ANPC

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Kruger National Park
29 November to 3 December 2023

Theoretical approaches describing low-lying dipole states

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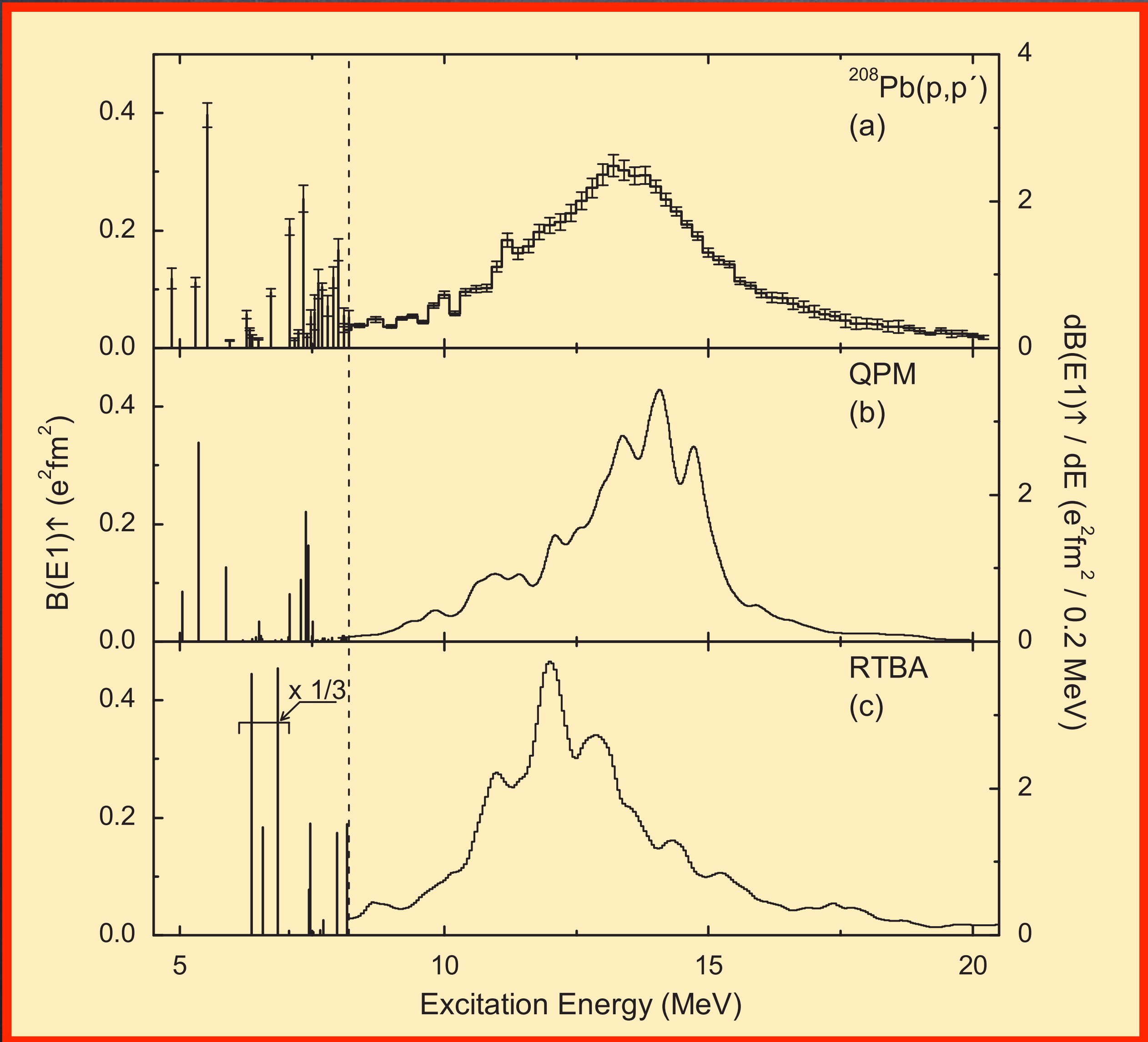
Congratulation to the Springboks!!
World Champions 2023!!

Experimental evidences for the PDR

Small peak, in the dipole strength distribution, at energies lower than the GDR (few % of EWSR). For nuclei with neutron excess.

A.Tamii et al., PRL 107 (2011) 062502

proton beam of 295 MeV at RCNP, Osaka, Japan



Quasiparticle-Phonon Model (QPM) calculations contain up to 3-phonon configurations at low energy

Relativistic Time-Blocking Approximation (RTBA) based on a particle-hole ⊗ phonon model space

Review papers

- N. Paar, D. Vretenar, E. Khan and G. Colò, Rep. Prog. Phys. 70, 691 (2007).
- T. Aumann and T. Nakamura, Phys. Scr. T152, 014012 (2013).
- D. Savran, T. Aumann and A. Zilges, Prog. Part. Nucl. Phys. 70, 210 (2013).
- A. Bracco, F. C. L. Crespi and E. G. Lanza, Eur. Phys. J. A 51, 99 (2015).
- A. Bracco, E. G. Lanza and A. Tamii, Prog. Part. Nucl. Phys. 106 (2019) 360.

Review papers
Theory

- E. G. Lanza, L. Pellegri, A. Vitturi and M. V. Andrés, Prog. Part. Nucl. Phys. 129 (2023) 104006
- E. G. Lanza and A. Vitturi, Theoretical Description of Pygmy (Dipole) Resonances, in Handbook of Nuclear Physics, Eds. I. Tanihata, H. Toki,T. Kajino

From the theoretical point of view they are studied with

Macroscopic model

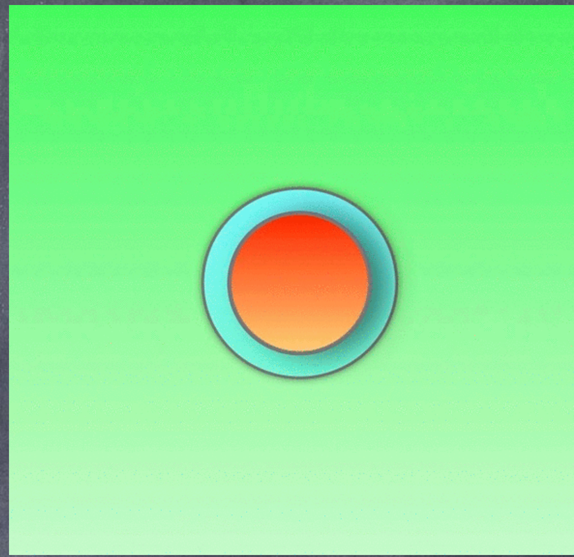
- Incompressible three fluid model: Steinwedel-Jensen
- Inert core oscillating against a neutron skin: Goldhaber-Teller

Microscopic model

Inert core oscillating against a neutron skin: Goldhaber-Teller

$$\rho(r) = \underbrace{\rho_p(r) + \rho_n^C(r)}_{\text{Core}} + \rho_n^V(r)$$

neutron Valence



$$\delta\rho_n(r) = \delta\left[\frac{N_V}{A}\frac{d\rho_n^C(r)}{dr} - \frac{N_C+Z}{A}\frac{d\rho_n^V(r)}{dr}\right]$$ neutron

$$\delta\rho_p(r) = \delta\left[\frac{N_V}{A}\frac{d\rho_p(r)}{dr}\right]$$ proton

$$\delta\rho_{is} = \delta\left[\frac{N_V}{A}\frac{d(\rho_n^C+\rho_p)}{dr} - \frac{N_C+Z}{A}\frac{d\rho_n^V}{dr}\right]$$

isoscalar

$$\delta\rho_{iv} = \delta\left[\frac{N_V}{A}\frac{d(\rho_n^C-\rho_p)}{dr} - \frac{N_C+Z}{A}\frac{d\rho_n^V}{dr}\right]$$

isovector

From the theoretical point of view they are studied with

Macroscopic model

- Incompressible three fluid model: Steinwedel-Jensen
- Inert core oscillating against a neutron skin: Goldhaber-Teller

Microscopic model

- HF + RPA with Skyrme interaction
- Relativistic RPA and relativistic QRPA
- HFB + QRPA with Skyrme or Gogny interactions
- Second RPA (SRPA) and Subtracted SRPA (SSRPA)
- Quasi particle phonon model (QPM)
- Relativistic Quasi-particle Time Blocking Approximation (RQTBA)
- ……

coupling to more complex configurations

Transition density for a state ν with an angular momentum λ in the RPA approach

$$\delta\rho^{\nu} = \frac{1}{\sqrt{4\pi}} \sum_{ph} \frac{\hat{j}_p \hat{j}_h}{\hat{\lambda}} (-)^{j_p + j_h - \frac{1}{2}} < j_h \frac{1}{2}\, j_p - \frac{1}{2} | \lambda 0 > \times \delta(\lambda + l_p + l_h, even) [X^{\nu}_{ph} - Y^{\nu}_{ph}] R_{l_p j_p}(r) R_{l_h j_h}(r)$$

Necessary to take into account the coupling to more complex configurations.

In second RPA (SRPA)

$$q^{\dagger}_{\nu} = \sum_{ph} [X^{\nu}_{ph} a^{\dagger}_p a_h - Y^{\nu}_{ph} a^{\dagger}_h a_p] + \sum_{p<p', h<h'} [X^{\nu}_{php'h'} a^{\dagger}_p a_h a^{\dagger}_{p'} a_{h'} - Y^{\nu}_{php'h'} a^{\dagger}_h a_p a^{\dagger}_{h'} a_{p'}]$$

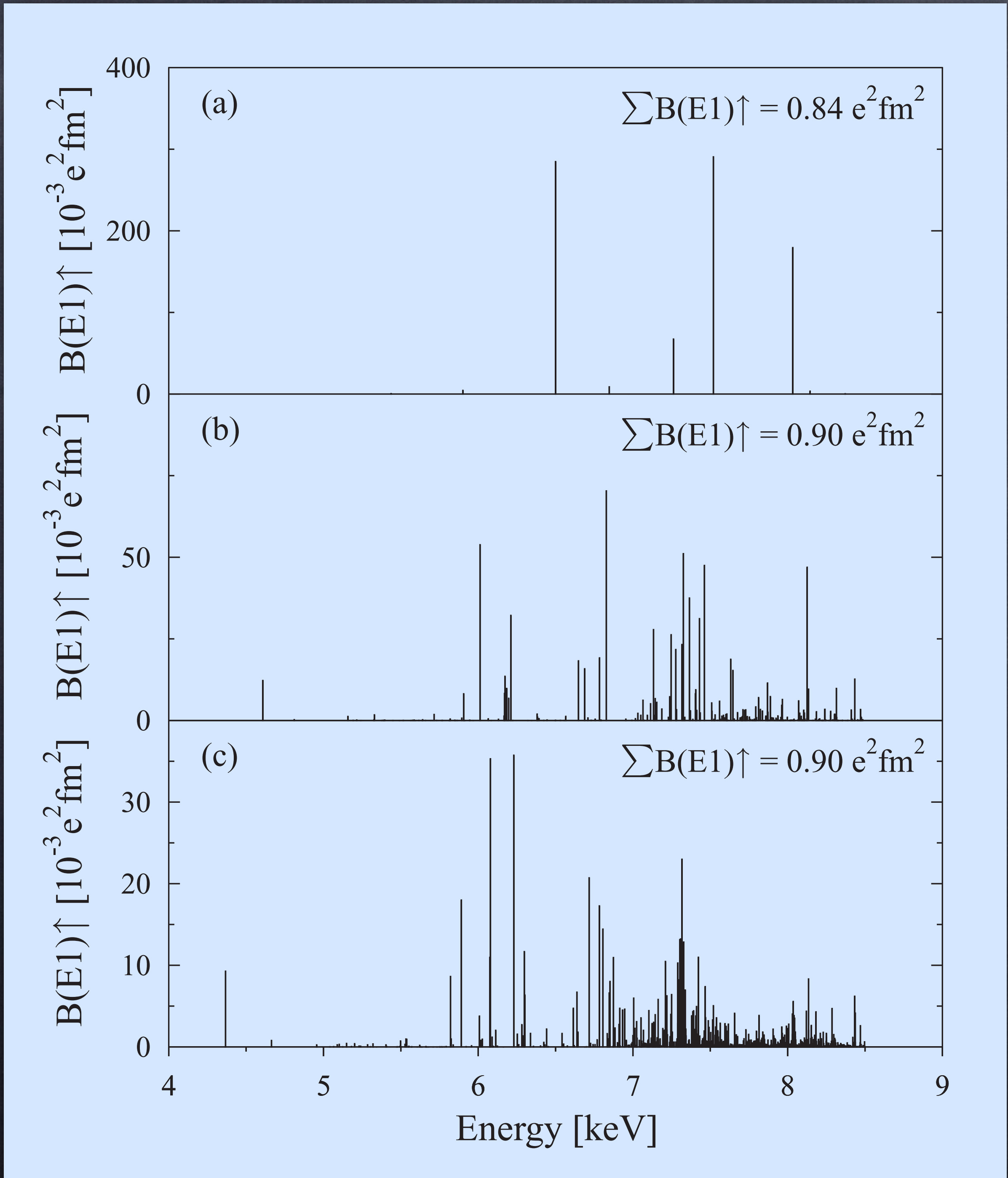
1p - 1h configuration 2p - 2h configuration

Subtracted second RPA (SSRPA) model to avoid double counting correlations

QPM and RQTBA explicitly couple the 1p - 1h configuration with two- or three-phonon states.

$$|\Phi_{\alpha} > = \sum_{\nu_1} c^{\alpha}_{\nu_1} | \nu_1 > + \sum_{\nu_1 \nu_2} c^{\alpha}_{\nu_1 \nu_2} | \nu_1 \nu_2 > + \sum_{\nu_1 \nu_2 \nu_3} c^{\alpha}_{\nu_1 \nu_2 \nu_3} | \nu_1 \nu_2 \nu_3 >$$

QPM for ^{136}Xe for several approximations



Coupling to only one-phonon states

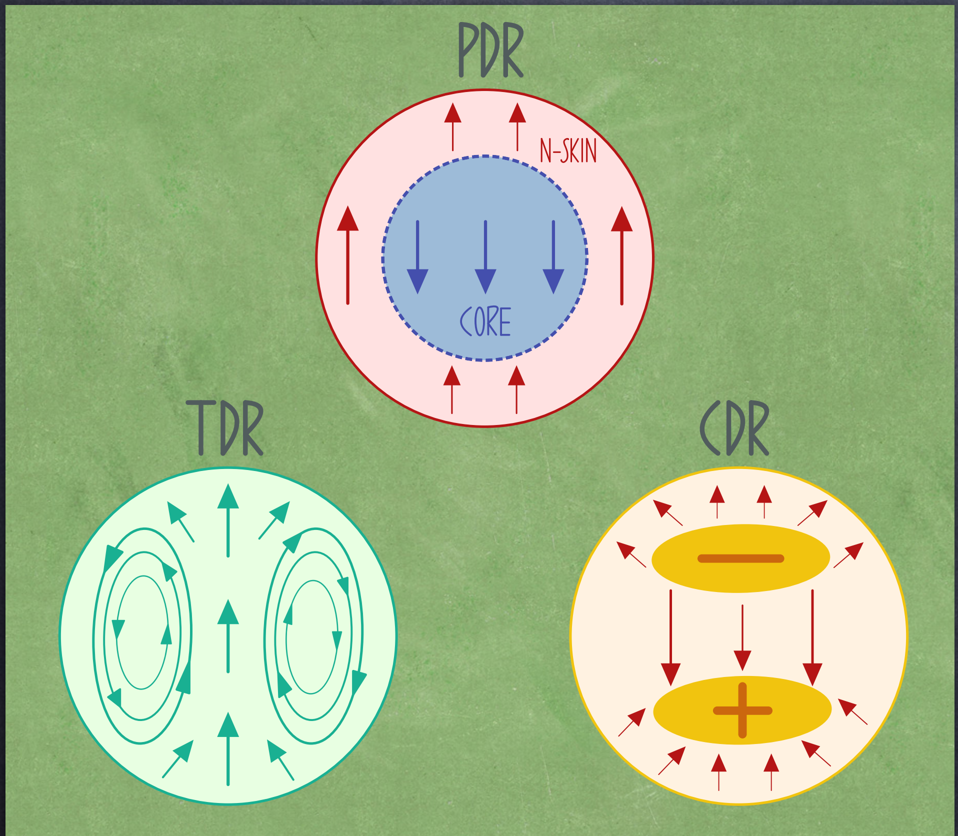
Coupling to also two-phonon states

Coupling to also two- and three-phonon states

The isoscalar dipole channel receive contributions from the toroidal and compressional modes.

The operators generating the toroidal and compressional modes are obtained as a second-order terms in a long wavelength limit of the electric multipole operator.

$$O_{1M}^{(Tor)} = -\frac{1}{10\sqrt{2}} \int d^3r \left[r^3 - \frac{5}{3} < r^2 > r \right] \vec{Y}_{11M}(\hat{r}) \cdot \left(\vec{\nabla} \times \vec{j}(\vec{r}) \right)$$



They were predicted many years ago, but clear experimental evidence is lacking so far.

See Peter von Neumann-Cosel talk

It is well established that the low-lying dipole states (PDR) have a strong isoscalar component.

Therefore they can be studied by both isoscalar and isovector probes

The low-lying dipole states can be a good laboratory to study the interplay between isoscalar and isovector modes

Experimentally they are studied with

Isovector probes

- Relativistic Coulomb excitation at GSI
- Nuclear resonance fluorescence (NRF) technique: (γ, γ') at Darmstadt
- Coulomb excitation by proton scattering: (p, p') in Osaka and iThemba LABS

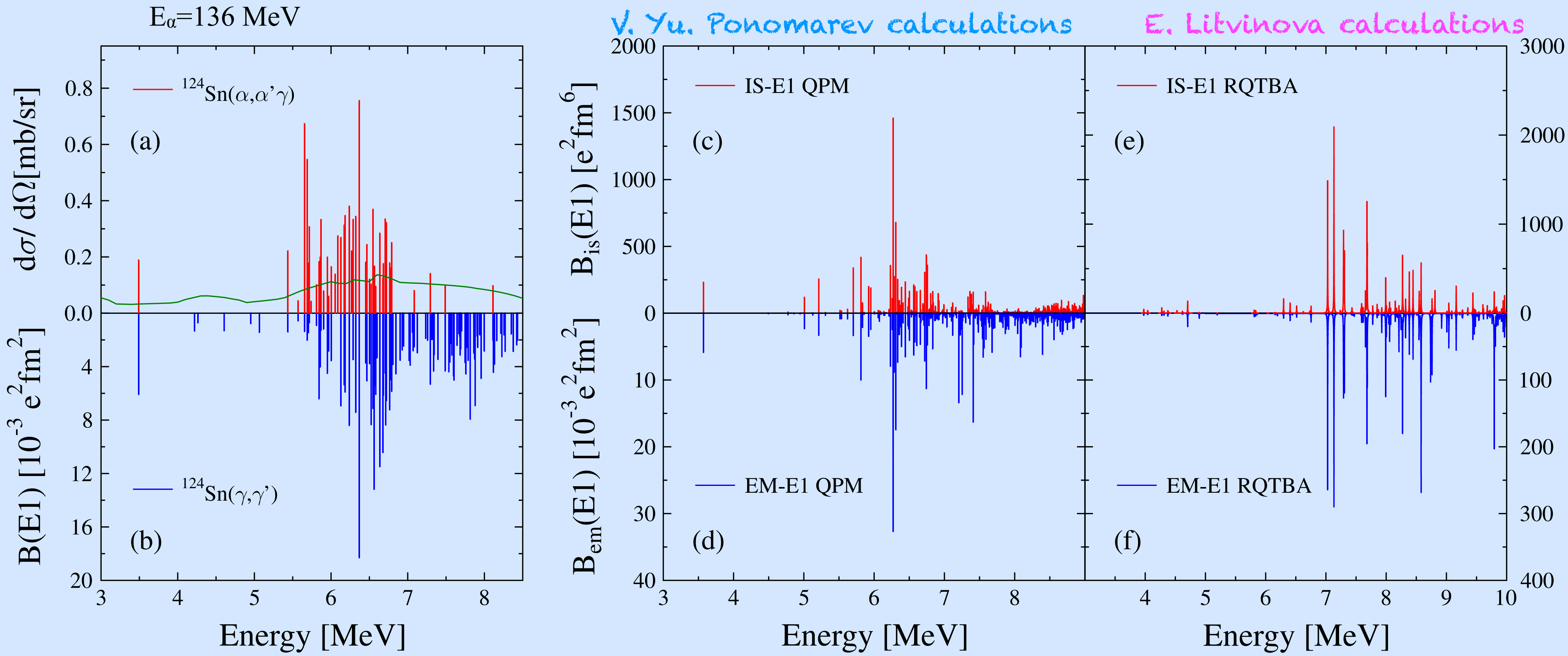
Isoscalar probes

- $(\alpha, \alpha' \gamma)$ At KVI
- $(^{17}O, {}^{17}O' \gamma)$ on various target ^{208}Pb, ^{90}Zr, ^{140}Ce at Legnaro lab (LNL-INFN)
- $(^{68}Ni, {}^{68}Ni' \gamma)$ on ^{12}C at INFN-LNS, Catania

For the Isoscalar probes, inelastic cross sections are also measured

Splitting of the low-lying dipole strength

J. Enders et al., PRL 105 (2010) 212503



The lower lying group of states is excited by both isoscalar and isovector probes while the states at higher energy are excited by photons only.

For the isoscalar case the comparison is between cross section and $B_{is}(E1)$

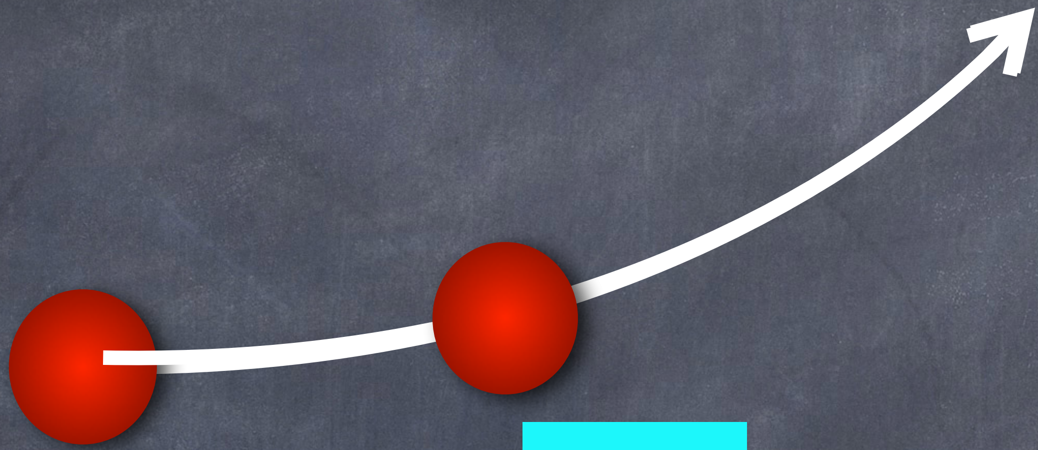
The description of inelastic cross section with isoscalar probes

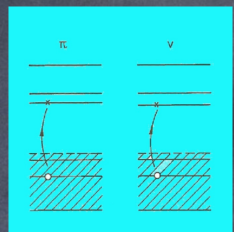
- DWBA, first order theory
- Coupled Channel, high order effect important
- Semiclassical approximations (semiclassical Coupled Channel Equations)

In semiclassical models it is assumed that the motion of the two nuclei can be described according to the classical mechanics. This is true when the De Broglie wave length is small with respect to the distance of closest approach.

$$\lambda = \frac{h}{\mu v} \quad << \quad d = \frac{Z_A Z_B e^2}{\mu v^2}$$

Time dependent Semiclassical Approximation to the Coupled Channel method





The two colliding nuclei move according to a classical trajectory determined by the Coulomb plus nuclear fields, while the inelastic excitations are described according to quantum mechanics.

This is realized by building a set of coupled first order differential equations for the time dependent coefficients $C(t)$ of the channels wave functions

Semiclassical Model

The two nuclei move according to a classical trajectory while quantum mechanics is used to describe the internal degrees of freedom

$$H = H_A + H_B$$

where

$$H_A = H_A^0 + W_A(t)$$

$$H_A^0 = \sum_i \epsilon_i a_i^\dagger a_i + \frac{1}{4} \sum_{ijlk} V_{ijlk} a_i^\dagger a_j^\dagger a_l a_k$$

$$W_A(t) = \sum_{ij} < i | U_B(\vec{R}(t)) | j > a_i^+ a_j + h.c.$$

t-dependence through R(t)

$$W = W^{00} + \sum_\nu W_\nu^{10} Q_\nu^\dagger + h.c.$$

The term W^{00} represents the interaction of the two colliding nuclei in their ground state; in the present case it has also an imaginary part that describes the absorption due to the nonelastic channels.

The term W^{10} connect states differing by one phonon

The wave function of the system

$$|\Psi(t)>=|\psi_A(t)>|\psi_B(t)>$$

To solve the Schrödinger equation

$$i\hbar\frac{\partial|\psi_A(t)>}{\partial t}=H_A|\psi_A(t)>$$

Calling $|\Phi_\alpha>$ the eigenstates of the internal Hamiltonian

The time dependent state is

$$H^0|\Phi_\alpha>=E_\alpha|\Phi_\alpha>$$

$$|\psi(t)>=\sum_\alpha C_\alpha(t)e^{-\frac{i}{\hbar}E_\alpha t}|\Phi_\alpha>$$

The Schrödinger equation can be cast into a set of linear differential equations

$$\dot{C}_\alpha(t)=-\frac{i}{\hbar}\sum_{\alpha'}e^{\frac{i}{\hbar}(E_\alpha-E_{\alpha'})t}<\Phi_\alpha|W(t)|\Phi_{\alpha'}>C_{\alpha'}(t)$$

SEMICLASSICAL COUPLED CHANNEL EQUATIONS

The semiclassical coupled channel equations have to be solved for each impact parameter, then $C(b,\alpha,t)$

Probability to excite the state Φ_α

b impact parameter

$$P_\alpha(b) = |C_\alpha(b, +\infty)|^2$$

its cross section is

$$\sigma_\alpha = 2\pi \int_0^{+\infty} P_\alpha(b) T(b) b \, db.$$

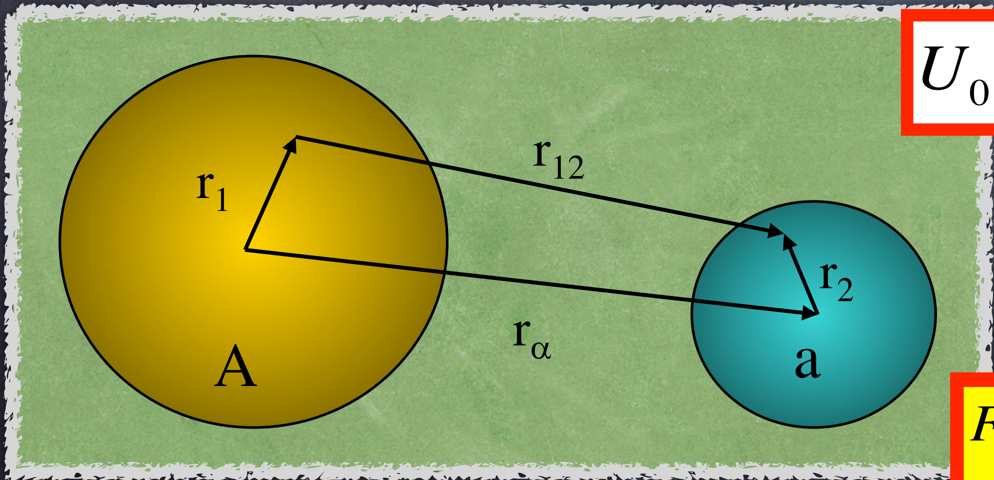
T(b): transmission coefficient taking into account process not explicitly included in the space model.

It falls to zero as the overlap between the two nuclei increases.

SEMICLASSICAL COUPLED CHANNEL EQUATIONS

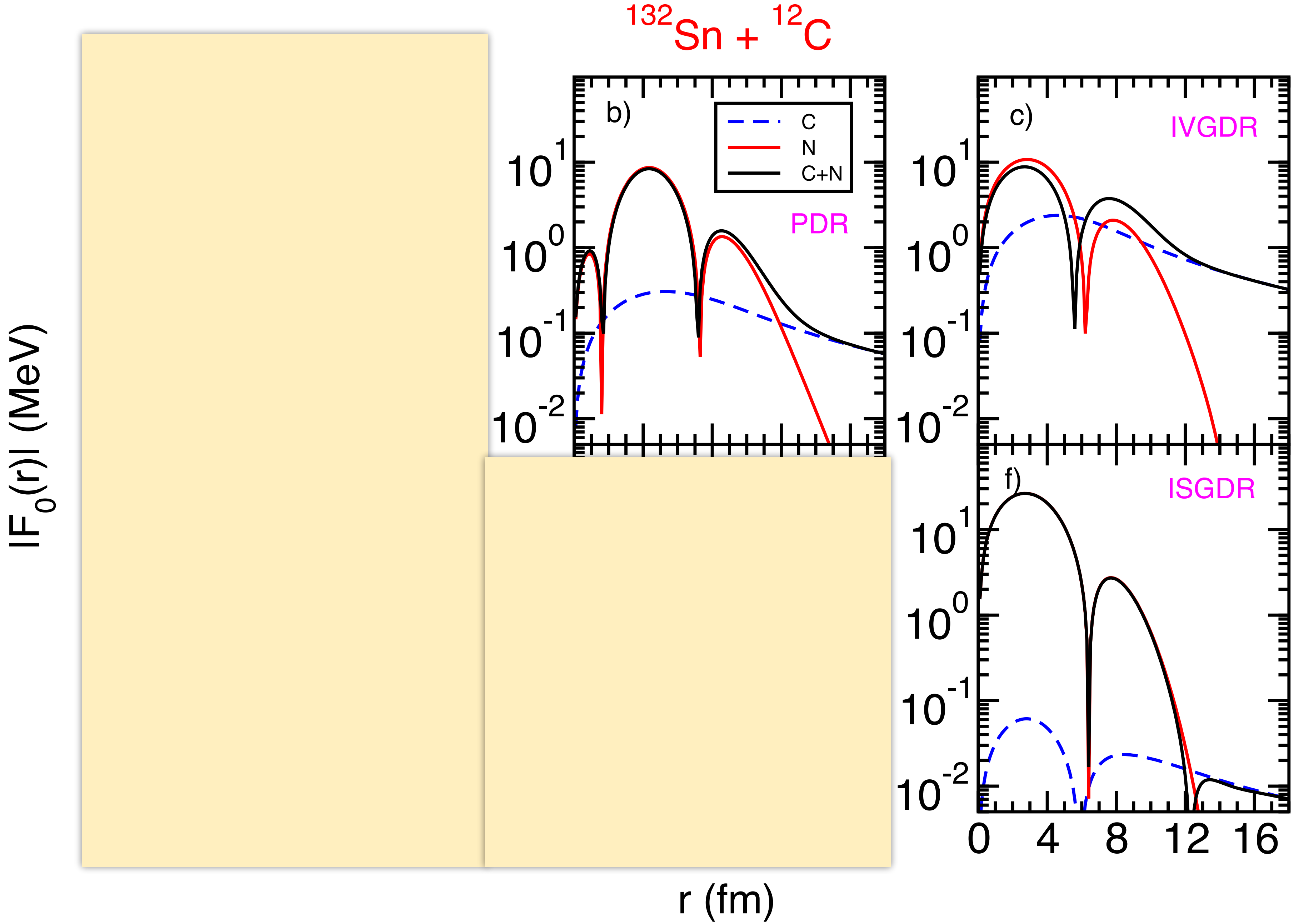
$$\dot{C}_\alpha(t) = -\frac{i}{\hbar}\sum_{\alpha'} e^{\frac{i}{\hbar}(E_\alpha - E_{\alpha'})t} < \Phi_\alpha|W(t)|\Phi_{\alpha'} > C_{\alpha'}(t)$$

The fundamental ingredients for the calculation of the excitation process are the optical potential and the radial form factor. Both of them are calculated within the double folding procedure.



$$U_0(\vec{r}_\alpha) = \iint \rho_A(\vec{r}_1)\, v_0(r_{12})\, \rho_a(\vec{r}_2)\, d\vec{r}_1\, d\vec{r}_2$$

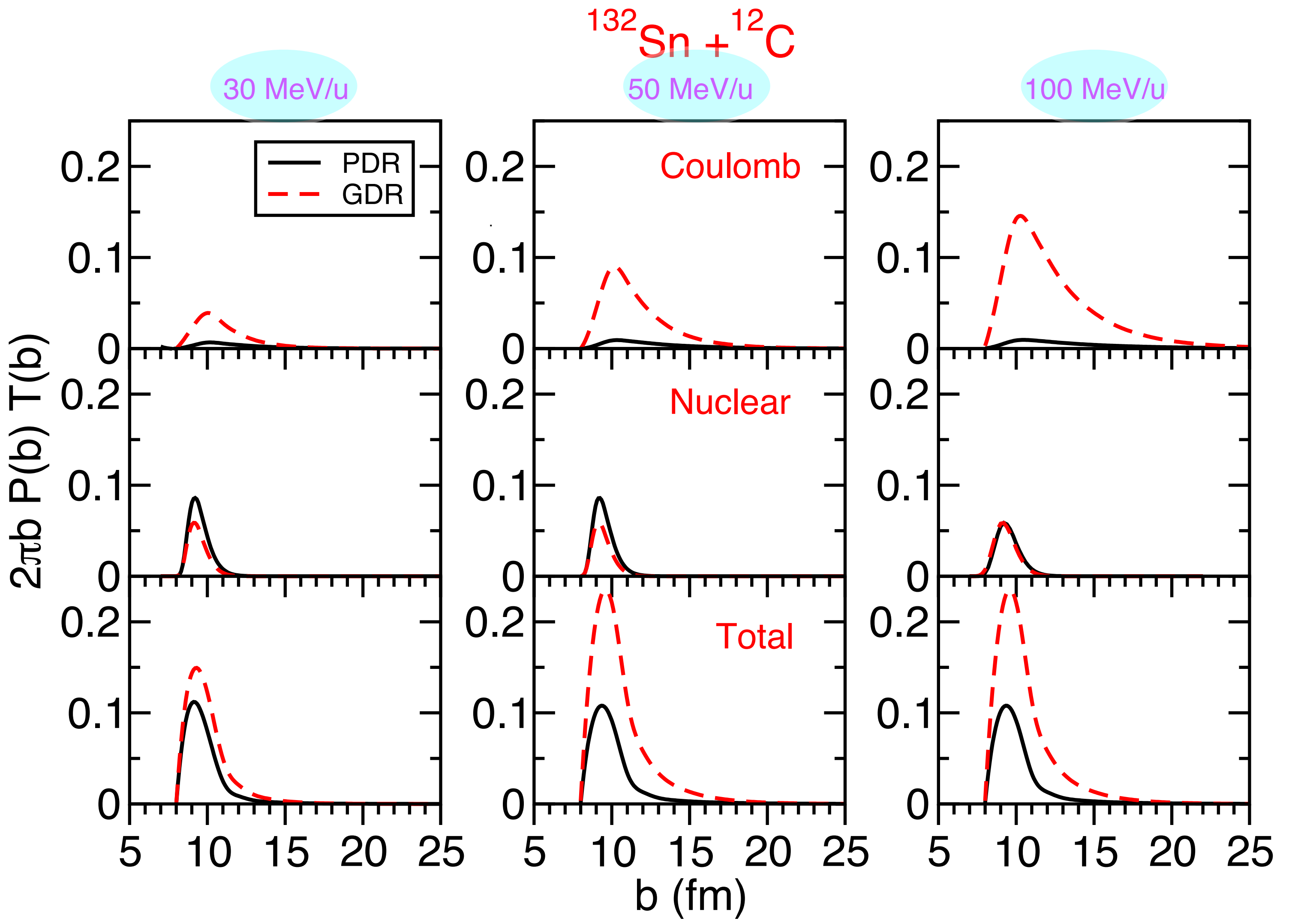
$$F_0(r_\alpha) = \iint \left[\delta\rho_{An}(\vec{r}_1) + \delta\rho_{Ap}(\vec{r}_1)\right] \times \\ \times v_0(r_{12}) \left[\rho_{an}(\vec{r}_2) + \rho_{ap}(\vec{r}_2)\right] r_1^2\, dr_1\, r_2^2\, dr_2$$



132Sn + 12C
b)
C
N
C+N
PDR
c)
IVGDR
f)
ISGDR
10^1
10^0
10^-1
10^-2
0
4
8
12
16
|F0(r)| (MeV)
r (fm)

Partial waves cross section as function of the impact parameter.

A limited range of impact parameters

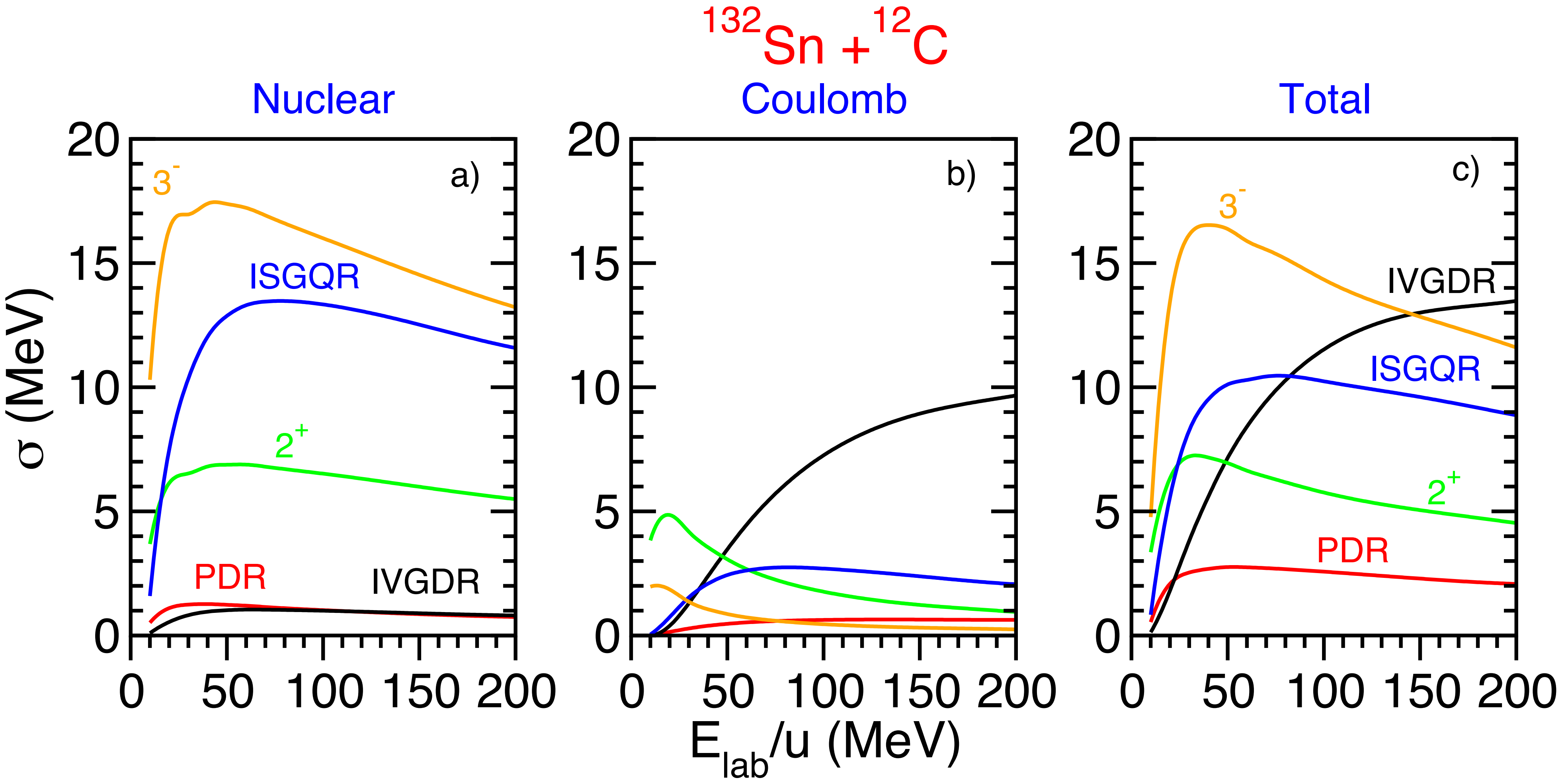


Only a limited range of impact parameters give contribution to the nuclear part; for the Coulomb part the range of b is much larger.

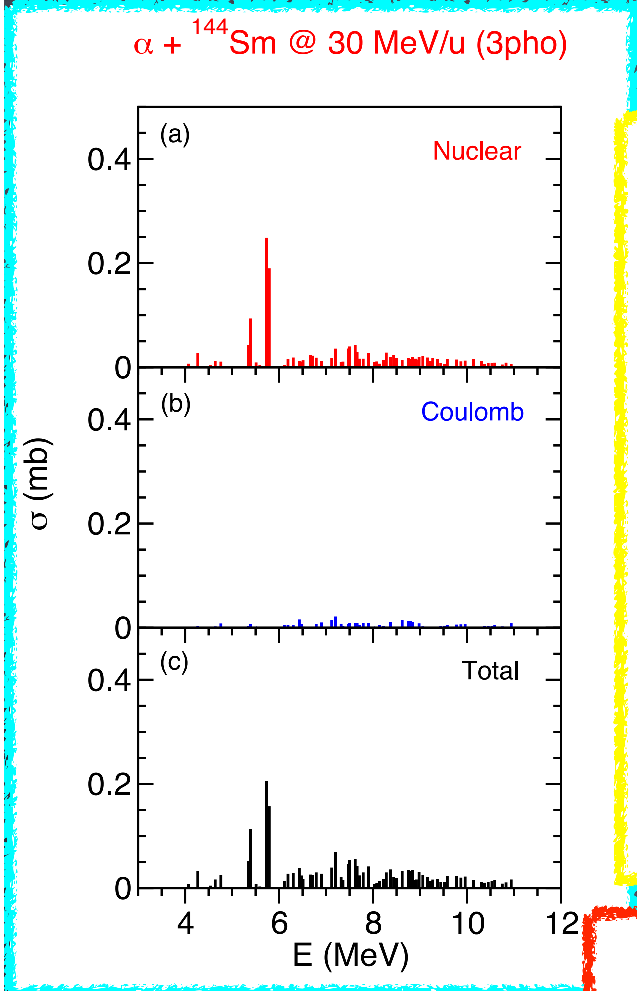
As the incident energy goes down, the range of impact parameters participating to the Coulomb excitation process is decreasing.

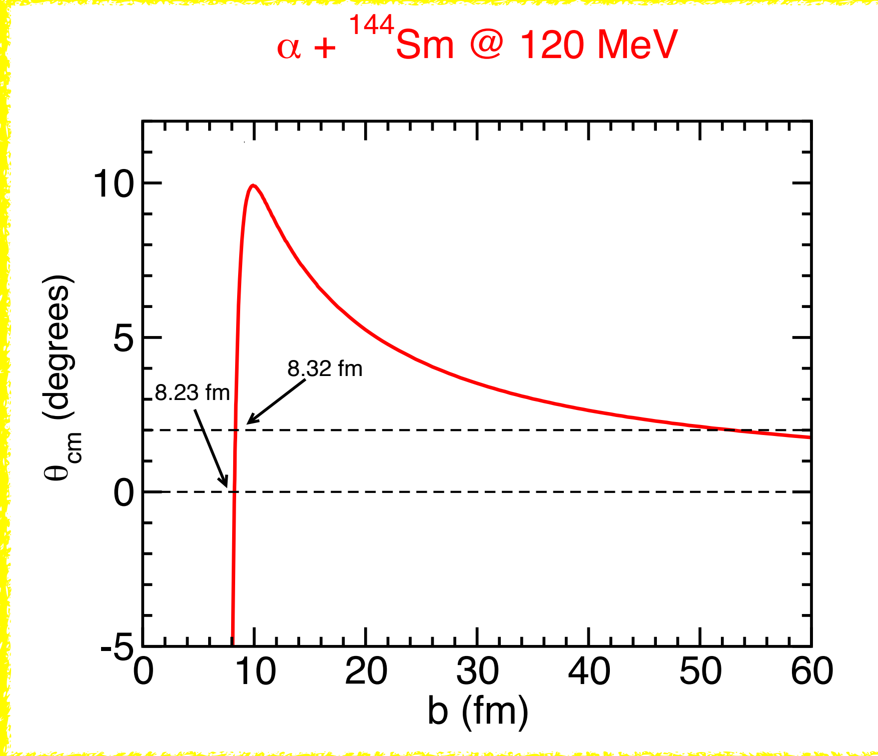
$$\sigma_\alpha = 2\pi \int_0^{+\infty} P_\alpha(b) T(b) b \, db.$$

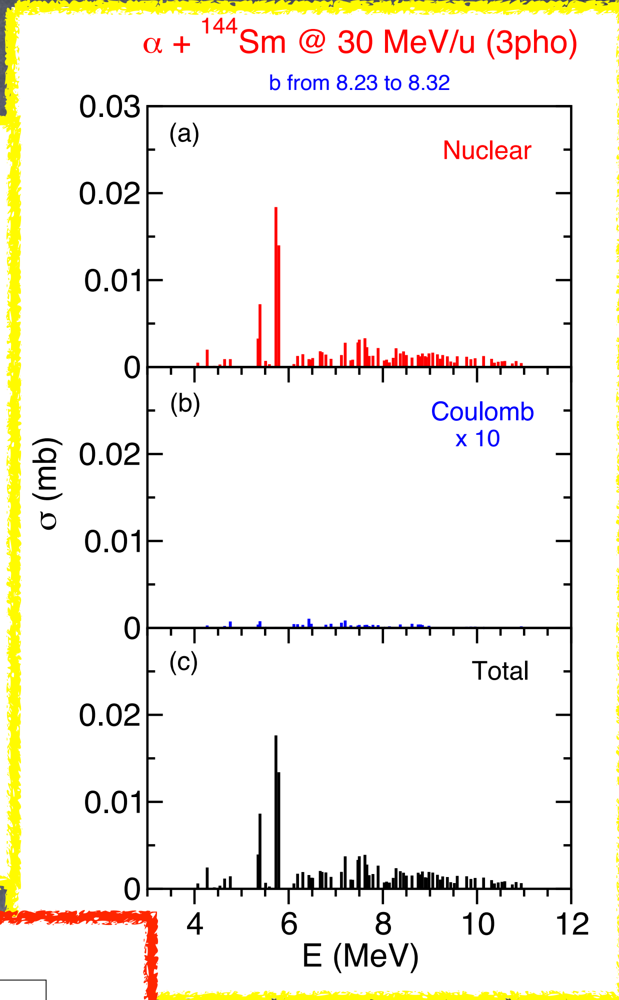
Total cross section

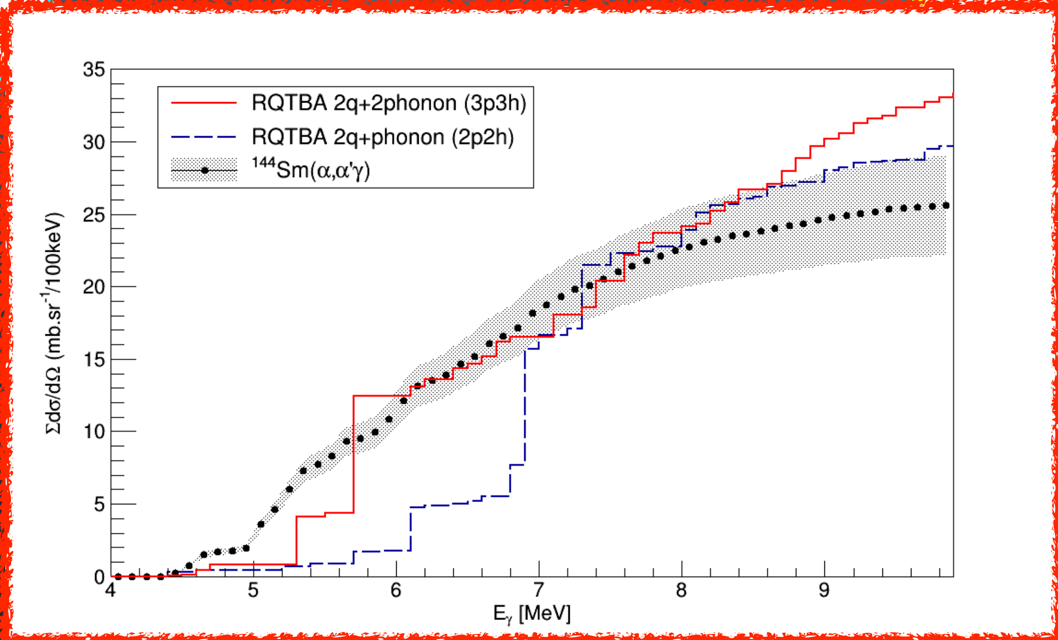


α + ^{144}Sm at 120 MeV at iThemba









RQTBA Calculation by Elena Litvinova

The model have been successfully employed in several physical problem involving heavy ion collisions.

Calculation of polarisation potential

Multiphonons excitation in heavy ion collisions

Isoscalar excitation of low-lying dipole (PDR) states in exotic and stable nuclei

Summary

Semiclassical model have been usefully used for calculations and interpretations of various nuclear phenomena.

The use of the semi-classical coupled-channel equations is more convenient than the quantum CC because the calculations can be guided by a physical insight and the number of channels included in the calculations can be orders of magnitude larger.

Combined reactions processes involving the Coulomb and nuclear interactions can provide a clue to reveal characteristic features of some particular states.

From the theoretical point of view the effort should be addressed to :

- a better knowledge of the “composition” of the low-lying dipole states,
- a better description of the response of deformed nuclei to isoscalar and isovector probes.
- improve the calculations of inelastic cross section (when isoscalar probes are used).

Thank you
for your attention

In collaboration with

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