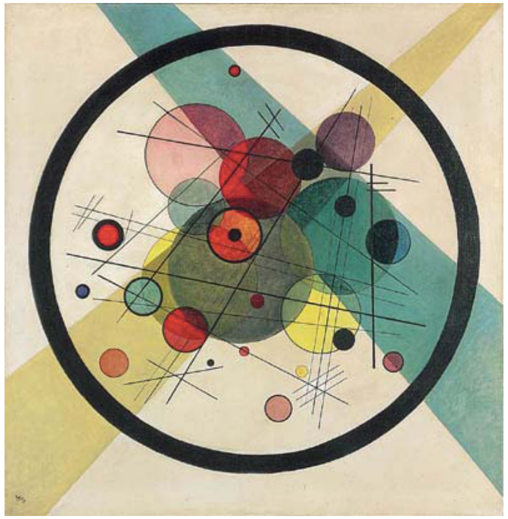
Dinamica delle reazioni nucleari a bassa energia



Low-energy reactions (with both light and heavy projectiles) are the traditional ideal tools for the study of the multi-facets aspects of nuclear many-body systems

It is the domain of the so-called direct reactions. They have played a decisive role for the study of both single-particle behavior and collective features in nuclei. After some years of relative decline, the possibility of exploring regions of the nuclear chart outside of the stability valley has started a period of new renaissance. Nuclear laboratories all over the world devote a large fraction of their human and financial resources to the study of direct reactions involving “exotic” nuclei

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.

From the theoretical point of view it is the domain not of exact solutions but of models, since it is necessary to introduce a number of simplifying assumptions to reduce the many-body problem to a tractable form. Need for consistent treatment of both reaction and structure aspects.

Why to study direct reactions?

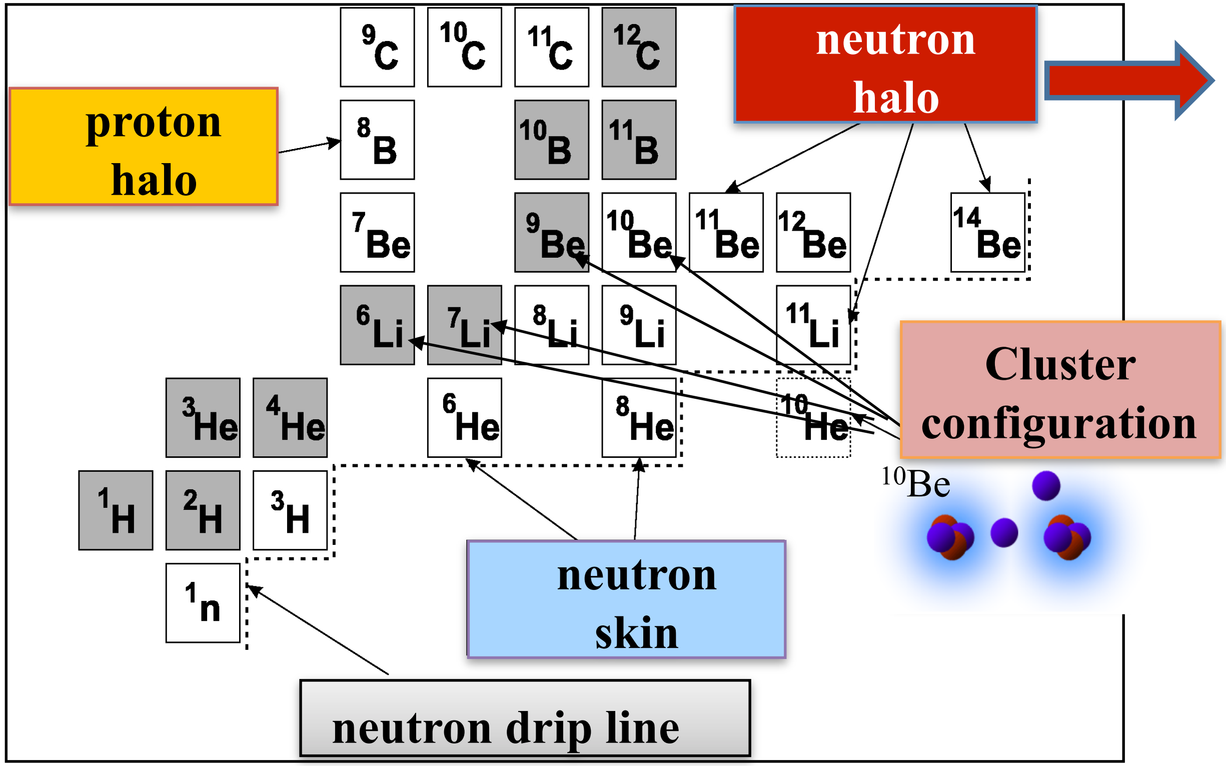
Nuclear quantum many-body systems offer a large variety of facets and behaviors, often coexisting in the same nucleus. Direct reactions offer a large variety of projectiles and bombarding energies and the scattering conditions can be tuned to probe selected parts of the ion-ion interactions. They are therefore able to investigate the response of the system to different operators and so to single out specific aspects of the many-body scenario (e.g. one-particle transfer for the mean-field, two-particle transfer for pairing correlations, Coulomb excitation for collective states and giant resonances, charge-exchange for spin-isospin modes, etc), In particular direct nuclear reactions have been fundamental to discover and investigate novel features (haloes, skins, shell evolutions, new collective modes, etc) in exotic nuclei

OBS The large variety of reactions and the need for exclusive measurements implies the development of different beams and different detectors (charge-particle spectrometers, neutron detectors, gamma detectors, etc)

1. Weakly-bound nuclei, haloes and the role of continuum: interplay between elastic, break-up and fusion in halo nuclei and the occurrence of surprisingly long ranged potential and couplings

Light nuclei at the drip lines: density distributions display long tails due to the last weakly-bound nucleons (haloes)

Obs: favored neutrons in $\ell = 0$ orbital state



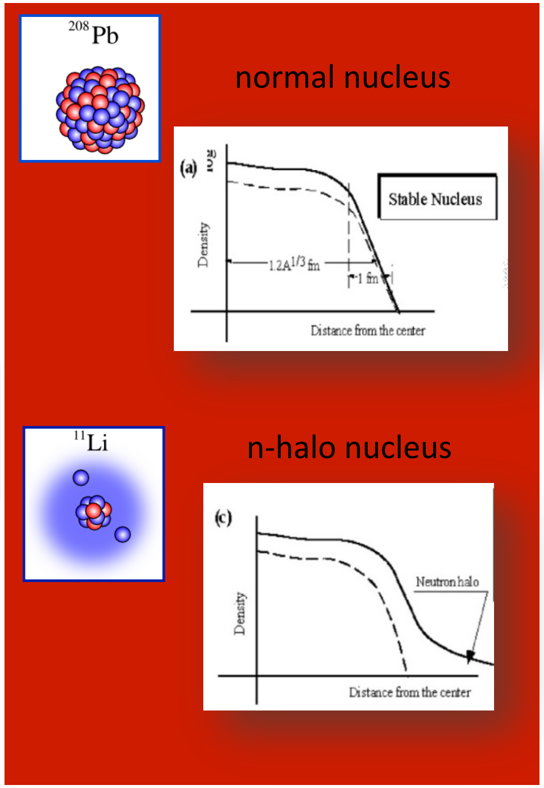
proton halo

neutron halo

Cluster configuration

neutron skin

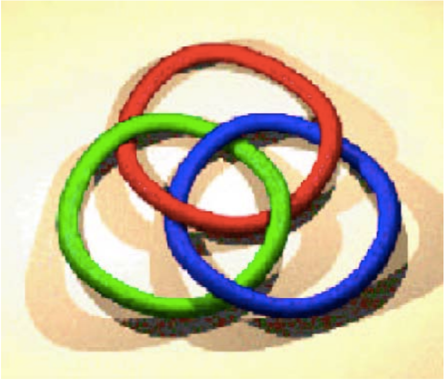
neutron drip line

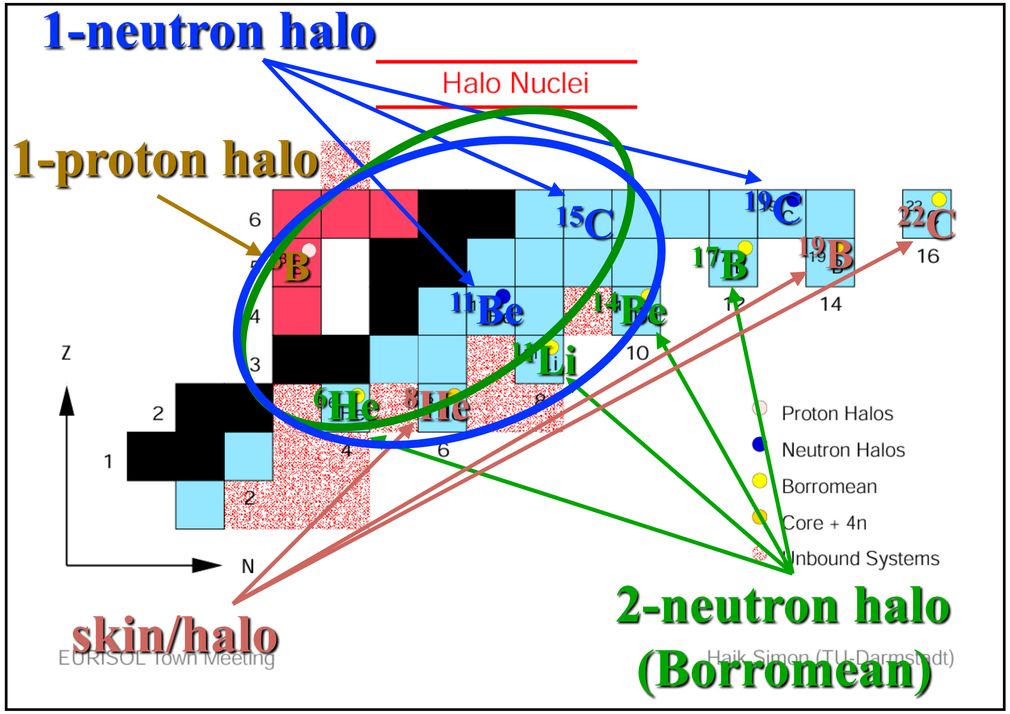


normal nucleus

n-halo nucleus

One-particle and two-particle haloes





Borromean nuclei

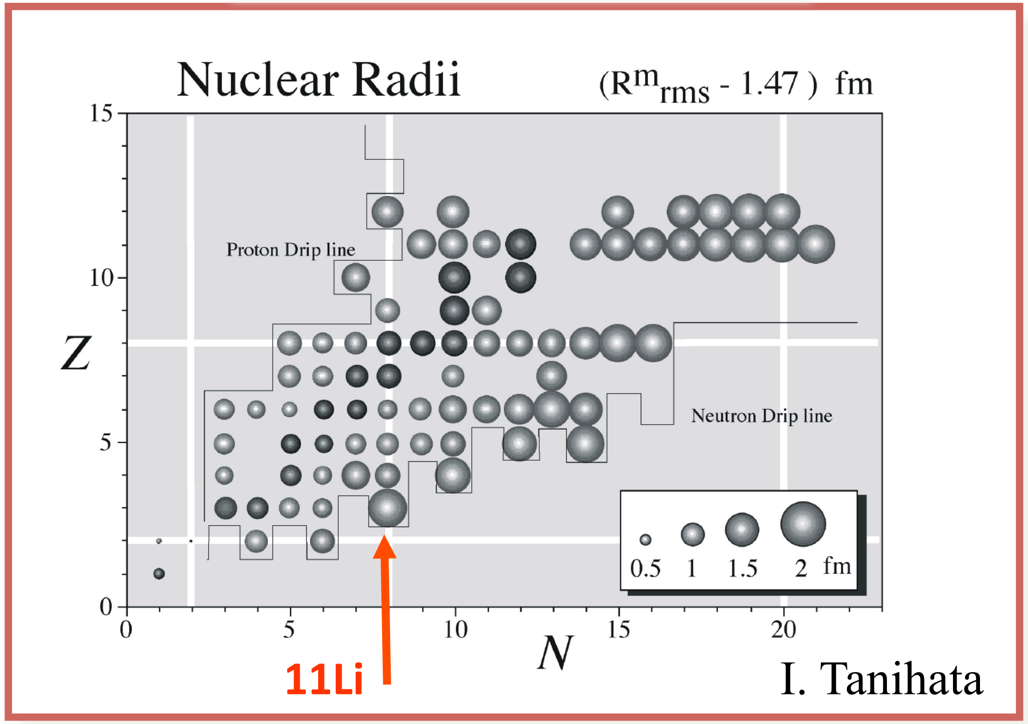
Systems with haloes made by more than one particle, kept bound by the residual interaction.

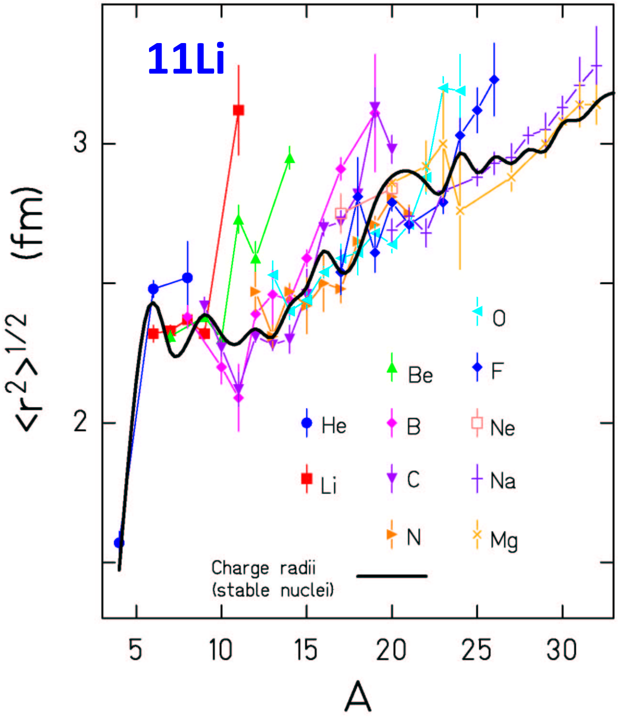
The name comes from the symbol of the Borromeo family, showing three rings bound in such a way that are bound if they are all, but if you remove any one, also the others separate (example:

11Li = 9Li+2n bound
but sub-systems
10Li= 9Li+n NOT bound
2n NOT bound)

Weakly-bound nuclei at the drip line: static halo effect measured via total cross sections

Textbooks: $R = r_0 A1/3$



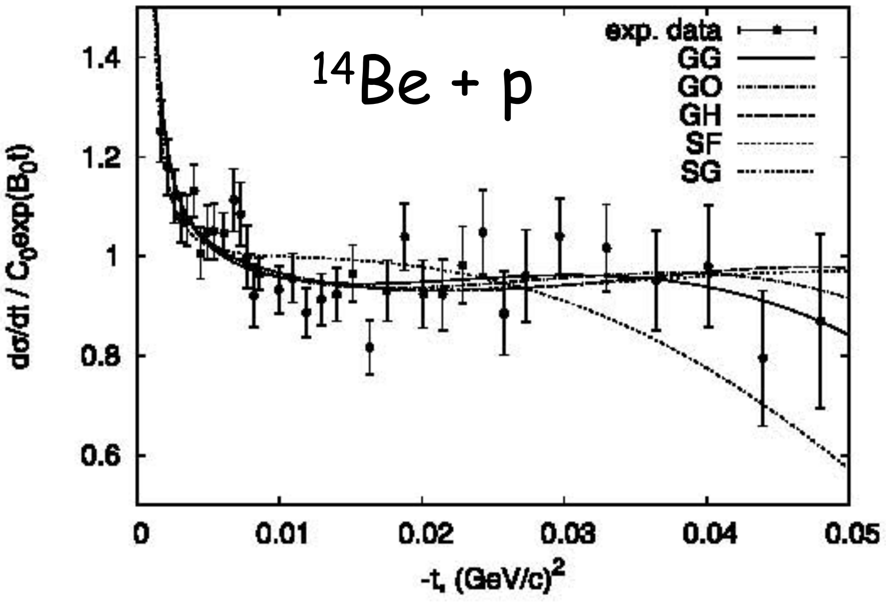


An example of direct reaction involving a radioactive beam: "static" nuclear-matter density distribution from high-energy elastic proton scattering in inverse kinematics.

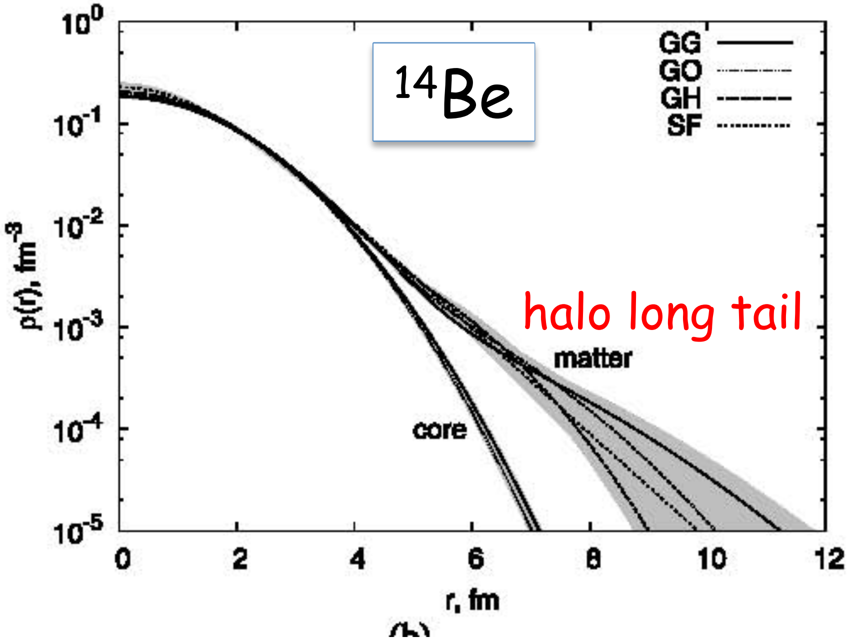
The case of the Borromean nucleus ^{14}Be

Glauber model analysis based on "frozen" density: sensisitivity to different phenomenological density parametrizations

elastic angular distribution



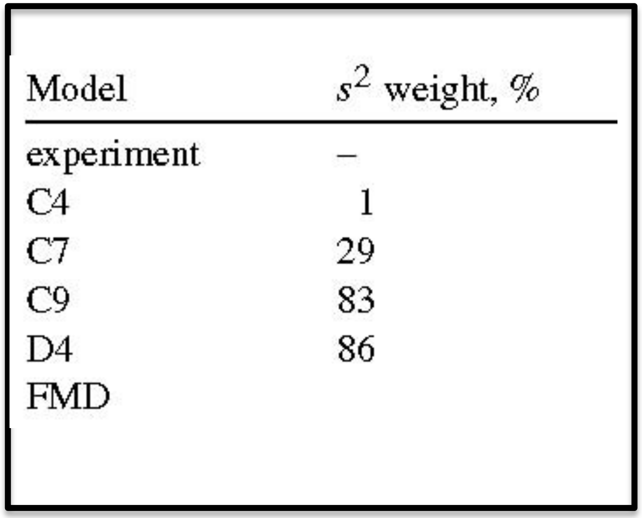
density distributions



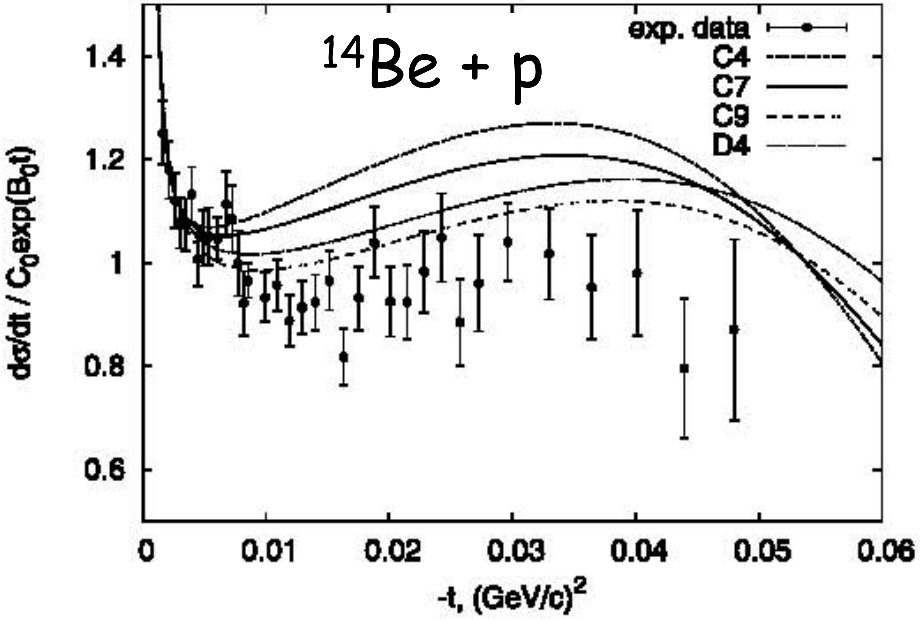
P+^{14}Be with inverse kinematics at 700 MeV/u at GSI (Ilieva etal, 2011)

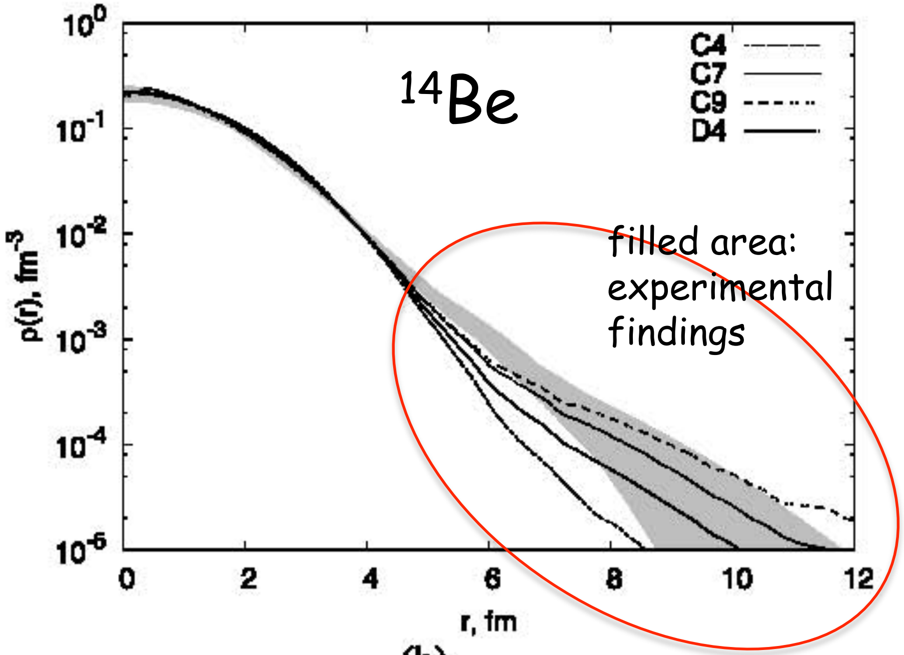
Glauber analysis: sensitivity to the density obtained within different theoretical models

Different mixtures of s^2 and d^2 components in the wf



Model	s^2 weight, %
experiment	–
C4	1
C7	29
C9	83
D4	86
FMD	





filled area: experimental findings

(b)

The interest in haloes and weak-binding is not so much in the "static" behavior but rather in the dynamical effects in the response of these systems to different probes (B(E1) distribution etc). From the reaction point of view the weak-binding nature of halo nuclei favors the dominance of break-up channels, and the key question is the effect of the strong break-up channels and coupling to continuum states on the different collision processes (elastic scattering, direct reactions, fusion, etc)

OBS: Pioneering works already in the nineties from the heavy-ion theory groups of Padova, Torino, Pisa, Milano, Catania

The coupling to continuum is reflected in the nuclear ion-ion potentials, absorptive potentials and couplings used in direct reactions that are normally short-ranged, with a shape that follows nuclear densities. The more striking effect in elastic scattering with weakly-bound halo nuclei is that one seems to need a long-ranged absorption that starts to be active also at bombarding energies well below the Coulomb barrier (and therefore at large distances), indicating the presence of long-ranged nuclear couplings in addition of the usual Coulomb interaction.

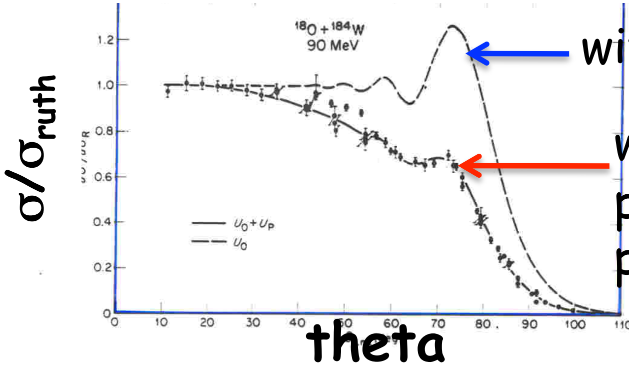
Cf: Dasso, Lenzi, Vitturi
Bonaccorso etal

Polarization potentials due to nuclear coupling are normally short-ranged.
On the opposite, the contribution due to coulomb excitation is long-ranged ($1/r^5$).
In the case of large couplings (as the coupling to the rotational 2+ state in the deformed ^{184}W), this gives rise to characteristic patterns in the elastic scattering angular distribution

Text-book example
$^{16}O + {}^{184}W$

Evidence for long-range Coulomb polarization potential

Elastic angular distribution

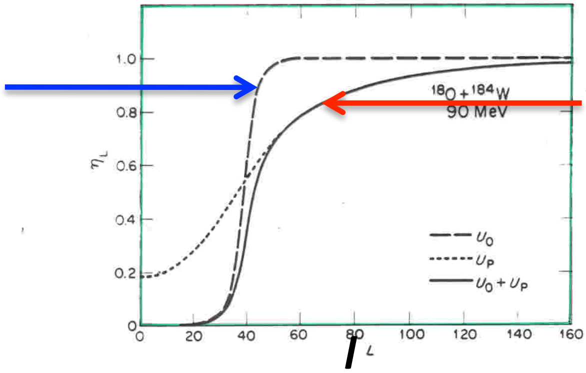


without

with long-ranged polarization potential

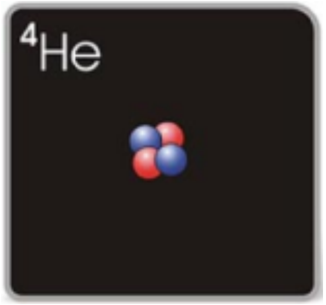
Transmission coefficient

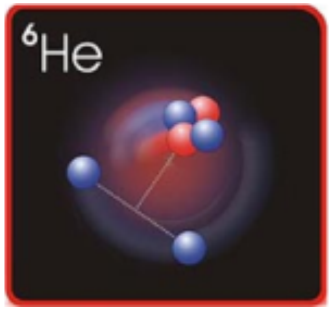
“standard”

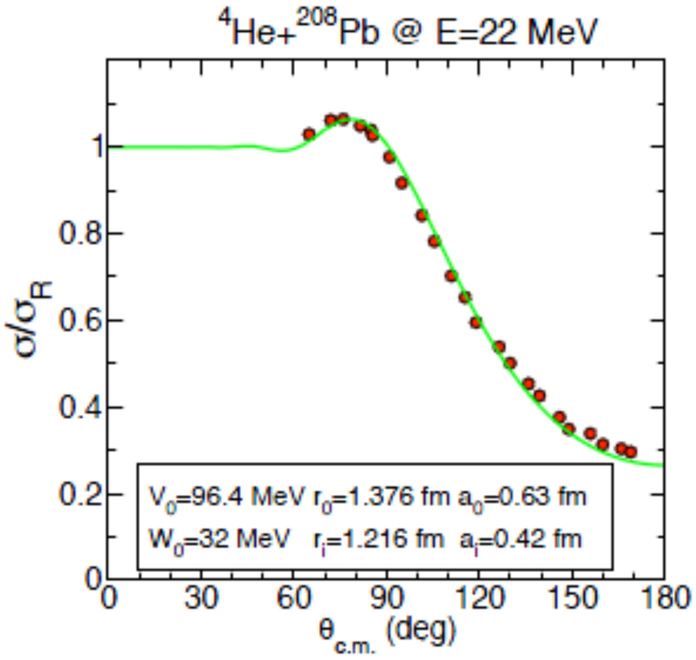


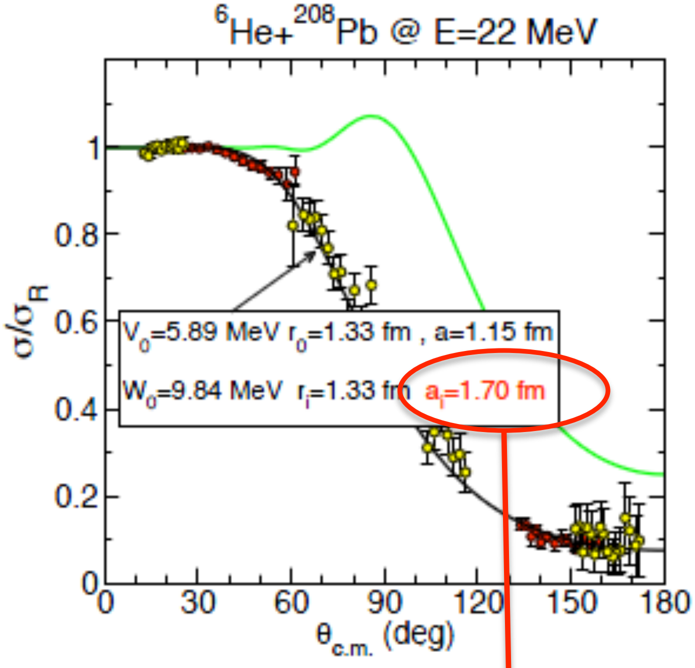
with long-ranged polarization potential

Normal versus halo nuclei: the He case









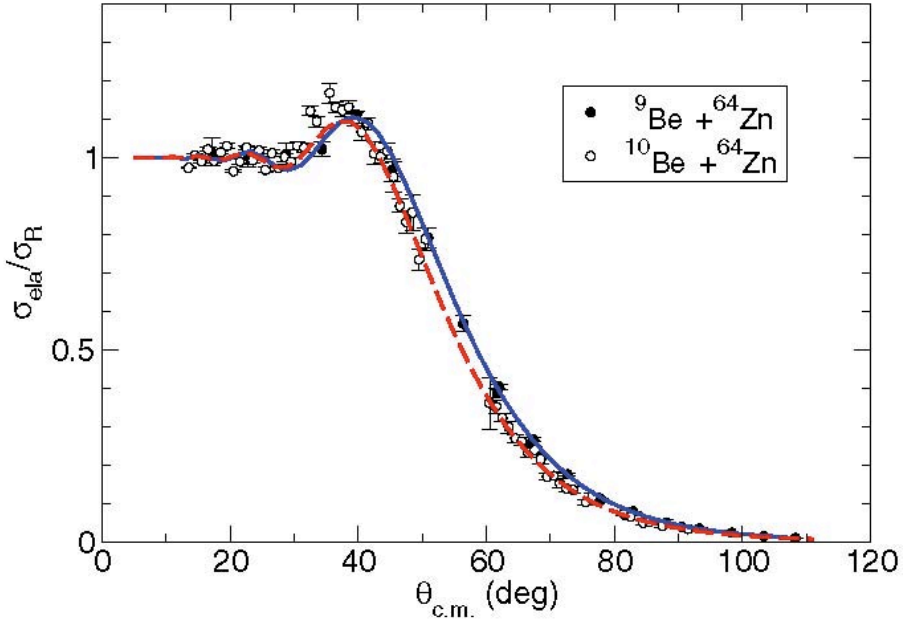
- ^{6}He+^{208}Pb shows a reduction in the elastic cross section due to the flux going to other reaction channels (transfer, break-up or fusion?).
- ^{6}He+^{208}Pb requires a large imaginary diffuseness
  long-range absorption

L. Acosta et al PHYS. REV. C **84, 044604 (2011)**

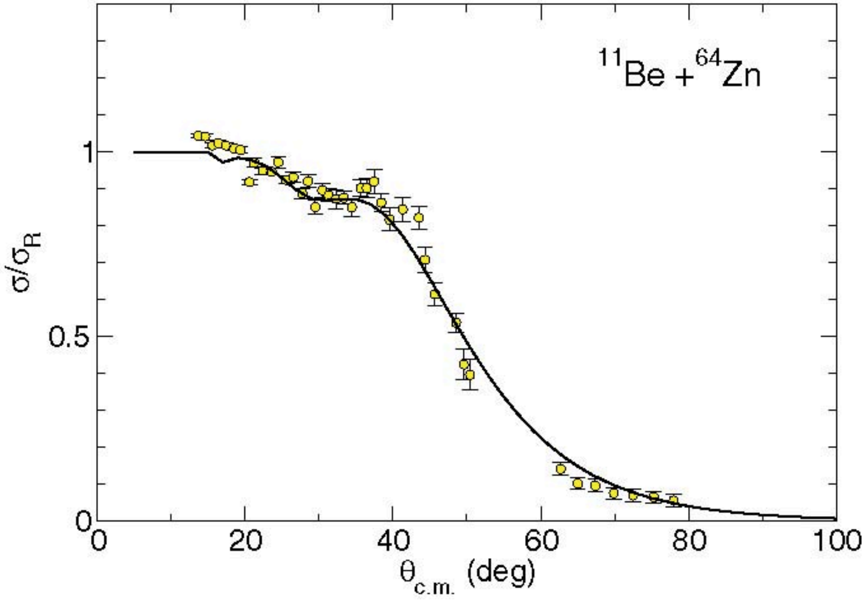
Best example: ^{9,10,11}Be + ^{64}Zn (Di Pietro etal, LNS, 2012)

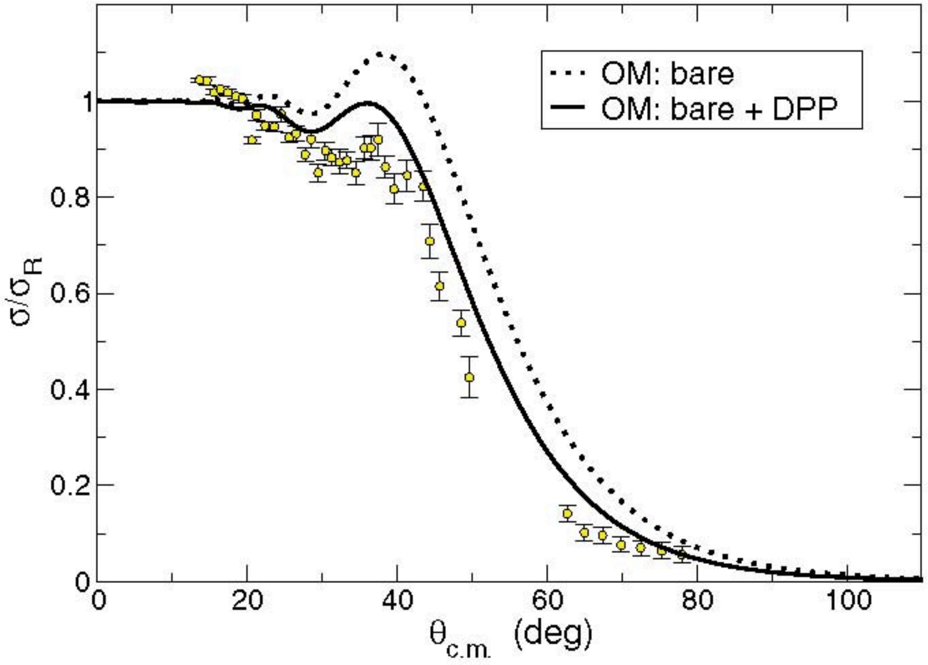
Optical model analysis

For ^{9,10}Be one can use a diffusivity
a = 0.7 fm (standard value)



But for ^{11}Be one needs to add a term
with a diffusivity a = 3 fm
(unusually long range)



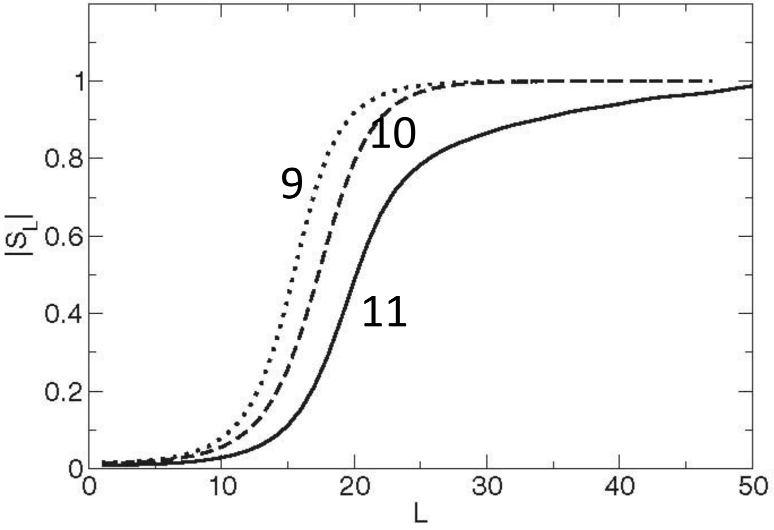


^{11}Be + ^{64}Zn

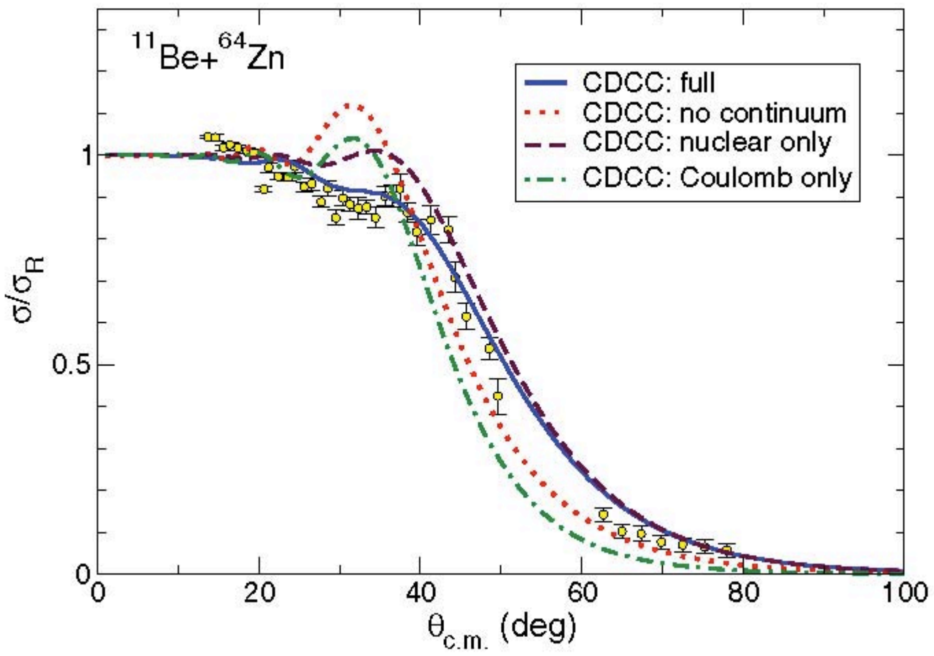
Effect of the long-range term
In optical potential

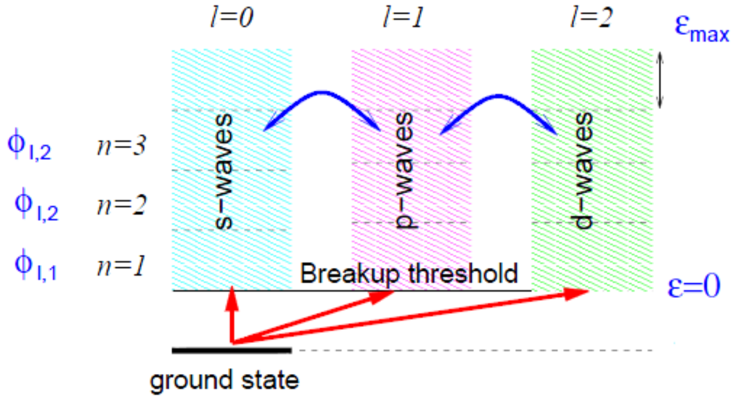
^{9,10,11}Be + ^{64}Zn

Transmission coefficient

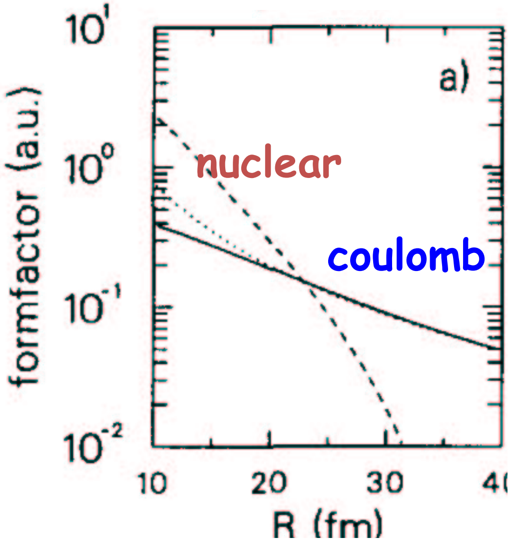


Origin of the long-ranged term from Coulomb and nuclear couplings to continuum (break-up) states

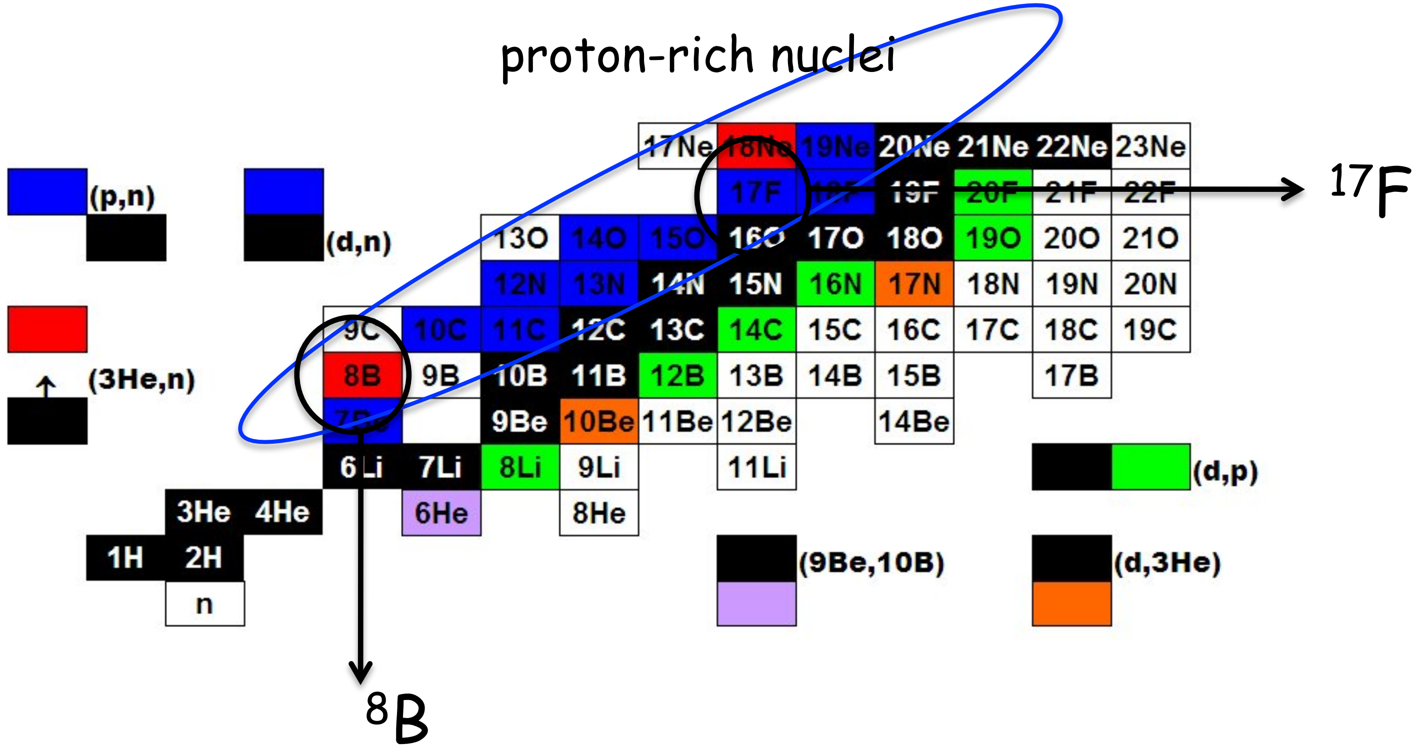




form factors to continuum states (theory, Dasso, Lenzi, Vitturi)



Production of secondary radioactive beams: search for possible proton haloes (EXOTIC collaboration)



^{17}F (S$_p$ = 600 keV): ^{1}H(^{17}O,^{17}F)n E = 3-5 MeV/u

Purity: **93-96 %** Intensity: **~ 10^5 pps**

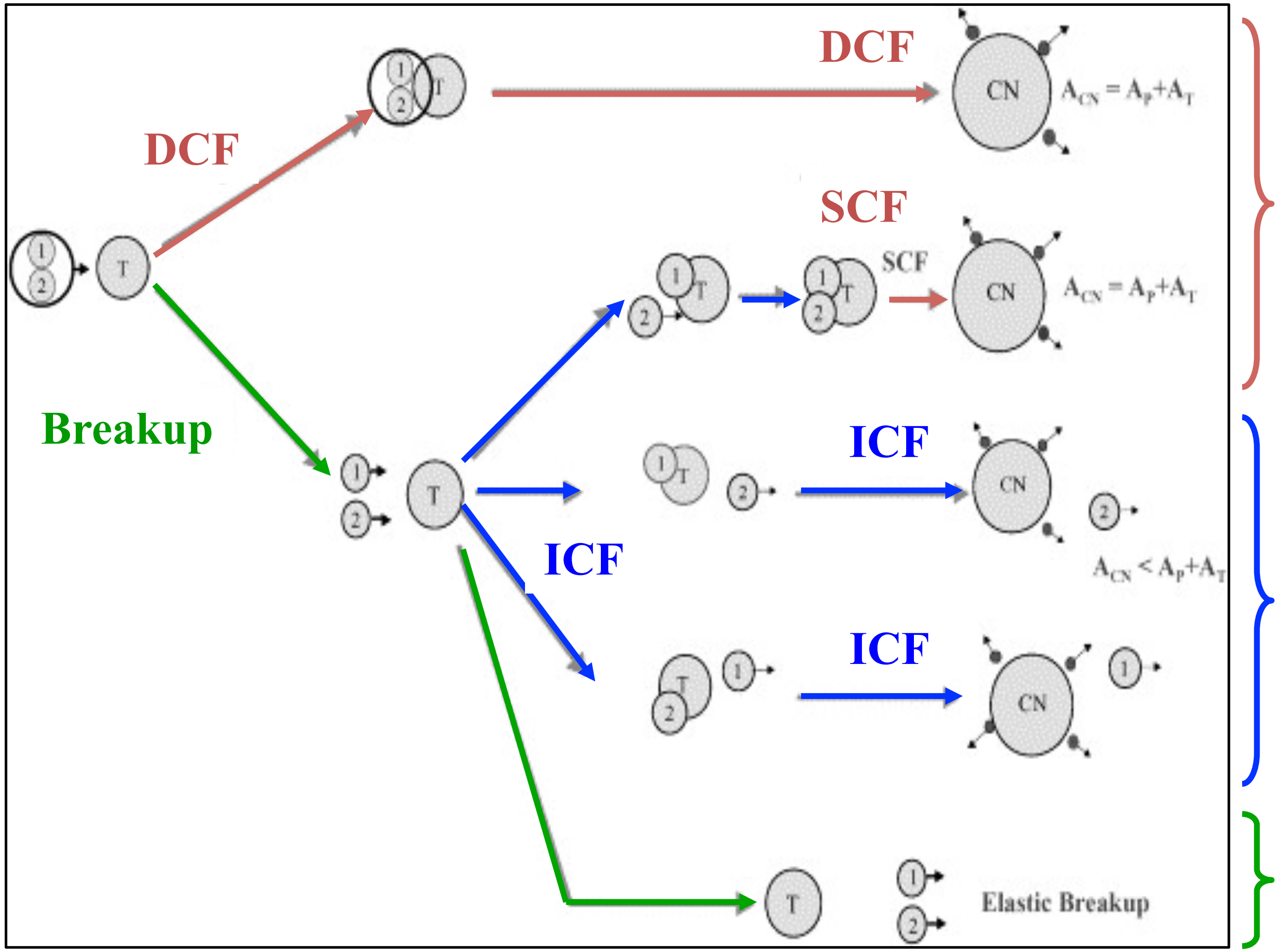
Experiments: ^{17}F+^{1}H, ^{58}Ni, ^{208}Pb (elastic and break-up)

^{8}B (S$_p$ = 137.5 keV): ^{3}He(^{6}Li,^{8}B)n E = 3 MeV/u

Purity: 40-50 % Intensity: 10^3 pps

Experiment: ^{8}B+^{28}Si (total and fusion)

Interplay of fusion and break-up: rather difficult problem to disentangle experimentally the different channels and the reaction mechanism (need for exclusive measurements)



Complete Fusion

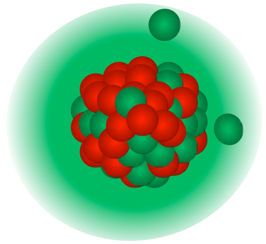
Incomplete Fusion

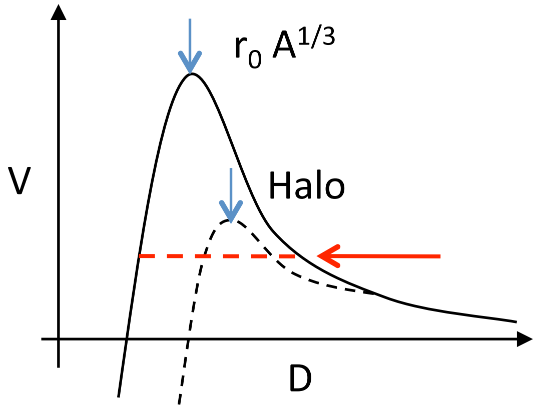
Breakup

Complete Fusion (CF) + Incomplete Fusion (ICF) = Total Fusion (TF)

How does halo affect fusion ?

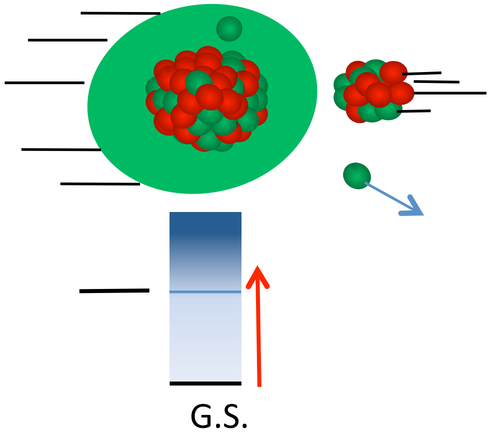
1. Static effect from extended density distribution





---

2. Dynamic effect due to coupling to strong breakup channels



Effect?

Like any other coupling process

Increased sub barrier fusion

Decreased flux at target

Decreased sub barrier fusion

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 50, NUMBER 1 JULY 1994

Theory

Does the presence of ^{11}Li breakup channels reduce the cross section for fusion processes?

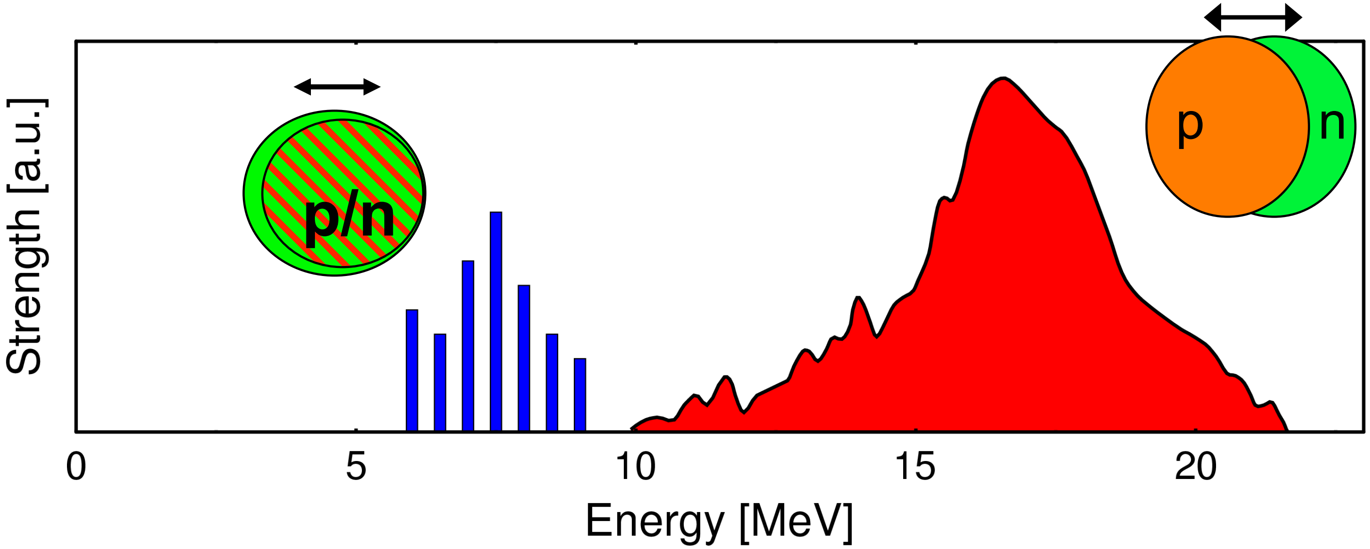
C. H. Dasso[1,2] and A. Vitturi[3]

EXP

Data from

LNS and LNL

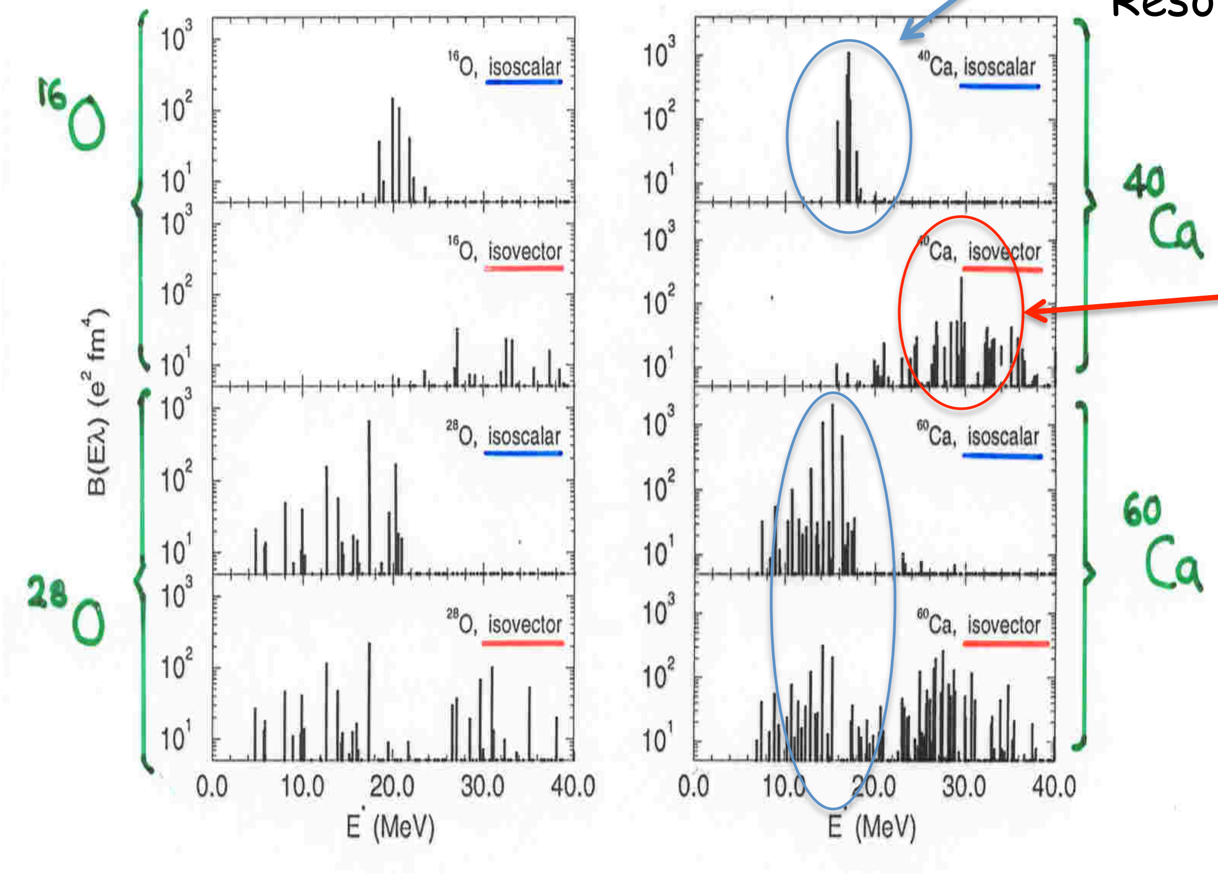
2. New modes of excitation in neutron-rich systems on and off the stability valley (in primis the Pygmy Dipole States)



Special interest has been devoted to the evolution of multipole response in neutron-rich nuclei and in particular to the possible existence of Pygmy Dipole modes

Data are still scarce. On the other side there are many predictions. Most work has been done within mean-field + RPA (non-relativistic, relativistic, discrete, continuum, ………). For the low-lying dipole strength different models predict similar amounts but may differ in the nature of these states.

Example of mass dependence of quadrupole strength in neutron-rich nuclei in Hartree-Fock plus RPA with Skyrme (SGII)



GQR
(Isoscalar
Giant Quadrupole
Resonance)

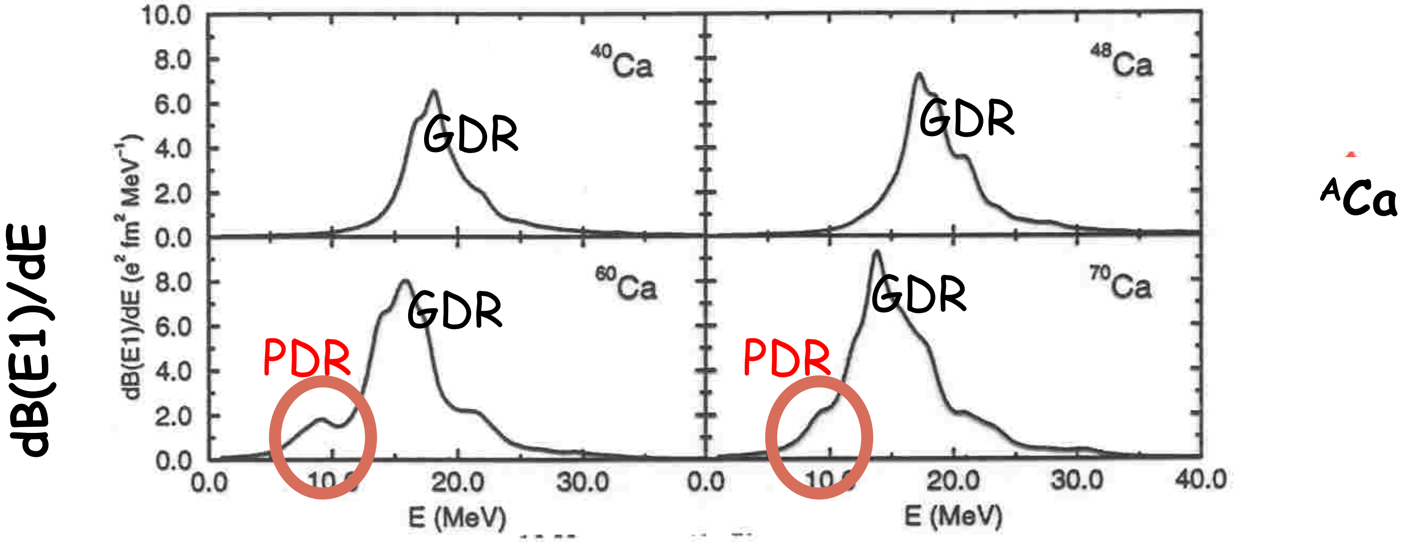
IVGQR
(Isovector
Giant
Quadrupole
Resonance)

OBS: Large mixing of isoscalar/isovector components in GQR for neutron-rich nuclei

Catara, Lanza, Nagarajan and Vitturi, 1995

Example of mass dependence of dipole strength in neutron-rich nuclei in Hartree-Fock plus RPA with Skyrme (SGII)

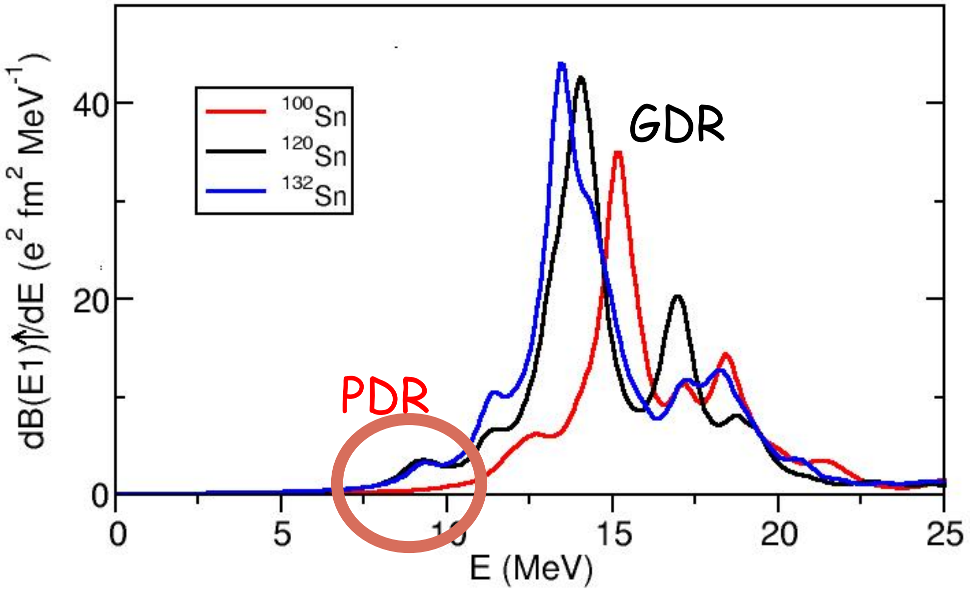
OBS: Appearance of low-lying dipole strength, Pygmy Dipole Resonance (PDR) in addition to the usual Giant Dipole Resonance (GDR)

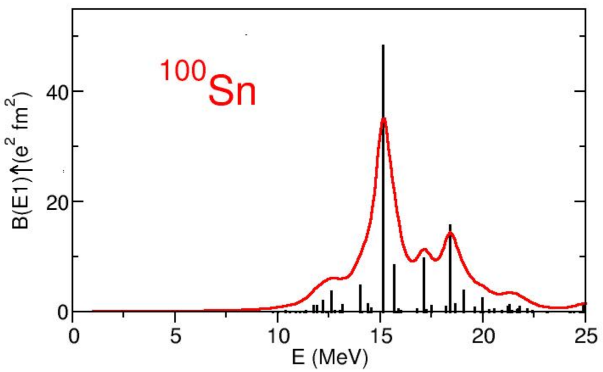


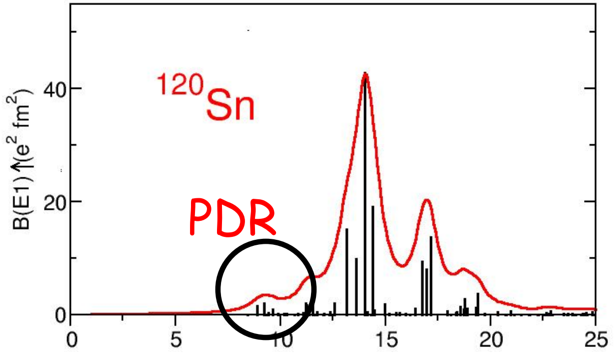
Catara, Lanza, Nagarajan and Vitturi, 1996

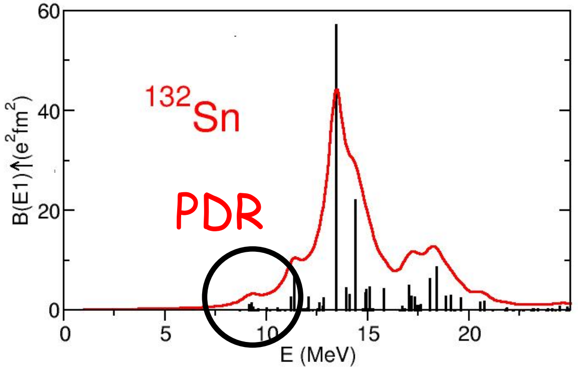
Other example:
Sn isotopes
(Lanza etal, 2009)

dipole strength



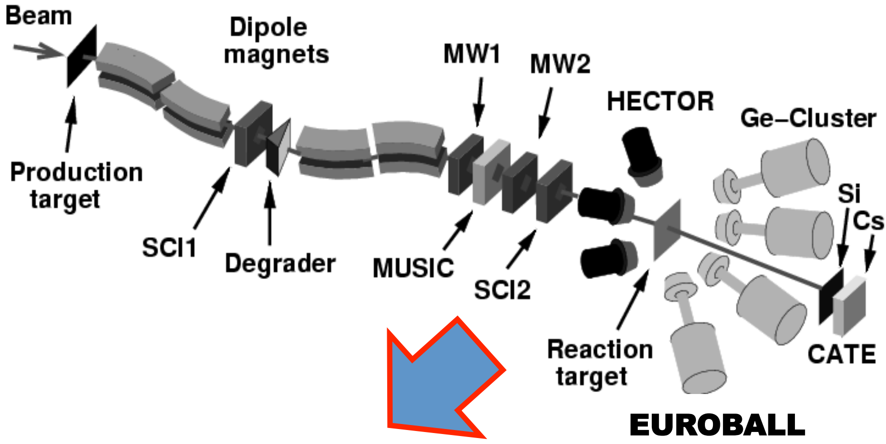


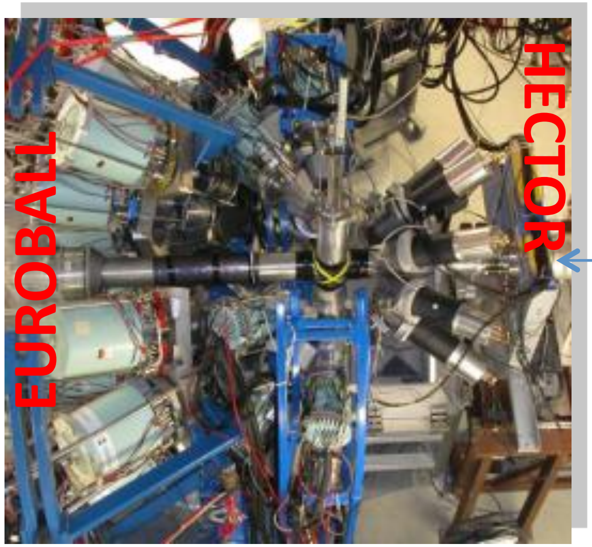




Pygmy dipole resonance in ^{68}Ni

RISING-SETUP=EUROBALL and HECTOR @ GSI





^{68}Ni-Beam
600AMeV

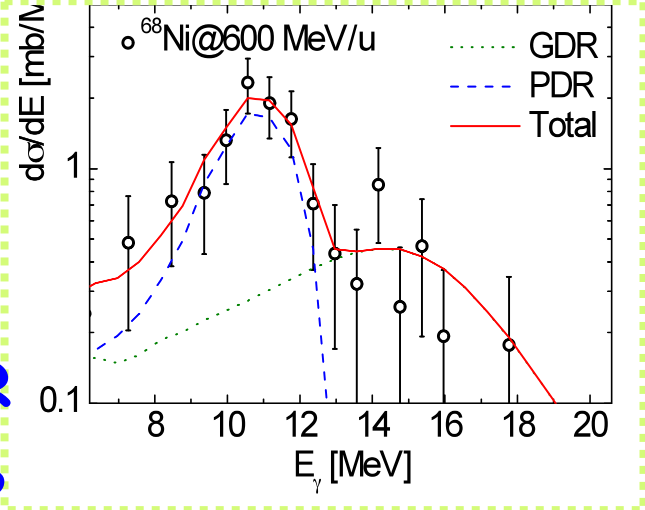
Relativistic Heavy-ion Coulomb Excitation: Virtual Photon Scattering

Pygmy in ^{68}Ni at 11 MeV

Width ≈ 2 MeV mainly due to Doppler Broadening

5 (p/m 1.5) % of the EWSR
B(E1) = 1.2 e^{2}fm^2

PDR 5%



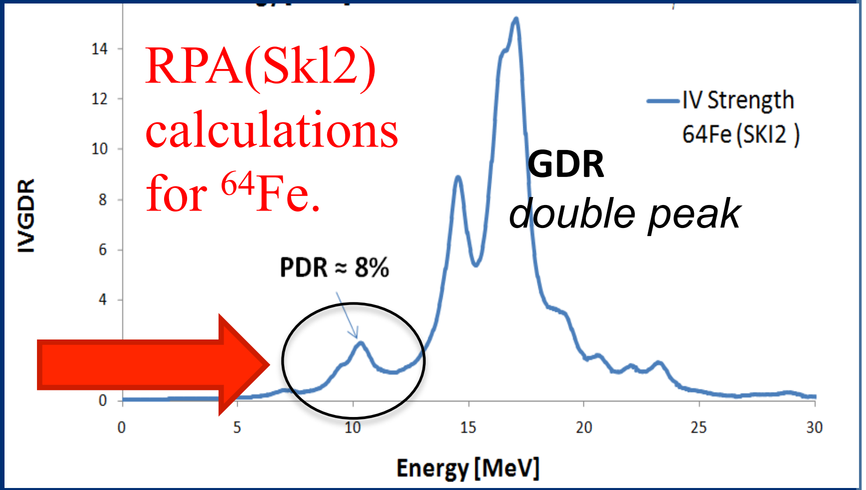
O. Wieland et al., PRL102(2009)092502

Pygmy dipole resonance in ^{64}Fe

2012

PRESPEC-SETUP=AGATA and HECTOR^{+} @ GSI

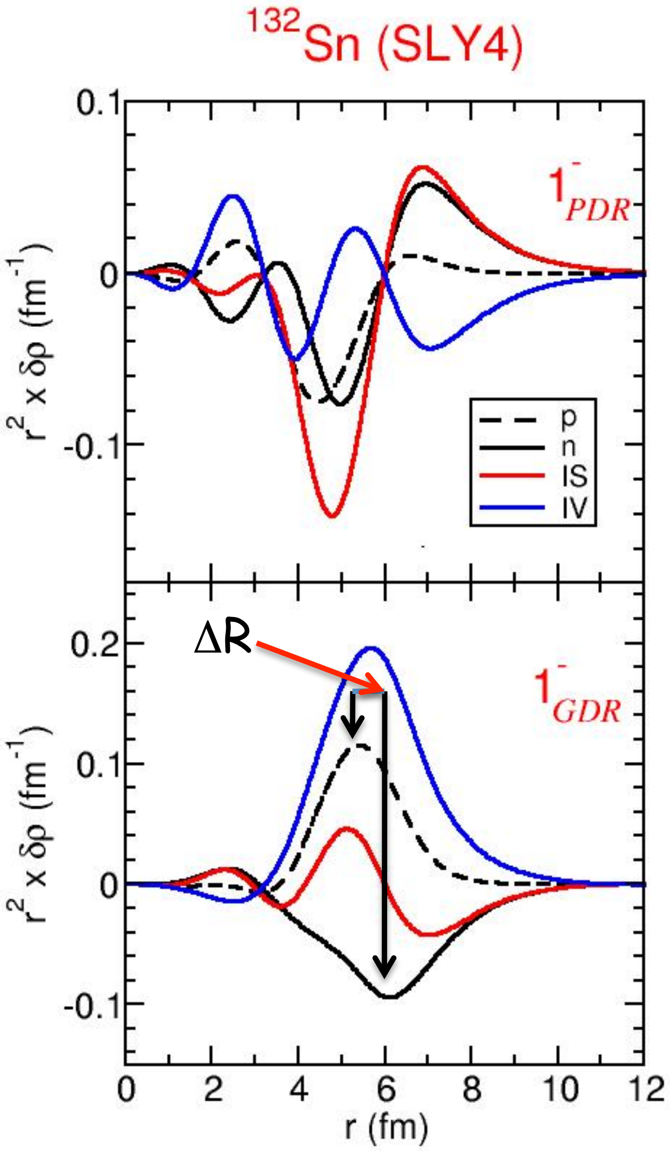
Virtual Photon Scattering technique (400AMeV ^{64}Fe) relativistic coulomb excitation!



To disentangle the PDR+GDR finestructure DOPPLER correction with AGATA is needed

The plan is to study the PDR (presence, resonance-parameters,shape) in the nucleus ^{64}Fe AND to infer the size of neutron skin by improving the technique used for ^{68}Ni.

The nature of the different dipole states can be inferred from the corresponding transition densities (neutron and proton components, isoscalar and isovector)



Rather different behaviour between high-lying (GDR) and low-lying (PDR) dipole states

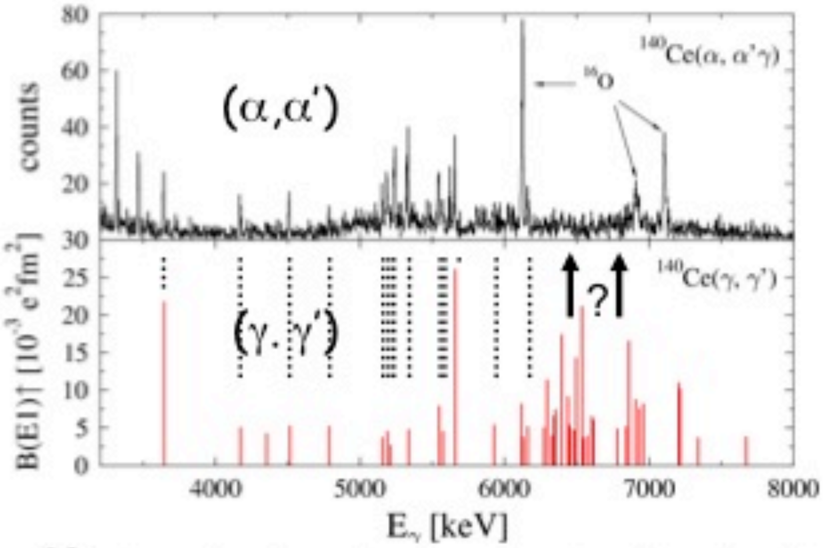
The GDR is associated to oscillations of the neutrons against the protons

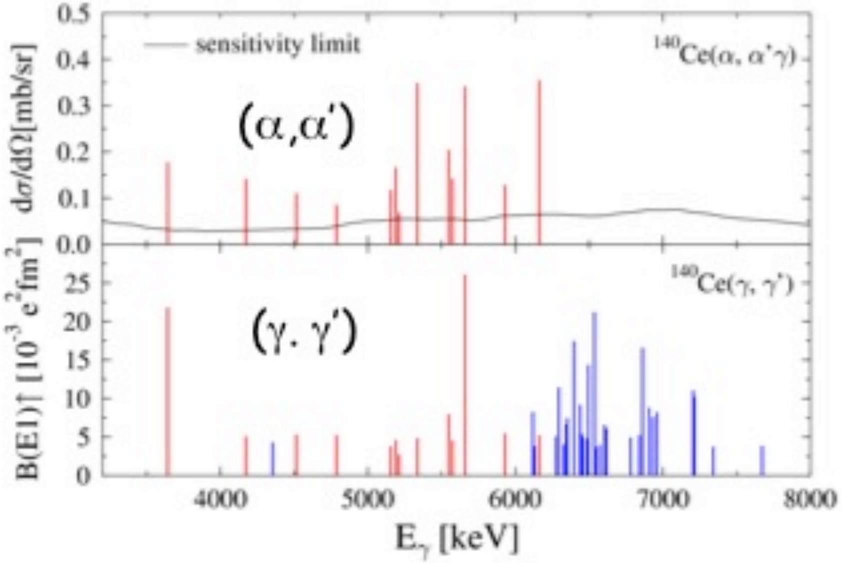
Possible interpretation as Pygmy Dipole Resonance: oscillations of the valence neutrons against the proton+neutron core

The nature of the states (isoscalar/ isovector) is however rather mixed and the mixture depends on the extension of the “neutron skin” ΔR

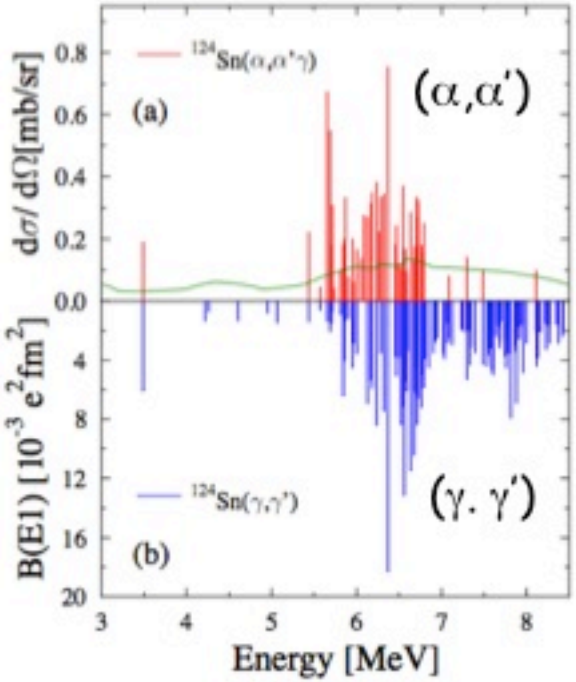
The different isoscalar/isovector character of the dipole states can be tested with different probes, as (α,α′) (sensitive to the isoscalar component) or (γ. γ′) (sensitive to the isovector component) or other heavy ions (active with Coulomb and isoscalar +isovector nuclear)

^{140}Ce



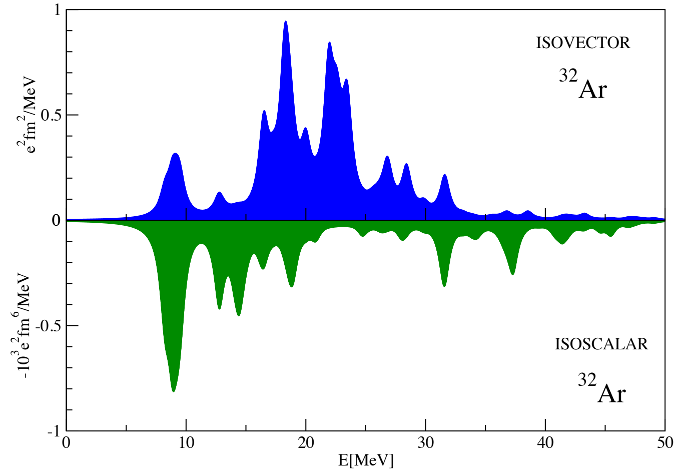


^{124}Sn



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

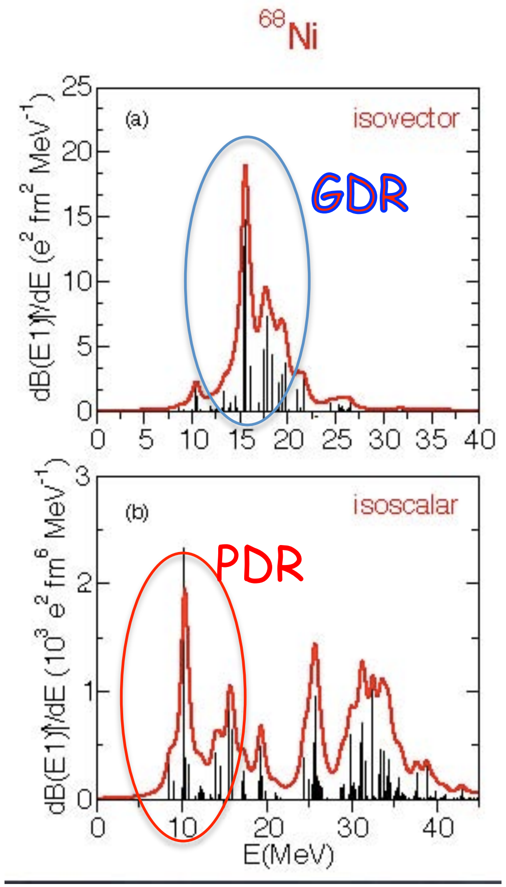
from theory one gets response to isovector dipole operator and to the (leading-order) isoscalar dipole operator



Dario Vretenar etal

isovector

isoscalar



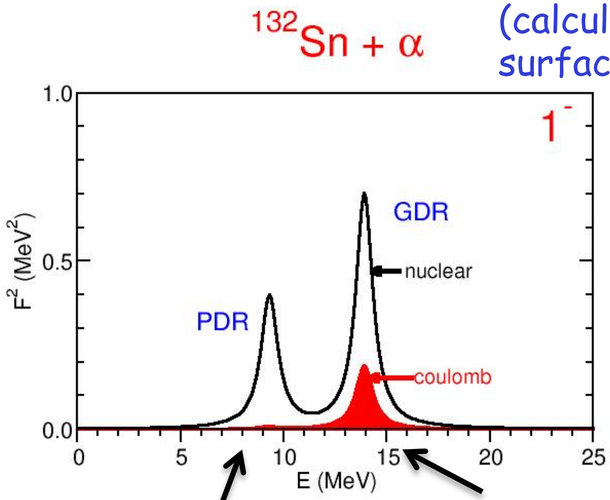
Edoardo Lanza etal

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

Heavy-ion reactions with the variety of projectiles (with different N/Z ratios, hence different isoscalar/isovector contents), bombarding energies (hence different energy cut-off and selection of different multipolarities) and scattering angles (hence different role of Coulomb and nuclear components) offer the possibility of testing the different aspects (magnitude, shape, isoscalar/isovector character) of the transition densities.

Nuclear and Coulomb formfactors (calculated at the surface)

Nuclear and Coulomb formfactors do not scale in the same way for all states, but their ratios depend on the properties of the transition densities

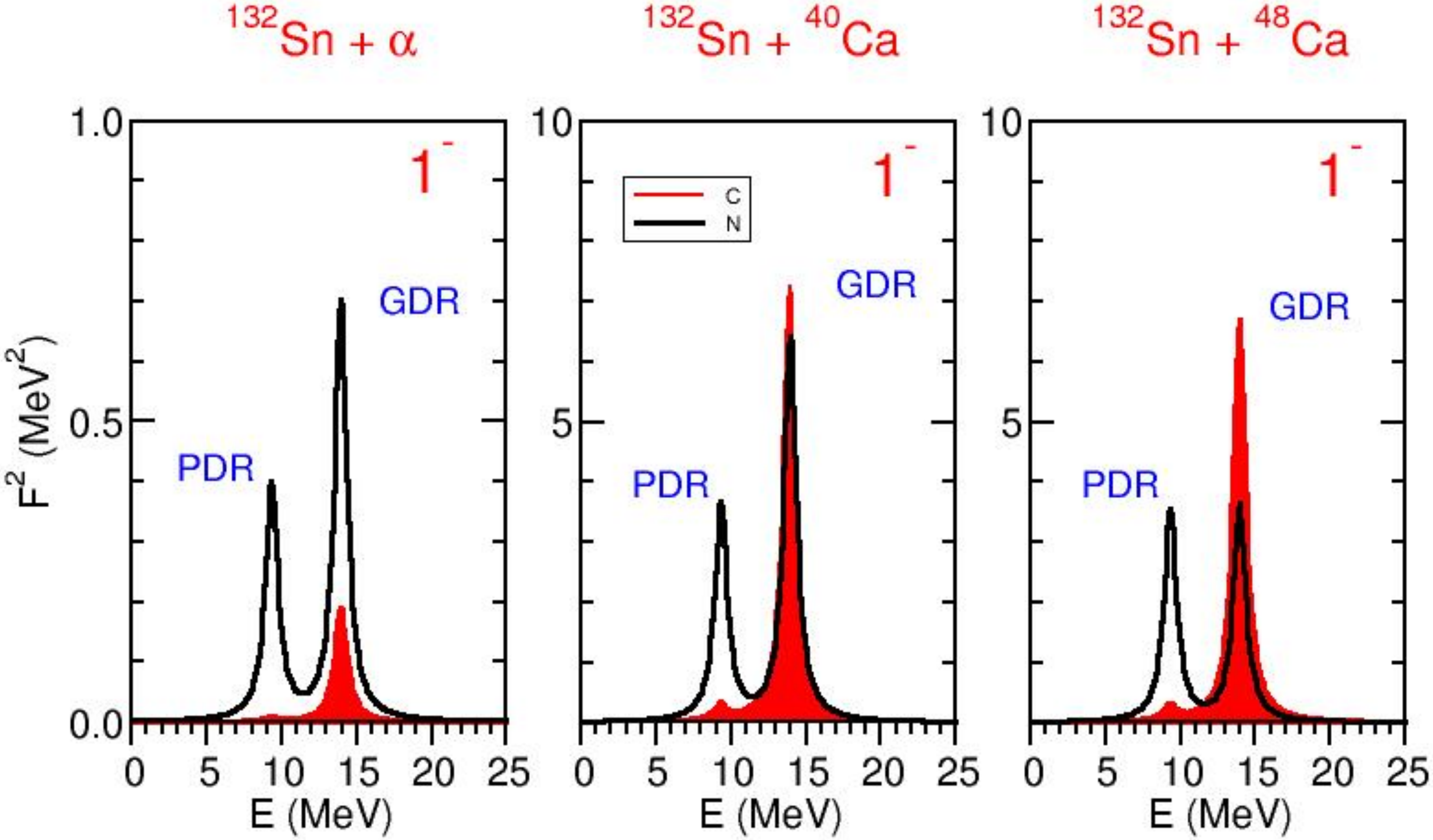


for PDR strong nuclear and weak Coulomb

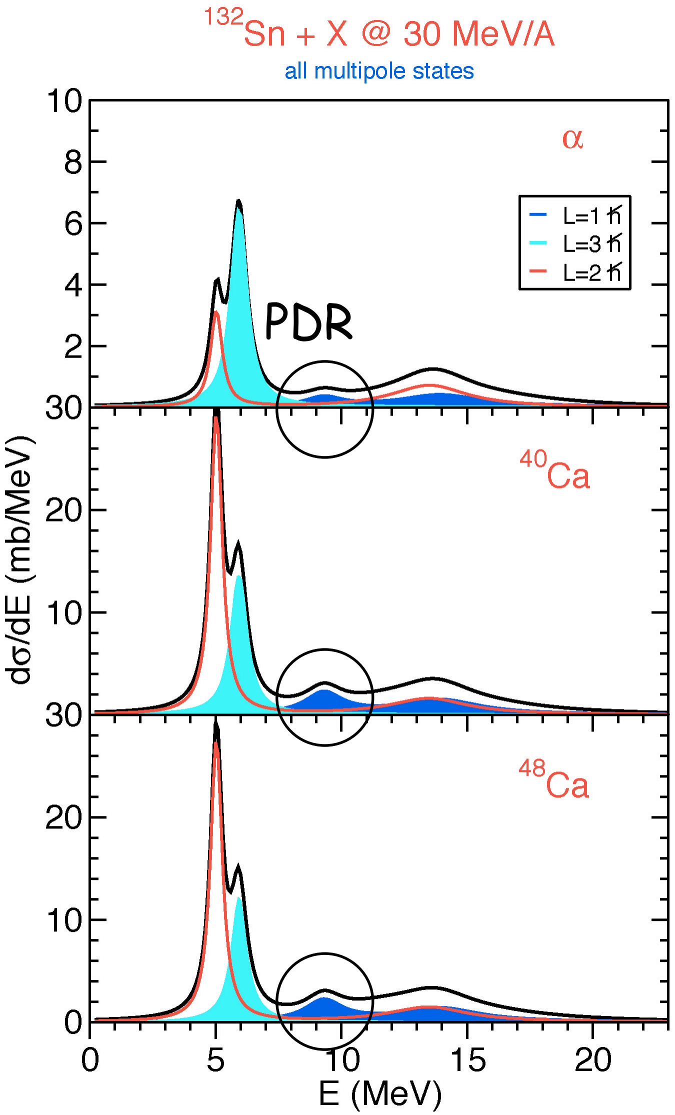
For GDR much relatively stronger Coulomb

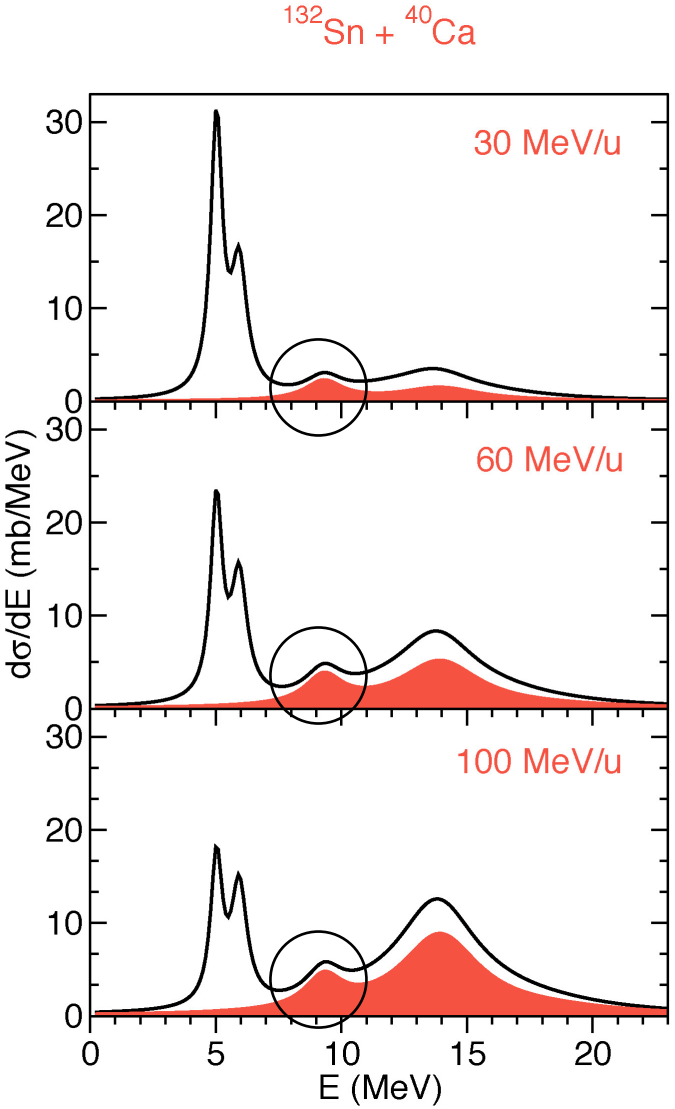
Changing projectile we can alter the relative weight of nuclear and coulomb, and within the nuclear component the isoscalar and isovector contributions

Nuclear and Coulomb formfactors (calculated at the surface)



Excitation of Pygmy Dipole Resonance in inelastic (nuclear +Coulomb) heavy-ion scattering

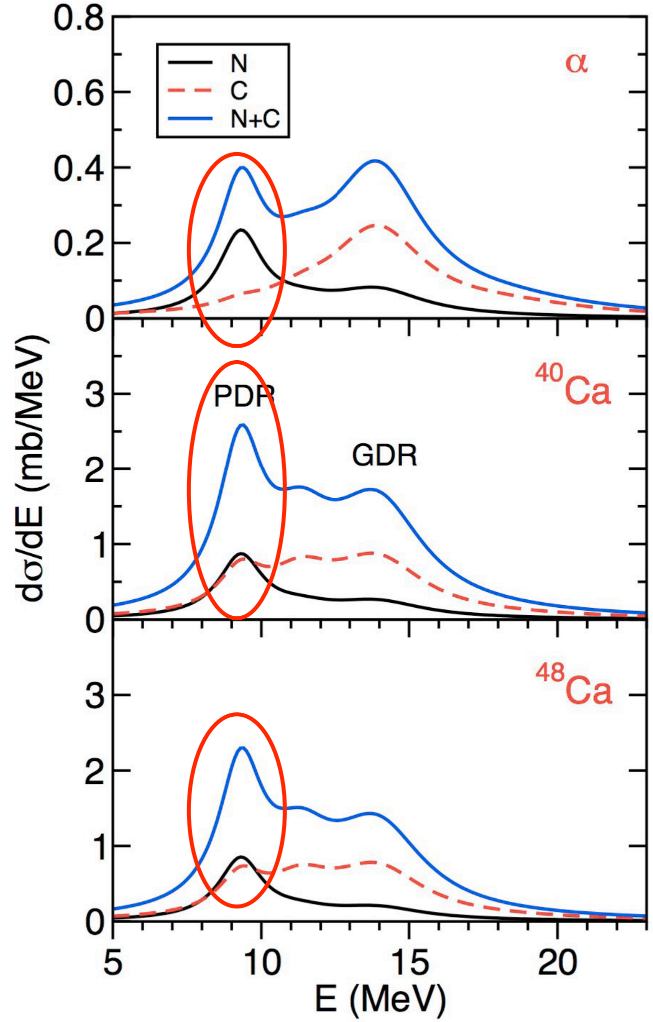




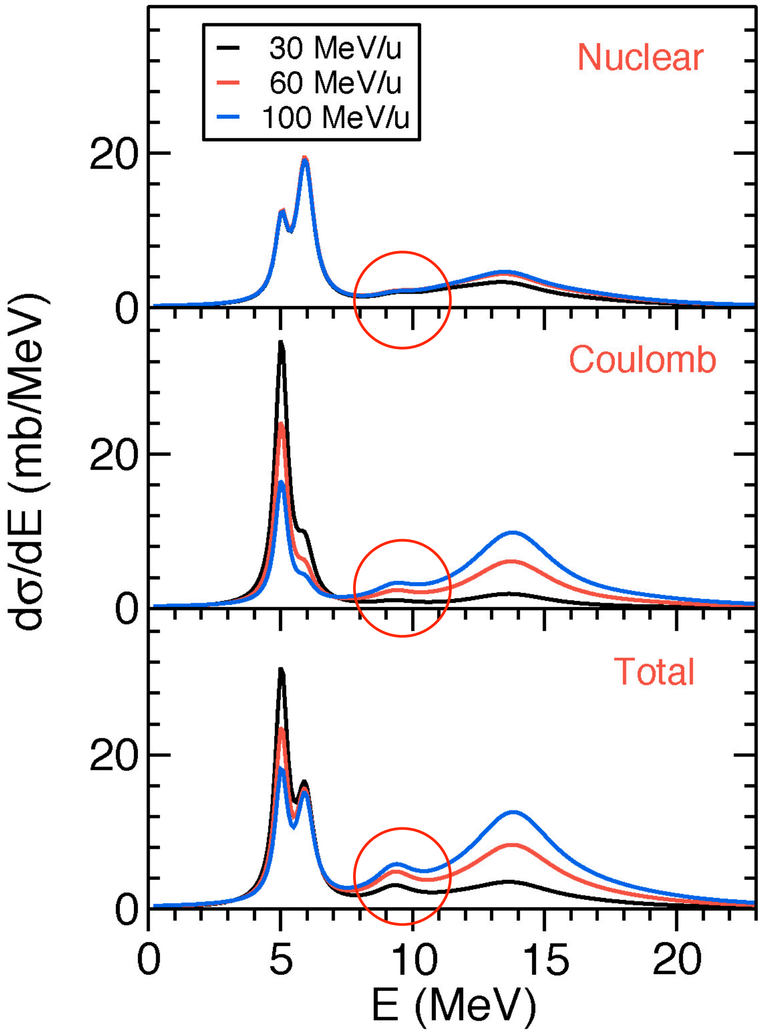
Lanza, Catara, Gambacurta, Vitturi, 2010

Separated nuclear and Coulomb contributions

^{132}Sn + X @ 30 MeV/u



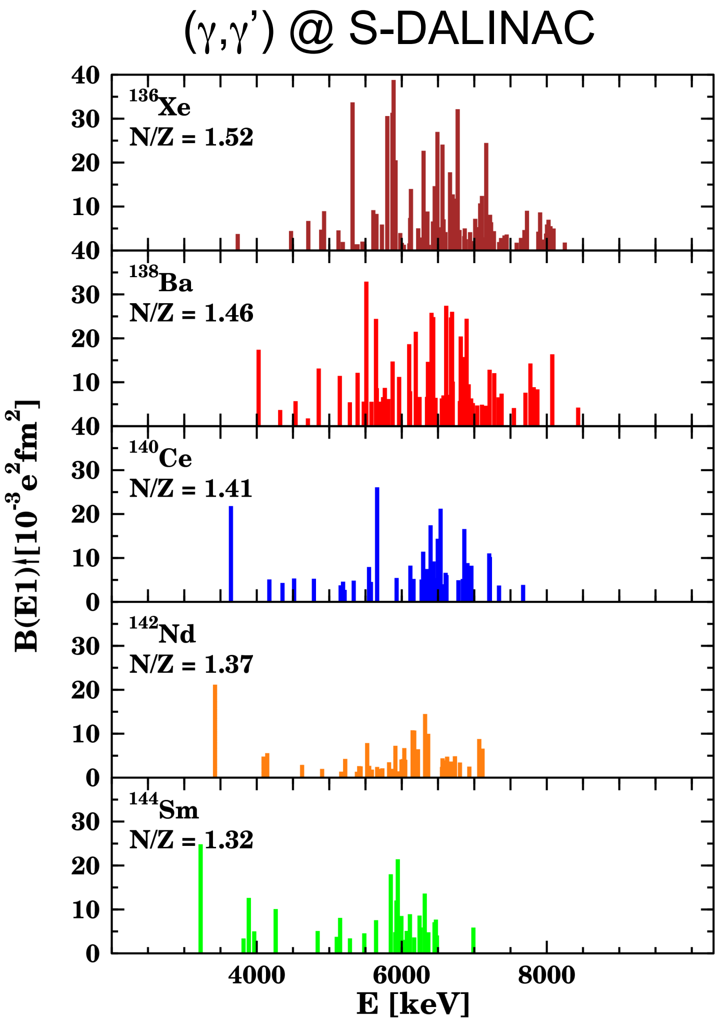
^{132}Sn + ^{40}Ca

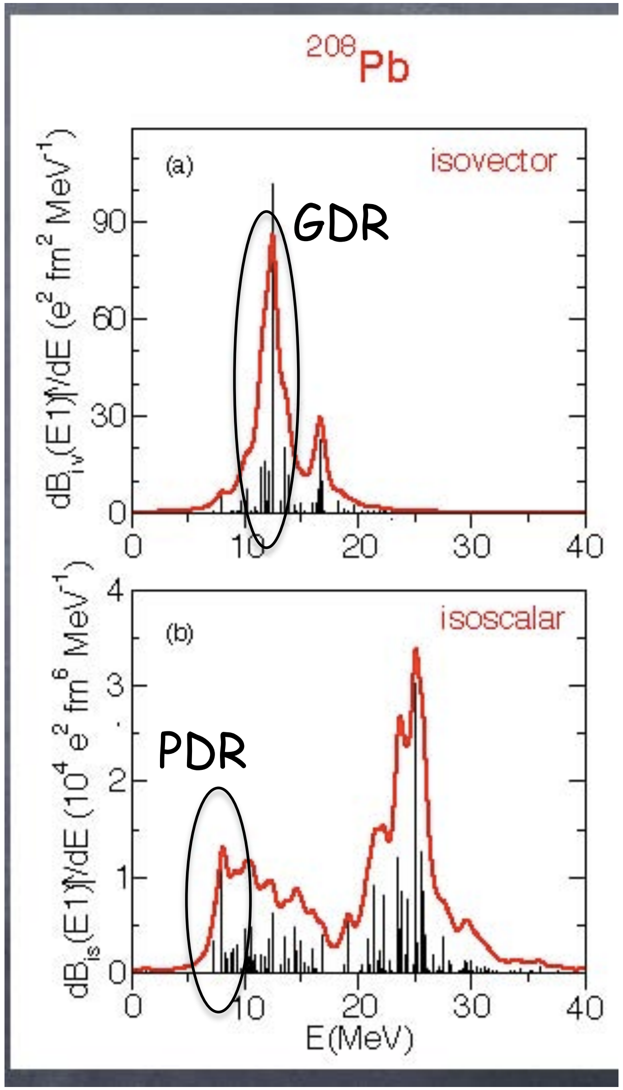


But low-lying dipole states are also present in stable nuclei …..

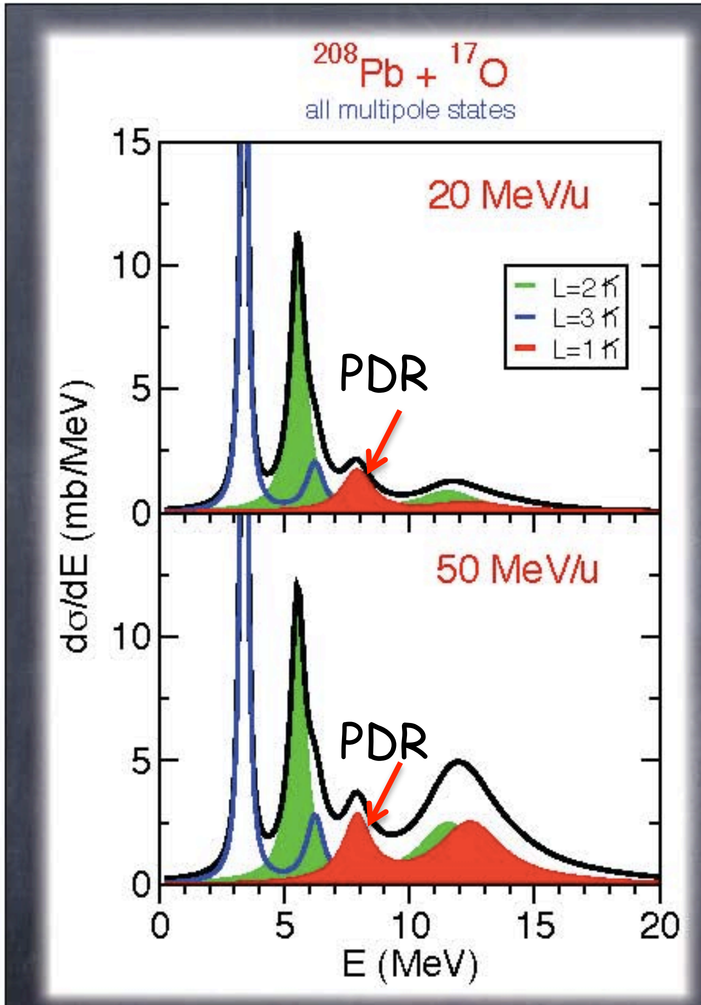
exp

Theory (Lanza etal)





…….. and can be excited via heavy-ion inelastic scattering



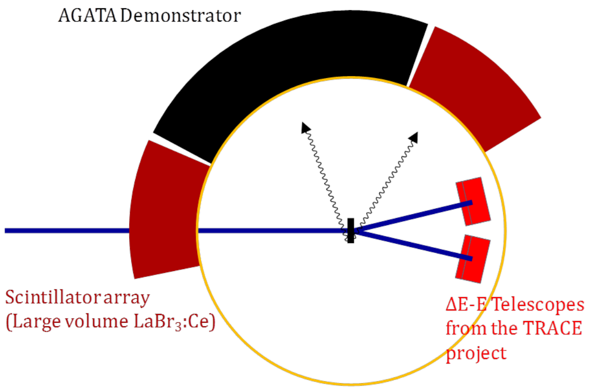
The pygmy states are present also in stable nuclei with neutron excess like ^{208}Pb.

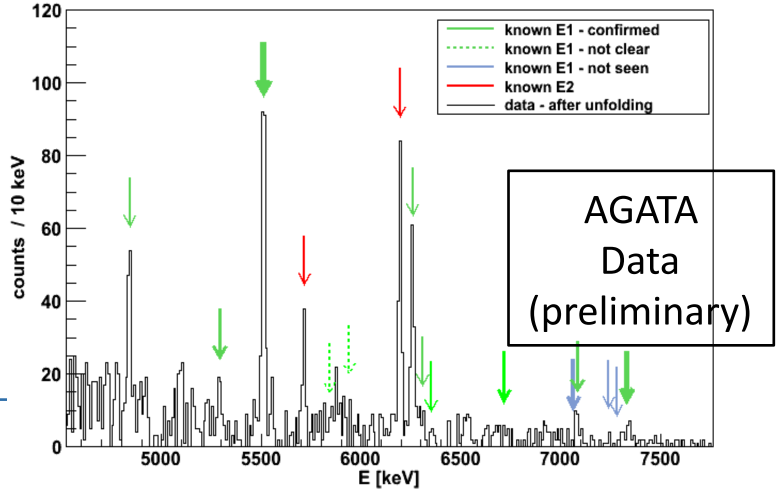
Therefore one can repeat the same analysis done until now for the ^{132}Sn, with the advantage that one is not limited in the possible range of incident energies as it should be the case for the radioactive beams.

State	E (MeV)	EWSR%
GMR	14.0	86
Pygmy	7.9	1.2
GDR	12.4	60
1^-_{hi}	16.7	17
2+	5.5	6
GQR	11.6	75
3^-	3.4	22
3^-	6.2	9

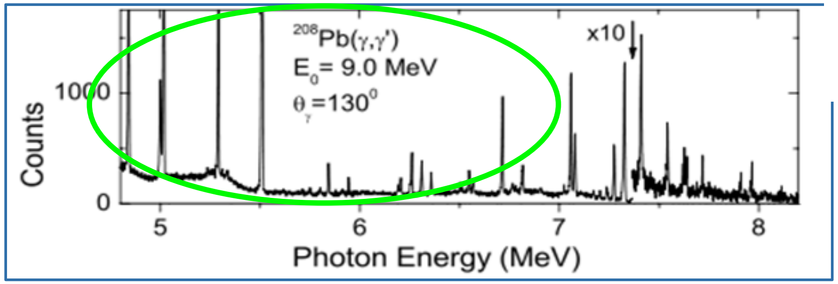
The peak at the Pygmy region is due to dipole states and this is true also for all the incident energies considered.

Preliminary results obtained by inelastic scattering of ^{17}O @ 20 MeV/u on ^{208}Pb + γ-rays in coincidence (Milano+Padova+LNL)

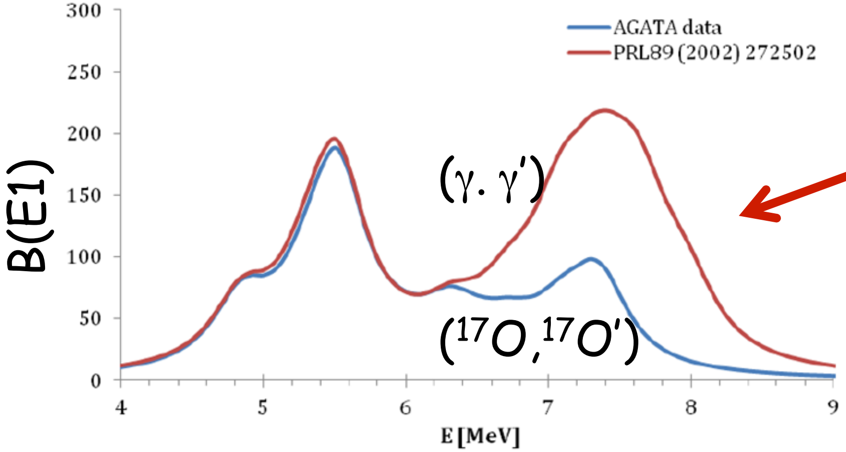




(γ. γ')



preliminary



Experimental values of the B(E1) of the PDR in ^{208}Pb measured with our setup (blue line) and with the NRF technique (red): *it seems to indicate that the states belong to two different groups one with a isoscalar character and the other with a isovector nature. This is similar to what was observed in other stable nuclei with $(\alpha,\alpha'\gamma)$ experiments.*

3. Dynamical study of nuclear pairing correlations via two-particle and multi-pair transfer reactions

How to use dynamics to study pairing correlations?

The main road is clearly provided by the study of those processes where a pair of particles in involved, e.g. transferred from/to another nucleus (two-particle transfer) or ejected onto the continuum (two-particle break-up).

Unfortunately, the situation is different, for example, from low-energy one-step Coulomb excitation, where the excitation probability is directly proportional to the
$B(E\lambda)$ values. Here the reaction mechanism is much more complicated and the possibility of extracting spectroscopic information on the pairing field is not obvious. The situation is actually more complicated even with respect to other processes (as inelastic nuclear excitation) that may need to be treated microscopically, but where the reaction mechanism is somehow well established.

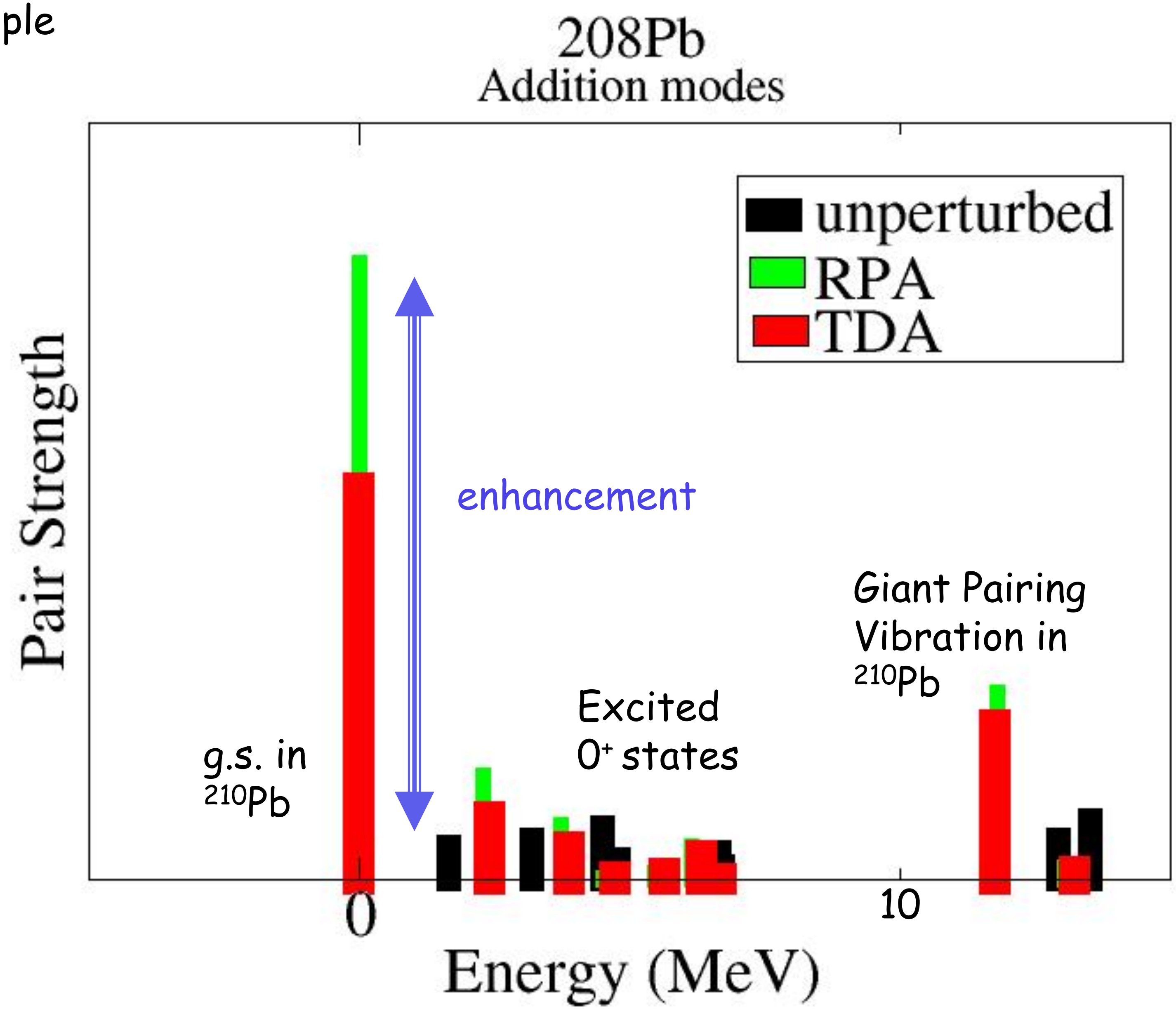
It is often assumed that the cross section for two-particle transfer just scale with T_0, the square of the matrix element of the pair creation (or removal) operator

$$P^+ = \sum_j [a^+_j a^+_j]_{00}$$

For this reason the easiest way to define and measure the collectivity of pairing modes is to compare with single-particle pair transition densities and matrix elements to define some "pairing" single-particle units and therefore "pairing" enhancement factors.

Obs: We discuss here monopole pairing modes, i.e. 0+states

Example



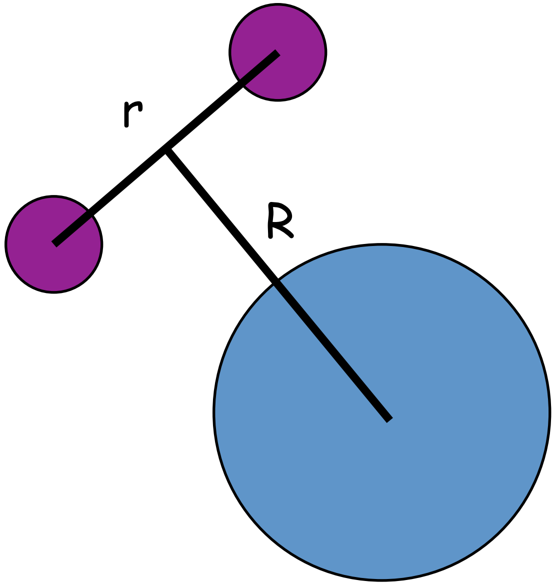
enhancement

g.s. in ^{210}Pb

Excited 0^+ states

Giant Pairing Vibration in ^{210}Pb

But the two-particle transfer process in not sensitive to just the pair matrix element. We have to look at the radial dependence, which is relevant for the reaction mechanism associated with pair transfer processes. The pairing interaction favor the “clustering” of the pairs in space



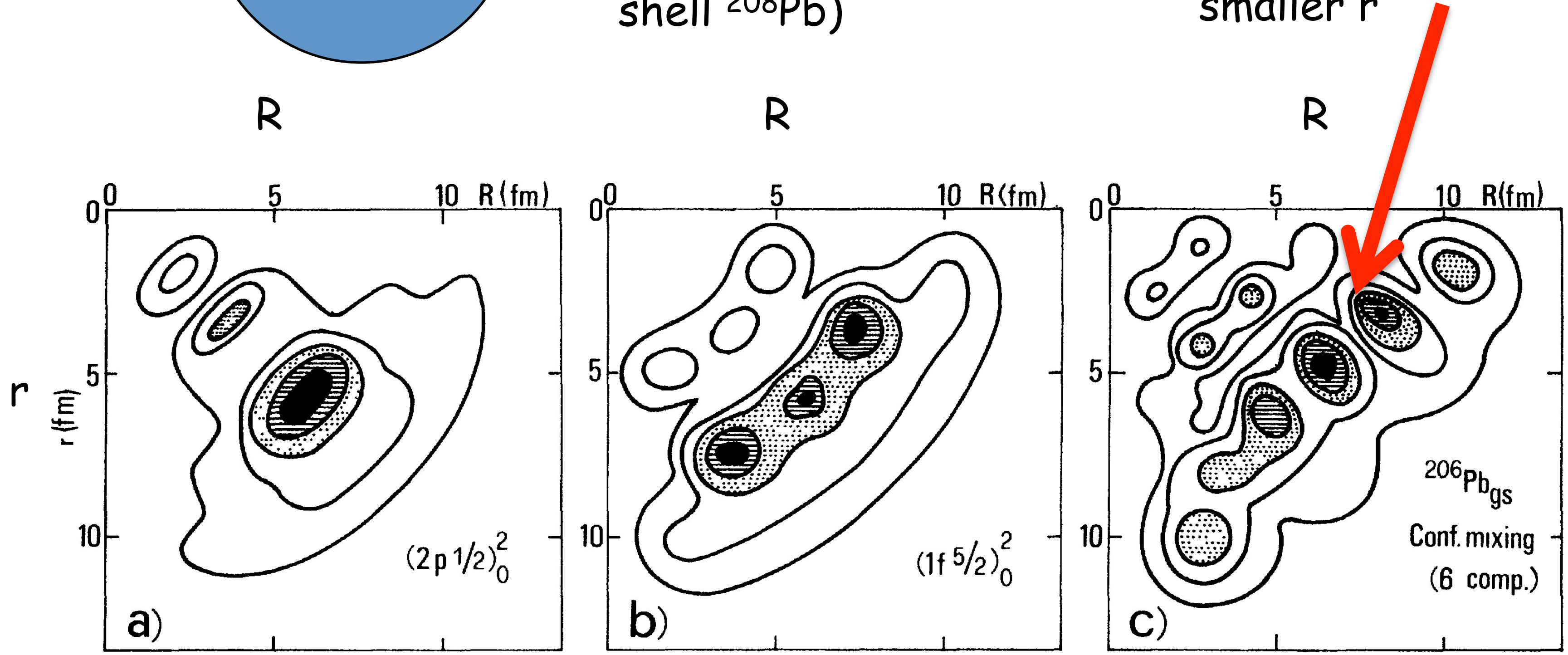
$\delta\rho_P(R,r)$

Catara, Insolia,
Maglione, Vitturi 1984

^{206}Pb (gs)

(pair removal mode
with respect to closed
shell ^{208}Pb)

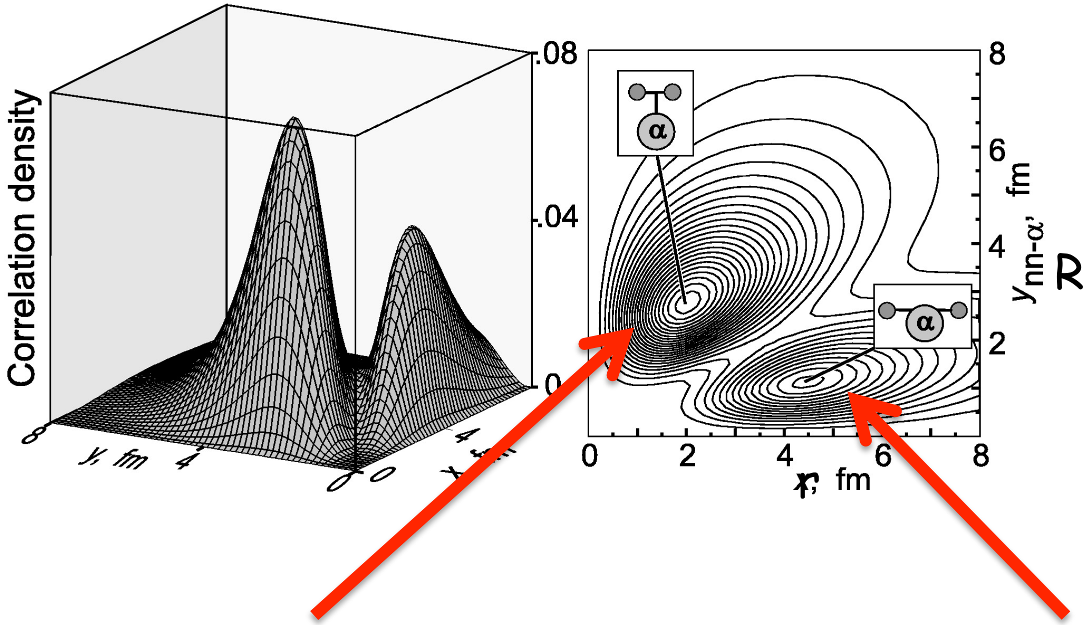
Obs: Larger R and
smaller r



$(3p1/2)^2$ $(2f5/2)^2$ Correlated g.s.

Interesting problem:
how is changed the picture as we move closer
or even beyond the drip lines?

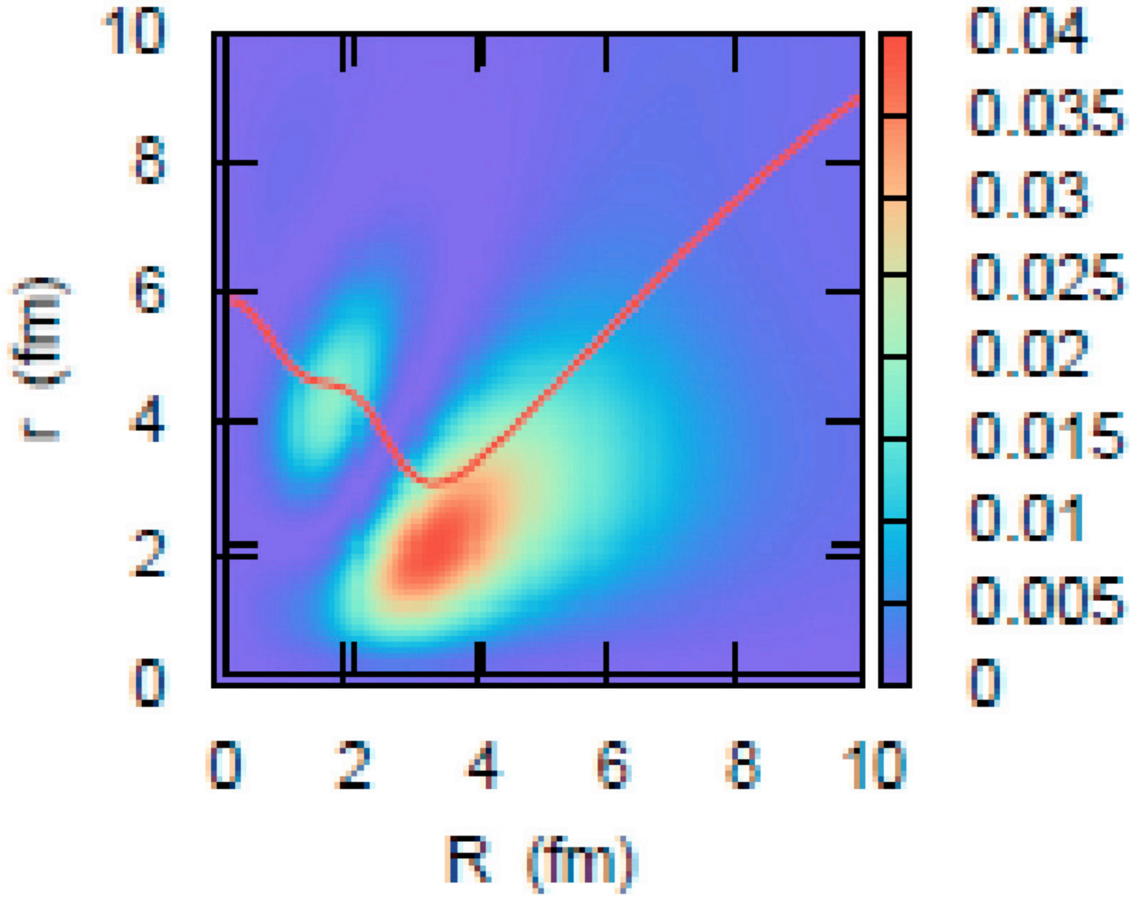
Example:
the case of
^{6}He

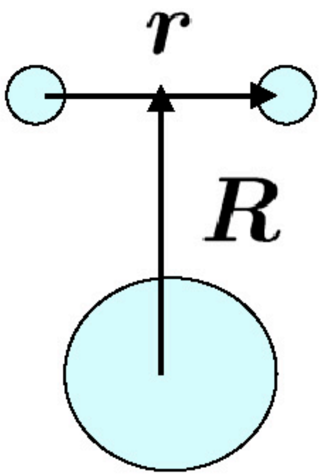


“cluster” configuration favored with respect to “sigar” configuration

Oganessian, Zagrebaev, Vaagen, 1999

Other example: the case of ^{11}Li





K.Hagino, H. Sagawa, and P. Schuck,
J. of Phys. G37(‘10) 064040.

Reaction mechanism and models for two-particle transfer processes

Large number of different approaches, ranging from macroscopic to semi-microscopic, from “cluster-like” to fully microscopic. They all try to reduce the actual complexity of the problem, which is a four-body scattering (the two cores plus the two transferred particles).
The issue is still open and controversial. Most popular and competing schools of thinking are those based on “di-neutron cluster” transfer and on coherent superposition of successive one-particle transfer

My personal favored approach: the fully microscopic

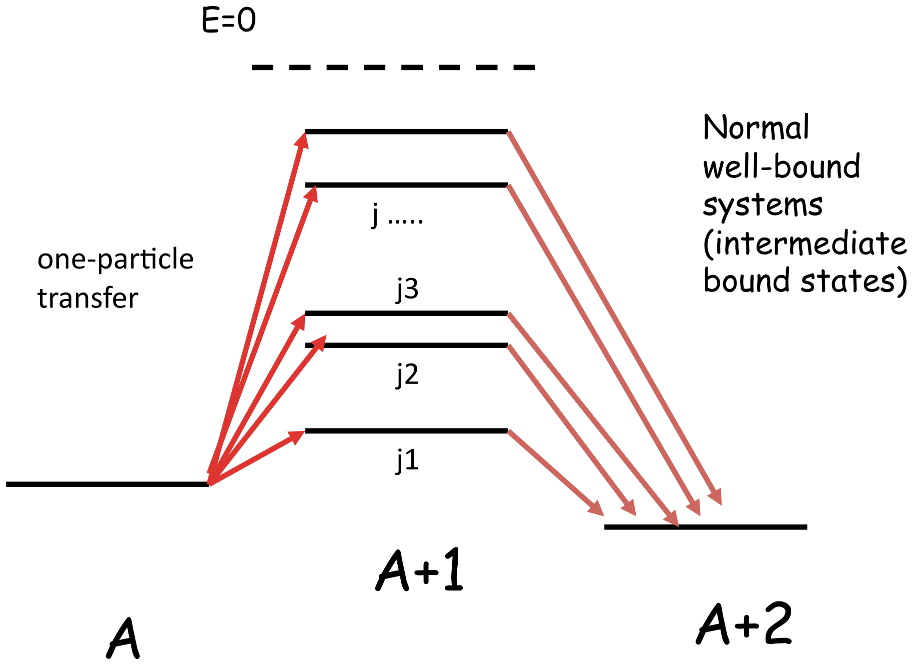
Reaction mechanism: Sequential two-step process (each step transfers one particle)

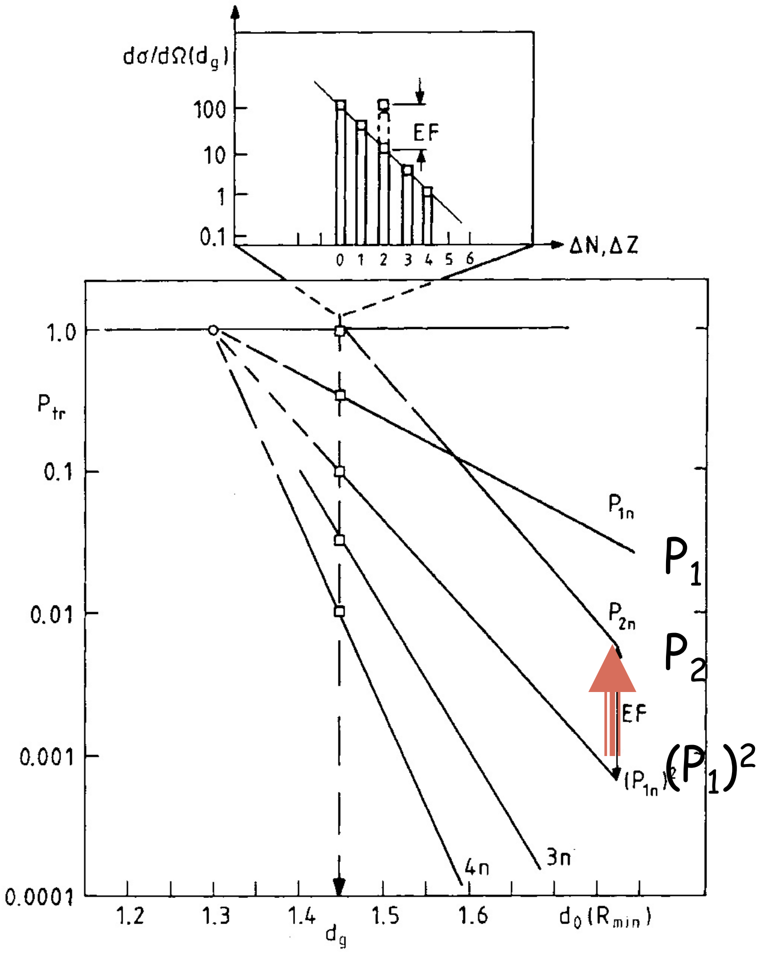
Microscopy: Pairing enhancement comes from the coherent interference of the different paths through the different intermediate states in (a-1) and (A+1) nuclei, due to the correlations in initial and final wave functions

Basic argument: residual pairing interaction is fundamental in determining the properties of nuclear many-body systems. But it is weak compared to the dominant mean one-body field, which causes the one-particle transfer processes. Therefore, in order to transfer two particles (although correlated by the pairing), the one-body field must act at least twice. So in perturbation theory, pair transfer is a "second-order" process

All microscopy and nuclear structure information are contained in the two-particle transfer amplitudes (from correlated initial and final wave functions, so provided by structure models), 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



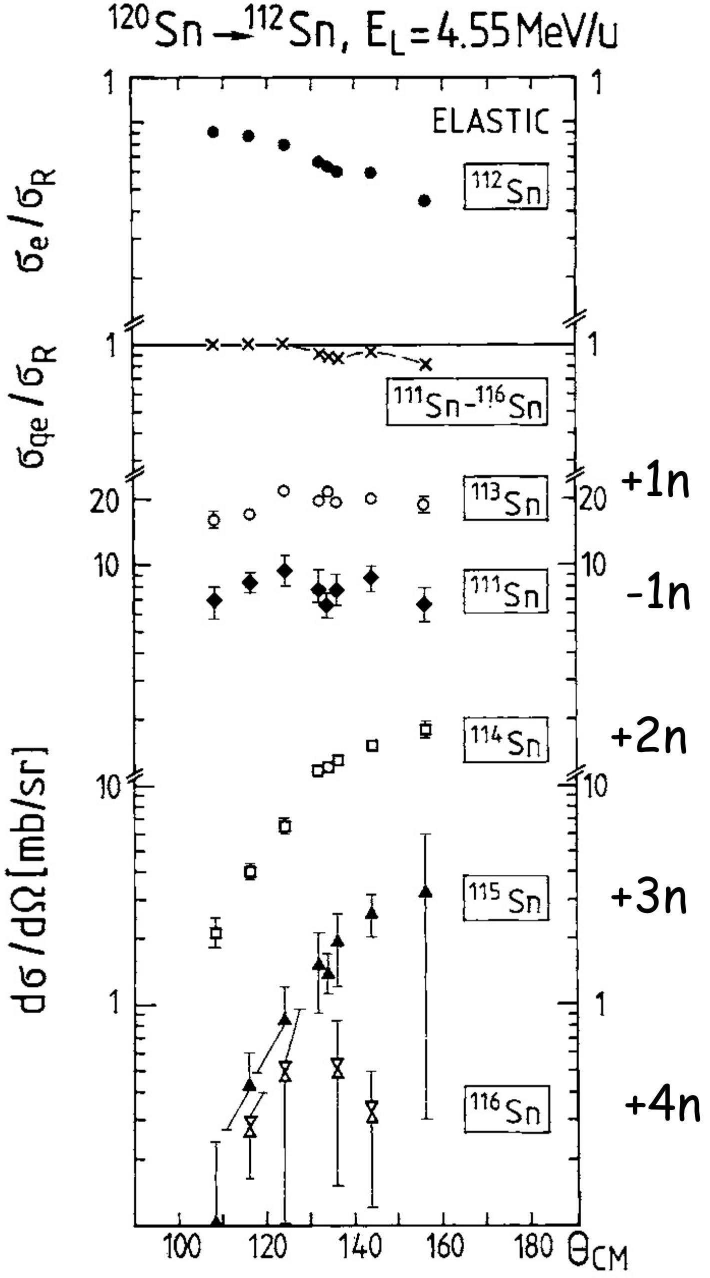


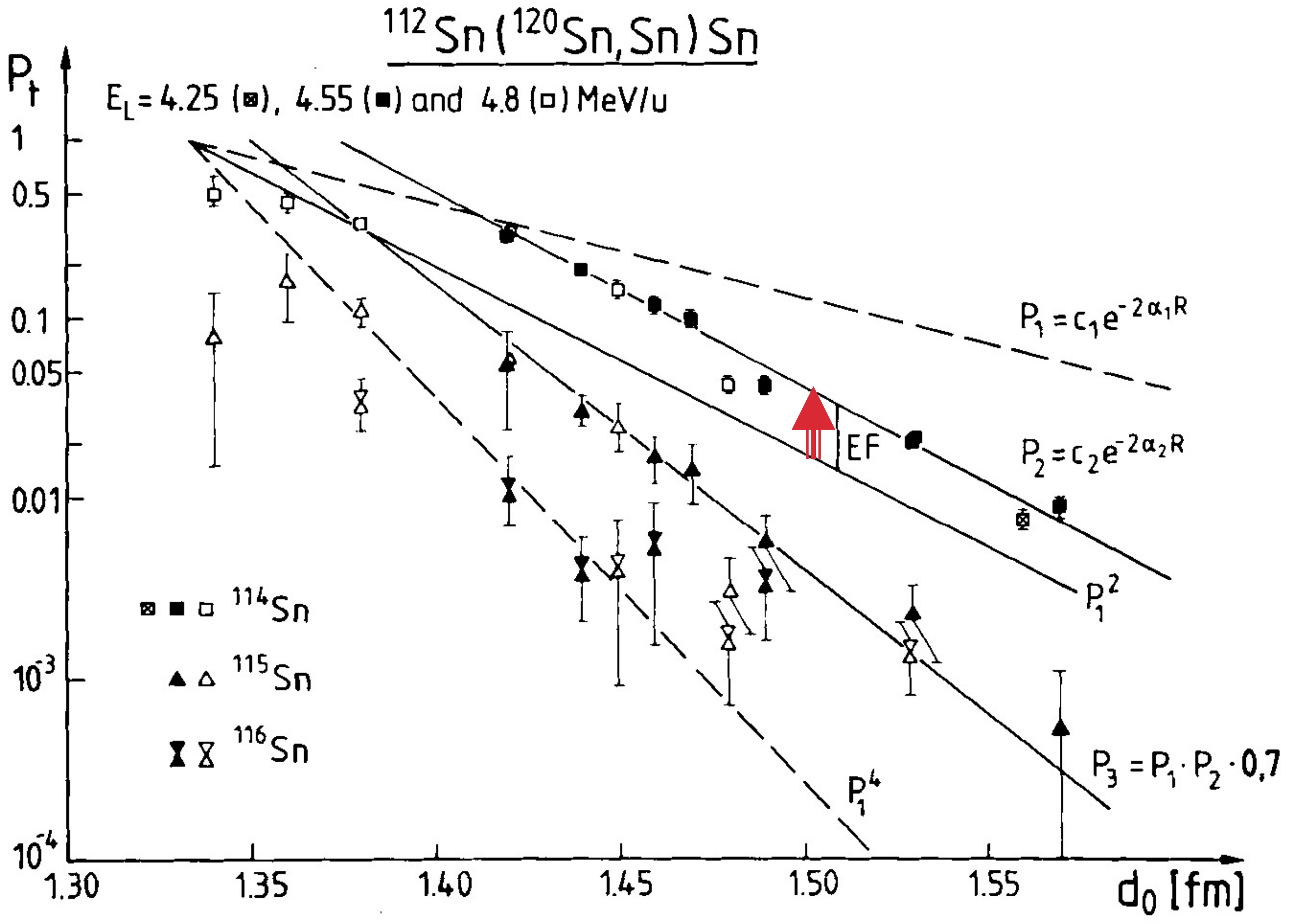
distance of
closest approach

Sequential transfer does not mean necessarely "uncorrelated" trasfer. As a matter of fact the way to define a pairing "enhancement" factor consists of plotting transfer probabilities not as function of the scattering angle, but as function of the distance of closest approach of the corresponding classical trajectory, and compare the "correlated" case with the prediction of the simple "uncorrelated" one (just the square of the probability of single-particle transfer)

The classical example:
Sn+Sn
(superfluid on superfluid)

Von Oertzen, Bohlen etal



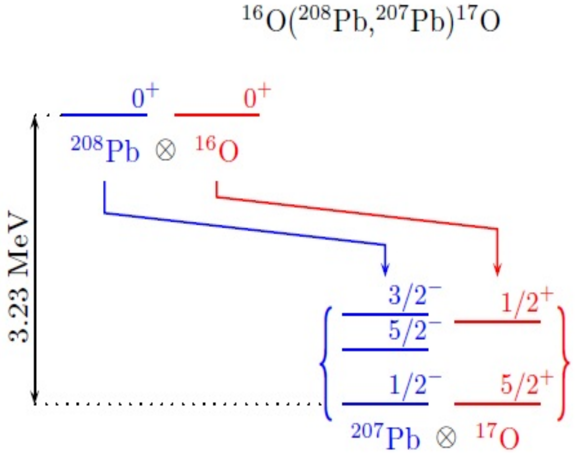


General problem: how separate the contribution of 0+ states? Q-distributions?

Theory: Example Two neutron pick-up $^{208}Pb(^{16}O,^{18}O)^{206}Pb$

Fortunato, Inci, Vitturi

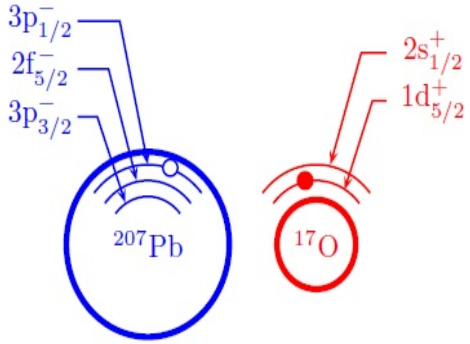
Intermediate channel

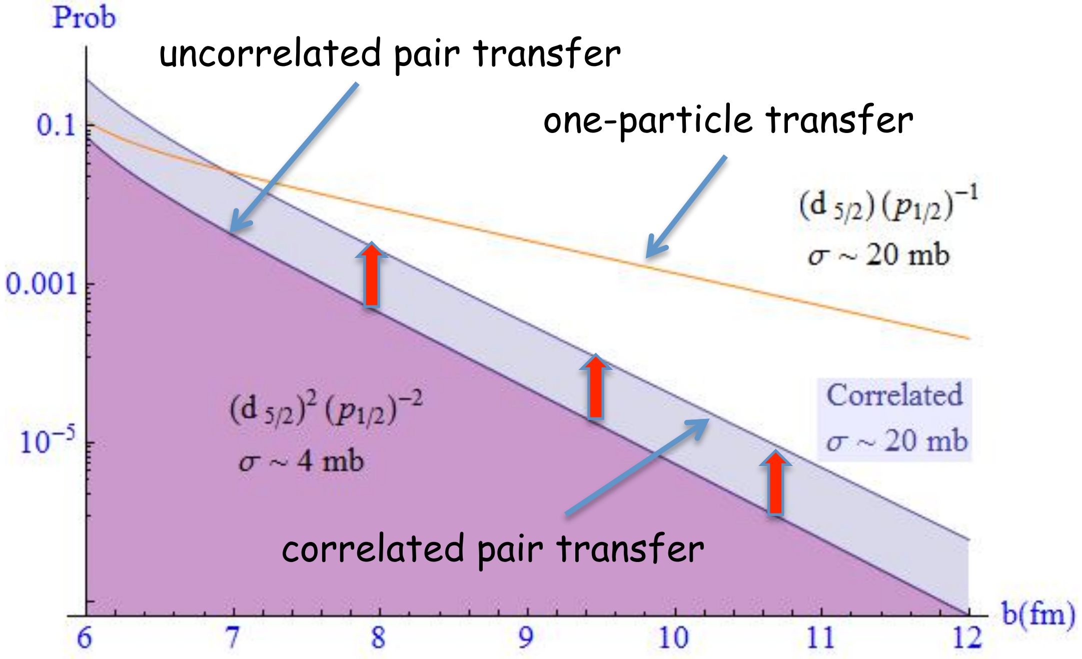

$^{16}O(^{208}Pb,^{207}Pb)^{17}O$

Correlated wave functions

^{206}Pb (gs)= 0.8 $(p1/2)^{-2}$ +
0.6 $(f5/2)^{-2}$ +

^{18}O (gs) = 0.8 $(d5/2)^2$ +
0.6 $(s1/2)^2$

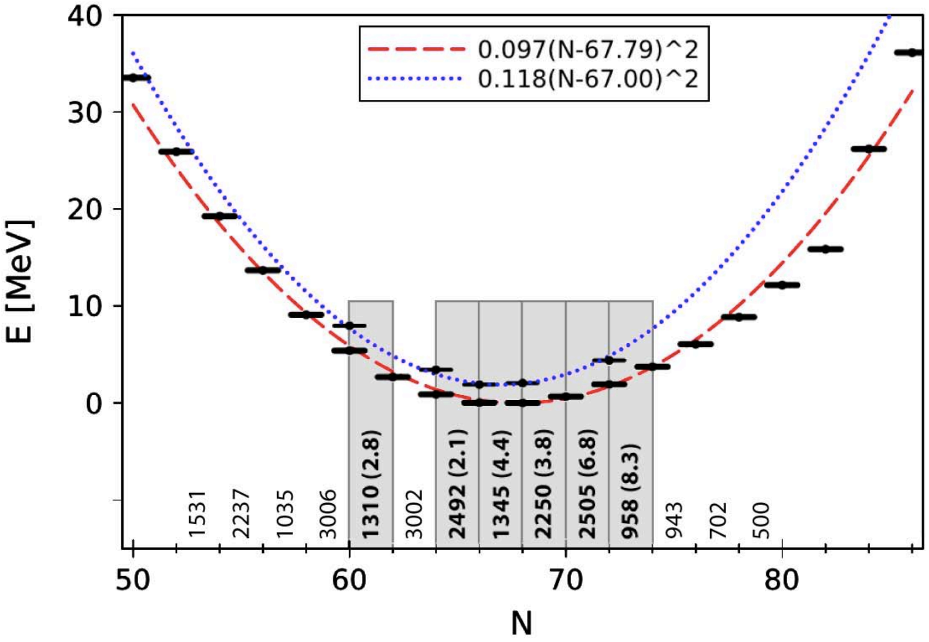



uncorrelated pair transfer

one-particle transfer

correlated pair transfer

Example: systematic (p,t) reactions on Sn isotopes
(typical example of pairing rotational band)

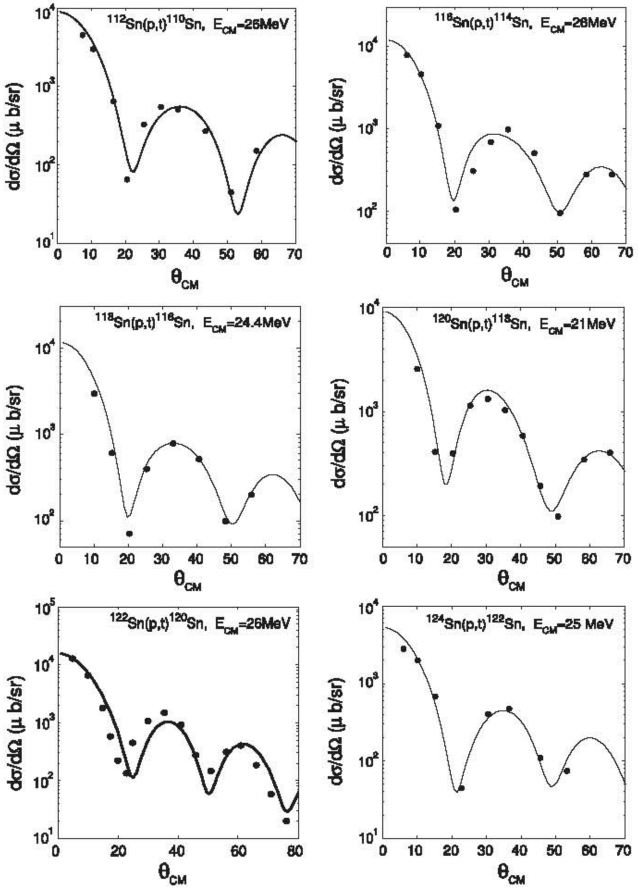


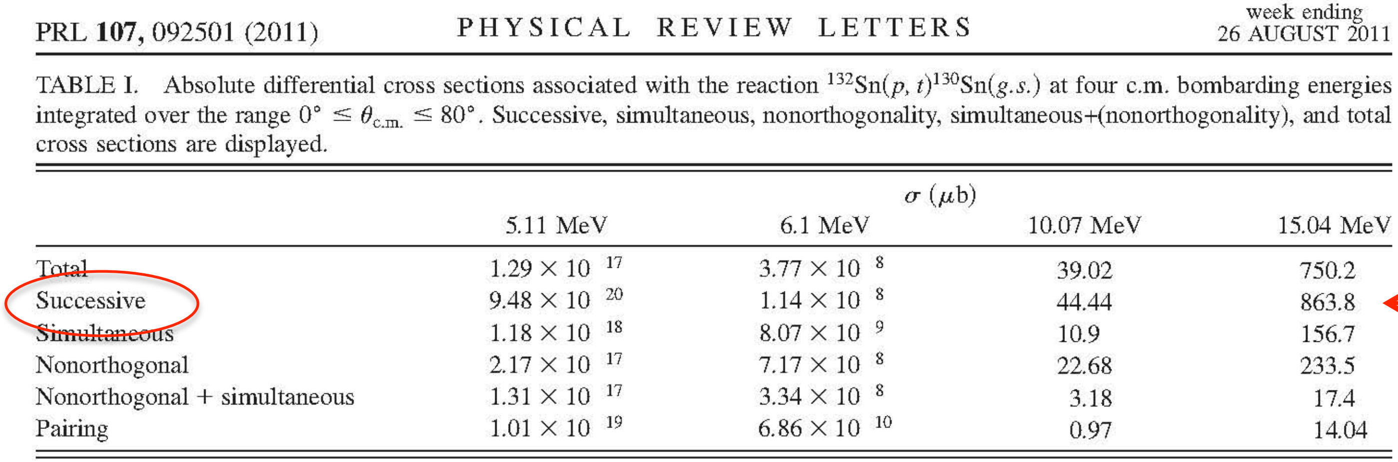
Theory: Potel, Broglia, Vigezzi, Barranco
BCS microscopic wf's for gs of Sn isotopes

Obs: absolute cross sections
(no theory renormalization)

Vigezzi etal

Importance of different two-particle trasfer mechanisms (dependence on the bombarding energy)





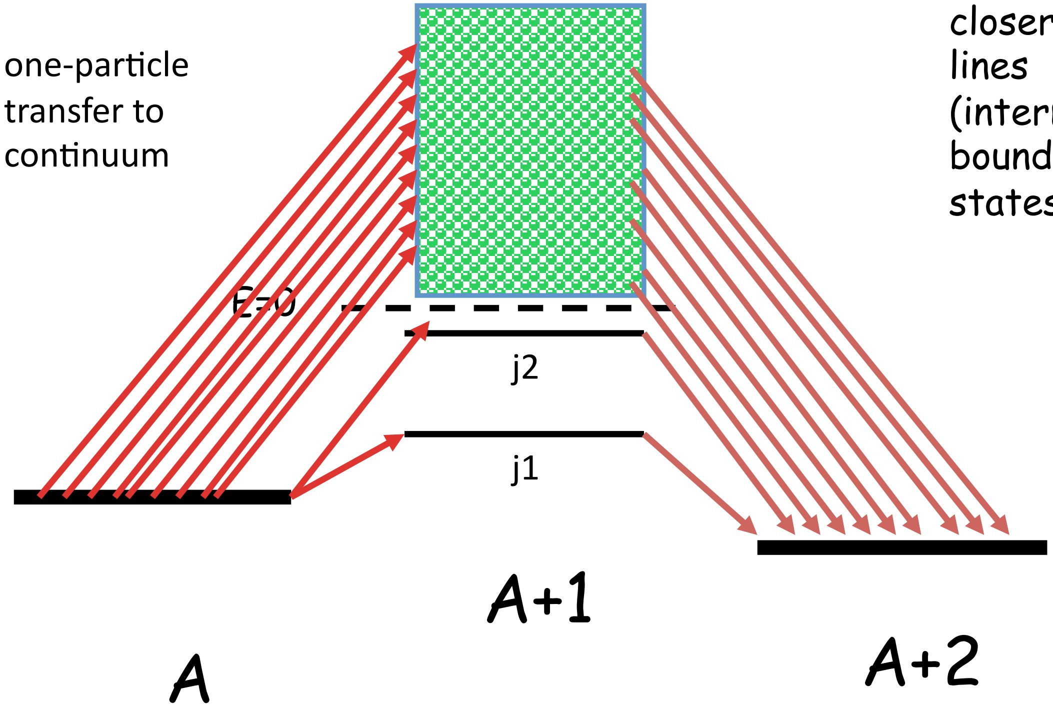
PRL **107,** 092501 (2011) PHYSICAL REVIEW LETTERS week ending 26 AUGUST 2011

TABLE I. Absolute differential cross sections associated with the reaction ^{132}Sn$(p, t)^{130}$Sn$(g.s.)$ at four c.m. bombarding energies integrated over the range $0° \leq \theta_{\mathrm{c.m.}} \leq 80°$. Successive, simultaneous, nonorthogonality, simultaneous+(nonorthogonality), and total cross sections are displayed.

	σ (μb)			
	5.11 MeV	6.1 MeV	10.07 MeV	15.04 MeV
Total	1.29×10^{17}	3.77×10^{8}	39.02	750.2
Successive	9.48×10^{20}	1.14×10^{8}	44.44	863.8
Simultaneous	1.18×10^{18}	8.07×10^{9}	10.9	156.7
Nonorthogonal	2.17×10^{17}	7.17×10^{8}	22.68	233.5
Nonorthogonal + simultaneous	1.31×10^{17}	3.34×10^{8}	3.18	17.4
Pairing	1.01×10^{19}	6.86×10^{10}	0.97	14.04

Basic problem:

how is changed the picture as we move closer
or even beyond the drip lines? Does the nature
of "pairing" interaction change in diluted systems?



one-particle
transfer to
continuum

Systems
closer to the drip
lines
(intermediate
bound and unbound
states)

Two examples with radioactive beams in inverse kinematics

^{11}Li+p -> ^{9}Li +t

^{8}He+p -> ^{6}He +t

^{11}Li+p -> ^{9}Li +t

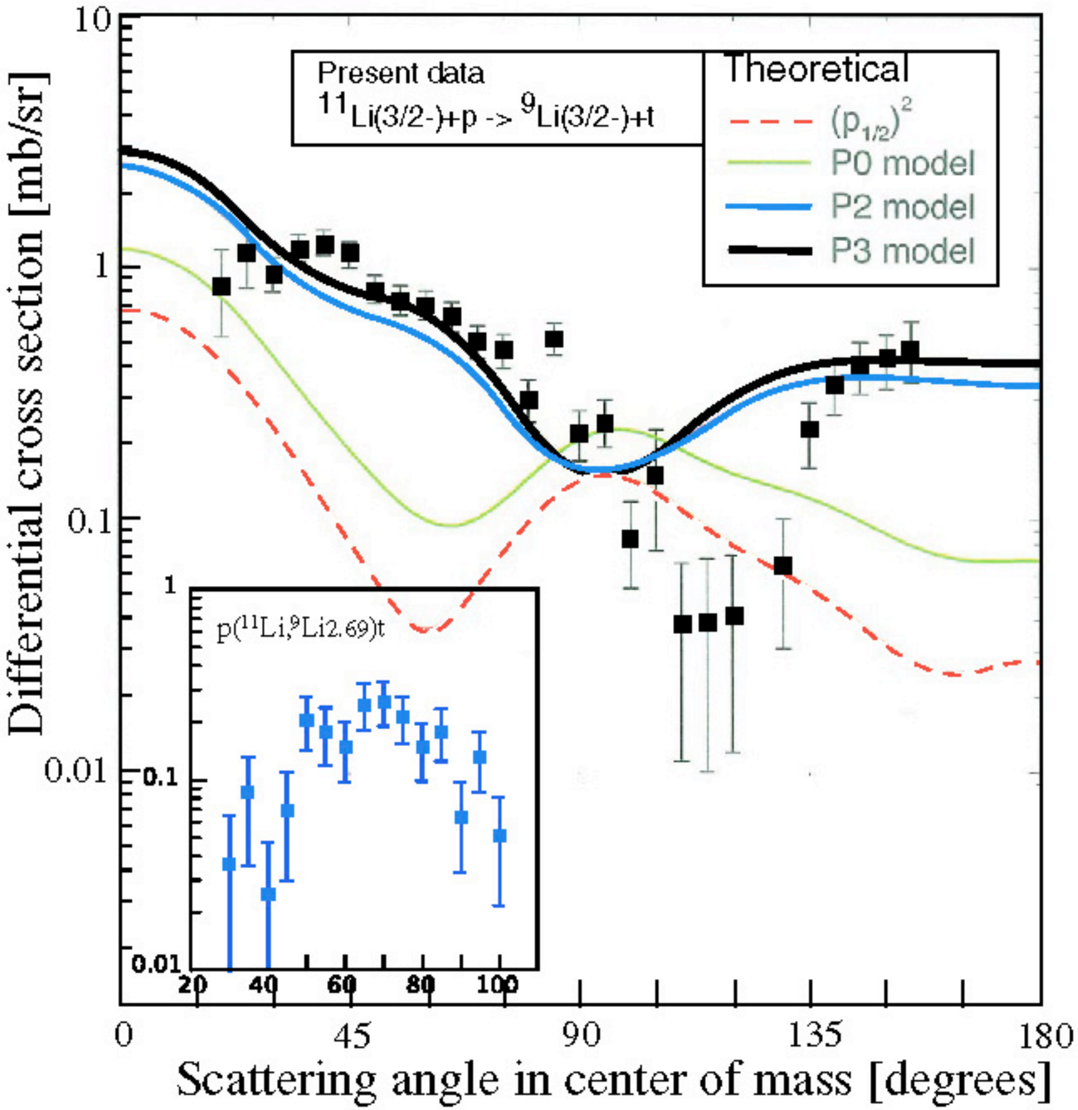
Isao Tanihata, Ian Thompson
Data from ISAC-2, TRIUMF

“correlated” sequential transfer
Sensitivity to
the pairing wave function in ^{11}Li (mixture of $(p_{1/2})^2$ and $(s_{1/2})^2$)

P0: 3% of $(s_{1/2})^2$

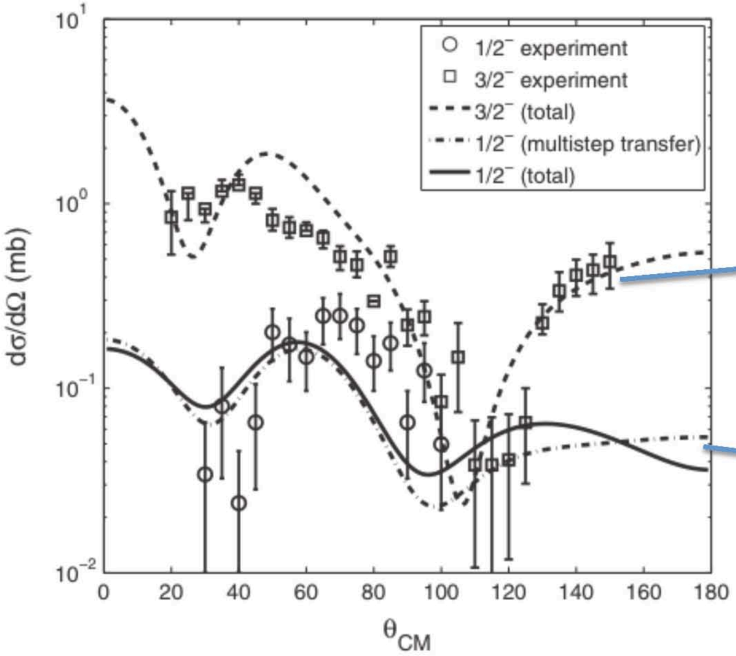
P2: 31% of $(s_{1/2})^2$

P3: 45% of $(s_{1/2})^2$



^{11}Li+p -> ^{9}Li+t

Excellent agreement has been obtained using more sophisticated wave functions with particle-vibration couplings in ^{11}Li and ^{10}Li

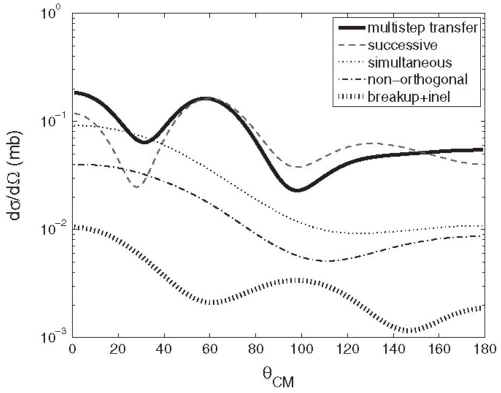


g.s.

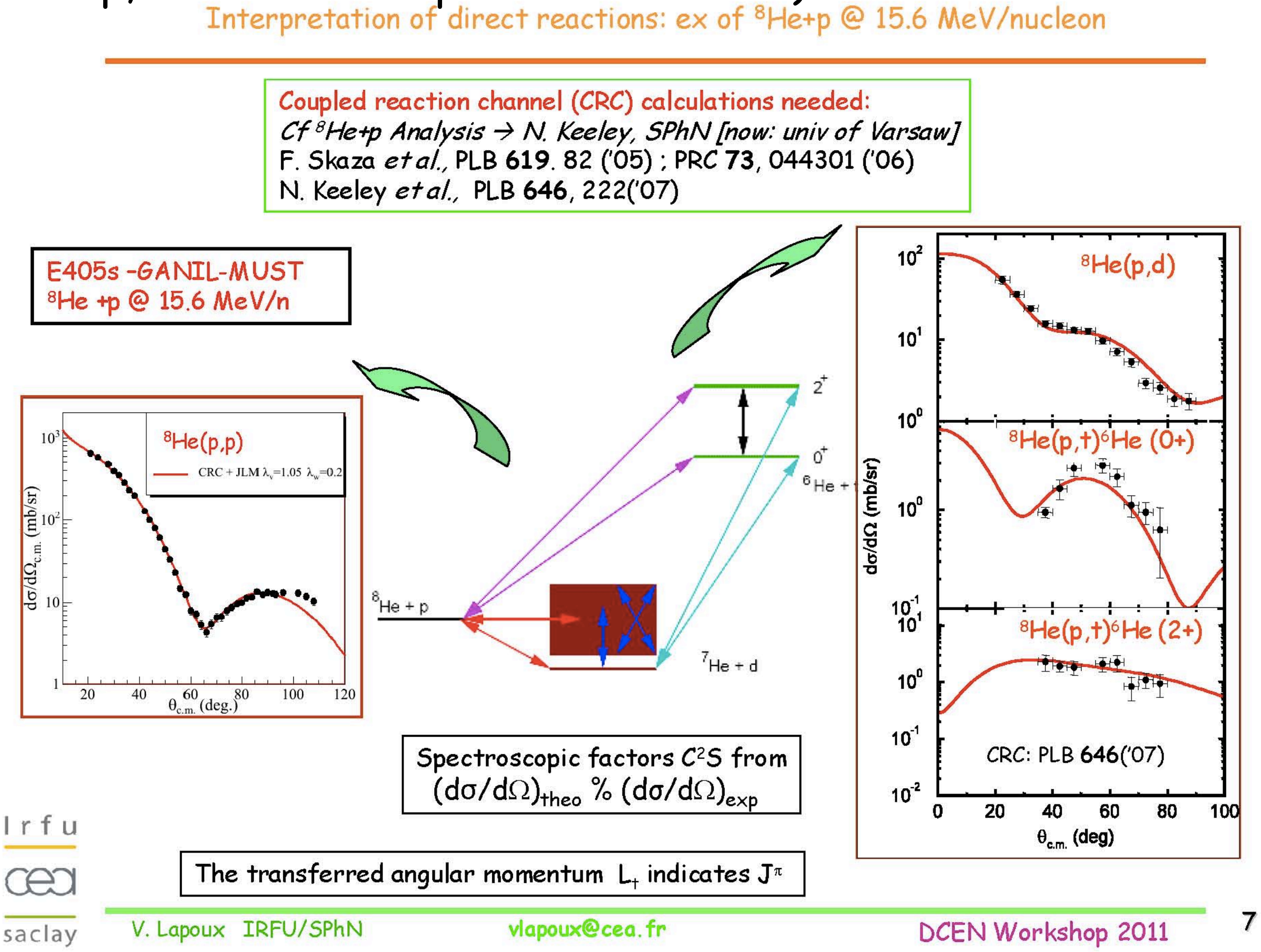
$1/2^-$ exc. state: $\pi(p3/2) \times 2^+$

Potel, Vigezzi etal, PRL, 2010

Obs: Dominance of correlated sequential transfer



Example: ^{8}He + p (rather complicate affair to get a complete measurement and a symultaneous account of elastic, inelastic, break-up, one- and two-particle transfer)



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

Coupled reaction channel (CRC) calculations needed:
Cf ^{8}He+p Analysis → 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}He +p @ 15.6 MeV/n

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

The transferred angular momentum L_t indicates J^π

Courtesy of Valerie Lapoux

Q-value effects and the search for high-lying collective pairing states

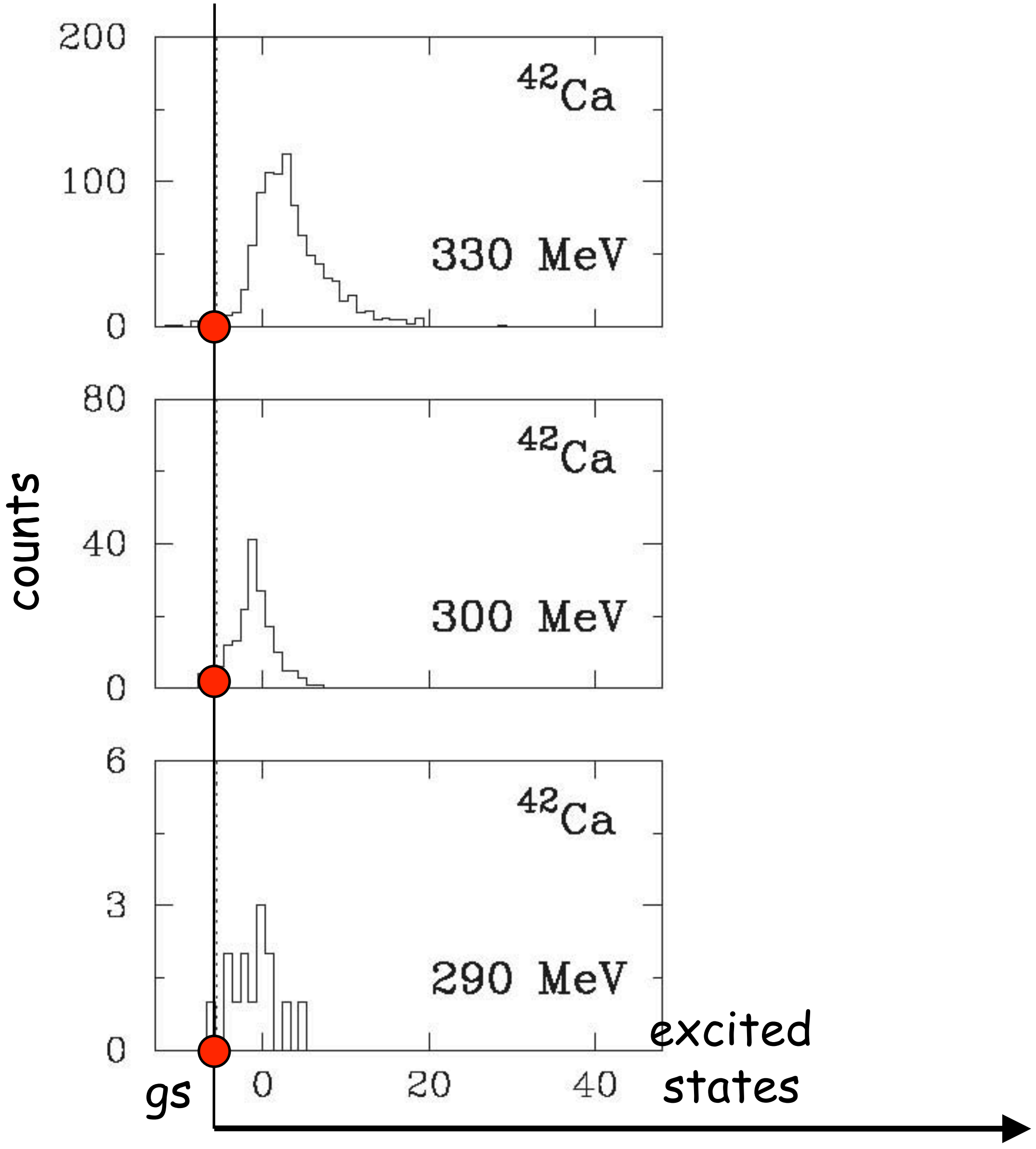
Keeping fixed any other parameter, the probability for populating a definite final channel depends on the Q-value of the reaction. The dependence (in first approximation a gaussian distribution centered in the optimum Q-value) is very strong in the case of heavy-ion induced reactions, weaker in the case of light ions.

The optimum Q-value depends on the angular momentum transfer and on the charge of the transferred particles. In the specific case of L=0 two-neutron transfer, the optimal Q-value is close to zero.

But the actual Q-value for two-particle transfer to the (pairing collective) ground states may be different from zero …..

Experimental evidence

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



Example

^{96}Zr+^{40}Ca

Selecting final
^{42}Ca mass partition
(two-neutron transfer)

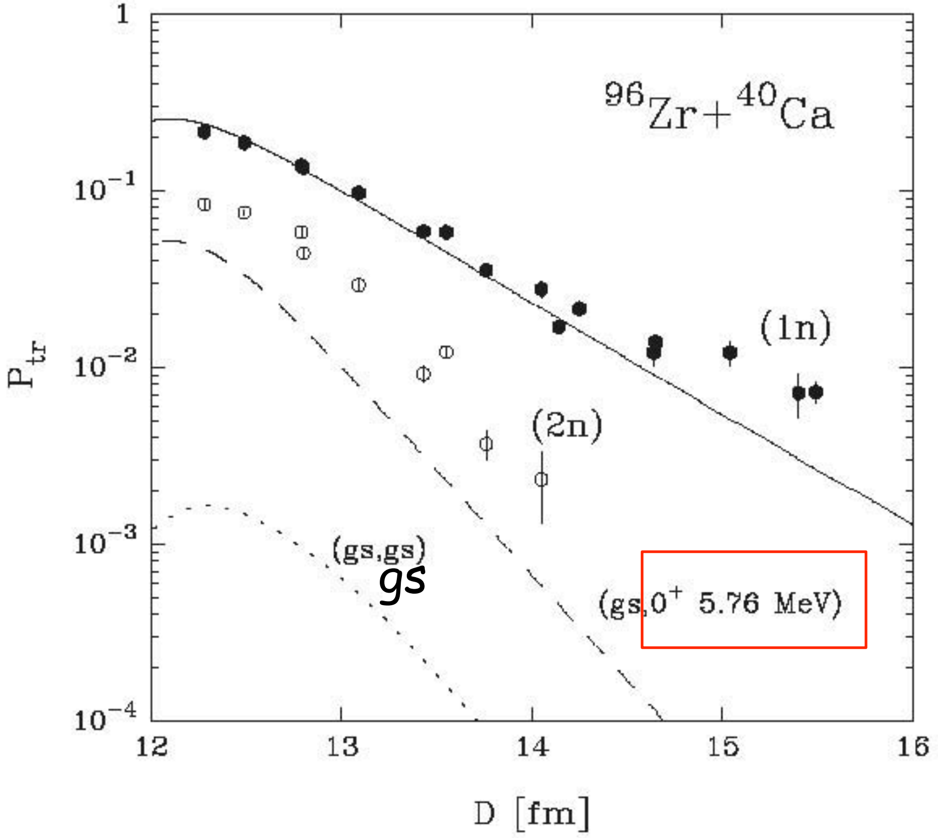
Total kinetic energy loss (MeV)
(or excitation energy in ^{42}Ca)

Corradi etal, LNL

As a result, the correlated states may be populated in a much weaker way than uncorrelated states

Example: ^{96}Zr+^{40}Ca, leading
to ^{42}Ca
In this case is
favored the excitation
of an “uncorrelated” 0+ state
at about 6 MeV

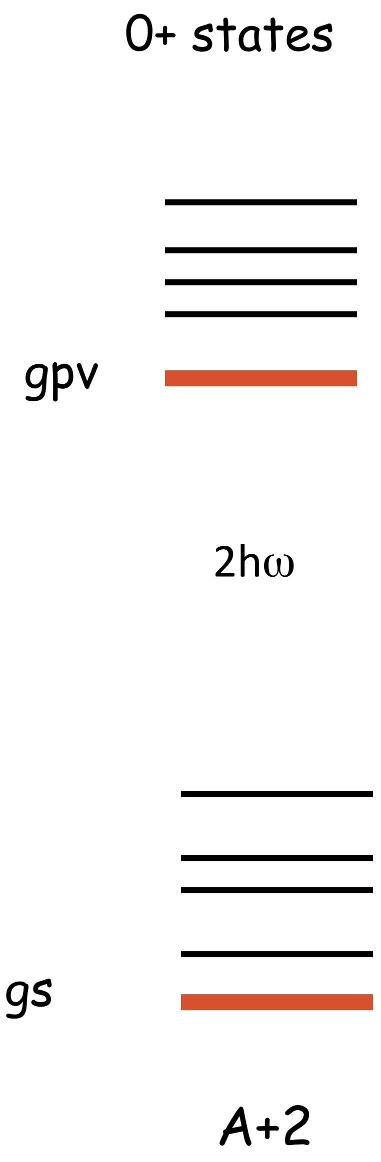
Corradi, Pollarolo etal, LNL



But the Q-value window can be used also with some profit. For example the occurrence of large positive Q-value for the ground state transition leads to optimal kinematics conditions for high-lying states. This is the region of the still hunted Giant Pairing Vibration (GPV)

High-lying pairing resonances (giant pairing resonances)

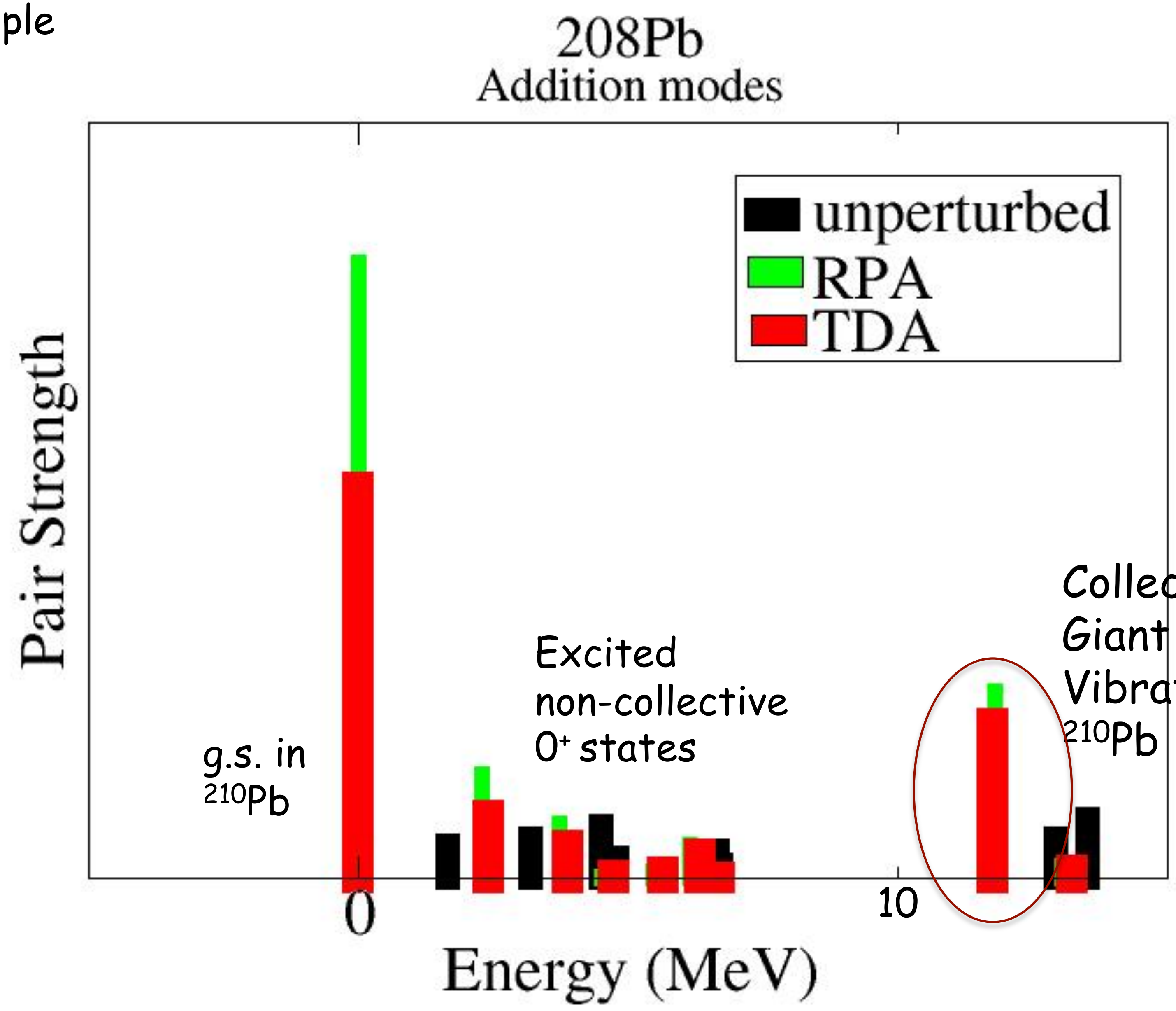
In addition to the lowest collective state one expects pair transfer strength at higher energies. This distribution will be strongly affected by the existence of major shells, such that the inter-shell distance is appreciably larger than the distance between the levels within a shell. In this case a concentration of pairing strength in a single state is expected for each major shell



🟥 collective

▬ non collective

Example

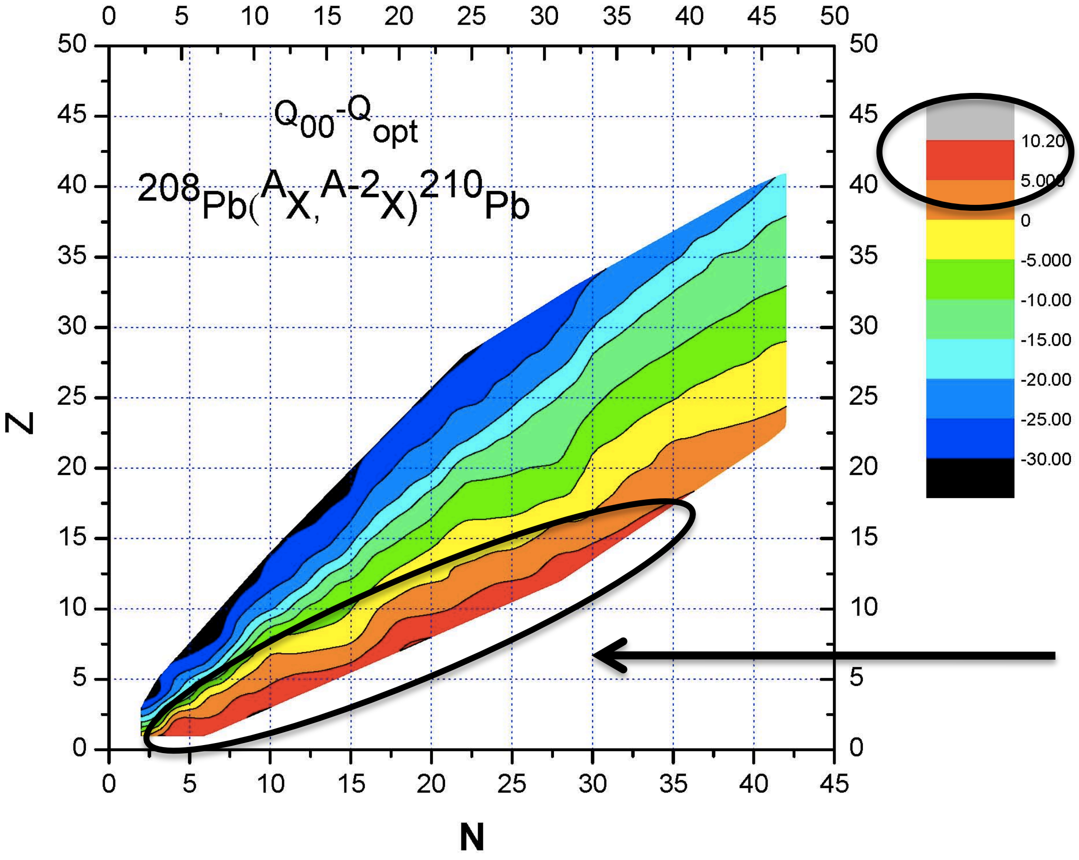


g.s. in ^{210}Pb

Excited non-collective 0^+ states

Collective Giant Pairing Vibration in ^{210}Pb

If our goal is to favor the excitation of a high-lying state, as in the case of the giant pairing vibration, it may be useful the use of a weakly-bound projectile (eg ^{6}He) to populate the GPV in a stable nucleus, to profit from favorable Q-value matching (cf Fortunato, Vitturi, Von Oertzen)

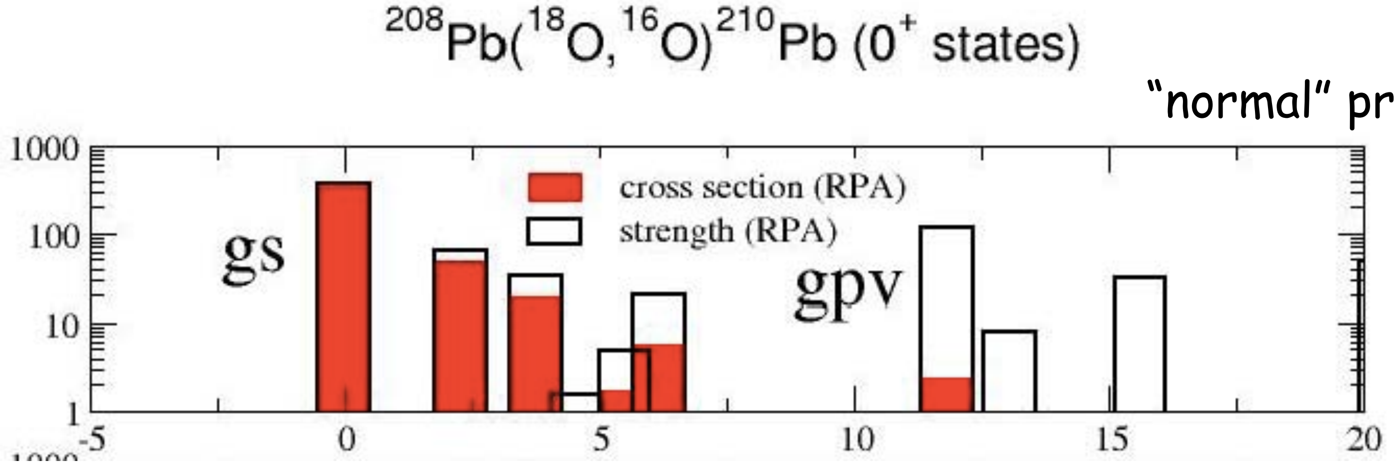


Q_{00}-Q_{opt} ≈ 10 MeV

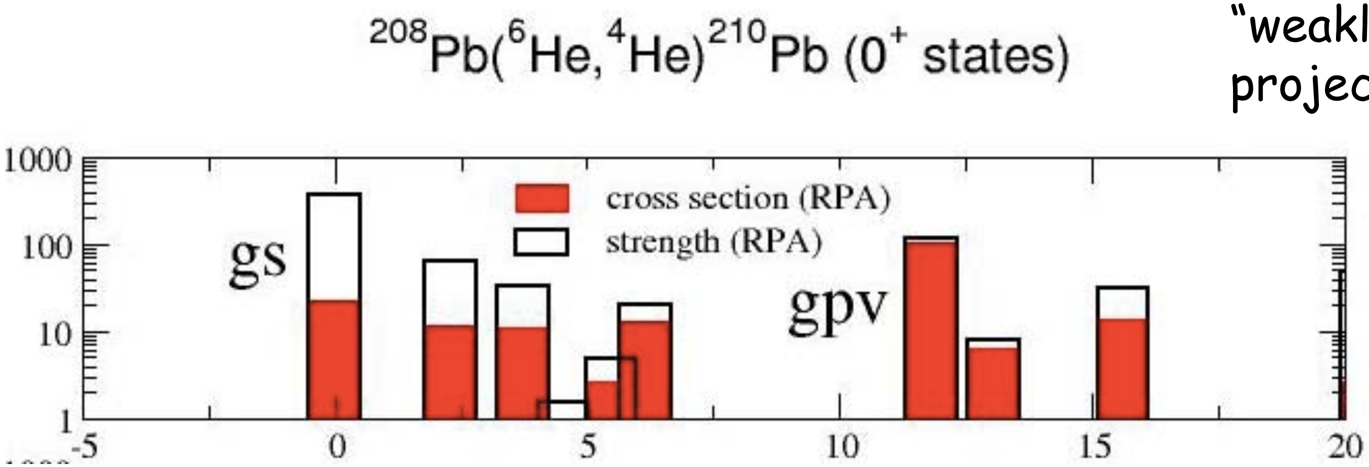
Projectiles that leads to large positive Q-values for two-particle transfer to the ground state

From pairing strength to pair-transfer cross section: Q-value effect

Pairing strength (Pair transfer cross section)



“normal” projectile



“weakly-bound” projectile

Fortunato, Sofia, Vitturi

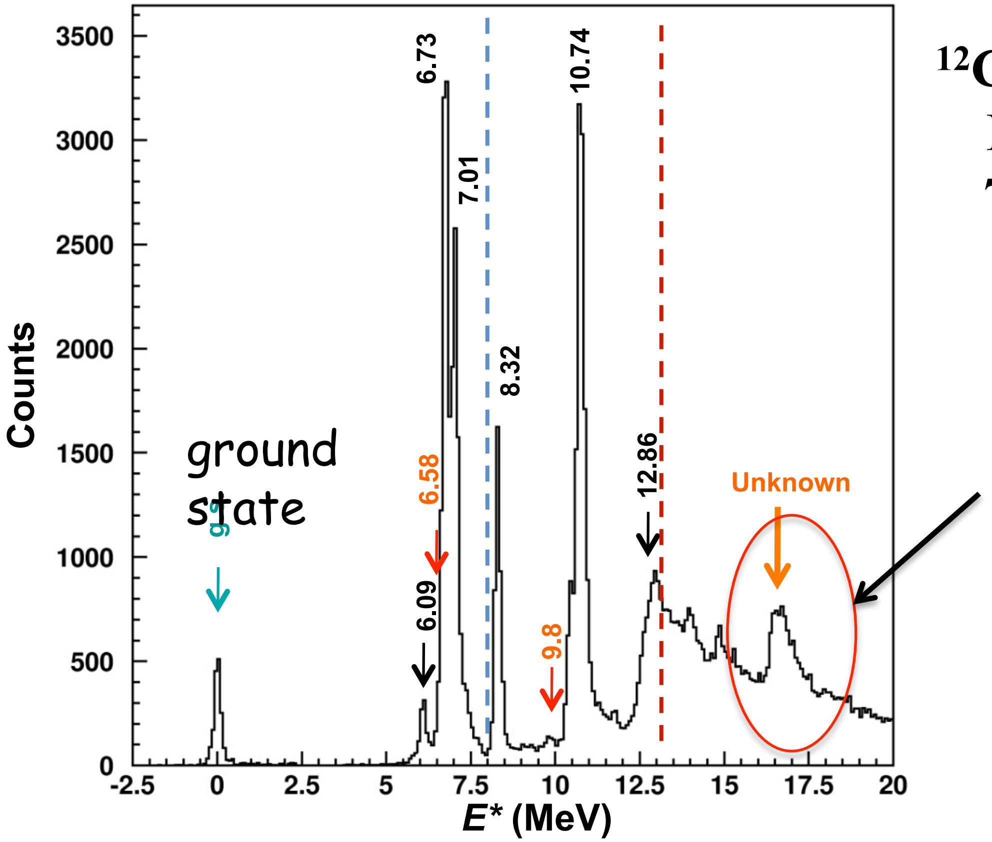
Very interesting results have been obtained in the campaign at LNS with the magnetic spectrometer MAGNEX in the region of light nuclei (around Carbon and Oxygen).

It is the region where mean-field, pairing, collective and cluster features are blended

Cappuzzello etal, LNS

Two-particle transfer at LNS with MAGNEX

^{14}C energy spectrum



$^{12}C\ (^{18}O,^{16}O)\ ^{14}C$

E = 84 MeV

$7° < \theta_{lab} < 16°$

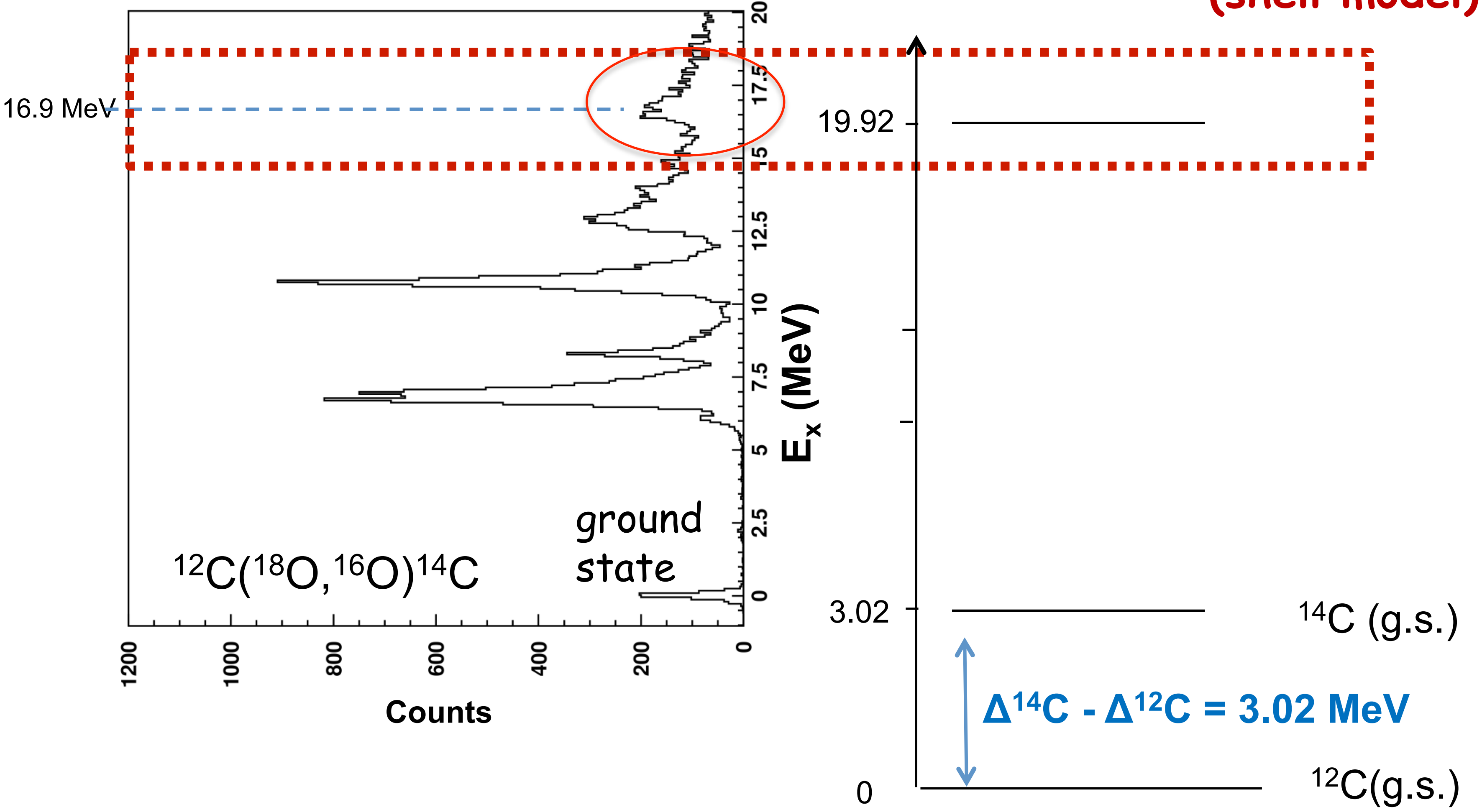
$^{12}C_{g.s.}(0^+) \rightarrow {}^{14}C_{g.s.}(0^+)$	L = 0	$^{12}C_{g.s.}(0^+) \rightarrow {}^{14}C_{7.01}(2^+)$	L = 2
$^{12}C_{g.s.}(0^+) \rightarrow {}^{14}C_{6.09}(1^-)$	L = 1	$^{12}C_{g.s.}(0^+) \rightarrow {}^{14}C_{8.32}(2^+)$	L = 2
$^{12}C_{g.s.}(0^+) \rightarrow {}^{14}C_{6.58}(0^+)$	L = 0	$^{12}C_{g.s.}(0^+) \rightarrow {}^{14}C_{9.8}(0^+)$	L = 0
$^{12}C_{g.s.}(0^+) \rightarrow {}^{14}C_{6.73}(3^-)$	L = 3	$^{12}C_{g.s.}(0^+) \rightarrow {}^{14}C_{10.74}(4^+)$	L = 4

$^{12}C(t,p)^{14}C$

S.Mordechai, et al., Nucl. Phys. A301 (1978) 463
W. Von Oertzen, et al., Eur.Phys.J. A21 (2004) 193

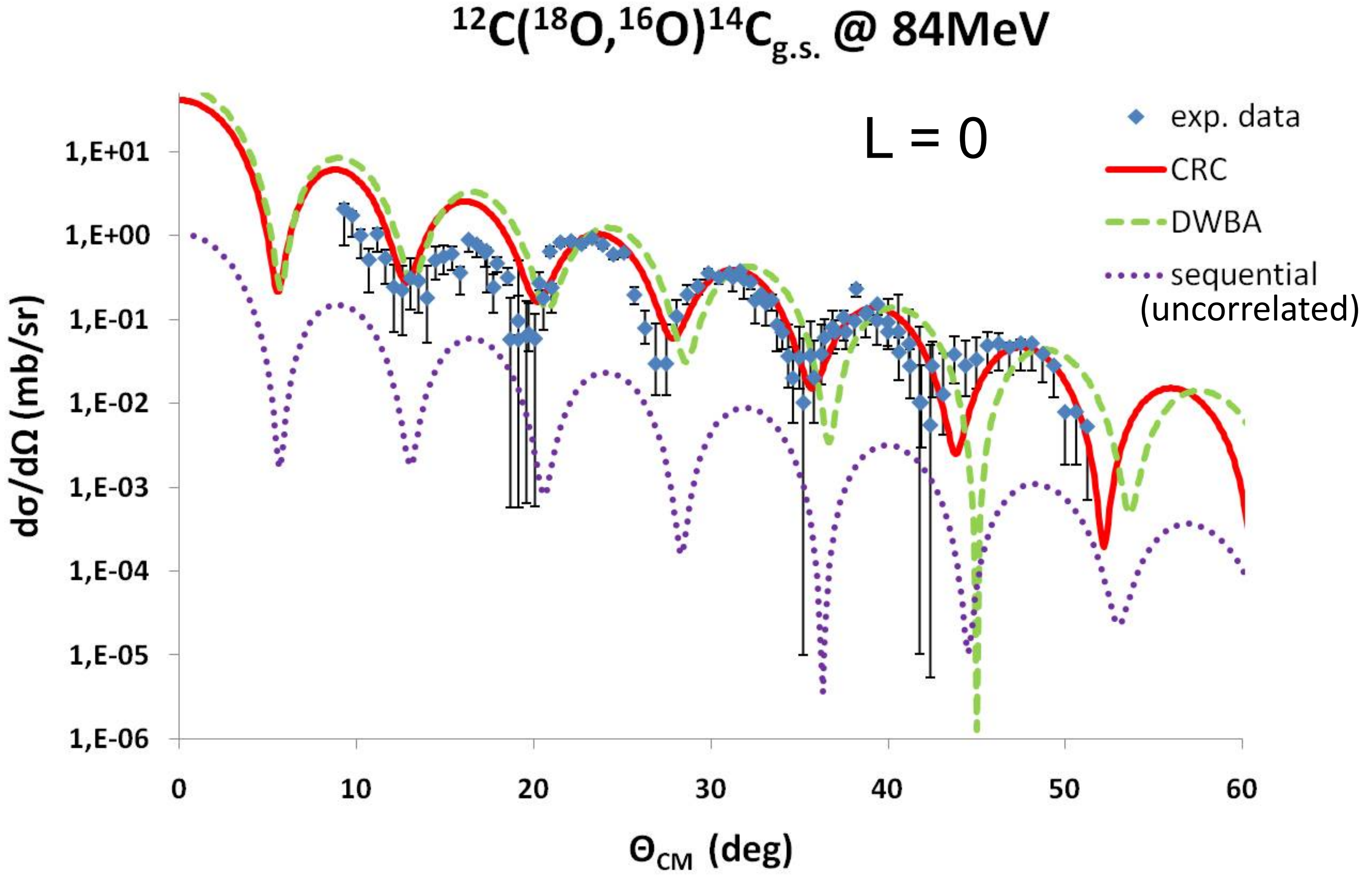
GPV in ^{14}C?

GPV theoretical predictions (shell model)



Angular distribution necessary to select L=0 states

DWBA & CRC calculations with SPP potential



Calculations by Jesus Lubian
UFF - Niteroi

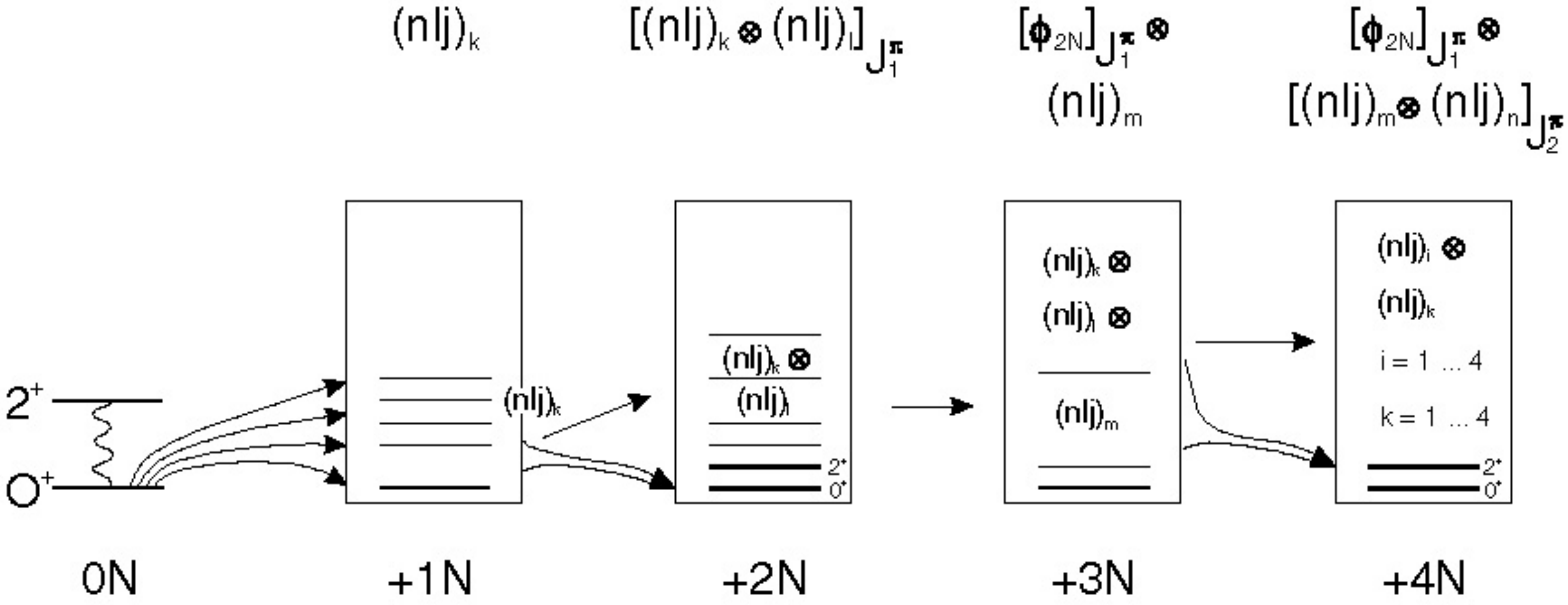
M.A.Candido Ribeiro,et. al. *Phys. Rev. Lett.* **78** (1997)3270
L.C.Chamon, D.Pereira, et. al. *Phys. Rev. Lett.* **79** (1997)5218
L.C.Chamon, et. al. *Phys. Rev. C* **66** (2002) 014610

Multi-nucleon transfer reactions

The situation is becoming orders of magnitude more complex in the case of multi-particle (or multi-pair) tranfers. By definition it cannot be treated as a "genuine" direct process. When restricted to the population of the 0+ ground states it is a key case as test of pairing modes in the "vibrational multiphonon-like" and in the "rotor-like" pairing cases. But in fact one is progressively populating also the excited states, and the whole process is highly coupled, involving pairing, single particle, collective excitations, non-collective excitations, etc. The whole process 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 …..

configurations in multi-nucleon transfer



$(nlj)_k$

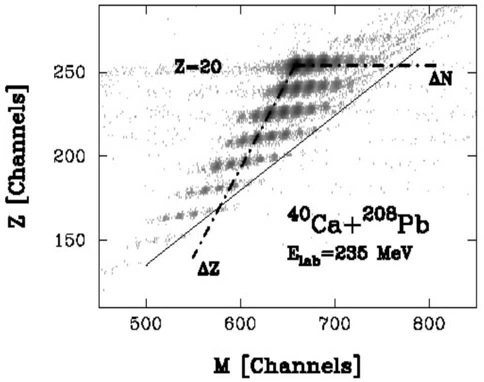
$[(nlj)_k \otimes (nlj)_l]_{J_1^\pi}$

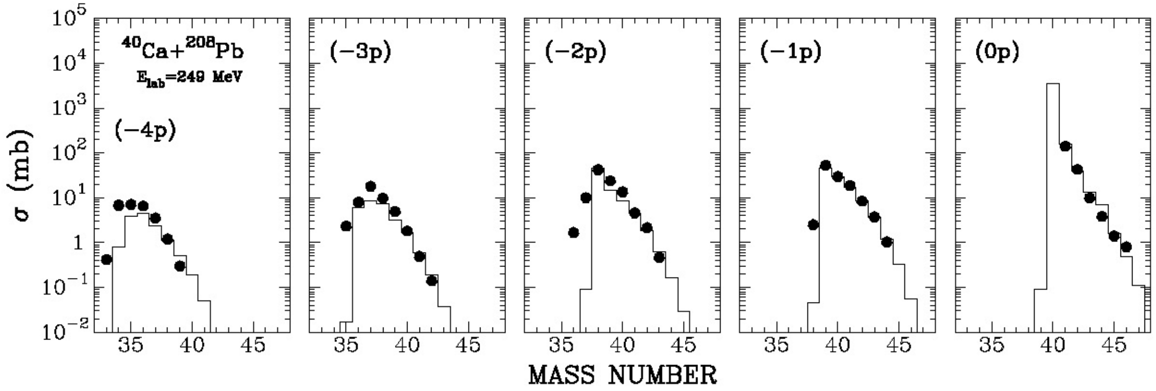
$[\phi_{2N}]_{J_1^\pi} \otimes (nlj)_m$

$[\phi_{2N}]_{J_1^\pi} \otimes [(nlj)_m \otimes (nlj)_n]_{J_2^\pi}$

Example of multi-nucleon transfers at Legnaro

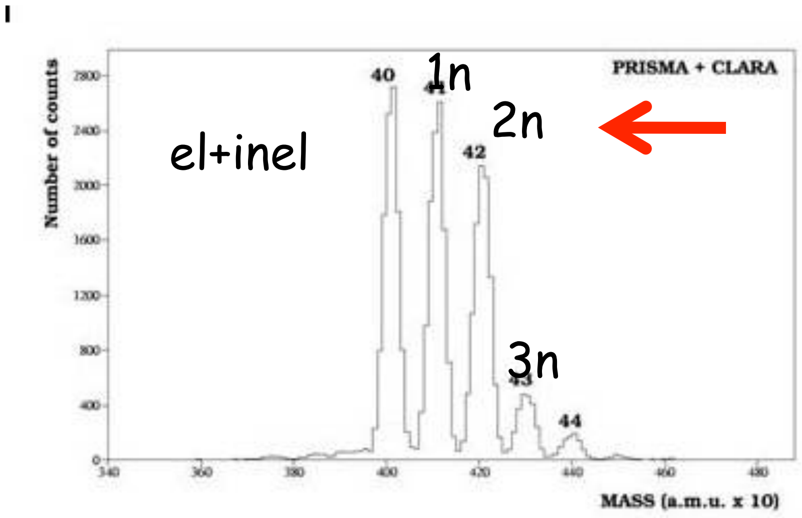
$^{40}Ca+^{208}Pb$





Obs: transfer of particles on both directions

Transition from direct to deep inelastic (cf Q distributions)



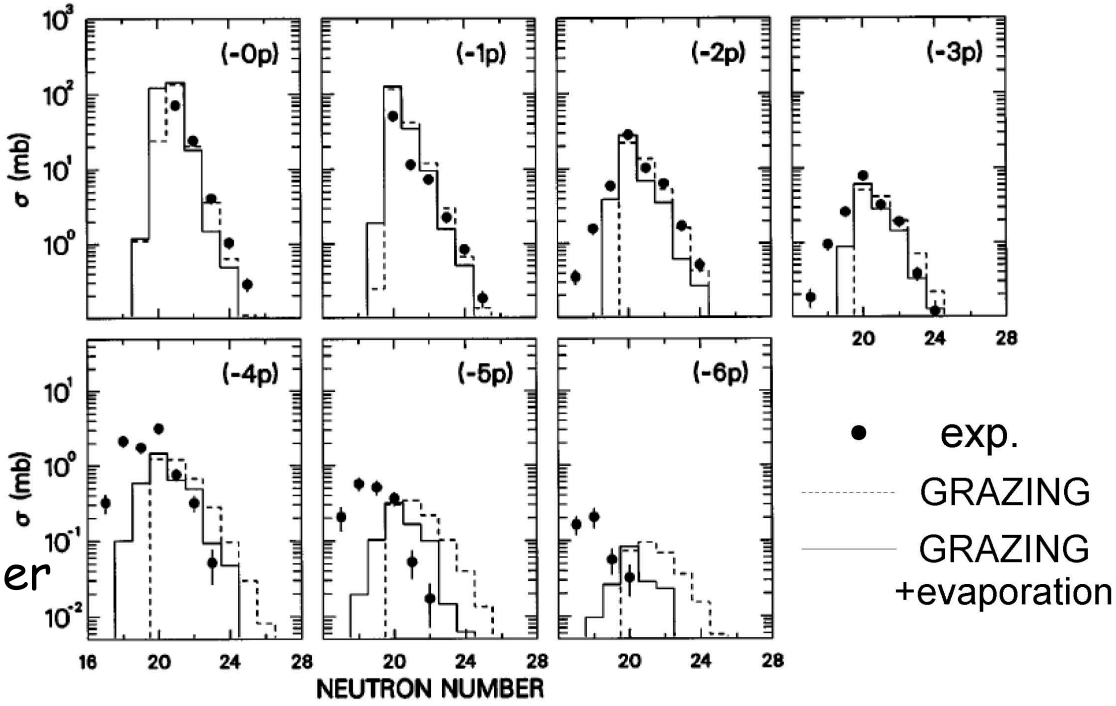
Example: Neutron transfer channels

(odd-even transfer effect? Structure effect?)

Basic and most popular approach: “Grazing model” (Nanni Pollarolo and Aage Winther), universally used

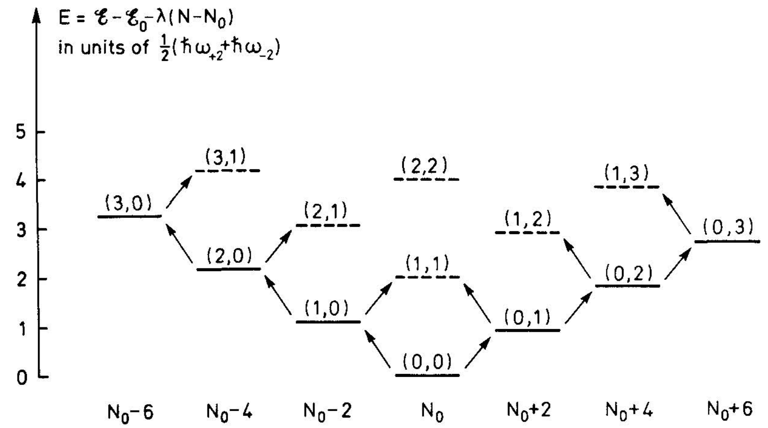
- semiclassical description of trajectory
- single-particle transfers
- two-particle transfers (double counting?)
- collective inelastic excitations
- sufficient phase-space for multi-transfer?
- “bare” ion-ion potential?
- structure information?
- excellent for “average” behavior. Specific cases? Weakly-bound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

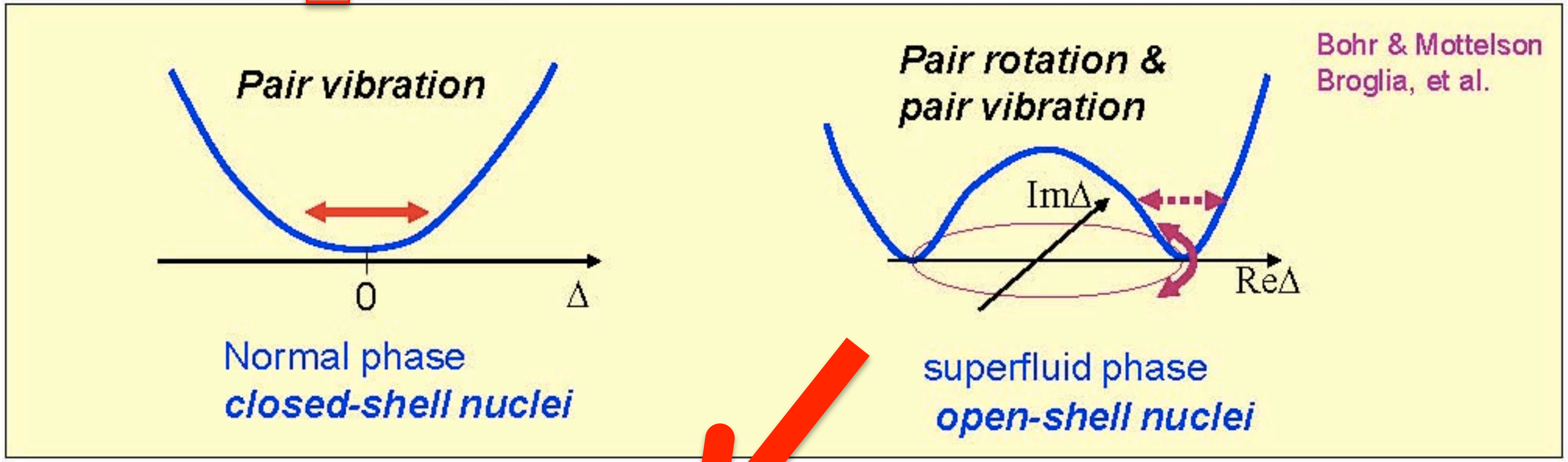
$^{40}\mathrm{Ca}+^{124}\mathrm{Sn}\ \mathrm{El}_{ab}=170$ MeV



Simple models (for the multi-pair transfer to the ground state sequence)

Simple models can be developed exploiting the formal analogy between “macroscopic” models for surface vibrations (and rotations) and “macroscopic” models for pairing, In the latter case, it is the mass number that can vibrate in a two-dimensional “*gauge*” space (regime of pairing vibrations) or lead to a stable deformation
(regime of pairing rotation) characterized by a “pairing” deformation parameter β_P (proportional to the pairing gap Δ), analogous to the “standard” deformation parameter β.
In the case of “superfluid” on “superfluid” one can expect very-enhanced pair transfer in analogy to the Josephson effect





Pair vibration

Normal phase

closed-shell nuclei

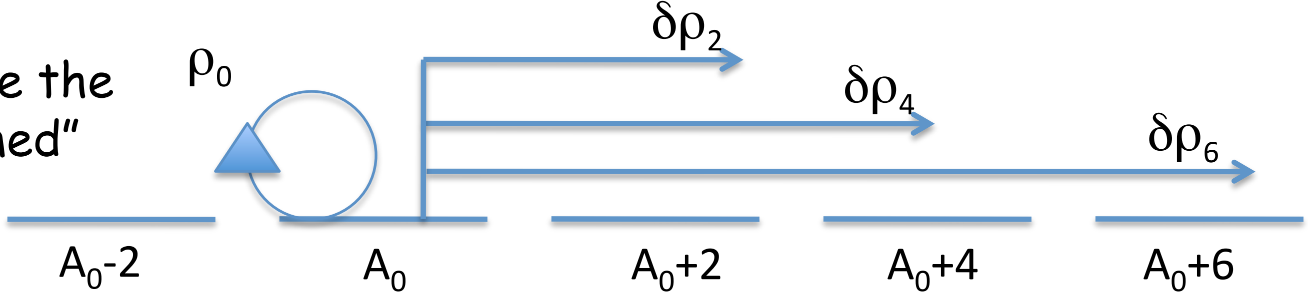
Pair rotation & pair vibration

superfluid phase

open-shell nuclei

Bohr & Mottelson
Broglia, et al.

$|A_0+\Delta N> = \exp\{i\ \Delta N\ \Phi\}\ |\psi^{A0}_{intr}>$



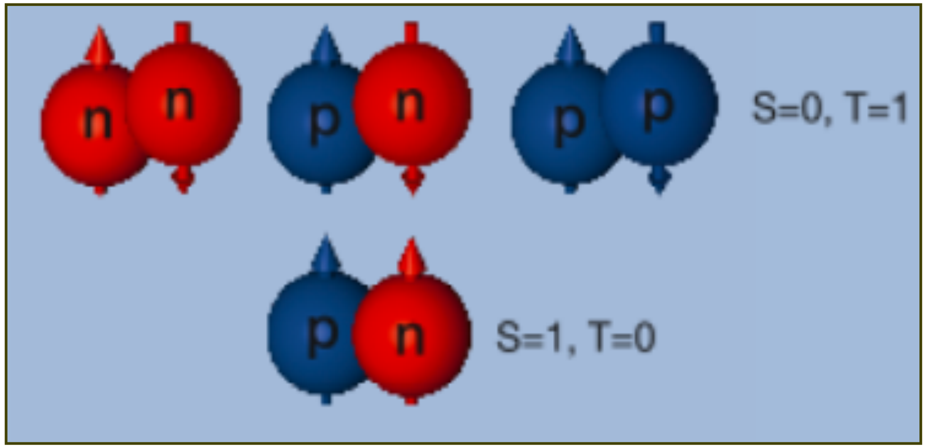
All ground states share the same intrinsic "deformed" states

I have discussed so far T=1 pair transfer (two neutrons or two protons). But what about neutron-proton correlations and one-proton plus one-neutron transfer?

n-p pair transfer as a dynamical tool to study the interplay of T=0 and T=1 pairing in proton-rich nuclei

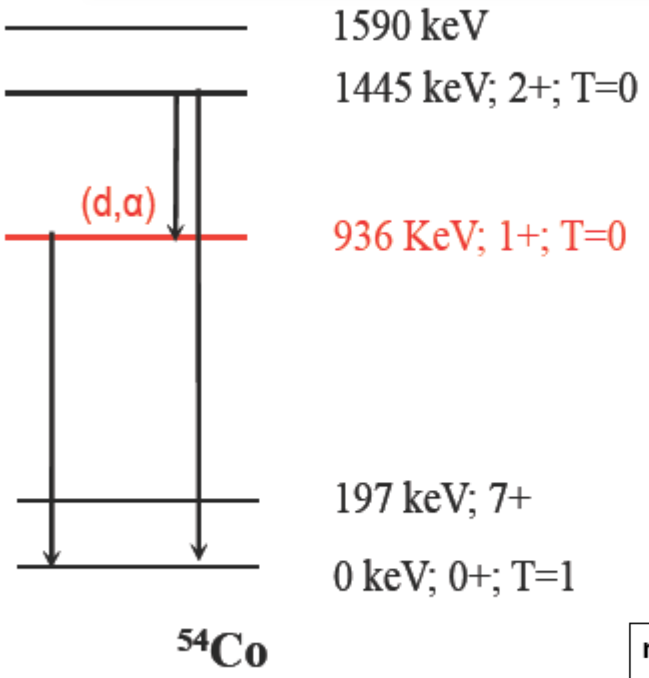
neutron-proton correlations

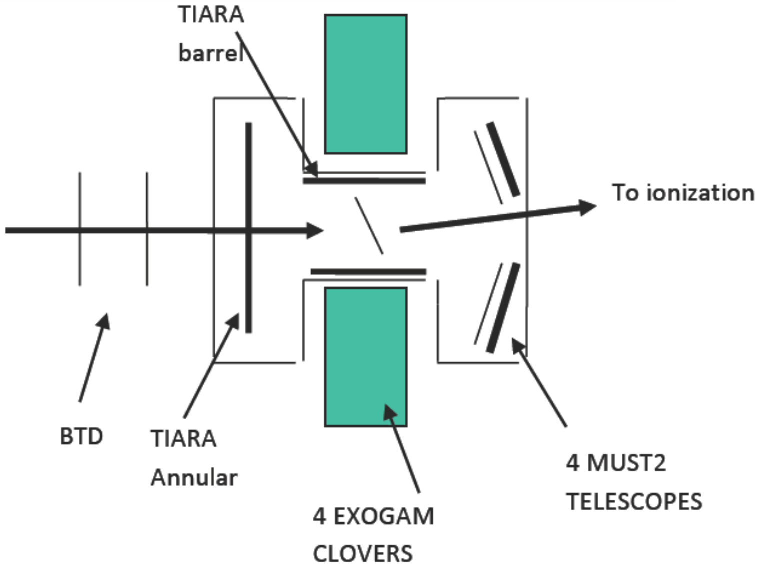
and the isospin degree of freedom

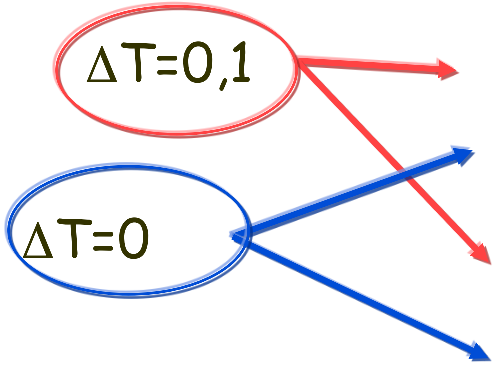


Key point: evidence for condensates of T=0 pairs in proton-rich nuclei along N=Z line?

Study of n-p pairing through two-nucleon transfer reactions with light ions







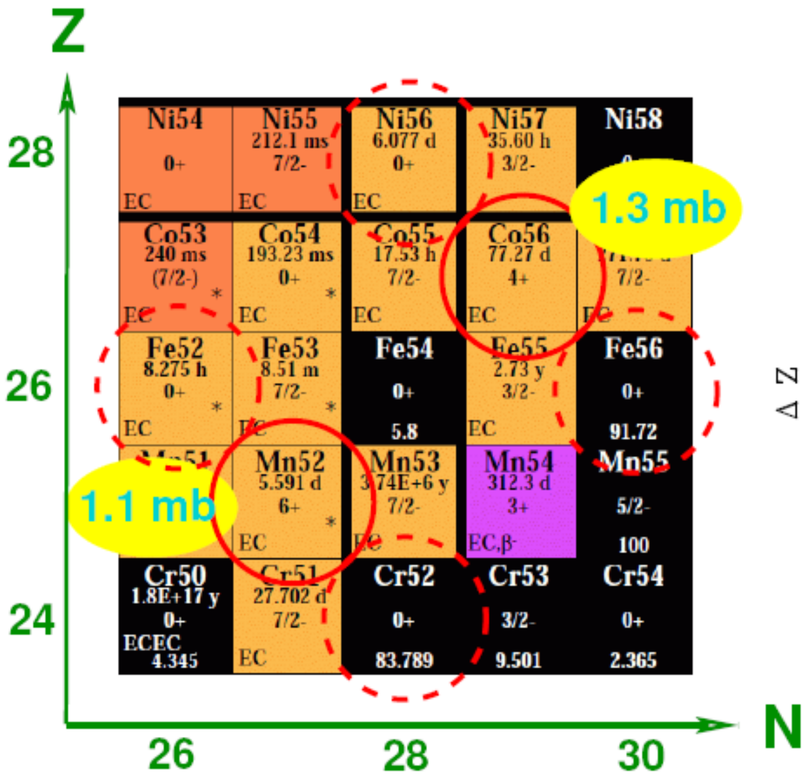
reaction	Beam intensity (pps)	Target thickness(mg/cm^2)	Counts/hour 1 level
^{56}Ni (p,^{3}He)	10^5	10	31
^{56}Ni(d,α)	10^5	10	14
^{48}Cr(p,^{3}He)	10^5	20	31
^{48}Cr(d,α)	10^5	10	14

M.Assie et al, GANIL PAC Proposal (Approved) Nov. 2011

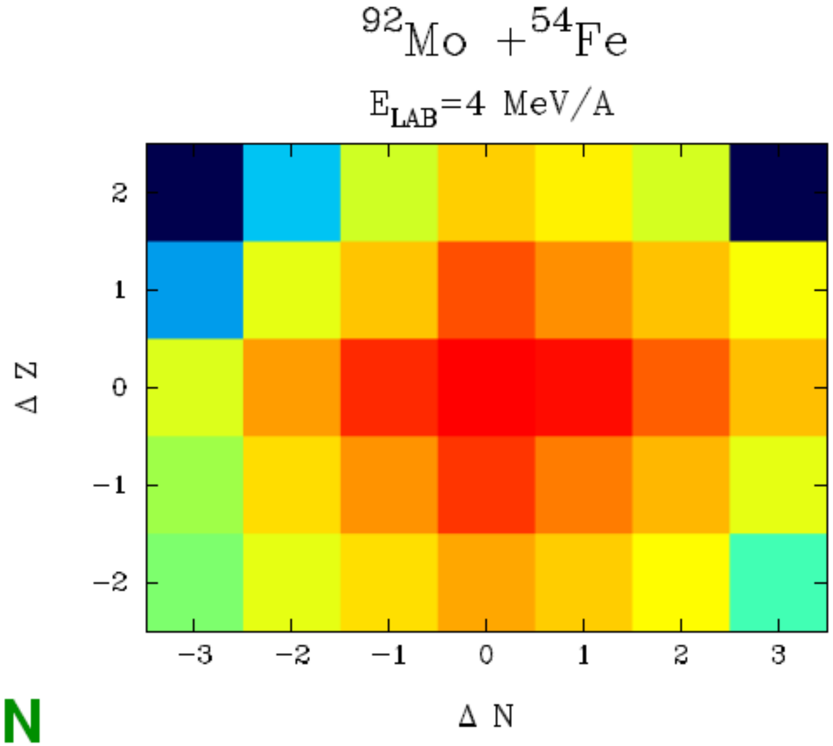
Population of (nn), (pp) and (np) channels with proton-rich beams

with proper heavy ions one can populate (nn), (pp) and (np) channels with comparable strength. In particular on can learn about (np) correlation properties

in the case of proton rich Mo and Fe nuclei, one gets as close as possible to the same N~Z region to be investigated in light ion induced reactions



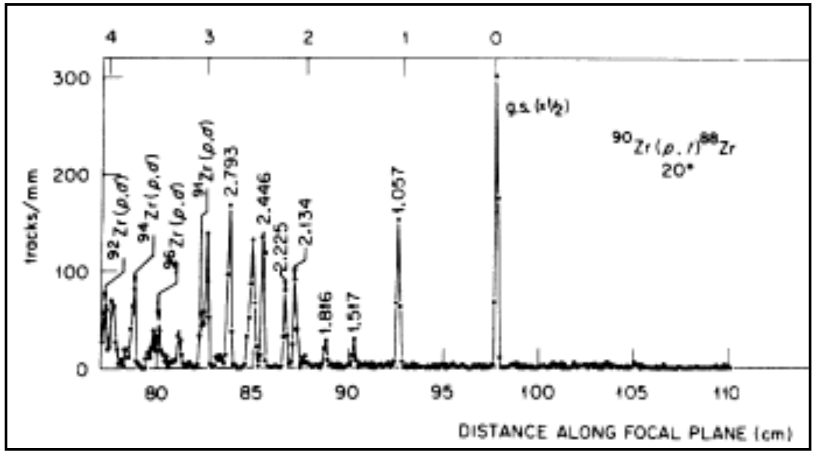
Grazing code calculations



S.Szilner, L.Corradi et al, May 2012 LNL PAC Proposal for PRISMA spectrormeter

light ion reactions

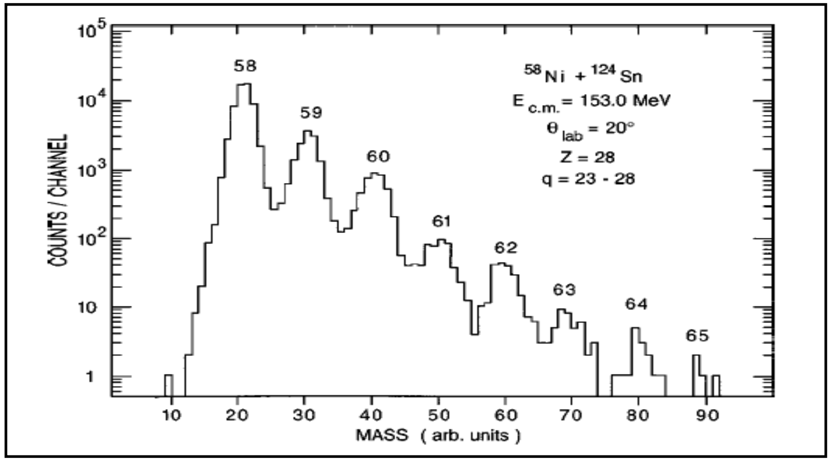
- probe single particle properties (spectroscopic factors, shell model)
- highly selective in energy and angular momentum transfer
- test for pairing and cluster properties



- radioactive beams in inverse kinematics

heavy ion reactions

- interplay between single particle and (multiple) pair transfer degrees of freedom
- simultaneous comparison of observables for nn/pp/np pairs
- optimum Q-value windows



- high intensity stable beams as well as radioactive beams

Thanks to

Angela Bonaccorso
Francesco Cappuzzello
Lorenzo Corradi
Fabio Crespi
Alessia Di Pietro
Marco Mazzocco
Oliver Wieland