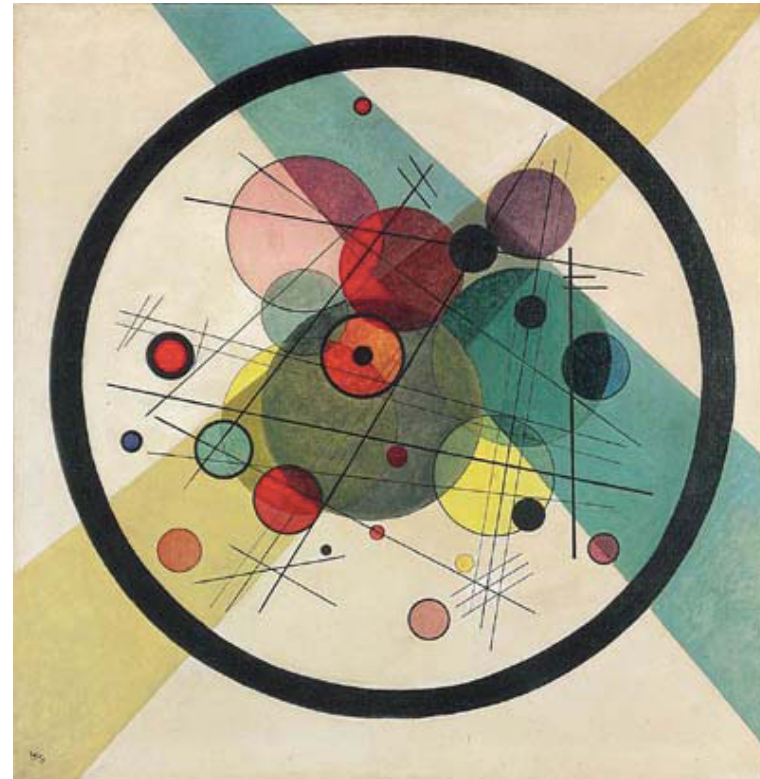


Open Questions and Perspectives in DREB Physics (from a theoretician point of view)





Direct reactions (from Wikipedia)

An intermediate energy projectile transfers energy or picks up or loses nucleons to the nucleus in a **single** quick (10^{-21} second) event.

Energy and momentum transfer are relatively **small**.

These are particularly useful in experimental nuclear physics, because the reaction mechanisms are often **simple** enough to calculate with sufficient accuracy to probe the structure of the target nucleus.

Role of theory (shopping list)

Standard models with better structure input

Check of selectivity of input information

Adjustment of standard model to accomplish new situations (e.g. weak binding)

Consistence of reaction models with structure models

Clarification of reaction mechanism

New genuine models (inspired by new development in nuclear structure)

Quoting Daphne Jackson: " In order to make theoretical predictions which may be compared with the experimental data on direct reactions, it is necessary to introduce a number of **simplifying assumptions** to reduce the many-body problem to a **tractable form**"

Traditional “pulling horses” in the description of direct reactions:

Optical potentials

Collective formfactors for inelastic modes

Single-particle formfactors for transfer reactions

Coupled channels

DWBA

Semiclassical approximations (for heavy-ion scattering)

Use of structure information is maximized by the introduction of **microscopic** potentials and formfactors, fully exploiting the knowledge of the nuclear many-body functions

Example of "simple" process from the reaction
mechanism point of view: radiative capture
(one-step process induced by pure e.m. field)
e.g. ${}^7\text{Be}(p,\gamma){}^8\text{B}$

Improvements come from the nuclear structure,
entering at different levels, both for the bound and the
continuum states

Simplest model uses bound and continuum single-particle wave functions

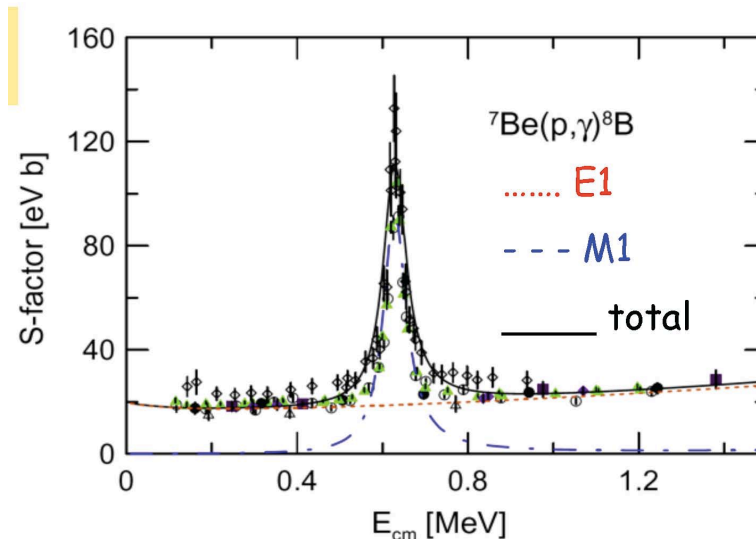
$$\int_0^\infty r^\lambda \psi^l(E_i, r) \psi^{l'}(E_f, r) dr$$

simply defined by a potential (e.g. Woods-Saxon)
generated by the inert ${}^7\text{Be}$ core

Schrödinger equation:

e.g., Woods-Saxon

$$-\frac{\hbar^2}{2\mu} \frac{d^2}{dr^2} \psi^l(r) + \left[V(r) + \frac{\hbar^2}{2\mu} \frac{l(l+1)}{r^2} \right] \psi^l(r) = E \psi^l(r)$$



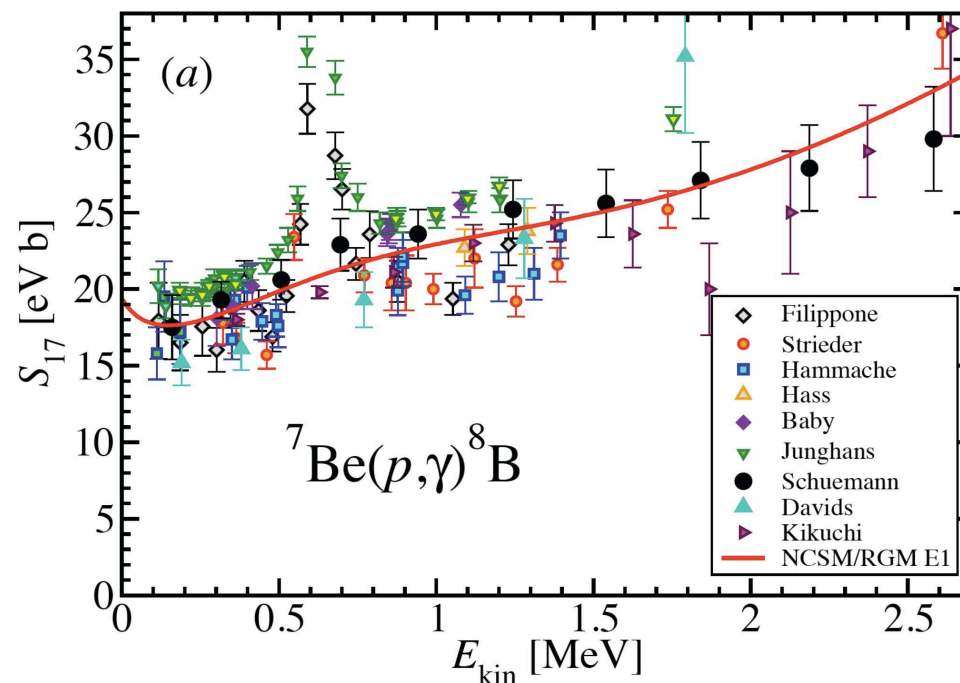
Bertulani
Z. Phys. A356, 293 (1996)

But now other models use more sophisticated many-body wave functions for both the bound and the scattering channels

Examples: Cluster, ab initio, no-core shell model, no-core shell model plus RGM

(Realistic interactions $H = T + \sum v_{ij} + \sum v_{ijk}$, accurate wave functions of ${}^7\text{Be}$, ${}^8\text{B}$ to deduce the ANC of ${}^8\text{B}$)

OBS: need for an equivalent treatment of both bound and unbound channels



Quaglioni, Navratil, Roth
PLB 704 (2011) 379

← E1

Other "simple" process: "safe" Coulomb excitation

Only structure information needed (or vice versa extracted): transition $B(E\lambda)$ and multipole moments

Reaction description: Coupled channels

Leftover problem: choice of the relevant model space and technical management of the coupled channel calculation, with delicate minimization procedures

Obs: correction to standard non-relativistic and relativistic Coulomb field

Elastic scattering and optical potentials ("mean field" domain)

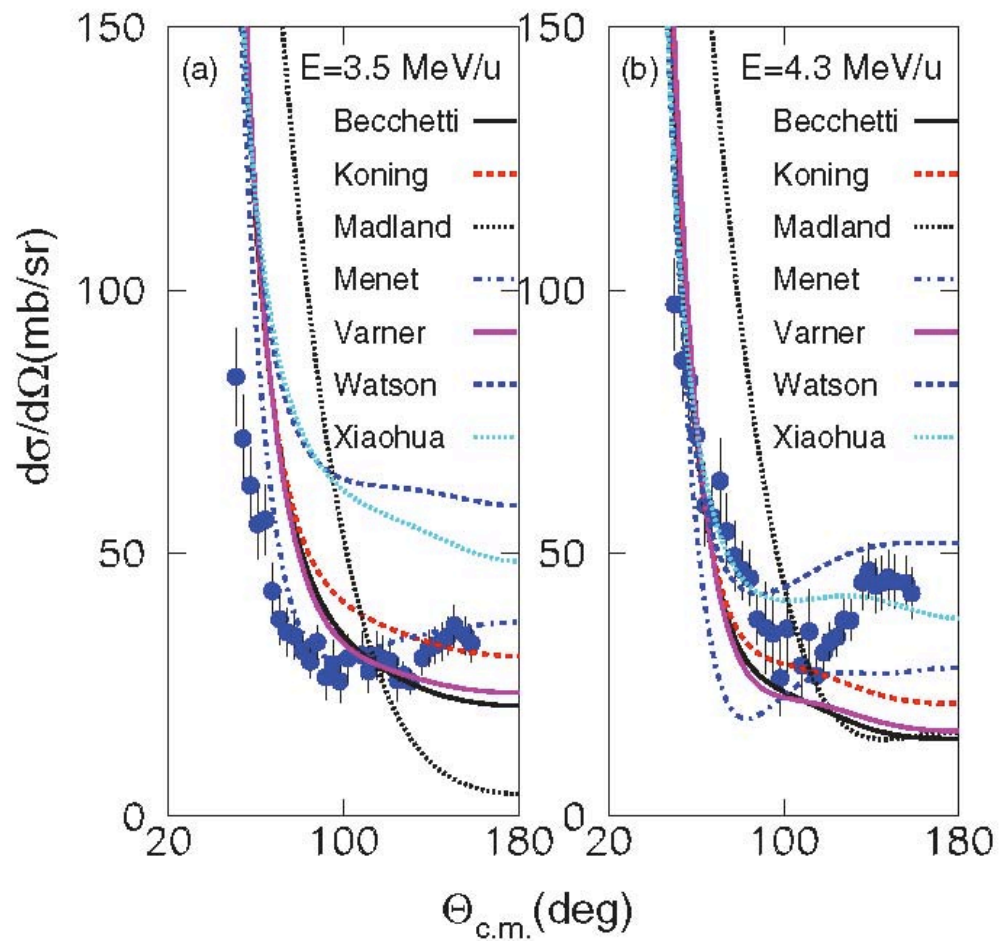
Basic tool: folding potentials of densities and NN interaction (M3Y, JLM,). Energy dependence. Novel interactions (NN+NNN+ ..., tensor force, ..)

Polarization part
(Feshbach theory, leading order, BWP, Sakuragi,).
Choice of the model space in CC formalism. Coupling to continuum

"universal" potentials, eg AW, São Paulo

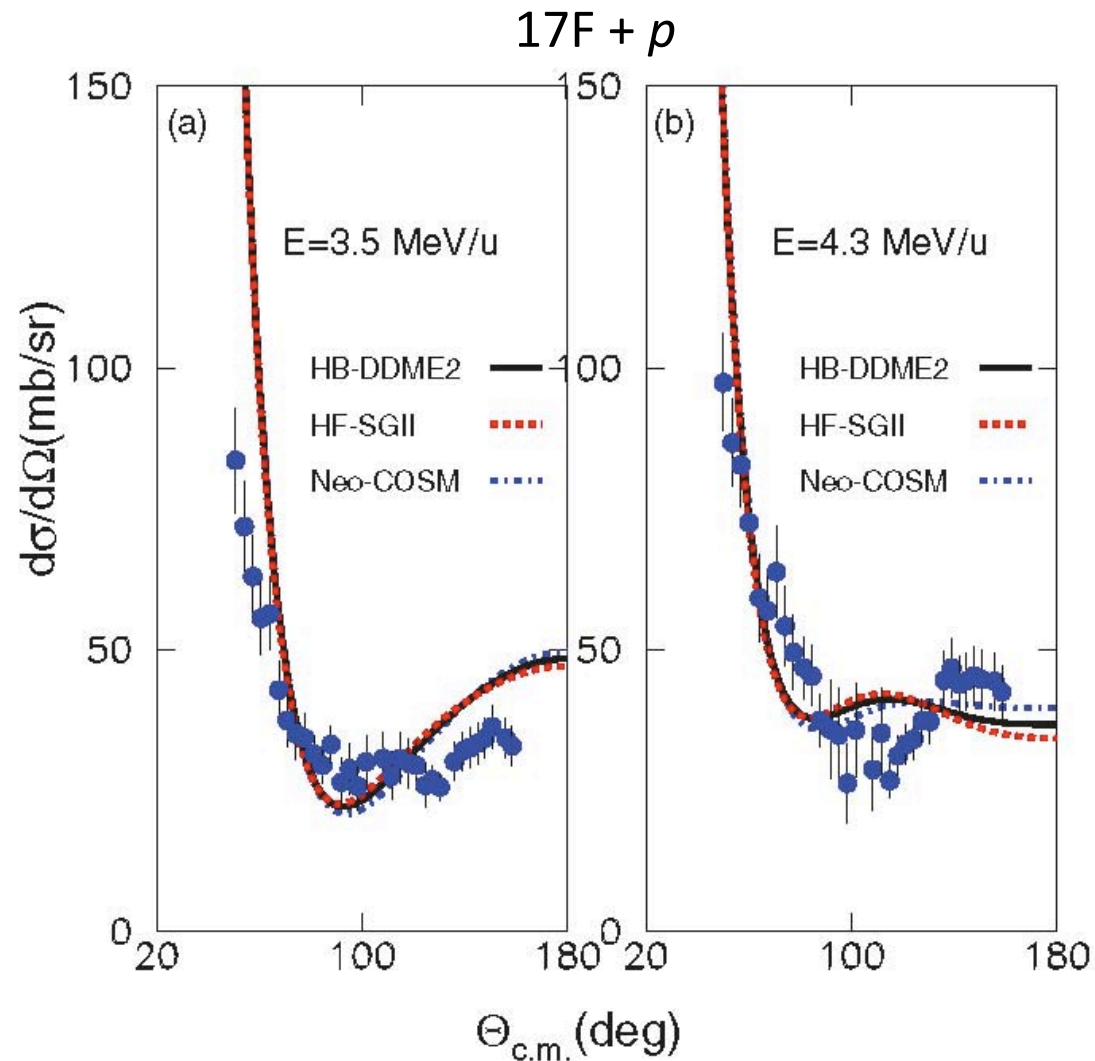
Example of sensitivity (or not) to different microscopic inputs

Elastic scattering $p+^{17}\text{F}$ at LNL (Pakou et al)



Using different
optical potentials
on the market

Now using JLM folding procedure with different structure options for the ^{17}F density: rather similar results, hence not great resolving power in this case



JLM Parameters at $E = 3.5$ (4.3)

COSM (cluster orbital shell model,
Masui, Kato, and Ikeda)

$\lambda_V = 0.8$ (0.93) $\lambda_W = 0.75$ (0.86)

DDME2 (Relativistic Mean Field,
G. Lalazissis,)

$\lambda_V = 0.85$ (0.99) $\lambda_W = 0.73$ (0.65)

HF-SGII (Hartree Fock, AV)

$\lambda_V = 0.86$ (0.90) $\lambda_W = 0.66$ (0.66)

Basic problem: consistent treatment of all relevant diagonal (potentials) and non diagonal (formfactors) matrix elements in a sufficiently large model space (to include explicitly all strongly coupled channels, but not too large to be numerically hard to treat). Transfer channels obviously included, with all consequent problems

OBS problems more explicit in the case of weakly-bound systems (**coupling to continuum states**

Rather complicate affair

Example: $^8\text{He} + p$

Interpretation of direct reactions: ex of $^8\text{He}+p$ @ 15.6 MeV/nucleon

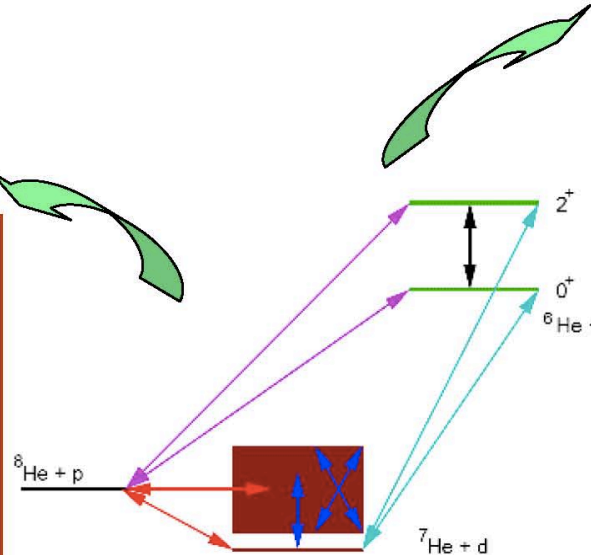
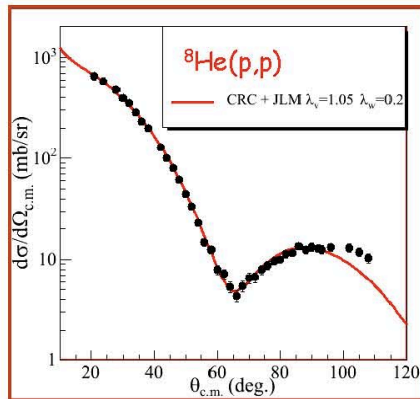
Coupled reaction channel (CRC) calculations needed:

Cf $^8\text{He}+p$ Analysis \rightarrow N. Keeley, SPhN [now: univ of Varsaw]

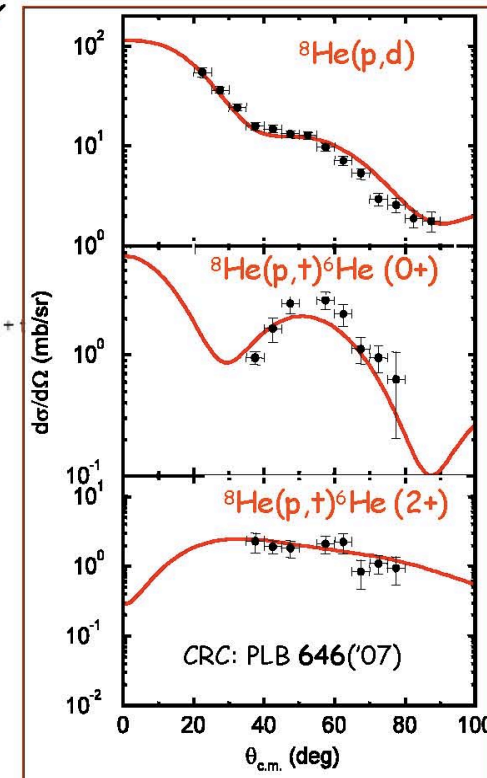
F. Skaza et al., PLB 619, 82 ('05) ; PRC 73, 044301 ('06)

N. Keeley et al., PLB 646, 222('07)

E405s -GANIL-MUST
 $^8\text{He} + p$ @ 15.6 MeV/n



Spectroscopic factors C^2S from
 $(d\sigma/d\Omega)_{\text{theo}} \% (d\sigma/d\Omega)_{\text{exp}}$

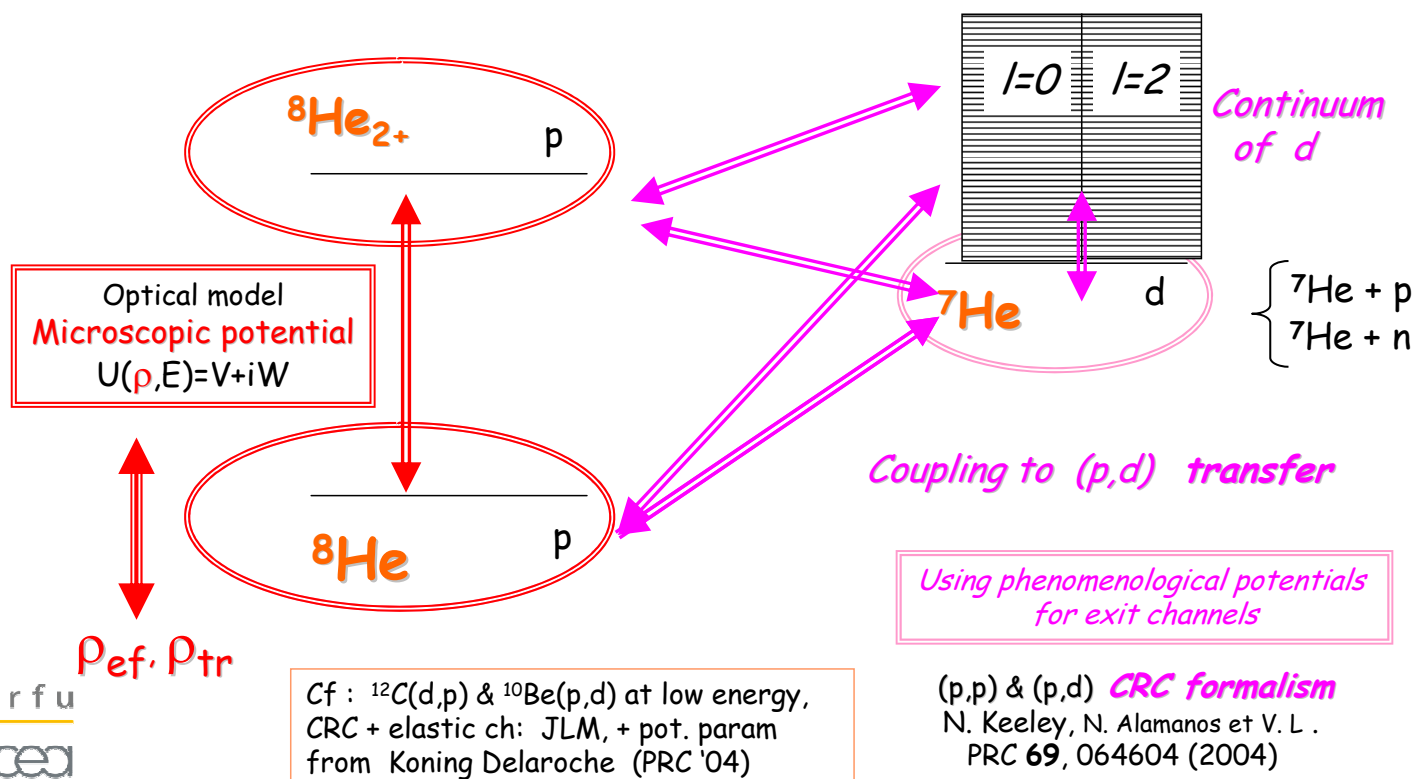


The transferred angular momentum L_t indicates J^π

Theoretical equipment: coupled reaction channel formalism + CDCC

**Probing
 ^8He
structure**

Ideal framework : 9 active nucleons (proj+target) interacting
And sharing the incident flux
At present...



CRC analysis: structure of ^8He extracted from direct reactions

PREVIOUS
INTERPRETATION



Data $^8\text{He}(p,t)$ @ 61.3 A.MeV - RIKEN
A.A.Korshennikov et al, PRL **90**, 082501 ('03)
DWBA analysis : $[^8\text{He}/^6\text{He}(0^+)] = [^8\text{He}/^6\text{He}(2^+)] = 1$
(only (p,t) no elastic data)

CRC ANALYSIS
INTERPRETATION
OF SPIRAL DATA



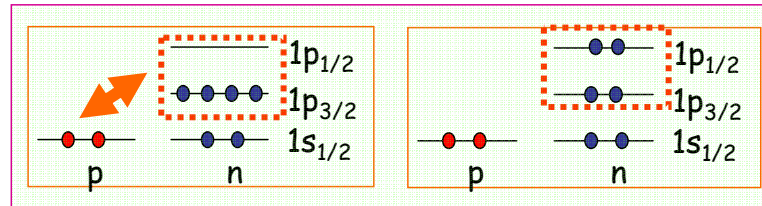
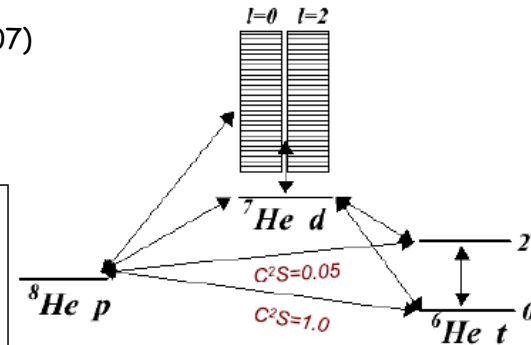
N. Keeley et al. : PLB **646**, 222('07)

$$^8\text{He}(p,d)^7\text{He} \quad C^2S = 3.4 \pm 1.3$$

complete set:
(p,p), (p,d) and (p,t)
@ 15.6 MeV/n

and re-analysis
of RIKEN data

(p,t) \rightarrow wave function $^8\text{He} \propto ^6\text{He}$
 $[^8\text{He}/^6\text{He}(0^+)] = 1$;
 $[^8\text{He}/^6\text{He}(2^+)] = 0.014$
Mixing: $(p3/2)^4$ and $(p3/2)^2(p1/2)^2$

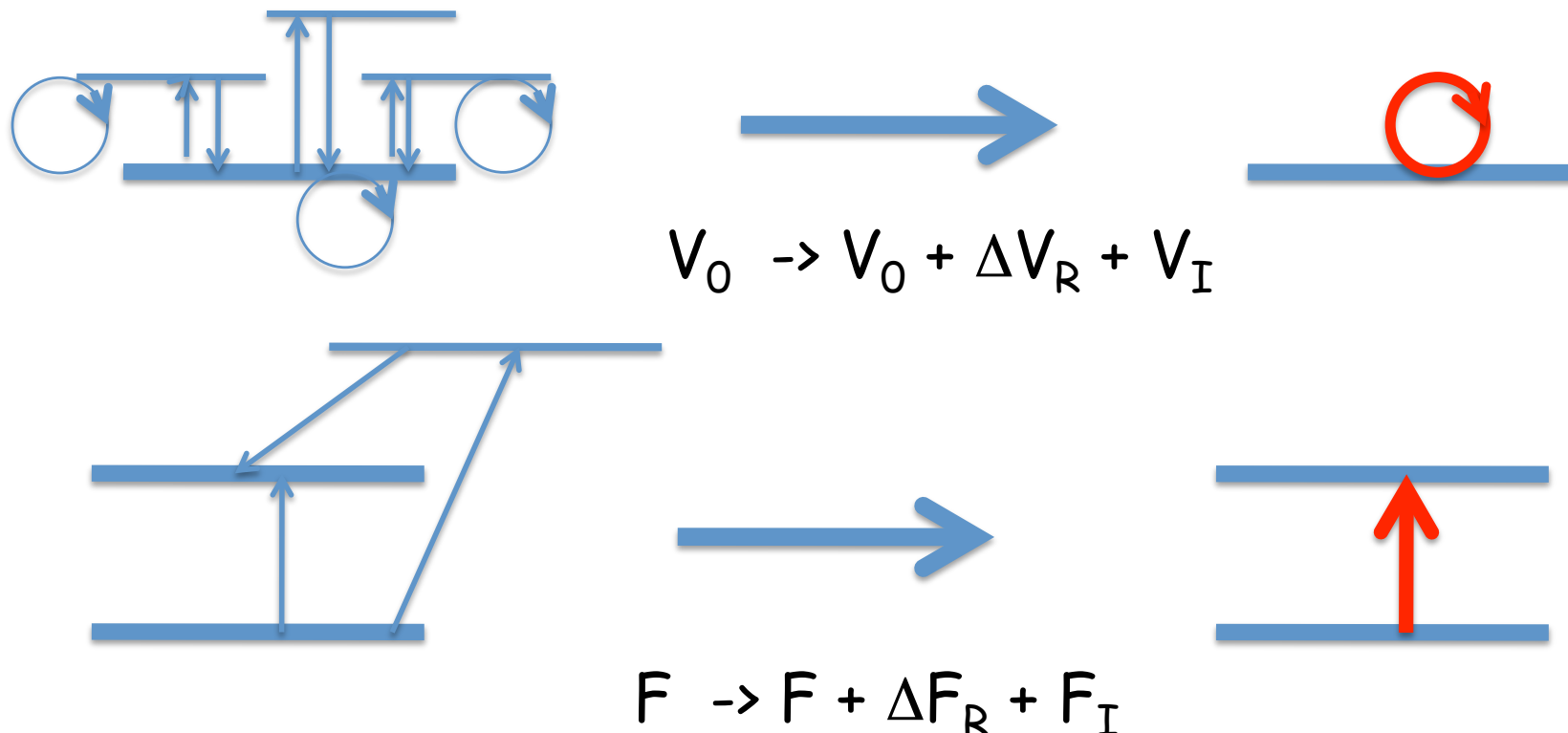


Consistent with the results from quasi-elastic scattering of ^8He at GSI,
LV Chulkov et al, NP **A759**, 43('05) $[^8\text{He}/^6\text{He}(0^+)] : 1.3 \pm 0.1$
And recent theoretical calculations: Hagino, Takahashi, Sagawa PRC **77**, 054317 ('08)
Neutron configurations % ^8He (gs.) : $(1p_{3/2})^4 : 34.9 \%$; $[(1p_{3/2})^2(1p_{1/2})^2] : 23.7 \%$

Polarization contribution for optical potential and formfactors
(due to the reduction of model space). Construction of effective
potentials and couplings

Need for simple and reliable prescription for the exploitation of the Feshbach
prescription, beyond the Coulomb excitation case and/or perturbative
situations (eg Broglia, Pollaro, Winther).

Complex bare couplings? Weakly-bound systems and continuum-continuum:
Repulsive polarization contribution?



Inelastic scattering
(the traditional domain of "collective modes")

Need for microscopic formfactors
(for collective and non-collective excitations)
Role of higher-order couplings (beyond standard
DWBA)

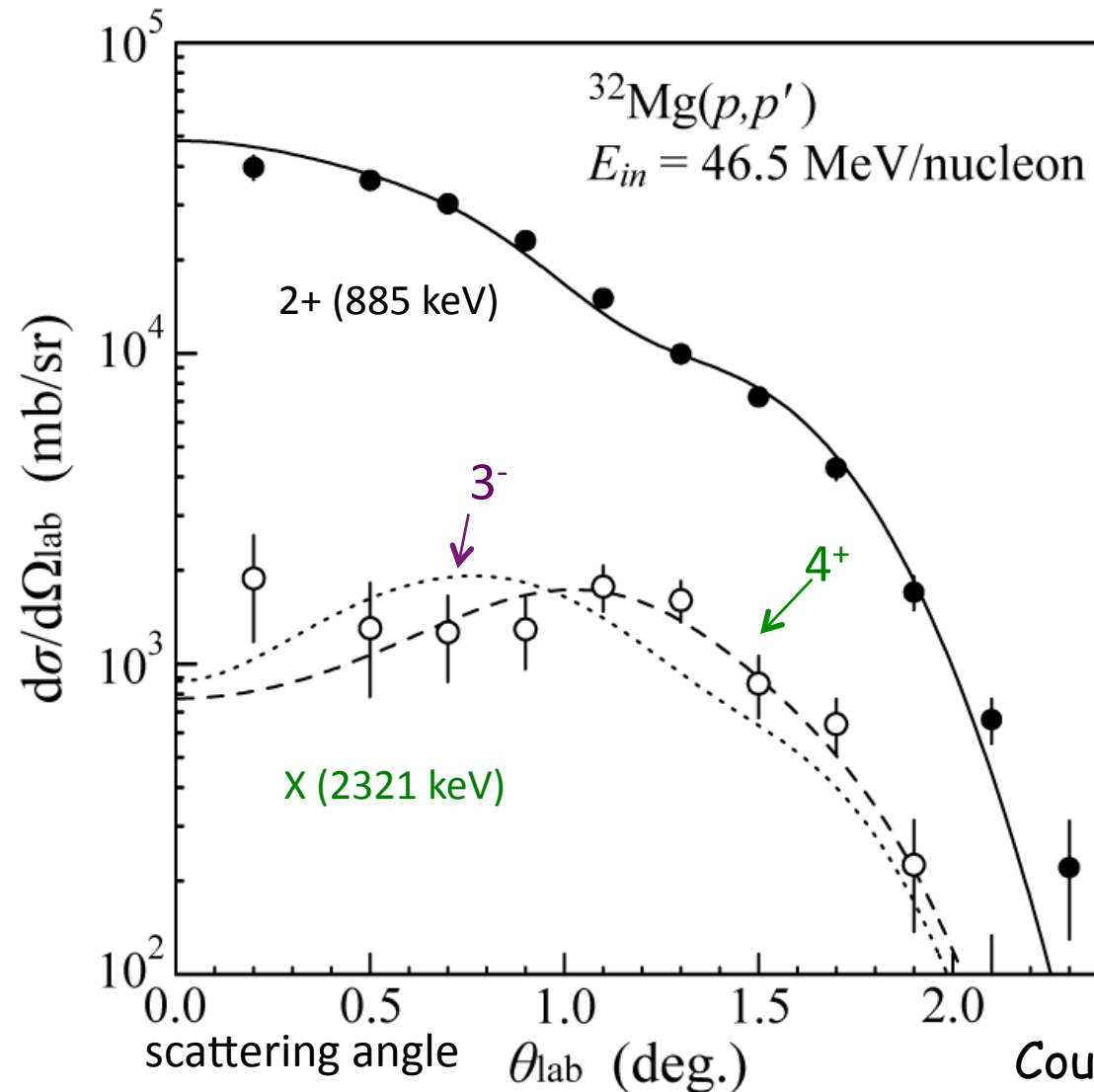
Polarization contribution to formfactors
(imaginary part?)

Excitation to unbound states

Example of inelastic scattering in a strongly coupled system

$^{32}\text{Mg}(p,p')$ in inverse kinematics at DALI2 (RIKEN)- the 2332 keV state

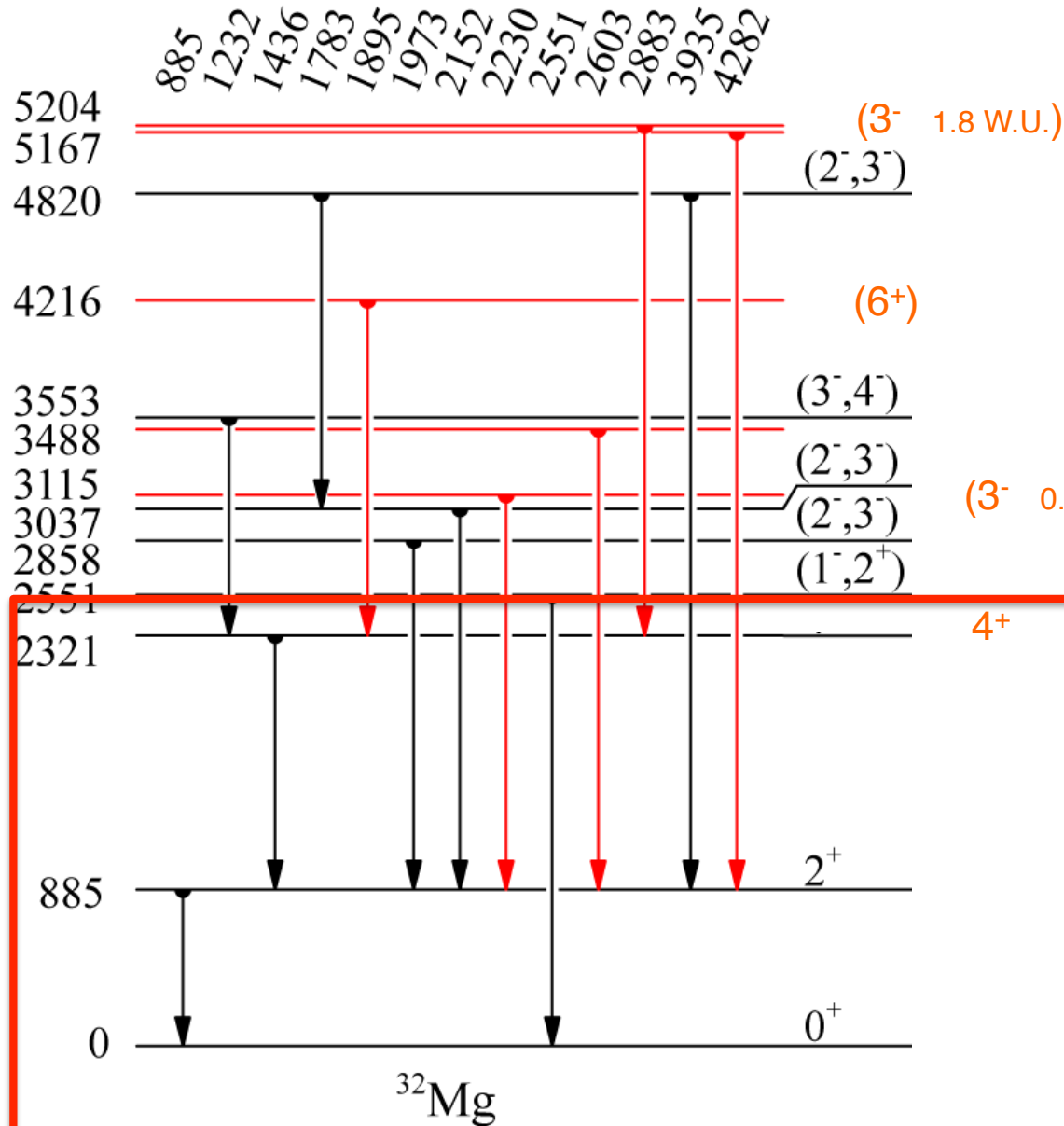
Angular distribution of (p,p')



Courtesy of Tohru Motobayashi

$^{32}\text{Mg}(p,p')$ - Coupled channel analysis with collective formfactors

Need for microscopic formfactors? Truncation of model space? Nuclear and Coulomb equal deformation parameters? Can we learn more from experiment?



$d\sigma/d\Omega_{\text{exp}}$
peak yield
with feeding correction
← level scheme

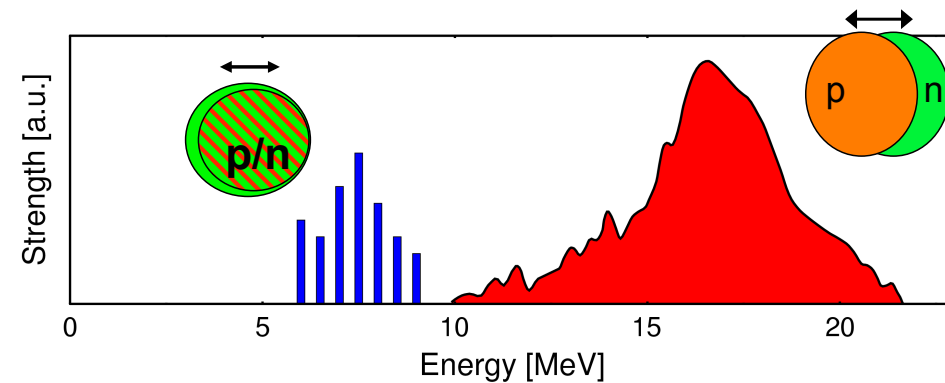
ANALYSIS

$d\sigma/d\Omega_{\text{exp}}$
coupled channel (ECIS)
 $0^+ - 4^+ + 0^+ - 2^+ - 4^+$

$\beta_2 = 0.43$ (common)
 $\beta_4 = 0.12$

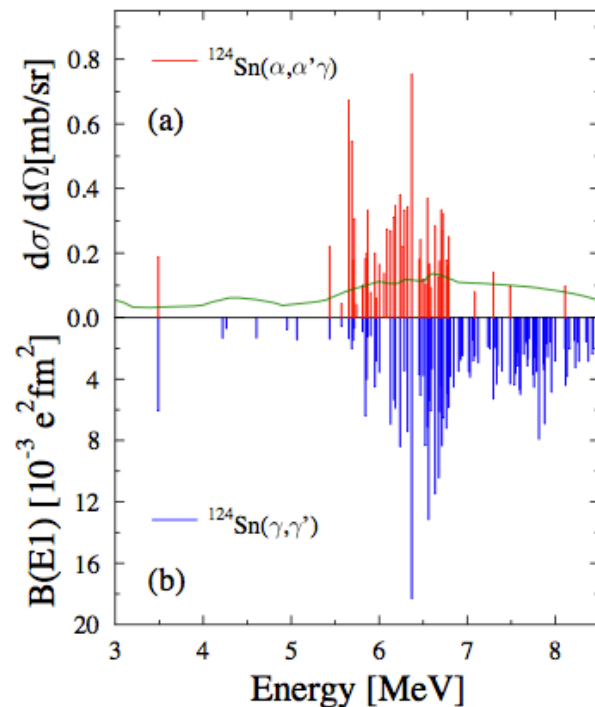
Model space for CC

An example where the use of microscopic formfactors is compulsory:
excitation of PDR (Pygmy Dipole States) in neutron-rich nuclei

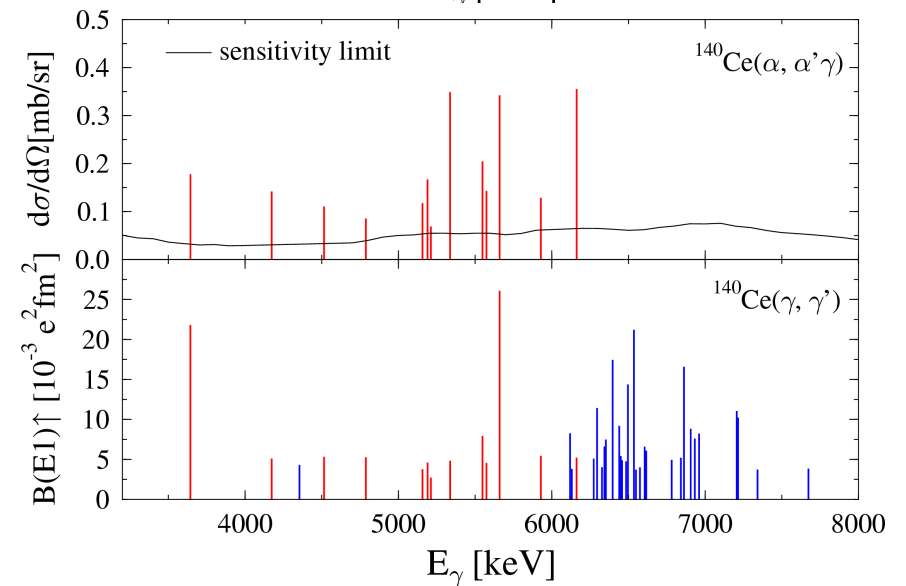
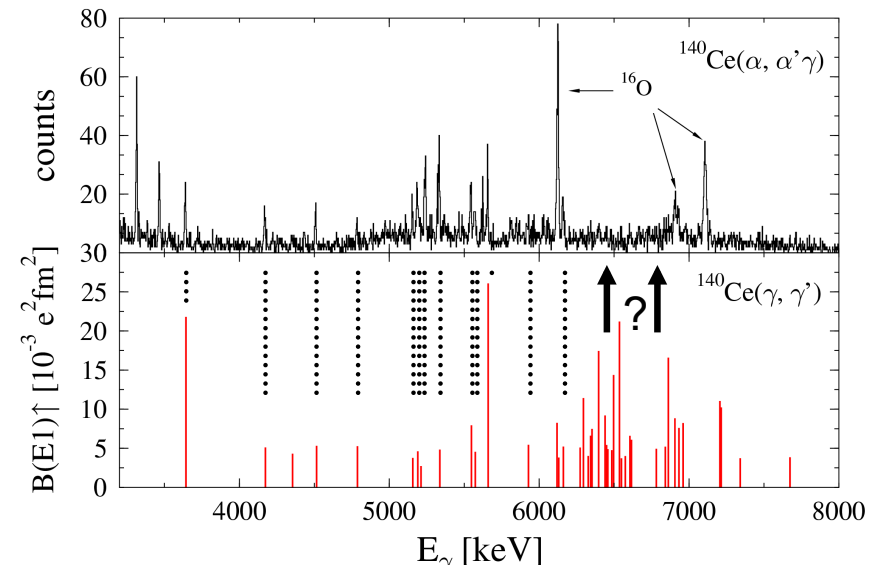


Low-lying dipole states have a mixed isoscalar/isovector character, leading to different excitation probabilities tested with different probes, as (α, α') or (γ, γ')

^{124}Sn

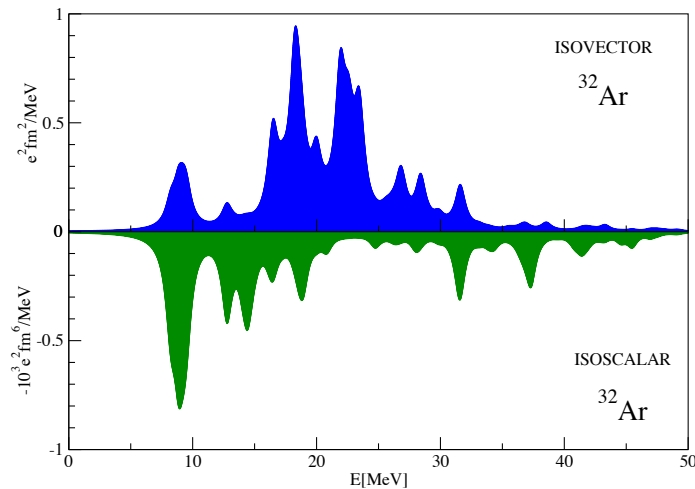


^{140}Ce

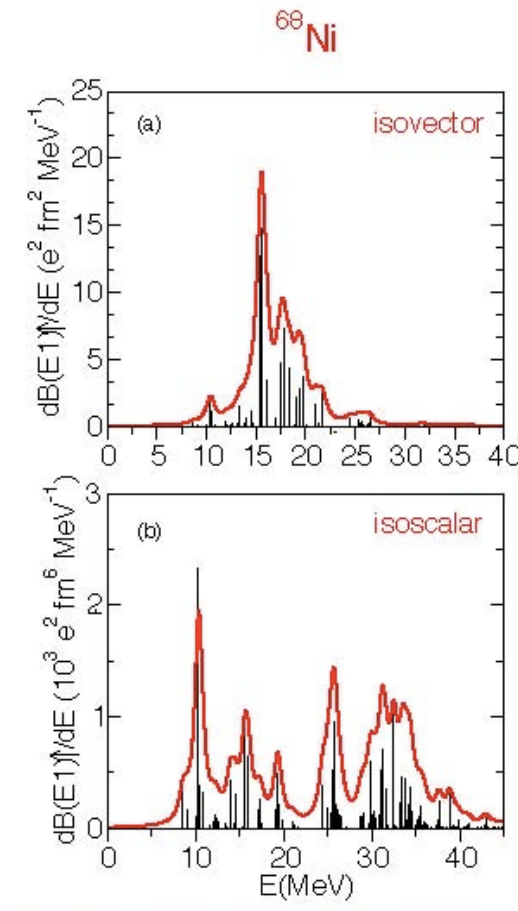


D. Savran et al., Phys. Rev. Lett. **97** (2006) 172502
 J. Endres et al., Phys. Rev. C **80** (2009) 034203
 J. Endres, et al., Phys. Rev. Lett. **105** (2010) 212503

from theory one gets response to isovector and (leading-order)
isoscalar dipole operator



Dario Vretenar et al



Edoardo
Lanza et al

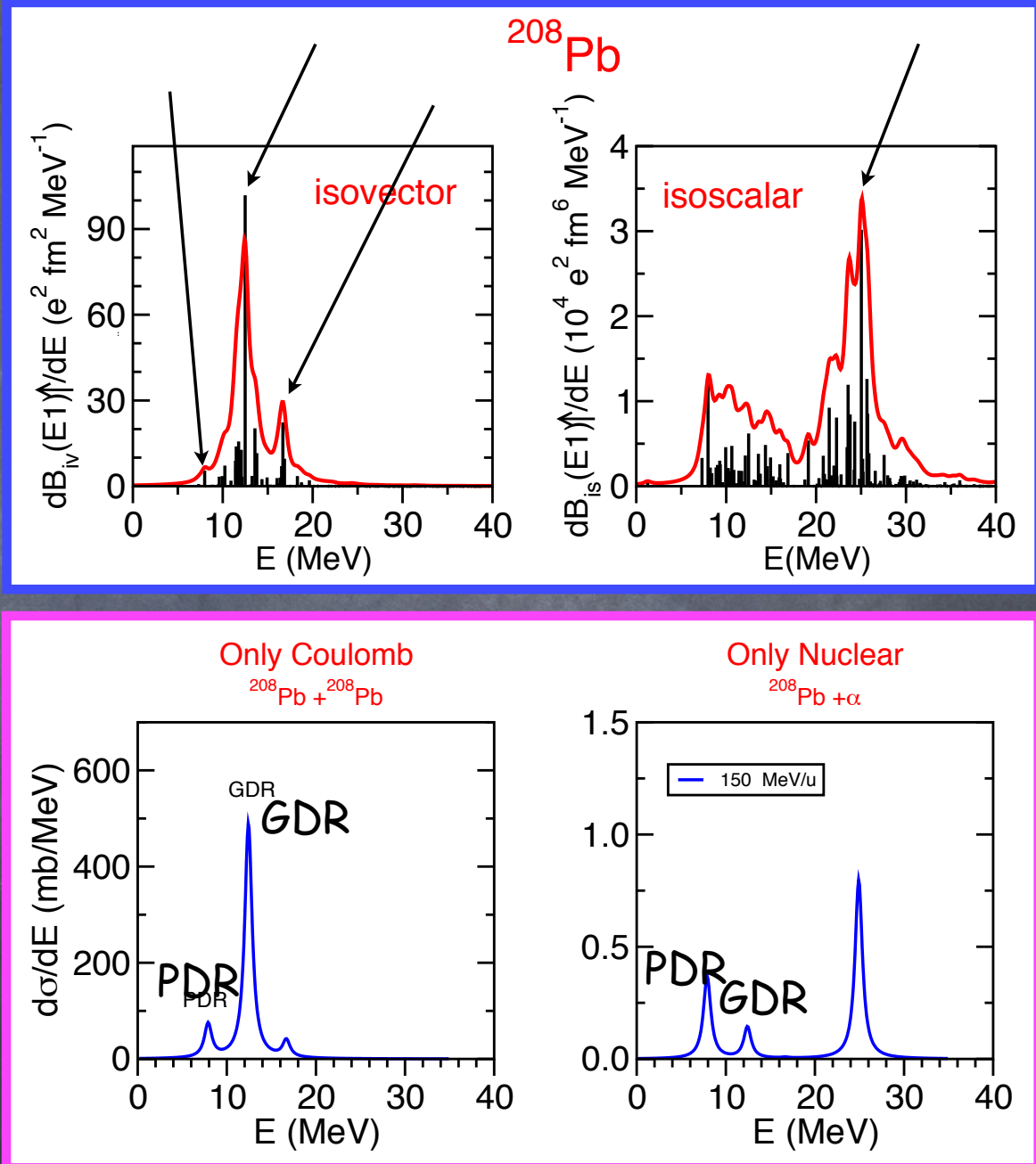
But how the cross sections for reactions as (α, α') depend on the (isoscalar) dipole response? They are connected, but not proportional. One has to pass through the explicit construction of microscopic formfactors using transition densities that must be provided by structure calculations

Calculations of
inelastic cross
section for **four**
selected states

Different relative
population of PDR and GDR
with different probes

Microscopic FF for nuclear
excitation have been
obtained from microscopic
RPA transition densities

Edoardo Lanza et al



One-particle transfer and knock-out
(the traditional domain of "single-particle degree of freedom")

Hot issue: the spectroscopic strength and its deviation from the "bare" single-particle picture

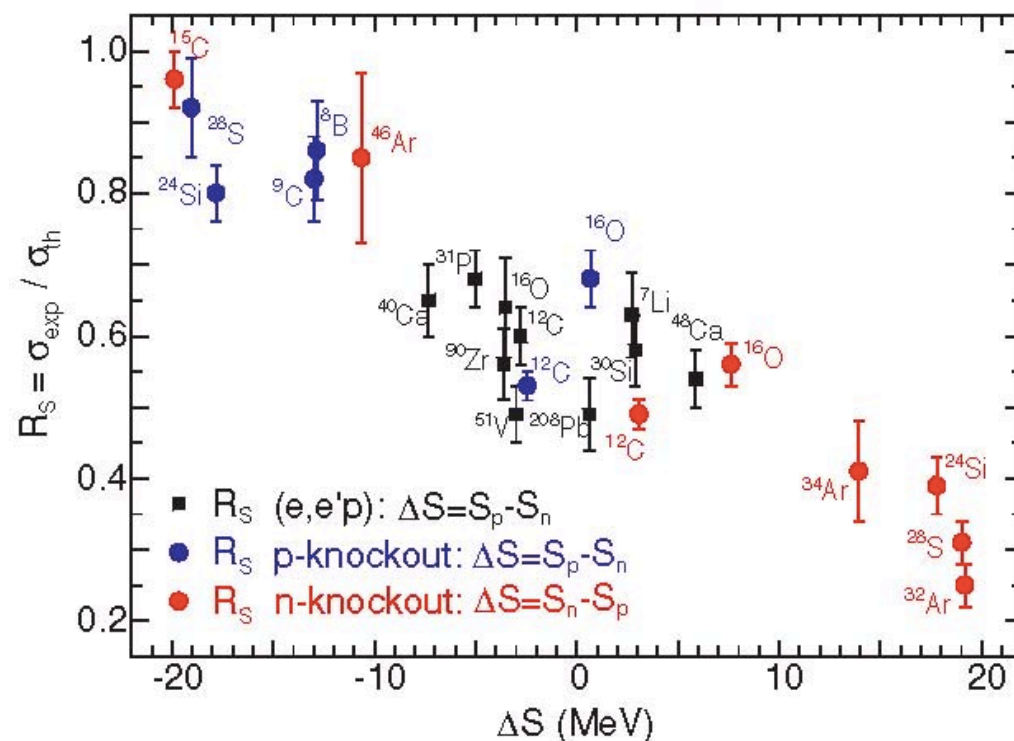
This implies solving quite a number of points, arising from

1. structure models

but also

2. reaction models and associated parameters
(optical potentials, mean-field potentials generating single-particle wf, higher-order processes, etc)

OBS All problems blow up in the case of
weakly-bound systems



Systematic behavior: spectroscopic factors as a function of the difference in the proton and neutron Fermi energy (a measure of proton/neutron mass asymmetry)

From Alexandra Gade

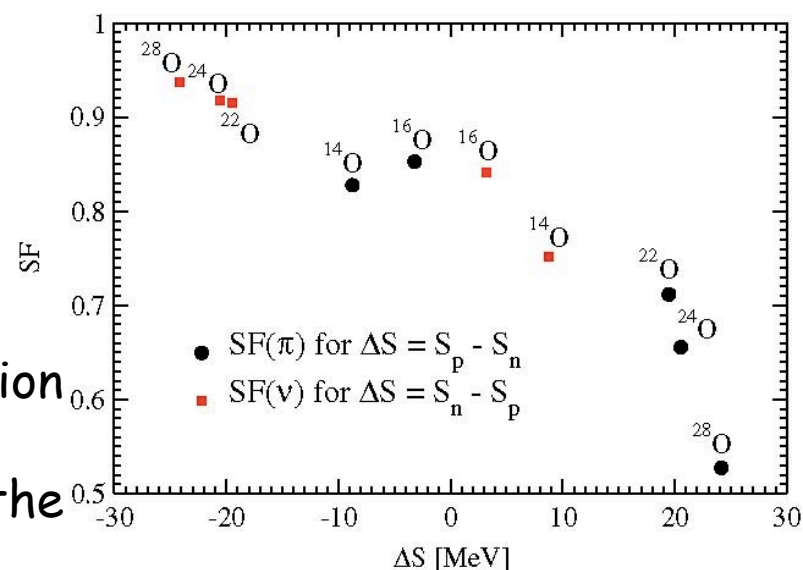
Quenching of spectroscopic Factors for Proton Removal in Oxygen Isotopes

Ø. Jensen et al, 2011

Example of "sophisticated" structure calculation

Coupled-cluster calculation N3LO

including coupling to scattering states above the neutron separation threshold



Quoting Alan Wuosmaa (Helios collaboration) for the light nuclei

Despite concerns about the reliability of reaction theory, good absolute agreement with *ab-initio* form-factor calculations can be achieved at the 20-30% level for (d,p), even for unbound states.

.

Other reactions are problematic: e.g. absolute (d,t) and (d, ^3He) results show a strong dependence on optical-model parameters

.

In all cases, it seems that **relative** spectroscopic factors can be reproduced very well by *ab-initio* or SM calculations in many (but not all) cases.

Interesting to extend studies further to **unbound states** to test structure calculations

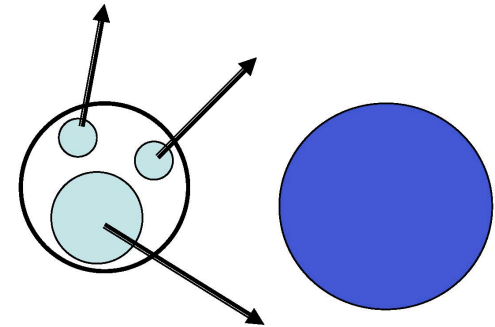
A wise opinion (John Schiffer)

Simple ways of treating data can allow us to extract essential structural information, even if reaction theorists are not completely happy.

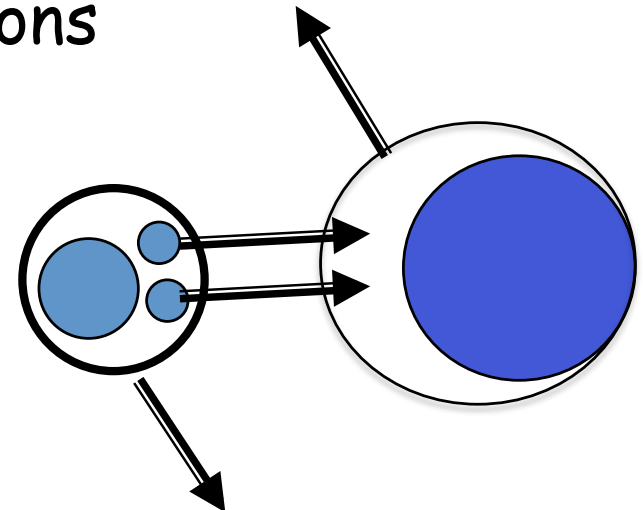
One hopes that a new generation will be able to start from what was Learned, and build on it, **and not get bogged down with the fascinating sophistries of reaction theories**. We need not have to rediscover all the blind alleys (of two-step processes, coupled channels ... etc) that obscured simple underlying information

Reactions involving pairs of nucleons (the traditional domain of “nuclear correlations”)

1. two-nucleon knockout reactions
2. two-nucleon break-up reactions



3. two-nucleon transfer reactions

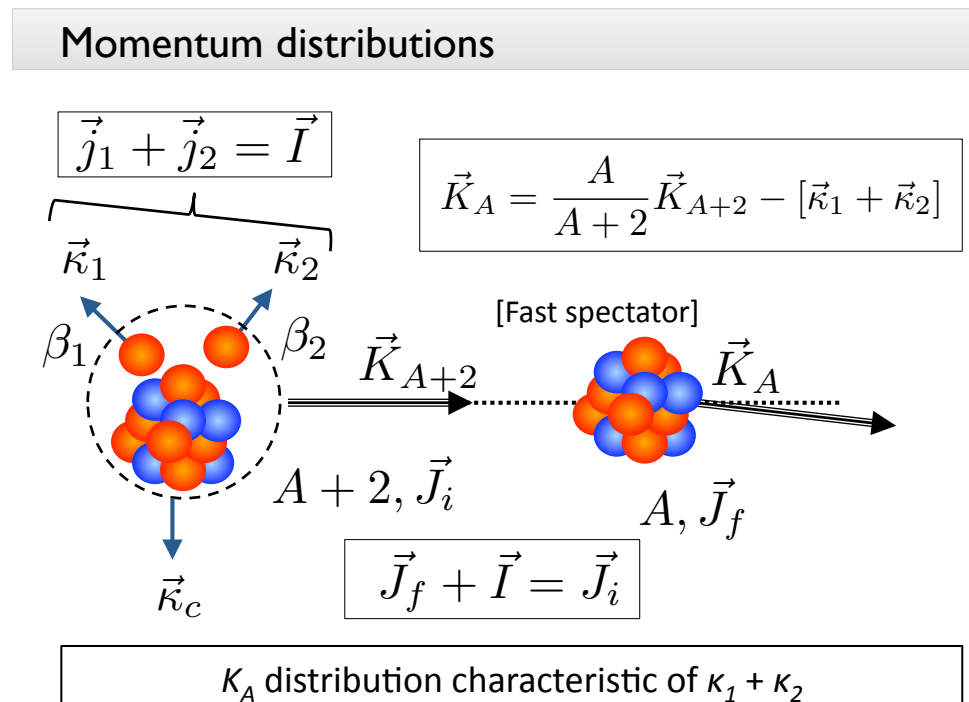


1. two-nucleon knockout reactions

Basic information arise from the momentum distribution, which turns out to be depending on the structure and the correlations in initial and final states

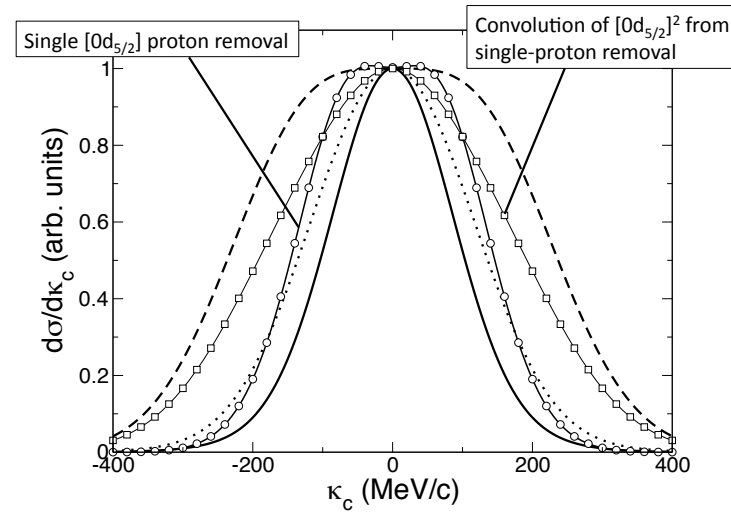
The process can be described in terms of two "correlated" knock-out of single neutrons
(Jeff Tostevin etal, Edward Simpson etal)

From a presentation
by Edward Simpson

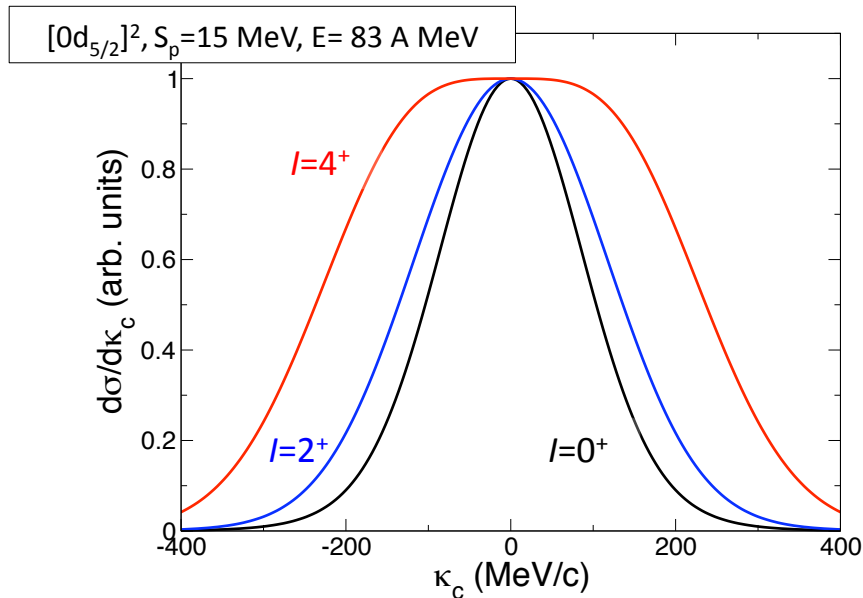


Dependence of momentum distribution on the angular momentum coupling of the two nucleons and on the specific orbitals

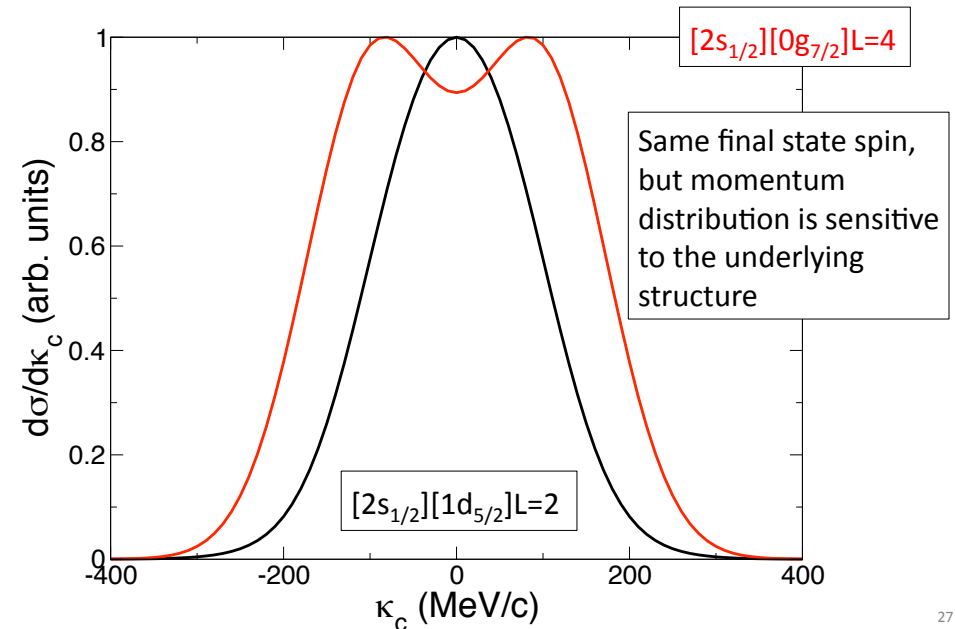
Example I: Single/Uncorrelated



Example I: $^{28}\text{Mg}(-2p) [0d_{5/2}]^2$

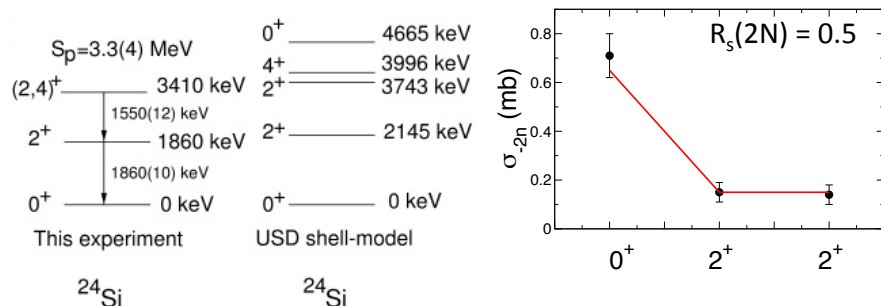


Example: $^{208}\text{Pb}(-2p) \rightarrow ^{206}\text{Hg}(J_f=3^+)$



$^{26}\text{Si}(-2n)$: Cross section results

Results



Shell model (sd-shell, USD) two-nucleon amplitudes

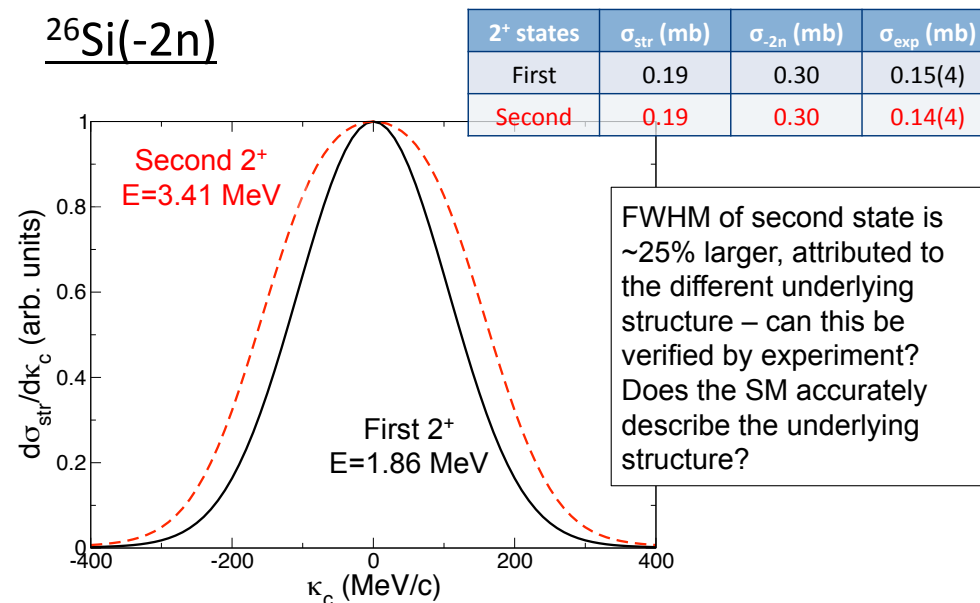
State	$[0d_{5/2}]^2$	$[0d_{5/2}, 0d_{3/2}]$	$[0d_{3/2}]^2$	$[1s_{1/2}, 0d_{3/2}]$	$[1s_{1/2}, 0d_{5/2}]$
2 ⁺ (First)	-0.70074	0.43499	0.00594	-0.00188	-0.02781
2 ⁺ (Second)	-0.38021	-0.12354	-0.12945	-0.15876	-0.58292
4 ⁺ (First)	1.57469	0.41519	-	-	-

Yoneda *et al.*, PRC 74, 021303(R) (2006)

An example of detailed “microscopic” calculation based on microscopic correlated WF’s

Requirement for full success: absolute cross section and momentum distribution

Structure Sensitivity

 $^{26}\text{Si}(-2n)$ 

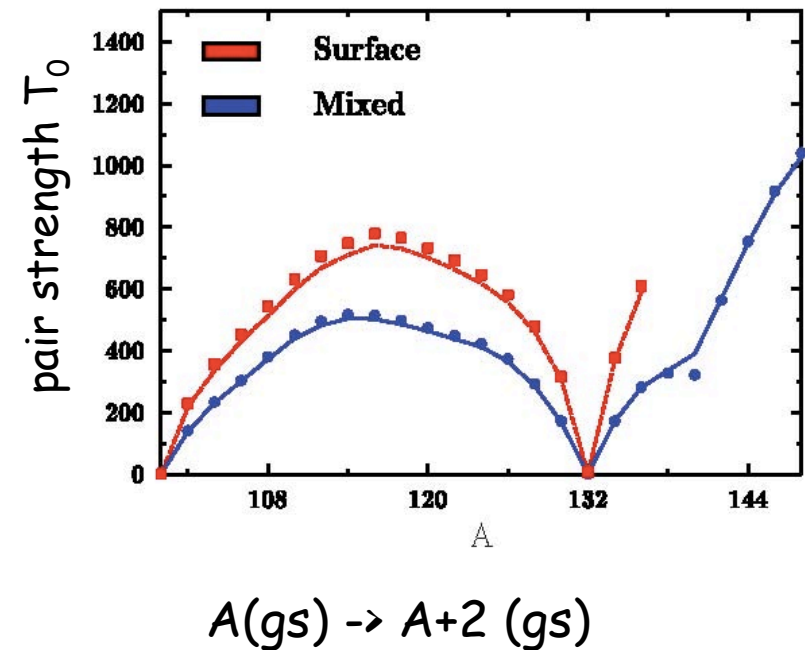
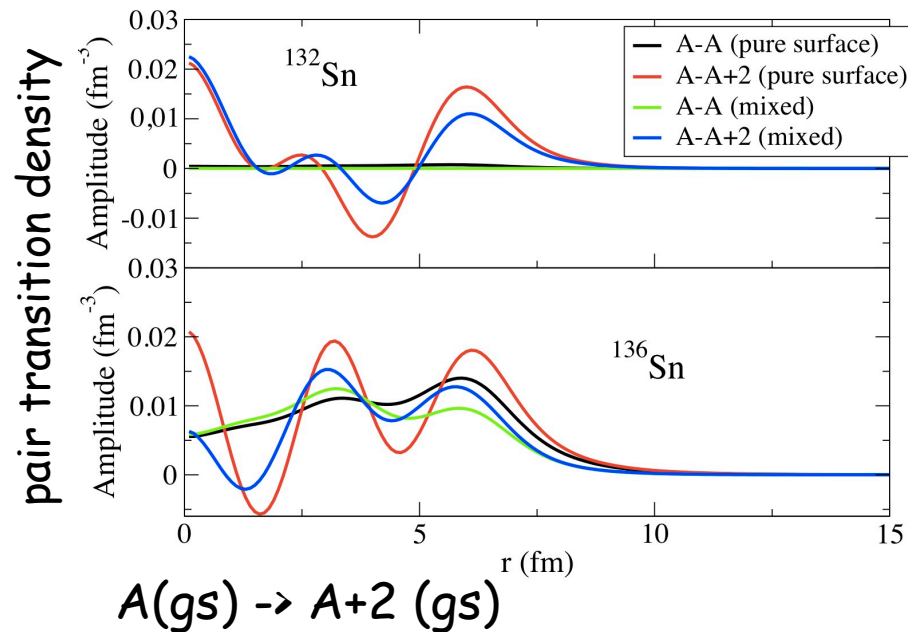
Simpson *et al.*, PRC 82, 044616 (2010)

A. Gade *et al.*, NSCL experiment 10002 (approved)

2. two-nucleon transfer reactions

It is widely accepted that pairing correlations strongly effect (and enhance) two-particle transfer reactions. But the quantitative connection is not obvious. Will cross section scale with the square of the two-particle transfer matrix elements? Or the radial dependence of the two-particle transition densities contain more information? And how this information enter into the reaction mechanism?

Example of structure investigation of pairing correlations: can we discriminate among different forms of pairing interactions? Example: can we distinguish pure surface pairing interaction from mixed (volume plus surface) in HFB calculations? (from Grasso, Lacroix, AV)



How the different behavior in the tail enter in the reaction mechanism? Is only the integrated value T_0 relevant?

BASIC PROBLEM: The reaction mechanism

Variety of models on the market

The fully microscopic approach 😊 is based on sequential two-step process (each step transfers one particle)

Microscopy: Pairing enhancement comes from the coherent interference of the different paths through the different intermediate states in $(a-1)$ and $(A+1)$ nuclei, due to the correlations in initial and final wave functions

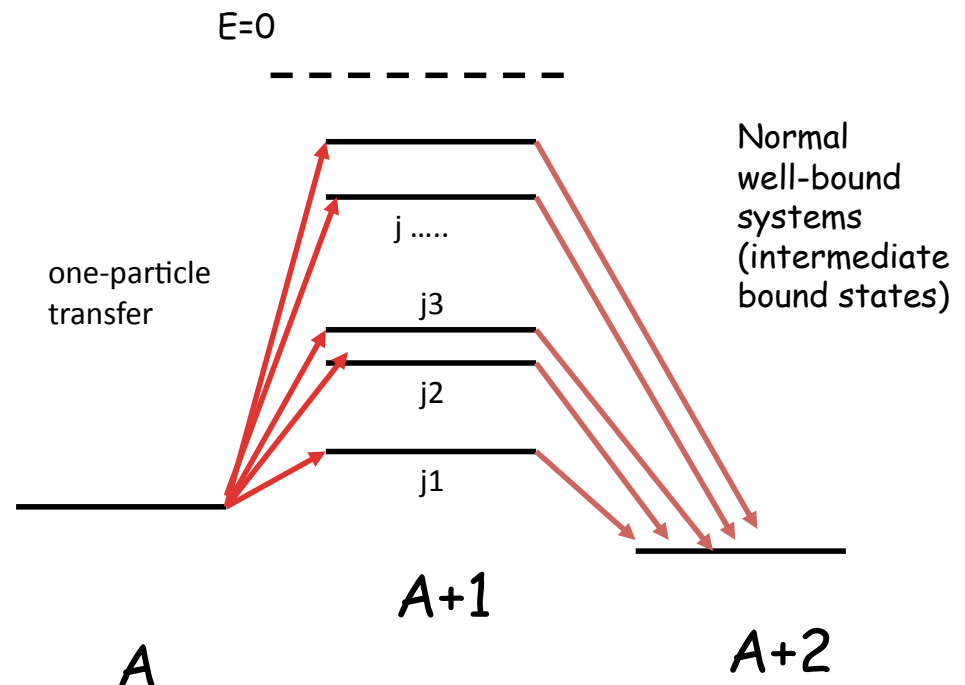
Building blocks: single-particle formfactors and wf's

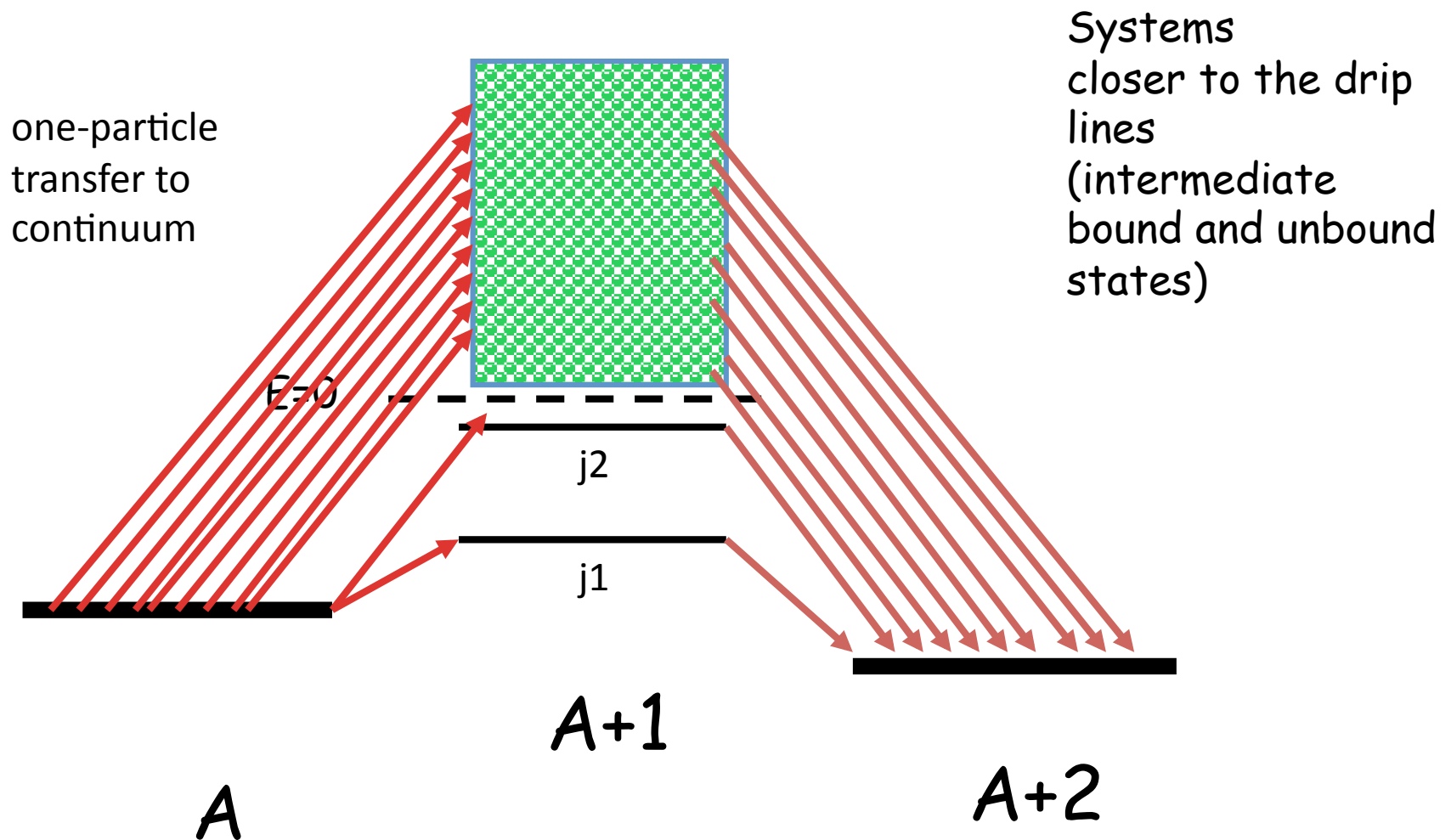
Problems: quantal calculations rather complex (taking into account full recoil), semiclassical more feasible (but approximate treatment of recoil)

All microscopy and nuclear structure information are contained in the two-particle transfer amplitudes (from correlated initial and final wave functions), which give the weight of each two-step path, and in the single particle transfer formfactors, which need single particle wavefunctions in target and projectile

Obs: Basic idea: dominance of mean field, which provides the framework for defining the single-particle content of the correlated wave functions

Examples in this meeting by
Ricardo Broglia and
Rituparna Kanungo

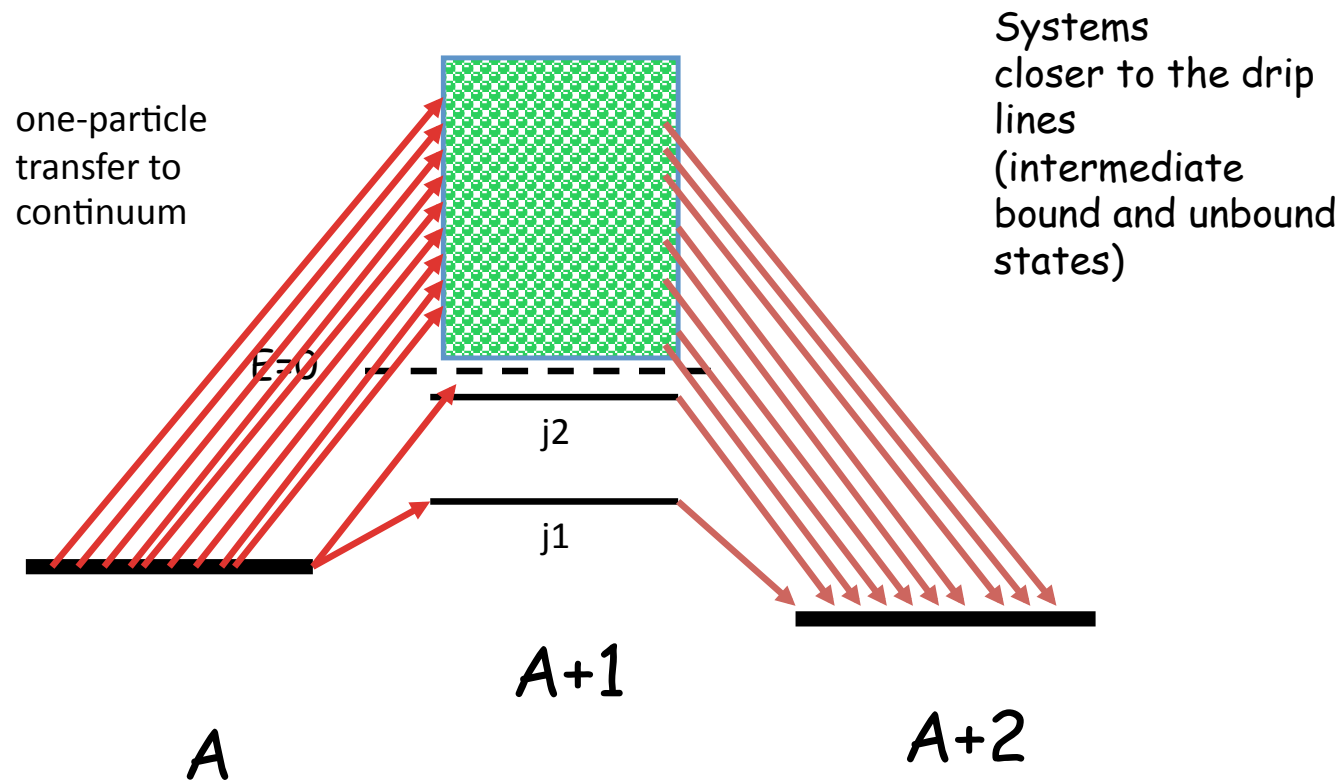


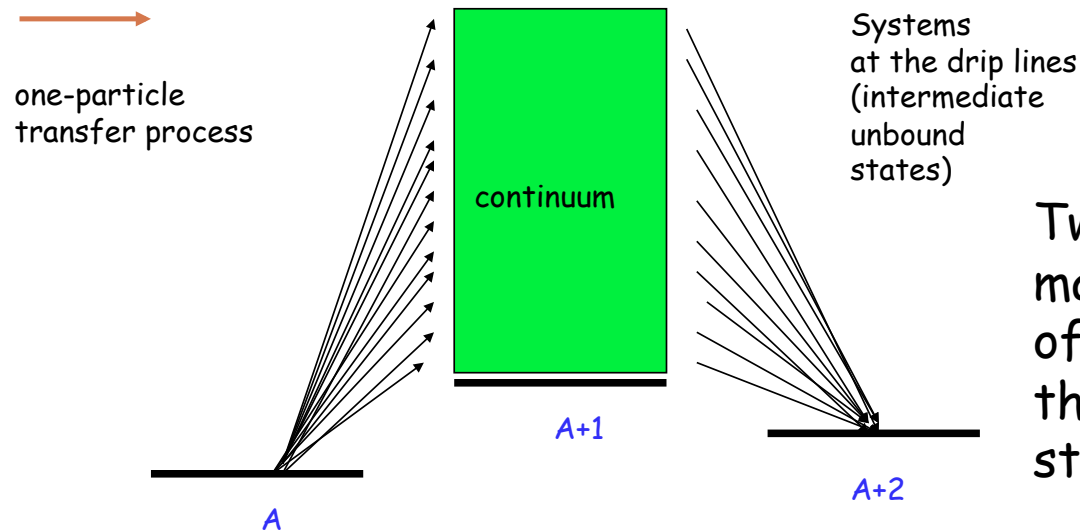


Example

$$|A=2\rangle = \left\{ \sum_i X_i [a_i^+ a_i^+]_0 + \int dE X(E) [a^+(E) a^+(E)]_0 \right\} |A\rangle$$

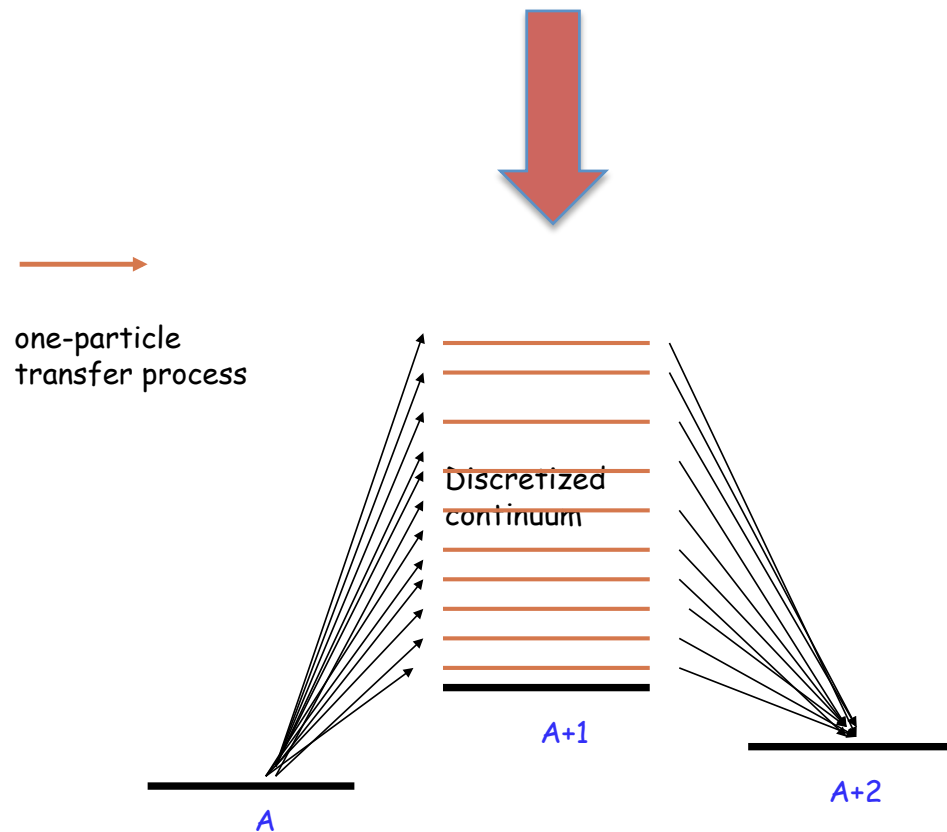
But moving from the stability line





Finally reaching the drip lines

Two-particle transfer will proceed mainly by constructive interference of successive transfers through the (unbound) continuum intermediate states

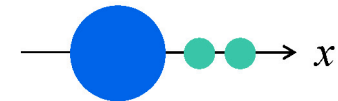


The integration over the continuum intermediate states can become feasible by **continuum discretization**: but how many paths should we include? Thousands or few, for example only the resonant (Gamow) states?

3. Two-particle break-up processes

Break-up of a two-particle halo system is a rather complex 4-body process. To make it simpler let us consider an one-dimensional case, that should hopefully display the essential features of the three-dimensional case

One-dimensional three-body model



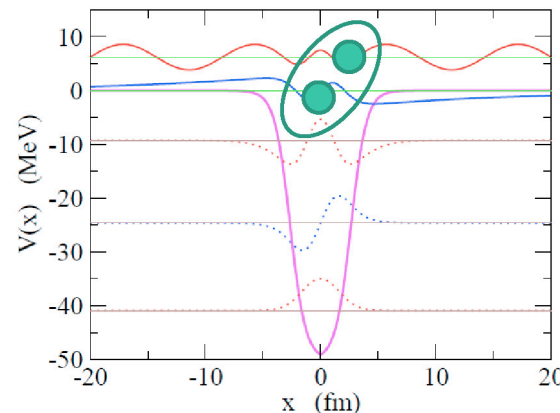
Two interacting neutrons in a one-dimensional potential well:

$$H = -\frac{\hbar^2}{2m} \frac{d^2}{dx_1^2} + V(x_1) - \frac{\hbar^2}{2m} \frac{d^2}{dx_2^2} + V(x_2) + v_{nn}(x_1, x_2)$$

density-dependent contact interaction:

$$v_{nn}(x, x') = -g \left(1 - \frac{1}{1 + e^{(|x|-R)/a}} \right) \delta(x - x')$$

Hagini, Vitturi,
Sagawa, PerezBernal
2011



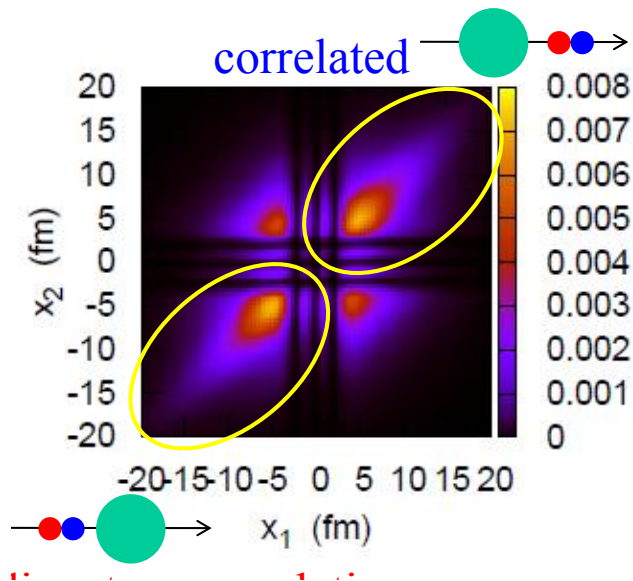
$$\Psi_{gs}(x_1, x_2) = \sum_{n \leq n'} \alpha_{nn'} \Psi_{nn'}(x_1, x_2)$$

$$\Psi_{nn'}(x_1, x_2) \propto \mathcal{S}[\phi_n(x_1) \phi_{n'}(x_2)] \times |S=0\rangle$$

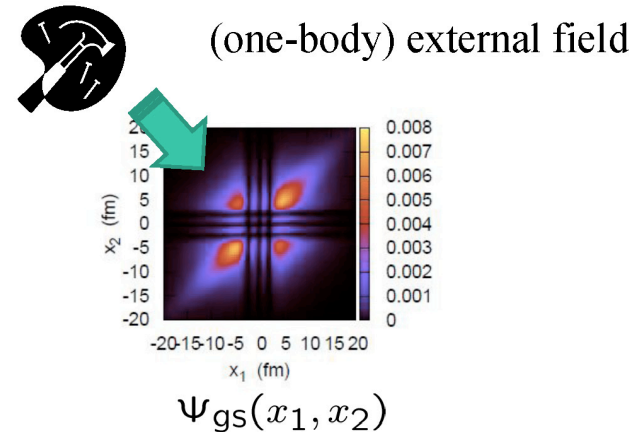
• **S = 0 state**: symmetric for the spatial part of wf

• n, n' : the same parity

two-particle density: $|\Psi_{\text{gs}}(x_1, x_2)|^2$



Nuclear Breakup Process



Time-dependent two-particle Schroedinger equation:

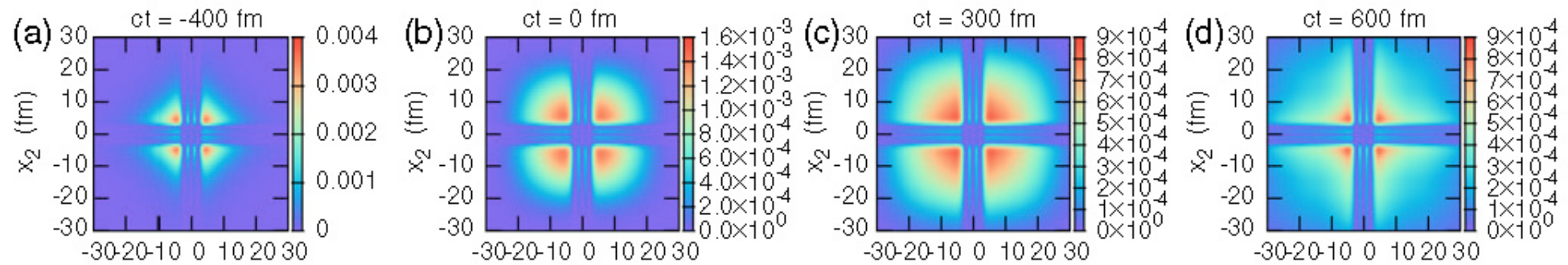
$$i\hbar \frac{\partial}{\partial t} \Psi(x_1, x_2, t) = [H + V_{\text{ext}}(x_1, x_2, t)] \Psi(x_1, x_2, t)$$

$$V_{\text{ext}}(x_1, x_2, t) = \sum_{i=1,2} V_c e^{-t^2/2\sigma_t^2} e^{-(x_i-x_0)^2/2\sigma_x^2}$$

$$V_c = 3 \text{ MeV}, \sigma_t = 2.1 \text{ hbar/MeV}, x_0 = 0$$

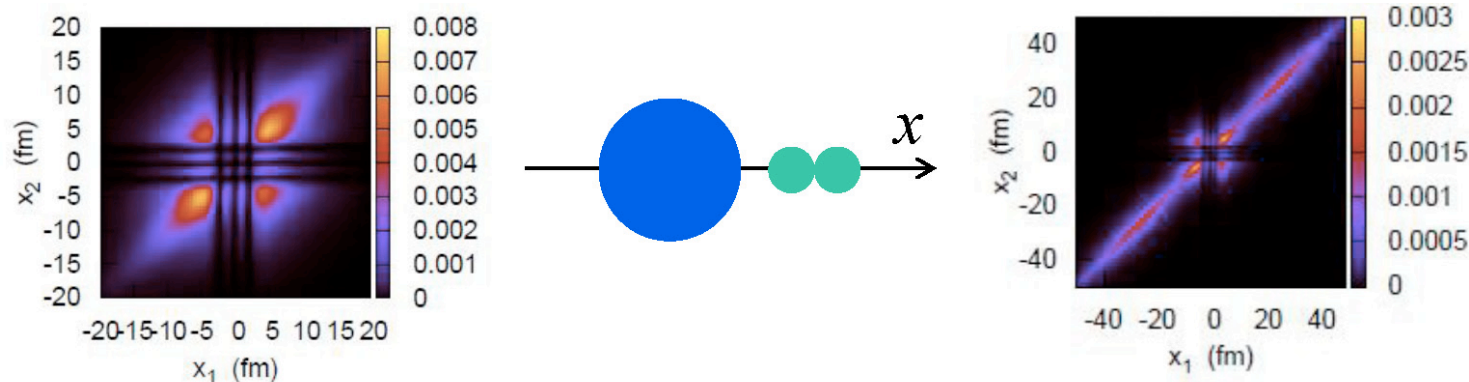
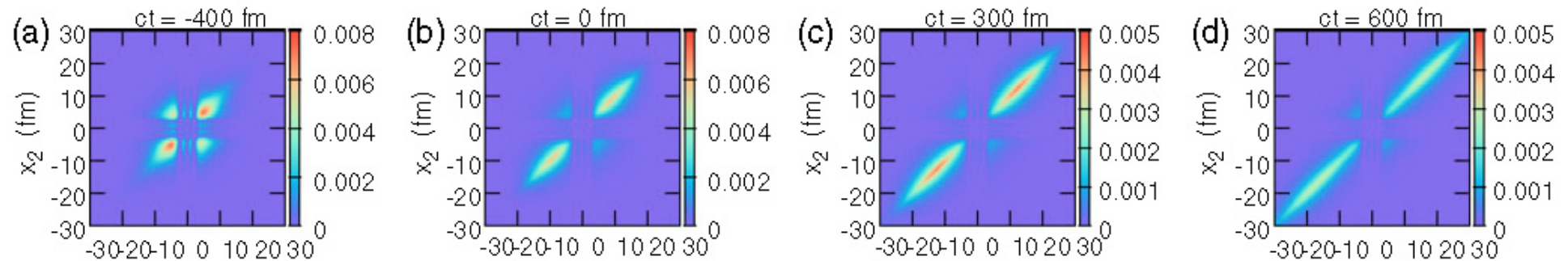
The perturbing interaction (that produces the break-up) is a **one-body field** (i.e. acting individually on each of the two particles). The enhanced two-particle break-up originates from the correlation in the two-particle wave function, and not from a forced two-neutron cluster reaction mechanism

Time evolution (uncorrelated case)



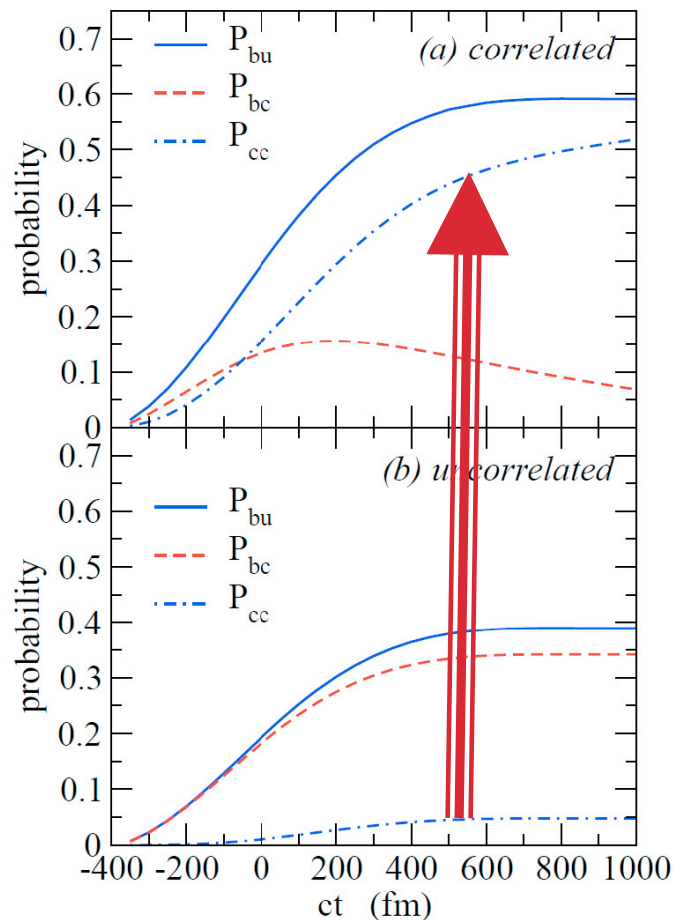
OBS: Large component with only one-particle in the continuum

Time evolution (correlated case)



Large di-neutron emission

As a net result, the two-particle break-up process is enhanced by the correlation (although the external perturbing field is of one-body nature)



➤ Pairing: enhances the breakup

➤ Correlated: (cc) process

➤ Uncorrelated: (bc) process

P_{cc} : 2 neutron breakup

P_{bc} : 1 neutron breakup

Sub-barrier heavy-ion fusion

Strictly speaking this is not a "direct" process (on the contrary), but strongly effected by the competing direct channels

Interplay of different coupled channels
(elastic, inelastic, transfer)

For weakly-bound systems still interesting issue of the effect of the coupling to continuum
(enhancement or suppression?)

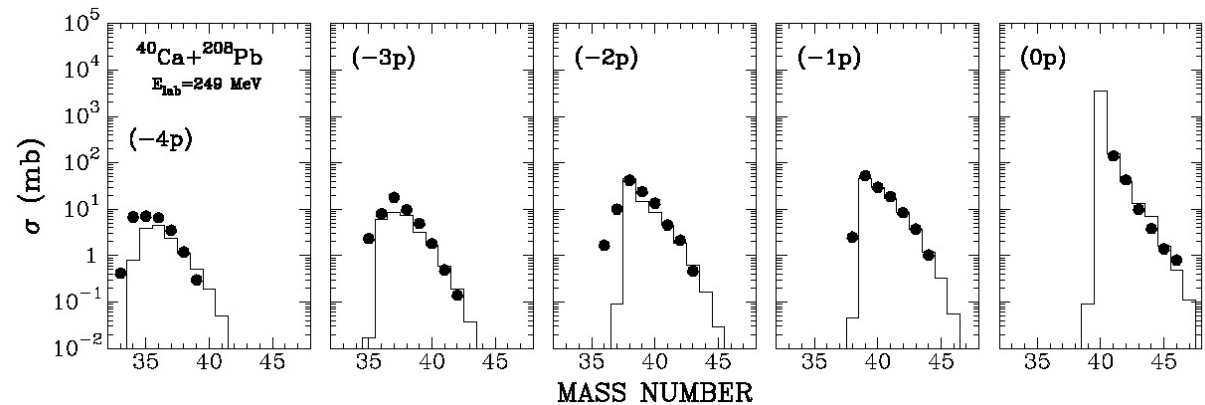
Multi-nucleon transfer reactions

Again, not a "genuine" direct process, but a key case as test of pairing modes in the "vibrational multiphonon-like" and in the "rotor-like" pairing cases. In the case of population of excited states is fundamental in describing the transition from grazing reactions to more central deep-inelastic collisions)

OBS: instrumental for structure studies with γ -spectroscopy for systems far from stability, but this is another story

Example of multi-nucleon transfers at Legnaro

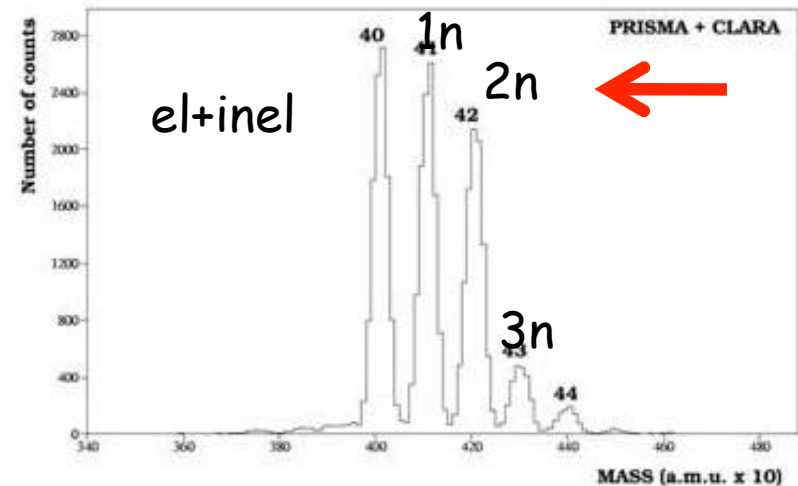
$^{40}\text{Ca} + ^{208}\text{Pb}$



Obs: transfer of particles on both
directions
Transition from direct to deep inelastic
(cf Q distributions)

Example: Neutron transfer
channels

(odd-even transfer effect?
Structure effect?)



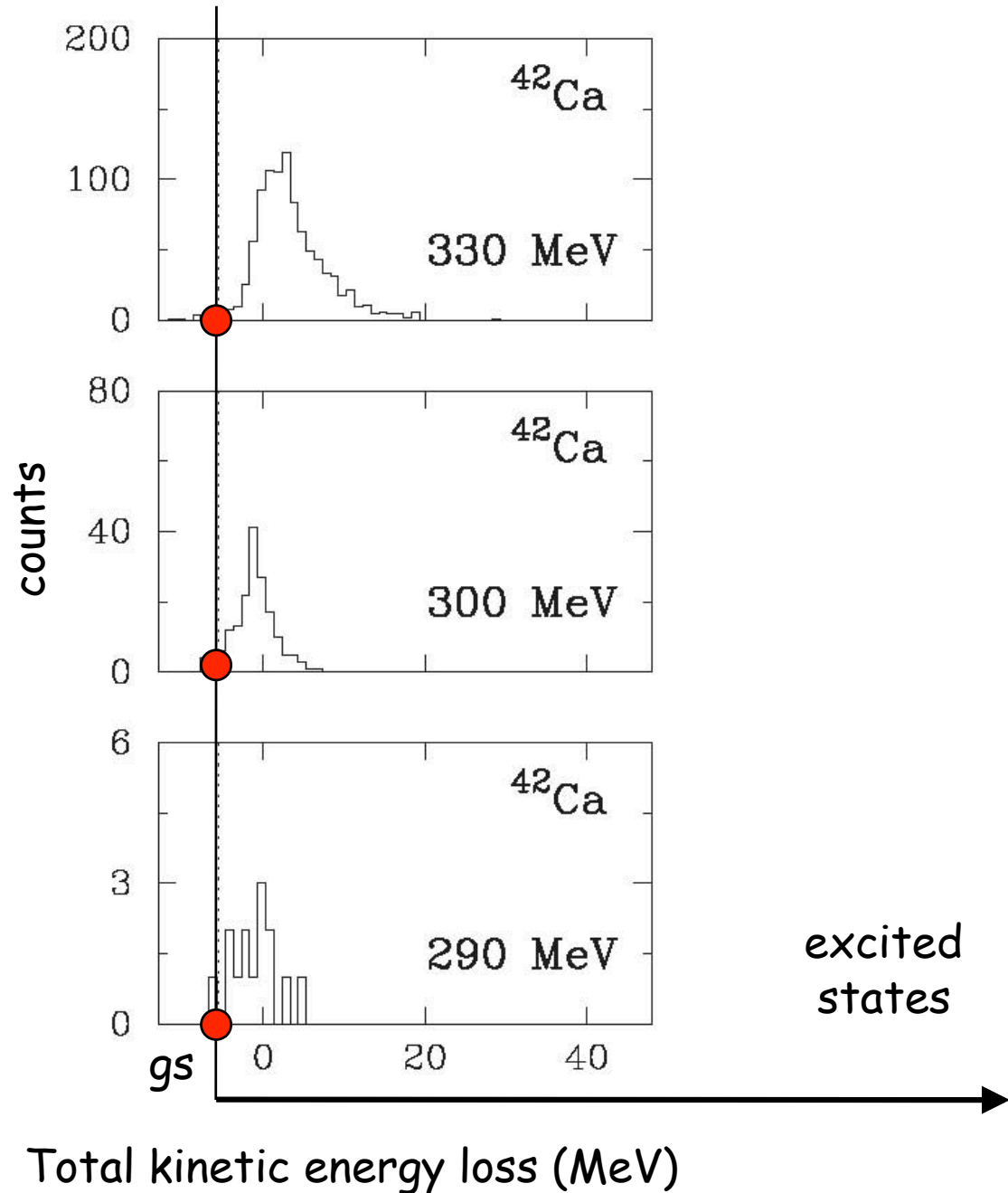
Experimental evidence

Negligible transitions to GS
due to Q-value effects.
What information on pairing
correlations?

Example

$^{96}\text{Zr} + ^{40}\text{Ca}$

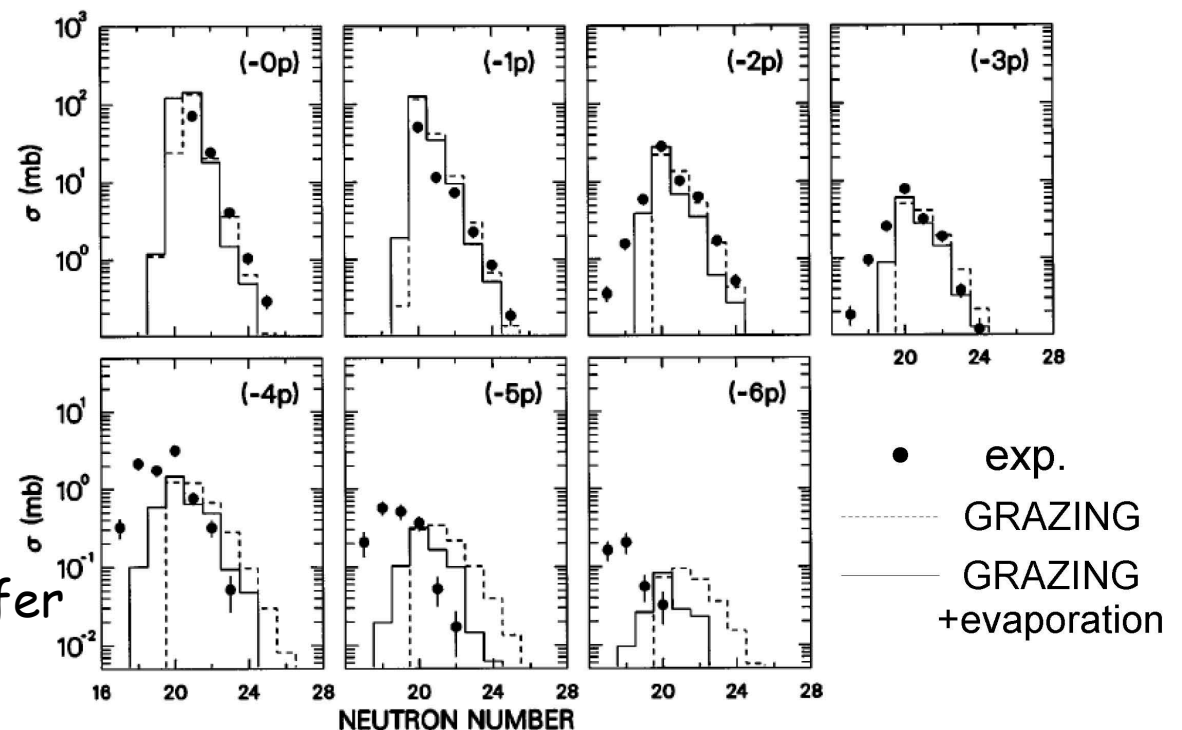
Selecting final
 ^{42}Ca mass partition



Basic and most popular approach: "Grazing model" (Nanni Pollarolo and Aage Winther)

- semiclassical description of trajectory
- single-particle transfers
- two-particle transfers (double counting?)
- collective inelastic excitations
- sufficient phase-space for multi-transfer?
- "bare" ion-ion potential?
- structure information?
- excellent for "average" behavior. Specific cases?
- Weakly-bound systems and treatment of continuum?
- collective vs non-collective transfer (and non $L=0$ pairs)

$^{40}\text{Ca} + ^{124}\text{Sn}$ $E_{\text{lab}} = 170$ MeV



Other approach: TDHF with particle number projection technique (Cedric Simenel), with reduction of computational time by a factor 100 (still *in fieri* and under discussion the range of validity: maximum number of transferred particles? Residual correlations? In particular pairing correlations? Reaction mechanism beyond mean field?)

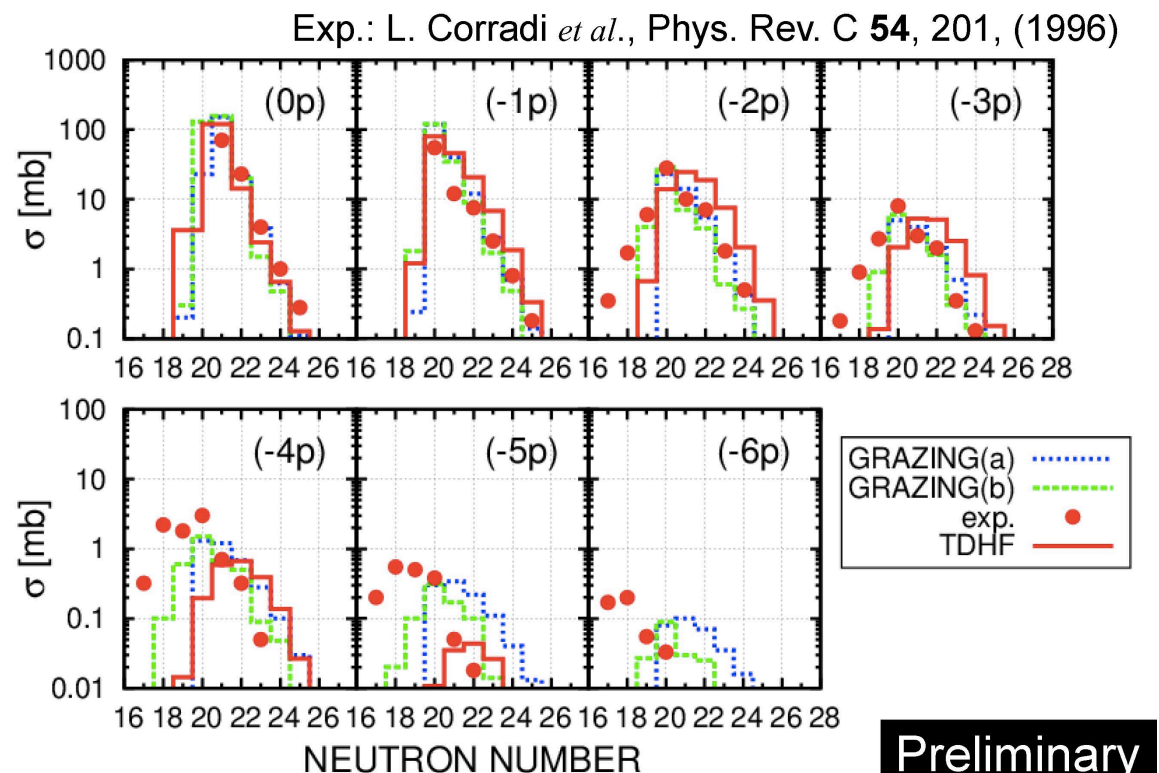
Example:

$^{40}\text{Ca} + ^{124}\text{Sn}$ $E_{\text{lab}} = 174 \text{ MeV}$

Sekizawa and Yabana

SLy5

OBS: Overall agreement is good when transferred proton number is small



Preliminary