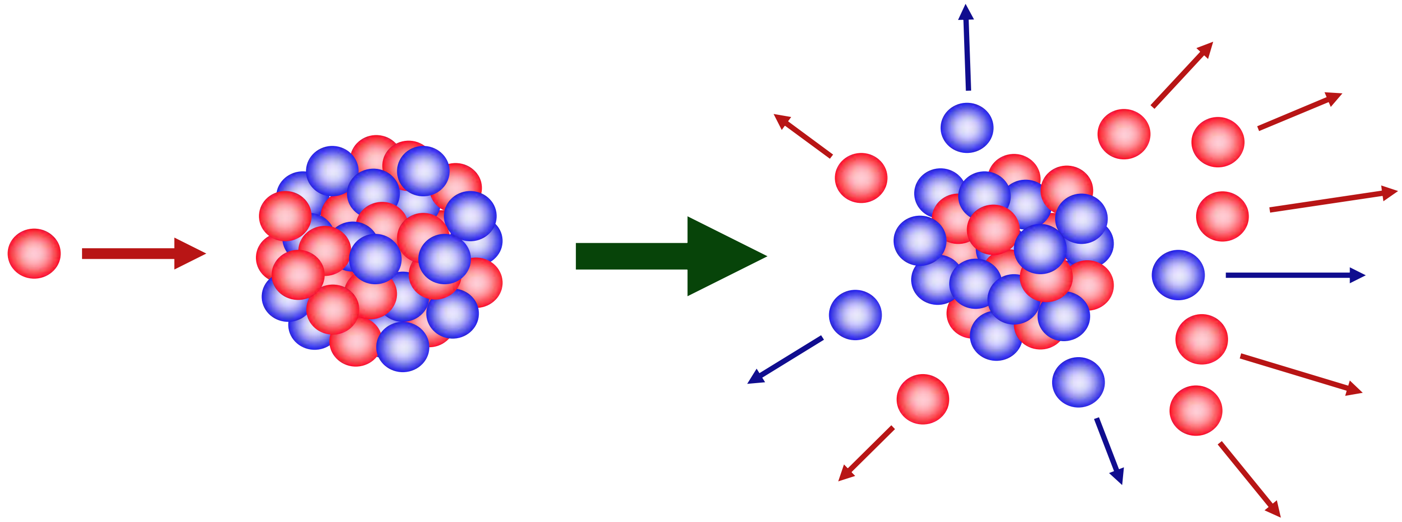


The neutron dripline in light nuclei



Exotic nucleus production - target fragmentation

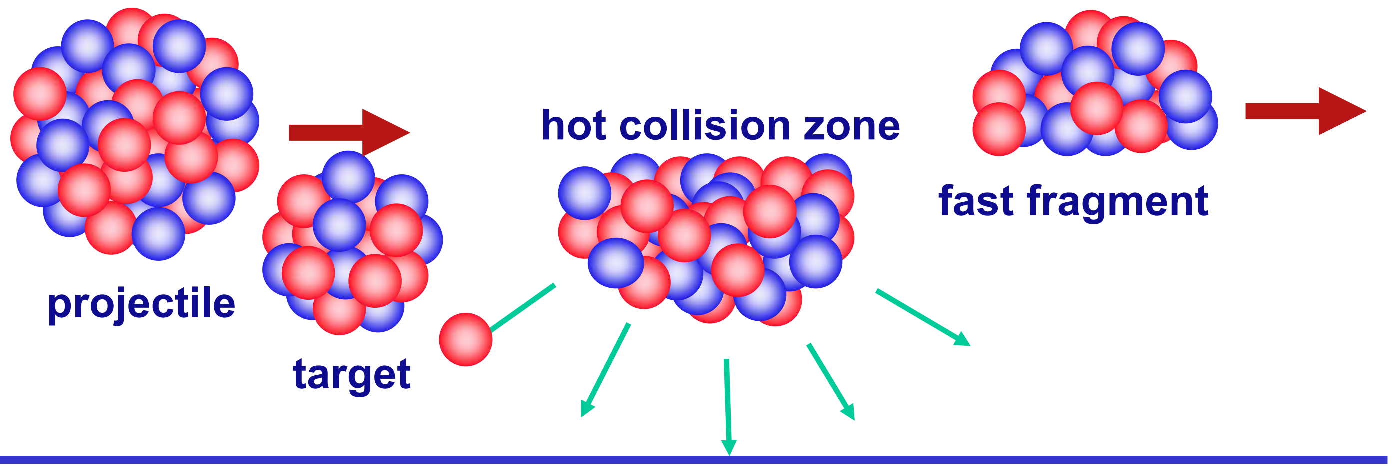
Random removal of protons and neutrons from heavy target nuclei by highly energetic light projectiles - e.g. protons - (pre-equilibrium and equilibrium emissions).



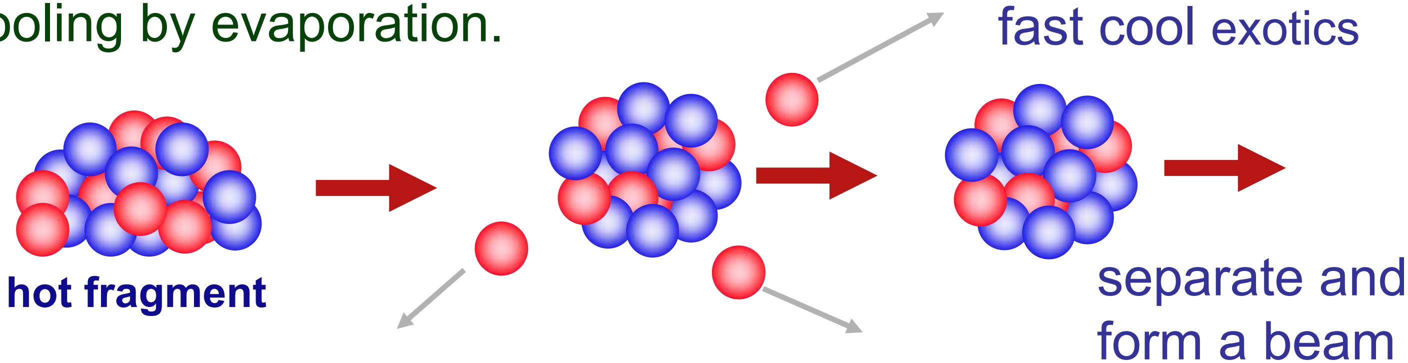
But need to extract and re-accelerate - quality beams - but relatively slow - limits species - ISOL facilities

High energy - projectile fragmentation RIBs

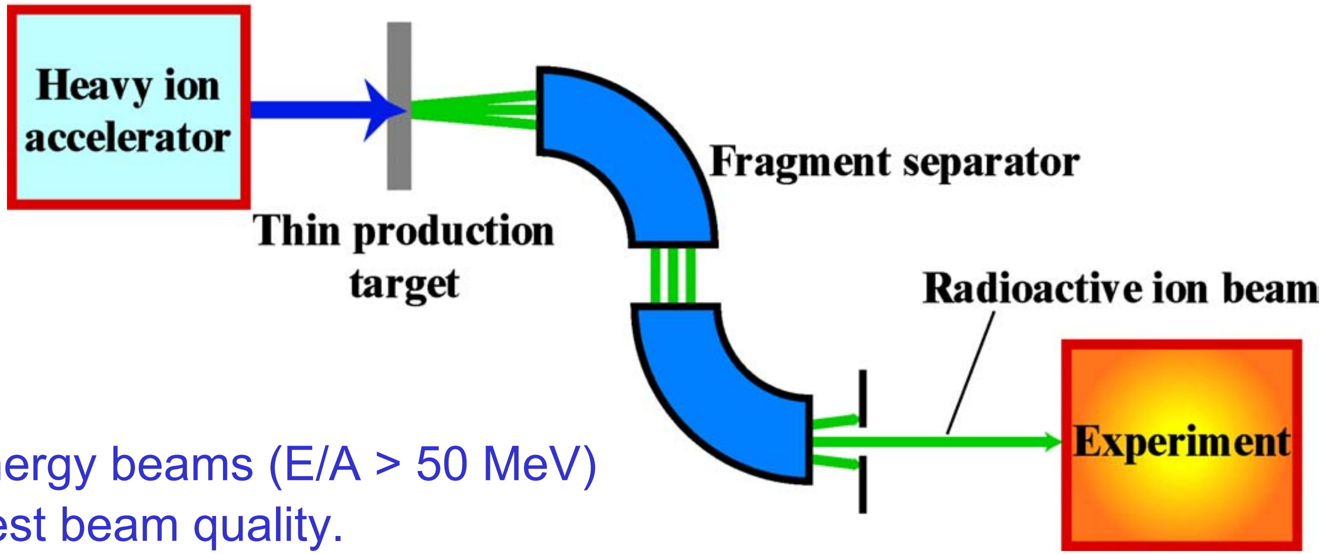
Random removal of protons and neutrons from heavy projectile in peripheral collisions at high energy - 100 MeV per nucleon or more



Cooling by evaporation.



Experimentation with fast fragmentation beams



High-energy beams (E/A > 50 MeV) of modest beam quality.

Physical method of separation, **no chemistry**.

Suitable for short-lived isotopes ($T_{1/2} > 10^{-6}$ s).

Can use thick secondary targets

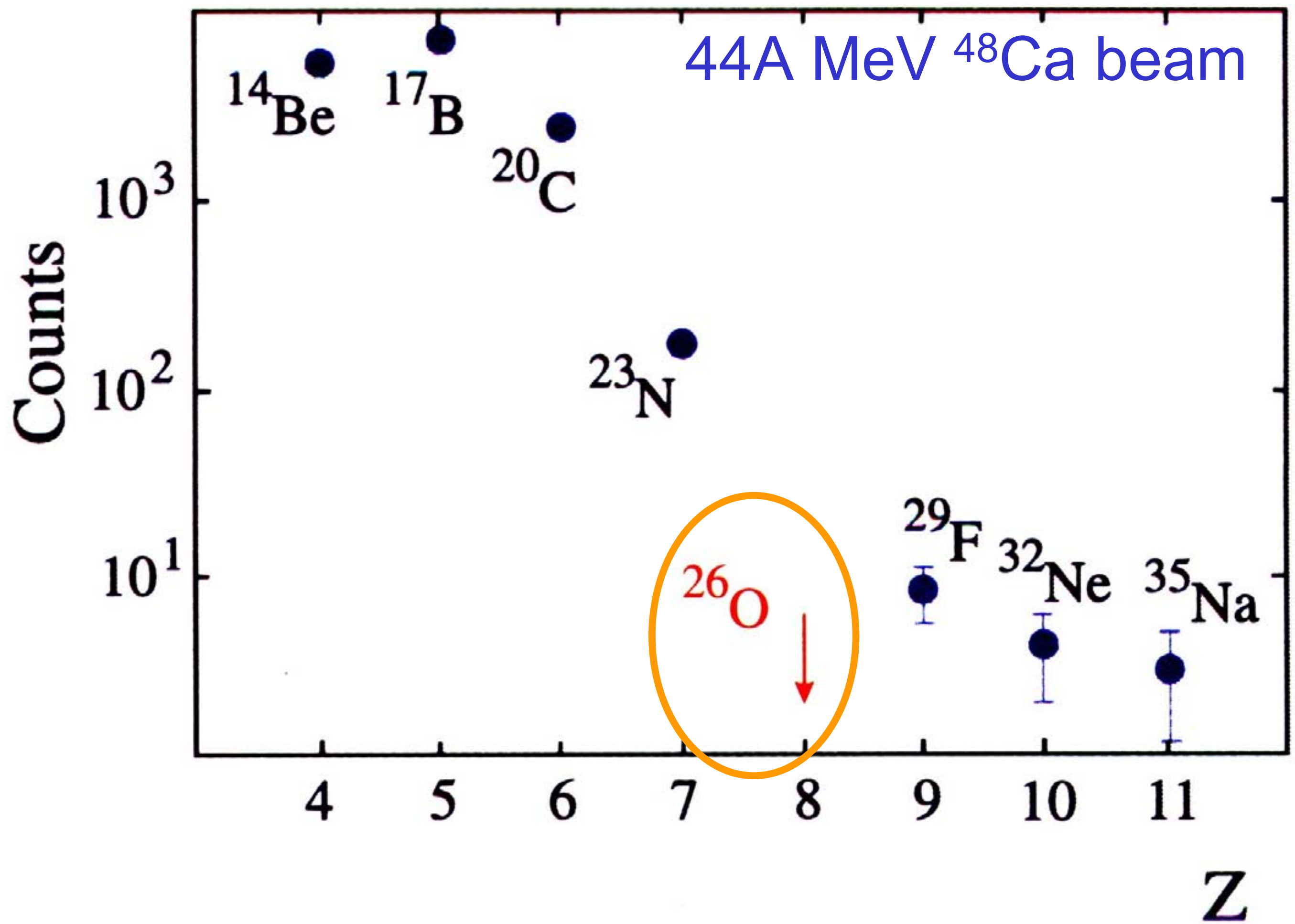
Efficient particle detection from strong forward focusing

e.g. MSU, GSI RIKEN, GANIL

Low-energy beams are difficult.

M. Thoennesson

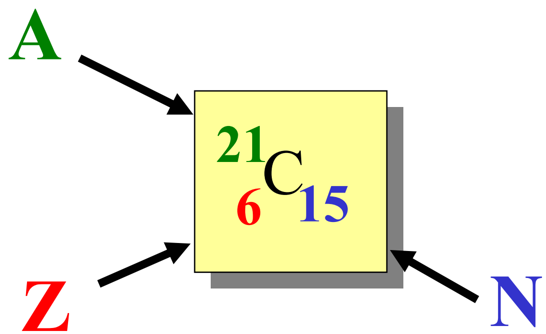
Where are the driplines - nuclear existence



D. Guillemaud-Mueller et al., Phys. Rev. C **41** (1990), 937

The isospin quantum number - $T_z=(N-Z)/2$

A = 21 isobars

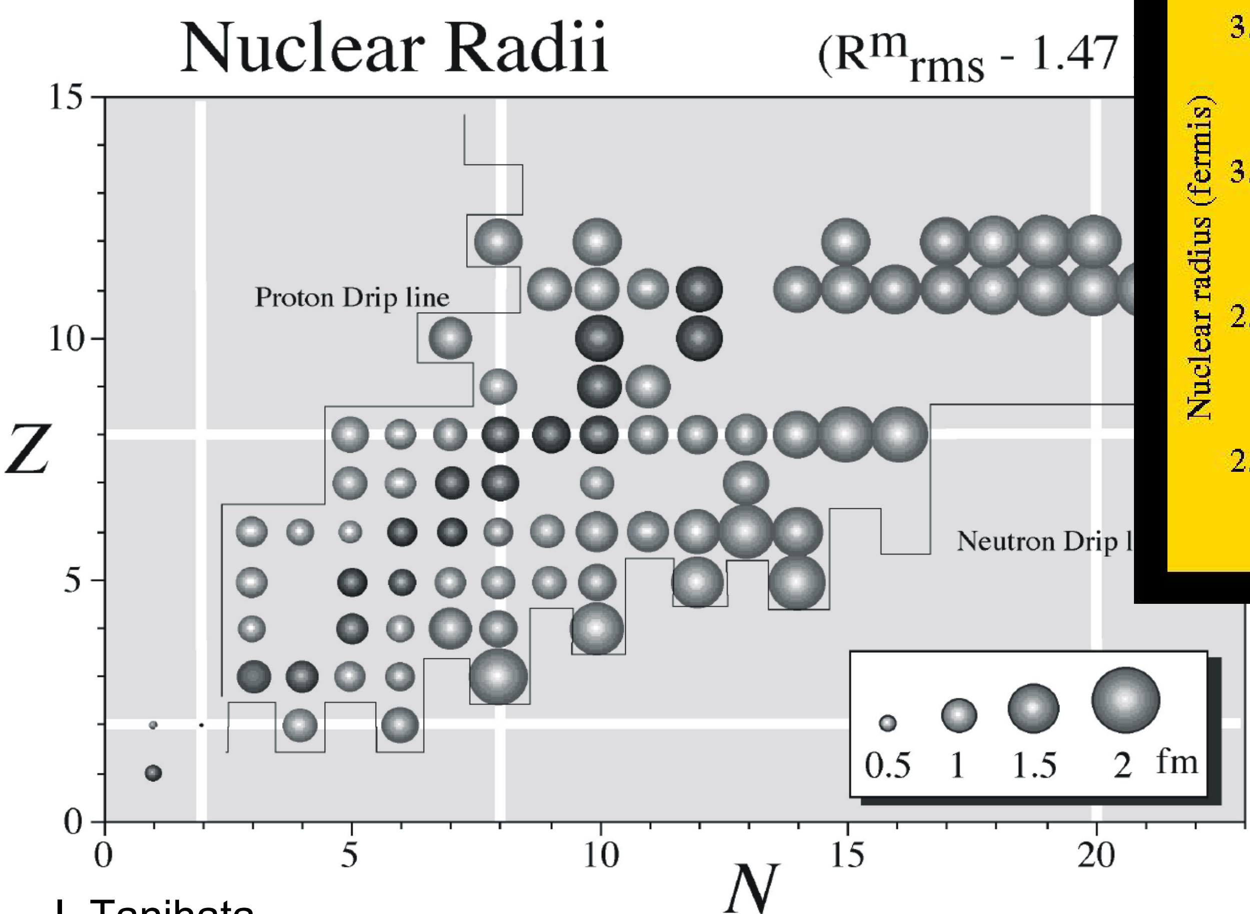


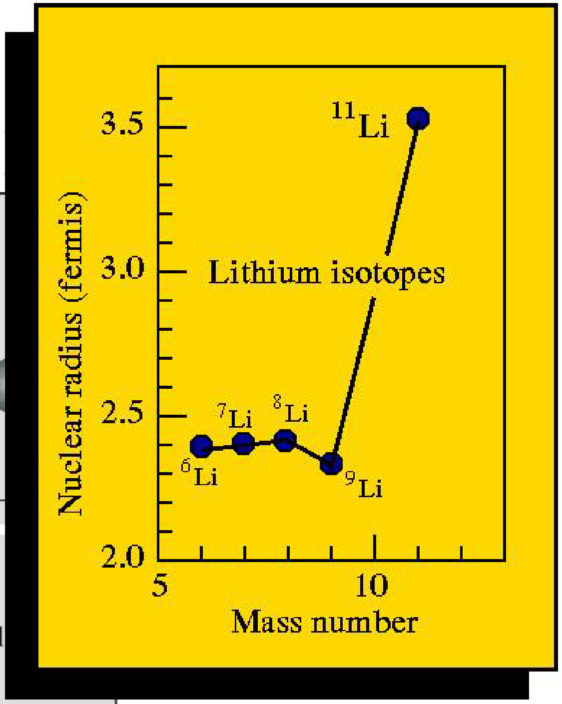
	$^{21}_{6}C_{15}$	$^{21}_{7}N_{14}$	$^{21}_{8}O_{13}$	$^{21}_{9}F_{12}$	$^{21}_{10}Ne_{11}$	$^{21}_{11}Na_{10}$	$^{21}_{12}Mg_{9}$	$^{21}_{13}Al_{8}$
T_Z	+9/2	+7/2	+5/2	+3/2	+1/2	–1/2	–3/2	–5/2

Neutron rich ← | → Proton rich

M. Thoennesson

Nuclear textbooks need to be revised





I. Tanihata

Lecture plans

How do we learn about nuclear single-particle motion in exotic and rare nuclei using nuclear reactions?

observables $\left\{ \frac{d\sigma}{d\Omega}, \sigma_R, \sigma_{-n}, \frac{d\sigma}{dp_{\parallel}} \Leftrightarrow \Phi_A, \phi_{n\ell j} \right\}$ structure

Methods available for practical analysis of data of reacting systems - key approximations, reliability, ……

Overview of concepts, current interests (selective). No reactions 'black box'. An awareness of reaction time scales, mechanisms, and interactions is needed.

Challenges of reaction studies with RI beams

Experimentally:
Quite weak secondary beams: 1pps - 10^5pps (unusual)
so many ‘tried and tested’ tools are not (yet) available
- for example no electron scattering, (e,e), (e,e´p)
or experiments are still very hard
- single-nucleon transfer, (p,p´), (p,2p).

Reaction theory: new regimes with very weak binding near the driplines - nuclear halo states - inclusive data
non-perturbative approaches are essential

Structure theory: is sophisticated - now precise shell- and few-body model predictions - are they correct?

Bringing structure and reactions together …..

Not easy, in general, to treat structure and reactions aspects with equal rigour - depends on experimental choices - energy, target charge and mass, detection geometry, etc. - appropriate choices need to be made

If possible, make choices which allow the use of theoretical approximations and which also make the structure of the theory and the theoretical inputs to the model transparent - e.g. stay with high energy beams

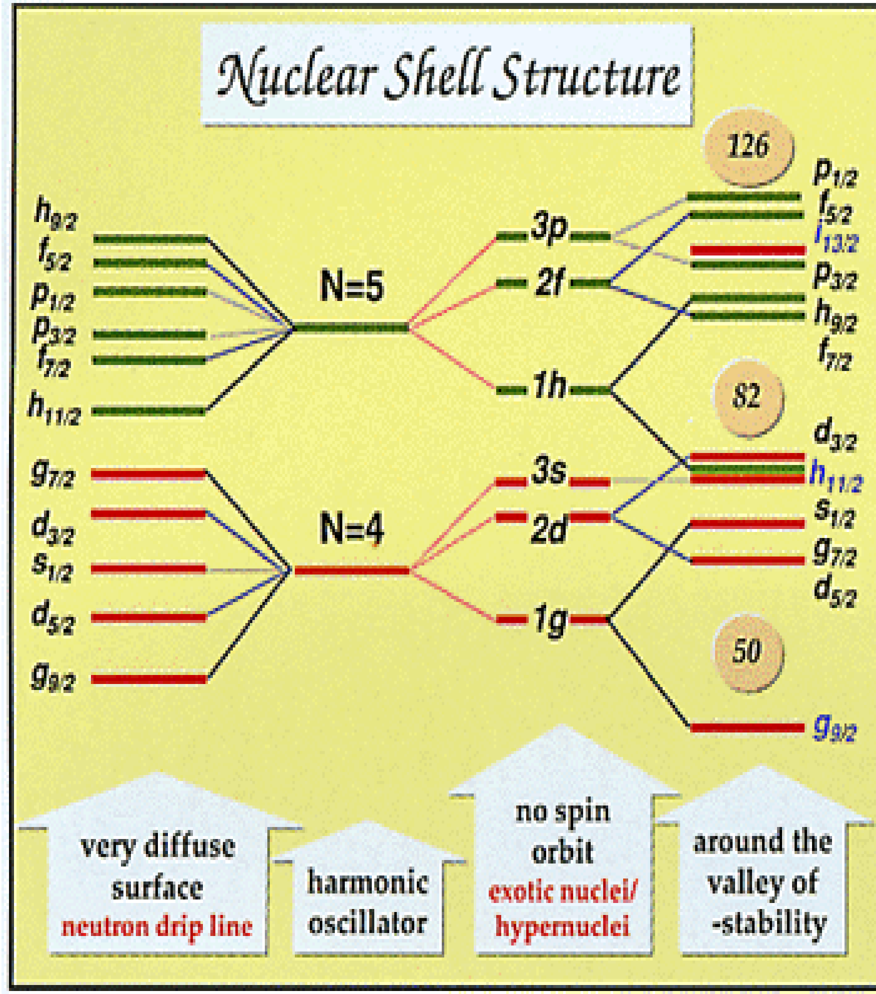
Single particle spectroscopy today

Must:

1) Use <u>direct reactions</u> which cause little rearrangement of the nucleons

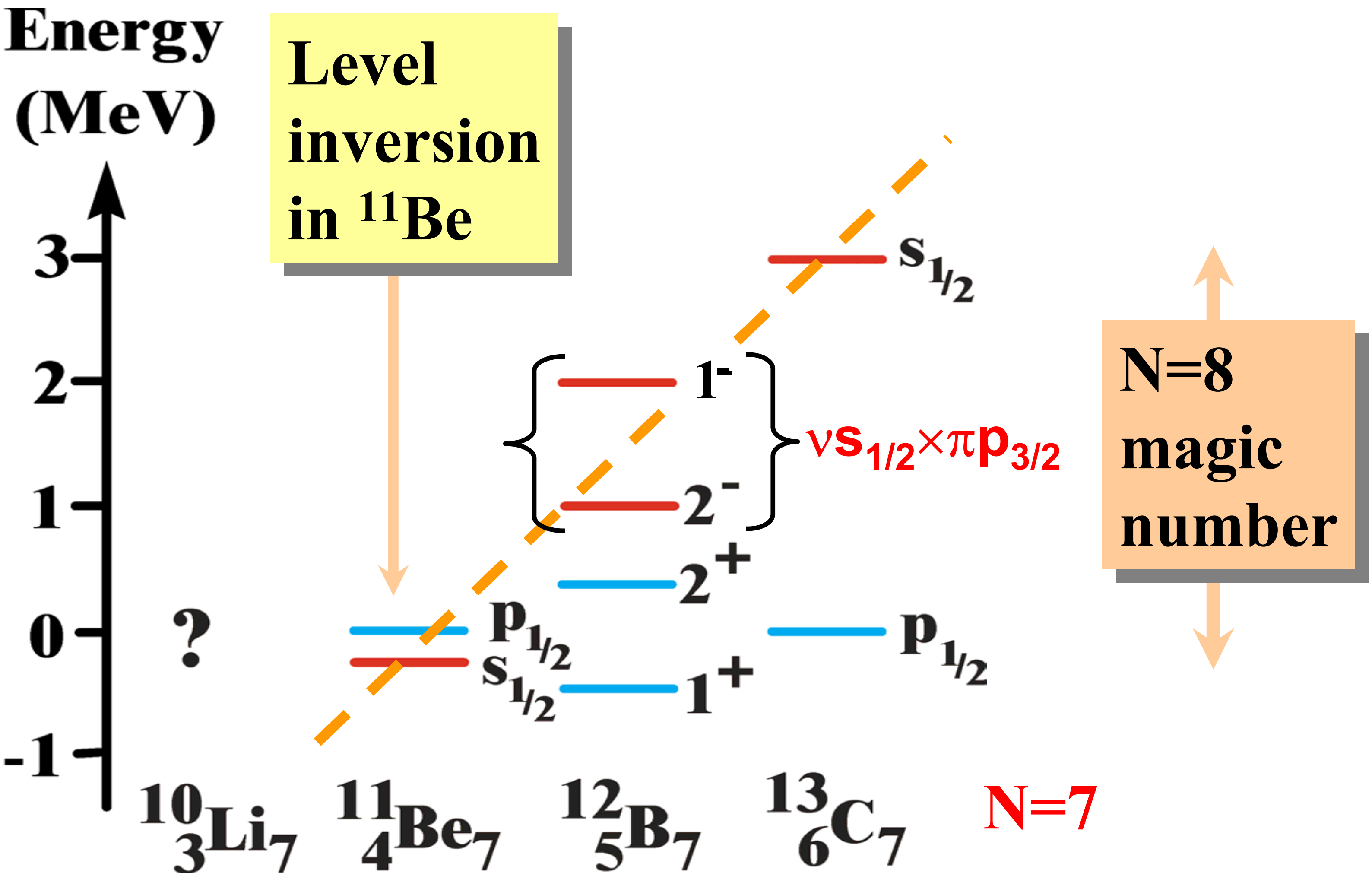
2) excite just a single nucleon, if possible, by use of:
   - single nucleon transfer
   - dissociation or breakup
   - one- or two-nucleon knockout reactions

3) more limited (less exclusive) data require new methods which need to be tested.

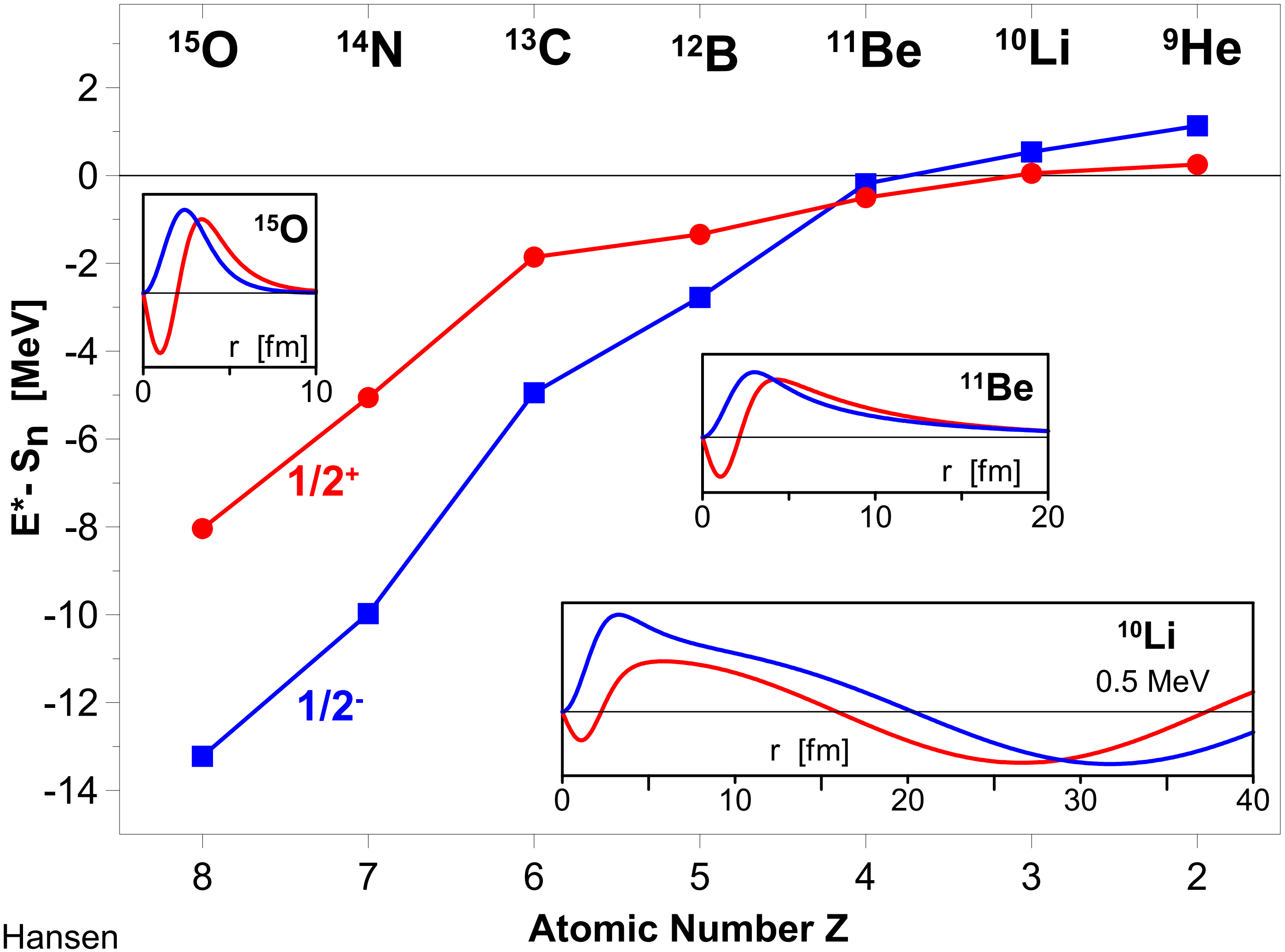


J. Dobaczewski et al, Phys Rev C **53** (1996) 2809

Single particle states in the N=7 isotones

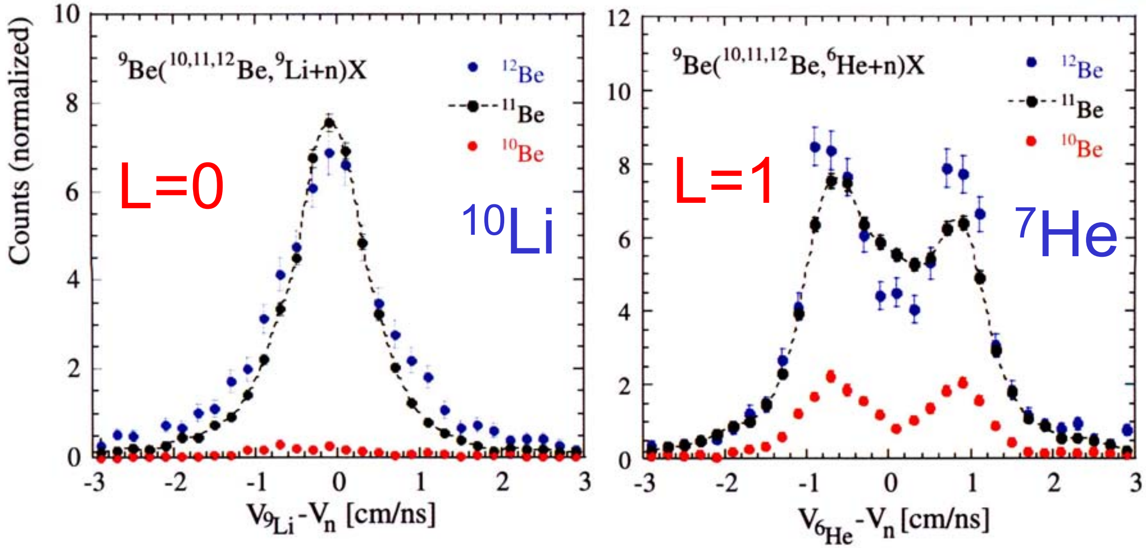


Migration of single particle strength for N=7



P.G. Hansen

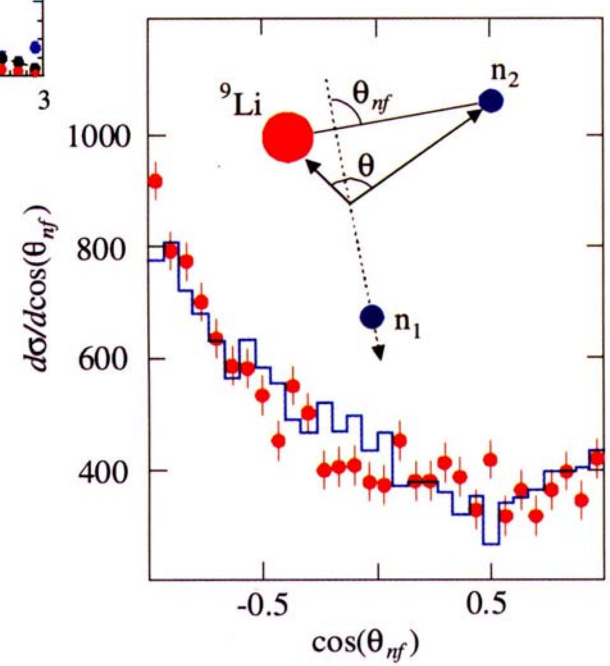
Velocities and angular correlations



L. Chen et al., Phys. Lett. B **505** (2001) 21
MSU measurements

H. Simon et al.,
PRL **83** (1999) 496
GSI measurements

L=0+1



Relative velocity and angular distributions of fragments reveal relative orbital angular momenta in final states

UniS

Understanding and questions now are:

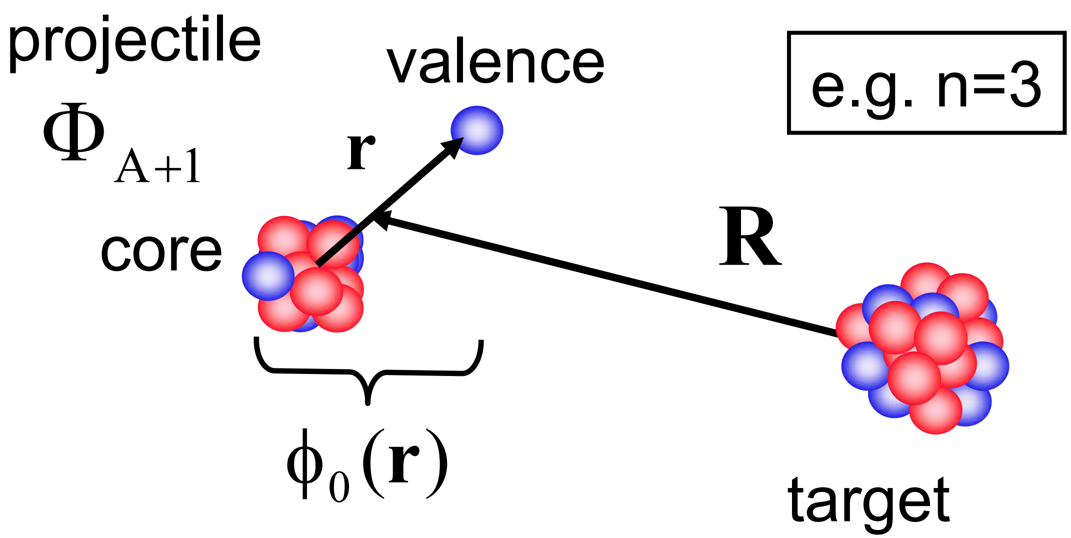
1) It is vital to take into account the loosely bound nature of exotic nuclei and their break-up channels in calculations of reaction observables

2) How accurate is spectroscopic information (spectroscopic factors and angular momentum assignments) deduced from approximate few-body models as a test of structure models?

3) How can one treat 'practically' few- and many-body nuclear reactions in a non-perturbative manner?

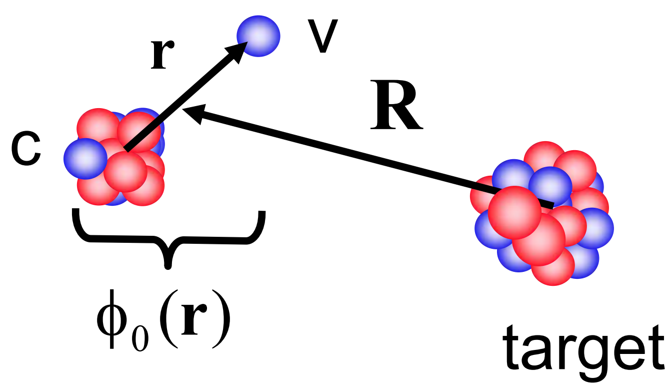
Few-body models of nuclear reactions

There are no practical many-body reaction theories - we construct model 'effective' few-body models (n=2,3,4 ...)



Construct an effective Hamiltonian H and solve as best we can the Schrödinger equation: $H\Psi = E\Psi$

Few-body reaction theory - definitions - notation

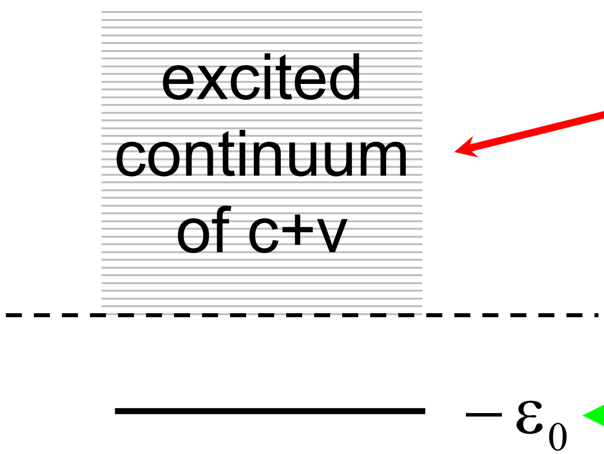


$$H = T_{\mathbf{r}} + V_{vc} + T_{\mathbf{R}} + V_{cT} + V_{vT}$$

($T_{\mathbf{r}} + V_{vc}$): projectile H_p

($V_{cT} + V_{vT}$): $U(\mathbf{r},\mathbf{R})$

total interactions with the target: excites projectile



$$H_p\phi_0(\mathbf{r}) = -\varepsilon_0\phi_0(\mathbf{r})$$

$$H\Psi_{\mathbf{K}}^{(+)}(\mathbf{r},\mathbf{R}) = E\Psi_{\mathbf{K}}^{(+)}(\mathbf{r},\mathbf{R})$$

with boundary conditions:

$$\Psi_{\mathbf{K}}^{(+)}(\mathbf{r},\mathbf{R}) \rightarrow e^{i\mathbf{K}\cdot\mathbf{R}}\phi_0(\mathbf{r}) + \text{outgoing waves}$$

structure enters only here, very indirect link to observables

Few-body models - effective interactions

$$H = T_{\mathbf{r}} + V_{vc} + T_{\mathbf{R}} + \underbrace{V_{cT} + V_{vT}}$$

binds projectile (V_{vc})

effective (complex) interactions
of c and v individually with target
(nuclear + Coulomb potentials)

(a) From experiment: potentials fitted to available data for c+T or v+T scattering at the appropriate energy per nucleon

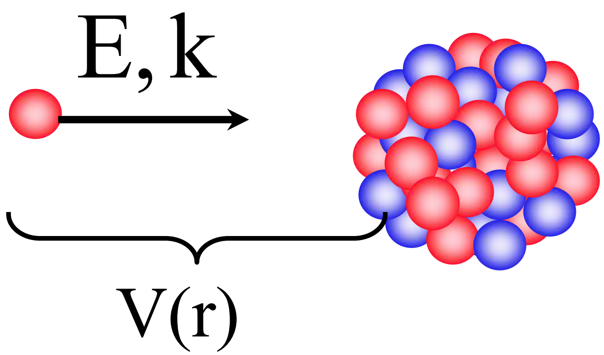
(b) From theory: multiple scattering or folding models, for example

$$V_{cT}(\mathrm{R}) = \int d\mathbf{r}_1 \int d\mathbf{r}_2\ \underbrace{\rho_c(\mathrm{r}_1)\,\rho_T(\mathrm{r}_2)}\ \underbrace{t_{\mathrm{NN}}(\mathbf{R} + \mathbf{r}_2 - \mathbf{r}_1)}$$

core and target densities

nucleon-nucleon t-matrix or effective NN interaction

Results from point particle scattering theory



$$k = \sqrt{2\mu E/\hbar^2}$$

$$\left[-\hbar^2\nabla^2/2\mu + V(r)\right]\Psi = E\Psi$$

+ scattering boundary conditions

Partial wave expansion solution:

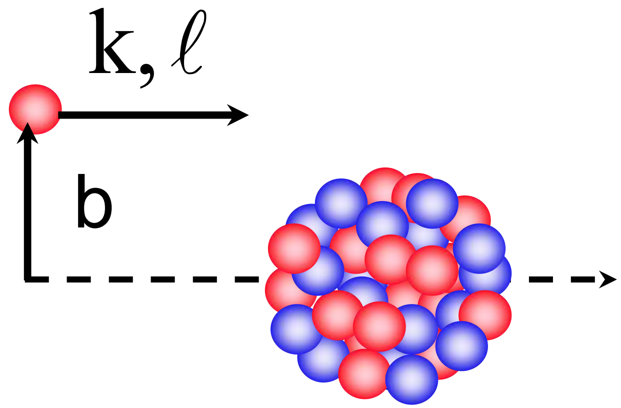
$$u_\ell(r) \xrightarrow[r\to\infty]{} (i/2)\{H_\ell^-(kr) - S_\ell H_\ell^+(kr)\}$$

incoming — outgoing wave

Partial wave S-matrix S_ℓ is amplitude of outgoing wave probability amplitude that projectile survives collision

$|S_\ell|^2$ = (survival probability) ≤ 1

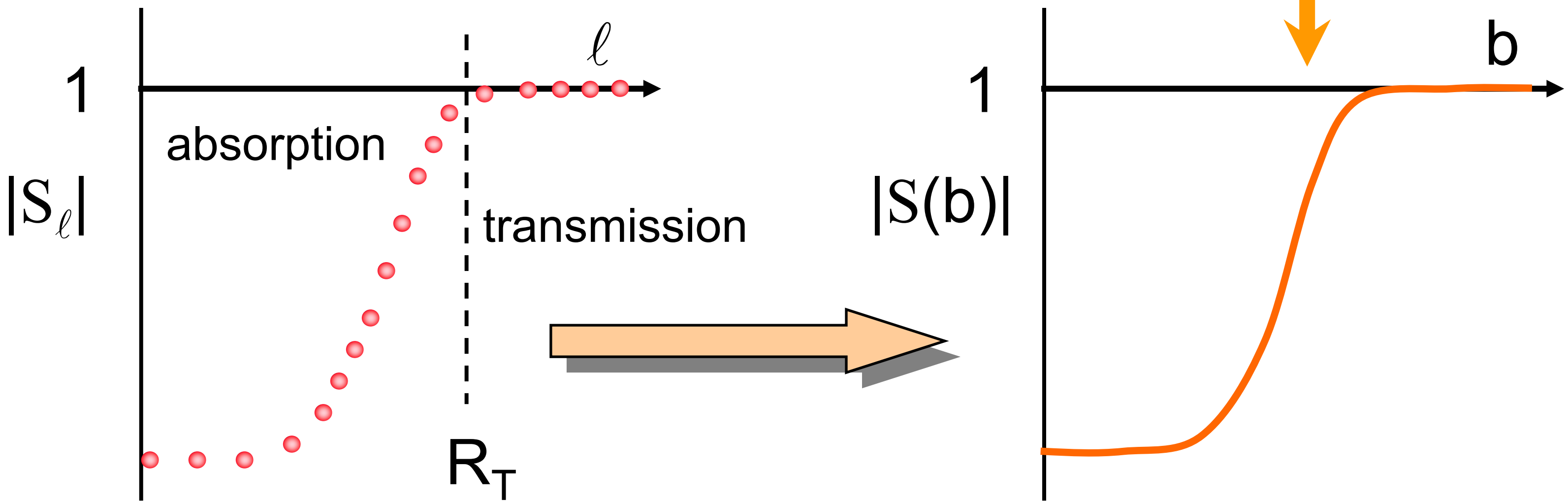
The semi-classical S-matrix - S(b)



b=impact parameter

for high energy/or large mass, semi-classical ideas are good

$kb \simeq \ell$, actually $\Rightarrow \ell + 1/2$



Point particle scattering - observables

All experimental observables can be computed from the S-matrix, in either representation

$$\sigma_{el} = \frac{\pi}{k^2}\sum_{\ell}(2\ell+1)\,|\,1-S_\ell\,|^2 \rightarrow \int d\mathbf{b}\,|\,1-S(b)\,|^2$$

$$\sigma_R = \frac{\pi}{k^2}\sum_{\ell}(2\ell+1)[1-|\,S_\ell\,|^2] \rightarrow \int d\mathbf{b}\,[1-|\,S(b)\,|^2]$$

$$\sigma_{tot} = \sigma_R + \sigma_{el} = 2\int d\mathbf{b}\,[\,1-\mathrm{Re.}S(b)\,],$$ etc.

and where $\int d\mathbf{b} \equiv 2\pi\int b\,db$

Eikonal approximation for point particles

Approximate (semi-classical) scattering solution

$$\left[\nabla^2 + k^2 - 2\mu V(r)/\hbar^2\right]\Psi_k = 0:\ \text{assume}\ \ \Psi_k(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}}\underbrace{\omega(\mathbf{r})}_{\text{all effects due to V}}$$

substitute

$$\left[2i\nabla\omega\cdot\mathbf{k} - 2\mu V(r)\omega/\hbar^2 + \nabla^2\omega\right]e^{i\mathbf{k}\cdot\mathbf{r}} = 0$$

high energy, large k
smooth V, neglected
$\nabla^2\omega << 2\nabla\omega.\mathbf{k}$

$$\frac{d\omega}{dz} = -\frac{i\mu}{\hbar^2 k}V(r)\omega$$

$$\omega(\mathbf{r}) = \exp\left\{-\frac{i\mu}{\hbar^2 k}\int_{-\infty}^{z} dz'\, V(r')\right\}$$

1D integral over a straight line path through V at the impact parameter b

Eikonal S-matrix in the point particle case

$$\Psi_{\mathbf{k}}(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}}\omega(\mathbf{r})$$

$$\omega(\mathbf{r}) = \exp\left\{-\frac{i\mu}{\hbar^2 k}\int_{-\infty}^{z} dz' V(r')\right\}$$

So, after the interaction and as $z \to \infty$

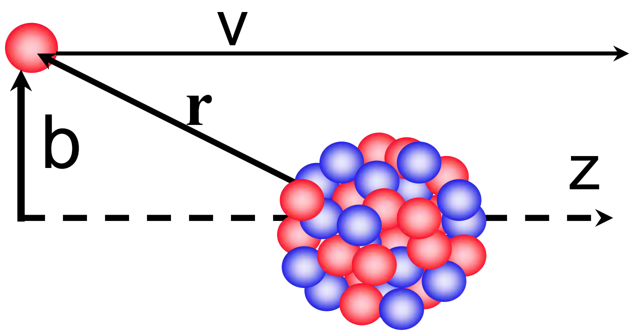
$\hbar k/\mu =$ classical velocity v

$$\Psi_{\mathbf{k}}(\mathbf{r}) = S(b)\, e^{i\mathbf{k}\cdot\mathbf{r}}$$

S(b) is amplitude of the outgoing waves from the scattering at b

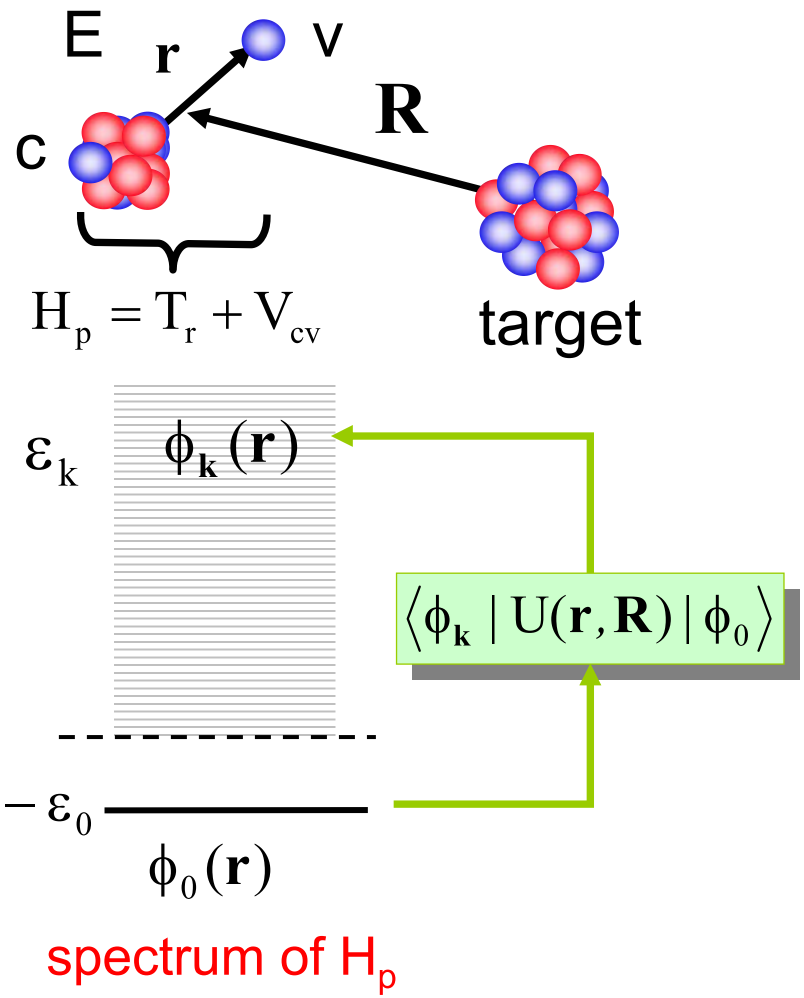
Eikonal approximation to the S-matrix $S(b)$

$$S(b) = \exp\left\{-\frac{i}{\hbar v}\int_{-\infty}^{\infty} dz' V(r')\right\}$$



Moreover, the structure of the theory generalises to few-body projectiles

Energetics of few-body composite systems



$$H = H_p + T_{\mathbf{R}} + U(\mathbf{r},\mathbf{R})$$

The tidal forces

$$U(\mathbf{r},\mathbf{R}) = V_{cT} + V_{vT}$$

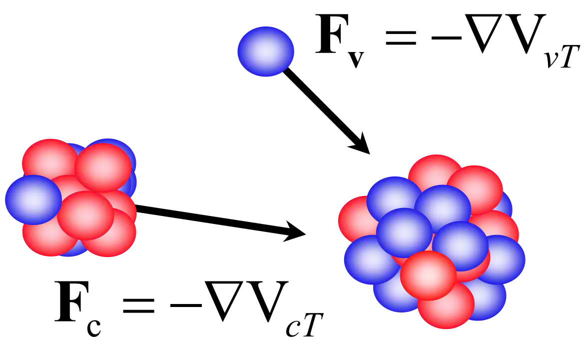
between c and v and the target cause excitation of the projectile to excited states of c+v and to the continuum states

$$H_p \phi_{\mathbf{k}}(\mathbf{r}) = \varepsilon_k \phi_{\mathbf{k}}(\mathbf{r})$$

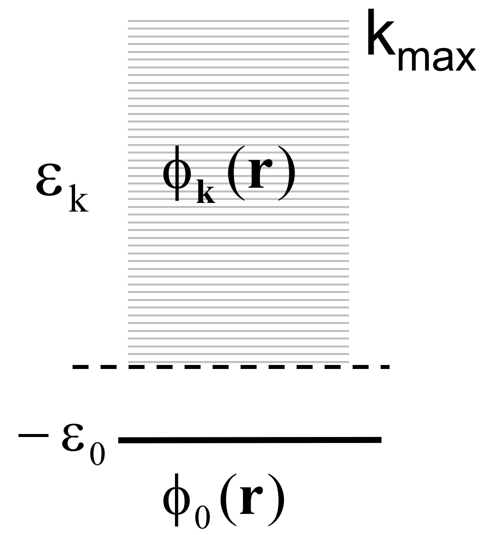
Which $\phi_{\mathbf{k}}(\mathbf{r})$ are excited?

Continuum excitations and interactions

A major simplification to the reaction dynamics is possible if $\varepsilon_k << E$



Those states excited (to k_{max}) are dictated by the geometry of the interactions



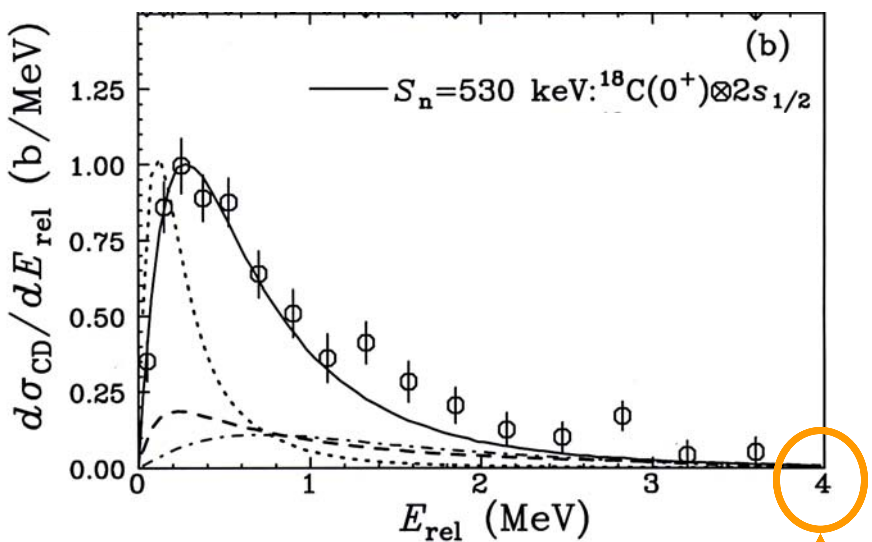
Nuclear forces, sharp surfaces, large $\mathbf{F}$, larger ε_k, universally, given surface diffuseness of nuclear potentials $\varepsilon_k \leq 20$ MeV

Coulomb forces, slow spatial changes, small $\mathbf{F}$, typically $\varepsilon_k \leq 4$ MeV (Nakamura et al, PRL **83** (1998) 1112)

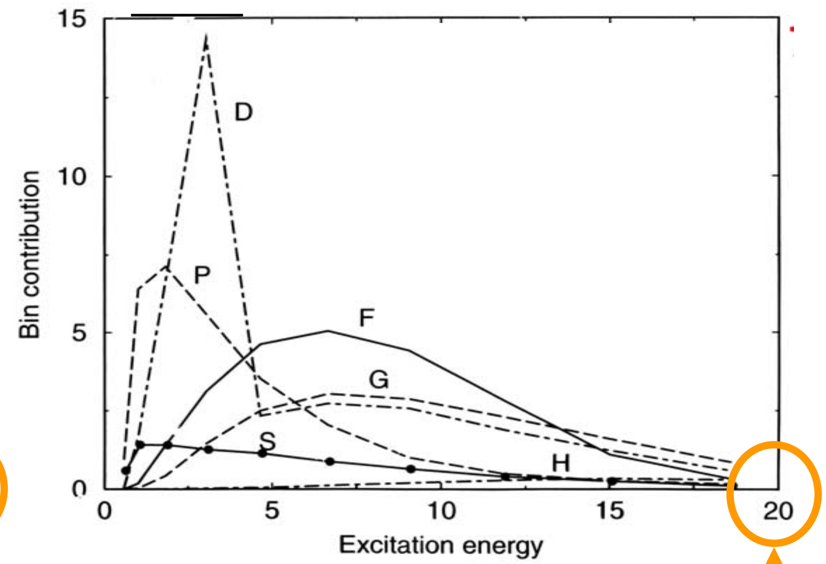
In both cases, for the energies if RI beams from fragmentation facilities (50-100 MeV per nucleon), typical $\langle H_p \rangle << E$

Break-up continua from nuclear and Coulomb

T. Nakamura et al, PRL **83** (1998) 1112



J.A. Tostevin et al, PRC **66** (2002) 024607



Experimental

^{19}C+Pb $\rightarrow$ ^{18}C+n+X
E= 67A MeV = 1.33 GeV
Coulomb dominated

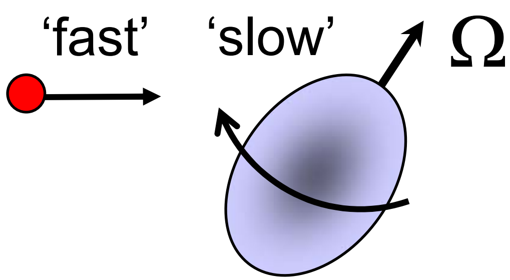
Theoretical

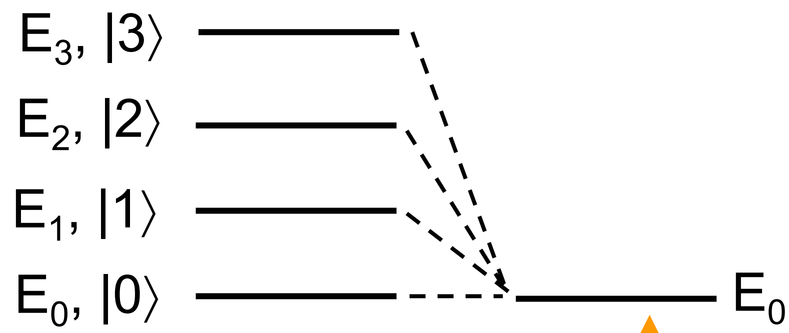
^{11}Be + ^{9}Be $\rightarrow$ ^{10}Be+n+X
E= 60A MeV = 660 MeV
Nuclear dominated

Adiabatic (sudden) approximations in physics

Identify high energy/fast and low energy/slow degrees of freedom

Fast neutron scattering from a rotational nucleus



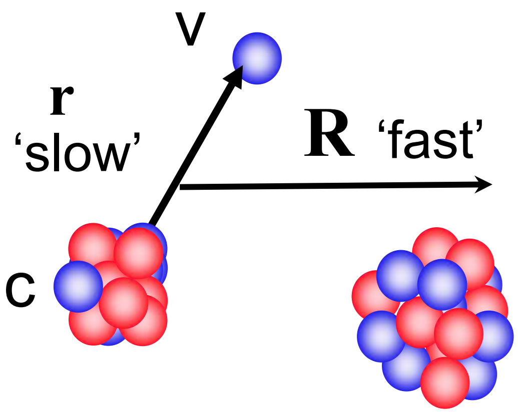


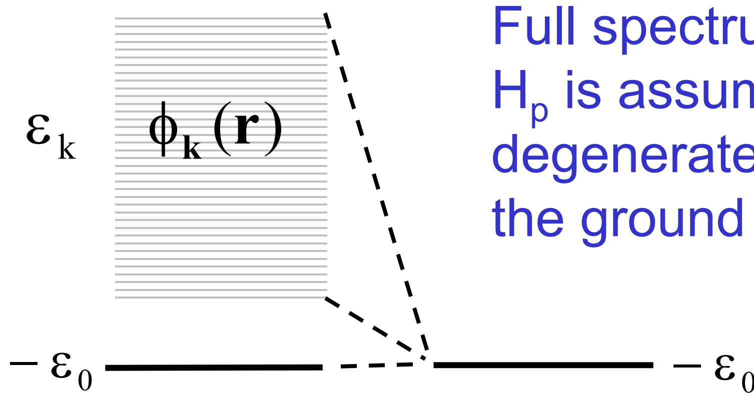
Fix Ω, calculate scattering amplitude $f(\theta, \Omega)$ for each (fixed) Ω.

moment of inertia $\rightarrow \infty$ and rotational spectrum is assumed degenerate

Transition amplitudes $f_{\alpha\beta}(\theta) = \langle \beta | f(\theta, \Omega) | \alpha \rangle_{\Omega}$

Adiabatic model for few-body projectiles





Full spectrum of H_p is assumed degenerate with the ground state

Freeze internal co-ordinate $\mathbf{r}$ then scatter c+v from target and compute $f(\theta,\mathbf{r})$ for all required fixed values of $\mathbf{r}$

Physical amplitude for breakup to state $\phi_{\mathbf{k}}(\mathbf{r})$ is then,

$$f_k(\theta) = \langle \phi_k \,|\, f(\theta, \mathbf{r}) \,|\, \phi_0 \rangle_{\mathbf{r}}$$

Achieved by replacing $H_p \rightarrow -\varepsilon_0$ in Schrödinger equation

Adiabatic approximation - time perspective

The time-dependent equation is

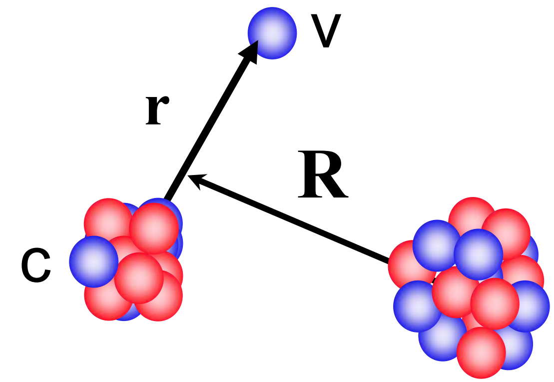
$$H\Psi(\mathbf{r},\mathbf{R},t) = i\hbar\frac{\partial\Psi}{\partial t}$$

and can be written

$$\Psi(\mathbf{r},\mathbf{R},t) = \Lambda\,\Phi(\mathbf{r}(t),\mathbf{R}),\quad \mathbf{r}(t) = \Lambda^{+}\,\mathbf{r}\,\Lambda$$

$\Lambda = \exp\{-i(H_p + \varepsilon_0)t/\hbar\}$ and where

$$[T_R + U(\mathbf{r}(t),\mathbf{R}) - \varepsilon_0]\Phi(\mathbf{r}(t),\mathbf{R}) = i\hbar\frac{\partial\Phi}{\partial t}$$



Adiabatic step assumes

$\mathbf{r}(t) \approx \mathbf{r}(0)=\mathbf{r}$=fixed or $\Lambda=1$ for the collision time t_{coll}

requires

$$(H_p + \varepsilon_0)t_{coll}/\hbar << 1$$

Adiabatic equation

$$[T_R + U(\mathbf{r},\mathbf{R})]\Phi(\mathbf{r},\mathbf{R}) = (E + \varepsilon_0)\Phi(\mathbf{r},\mathbf{R})$$

Time for a coffee break …….