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# Pygmy Dipole Resonances within a semiclassical coupled channel model

E. G. Lanza
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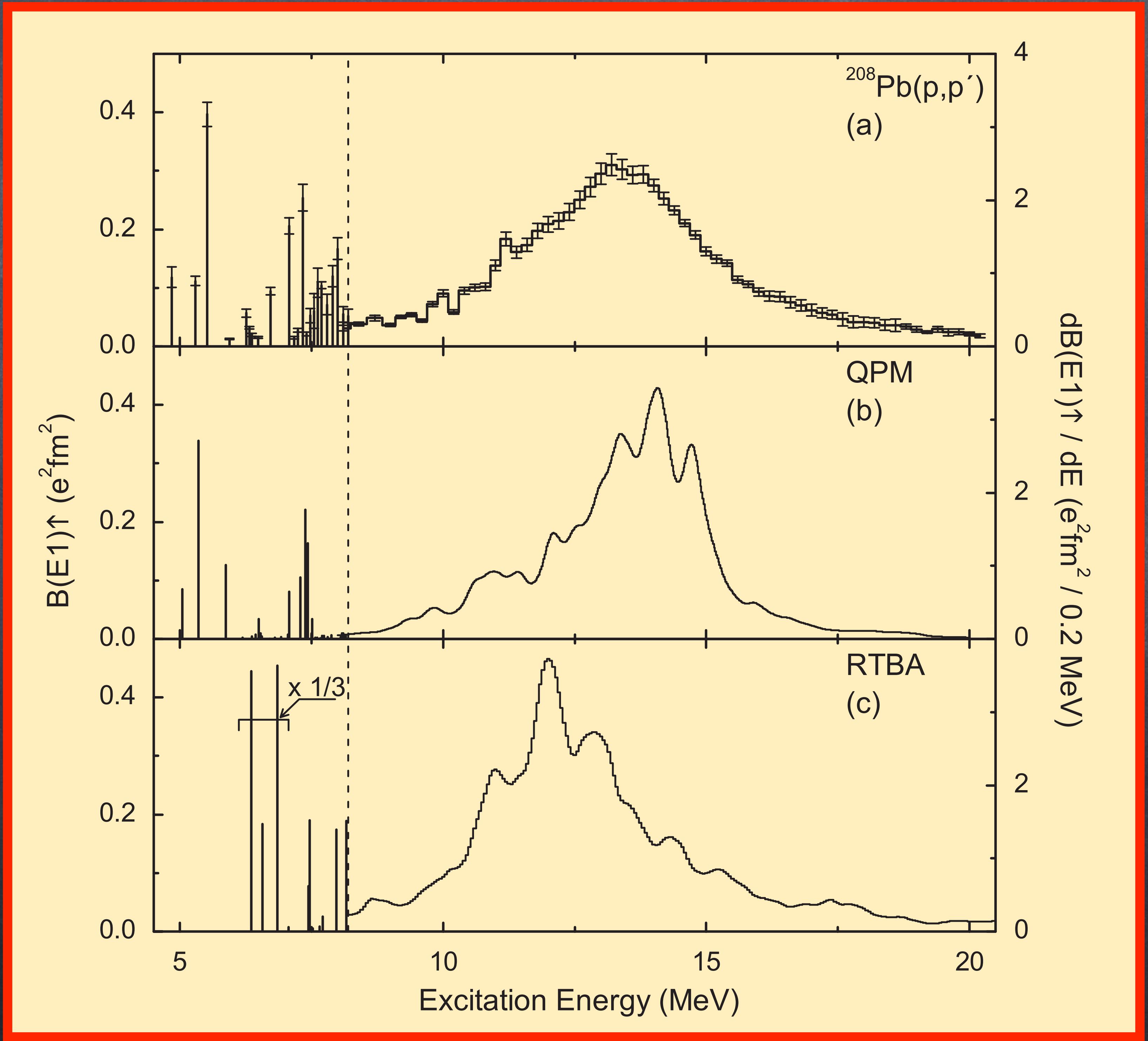

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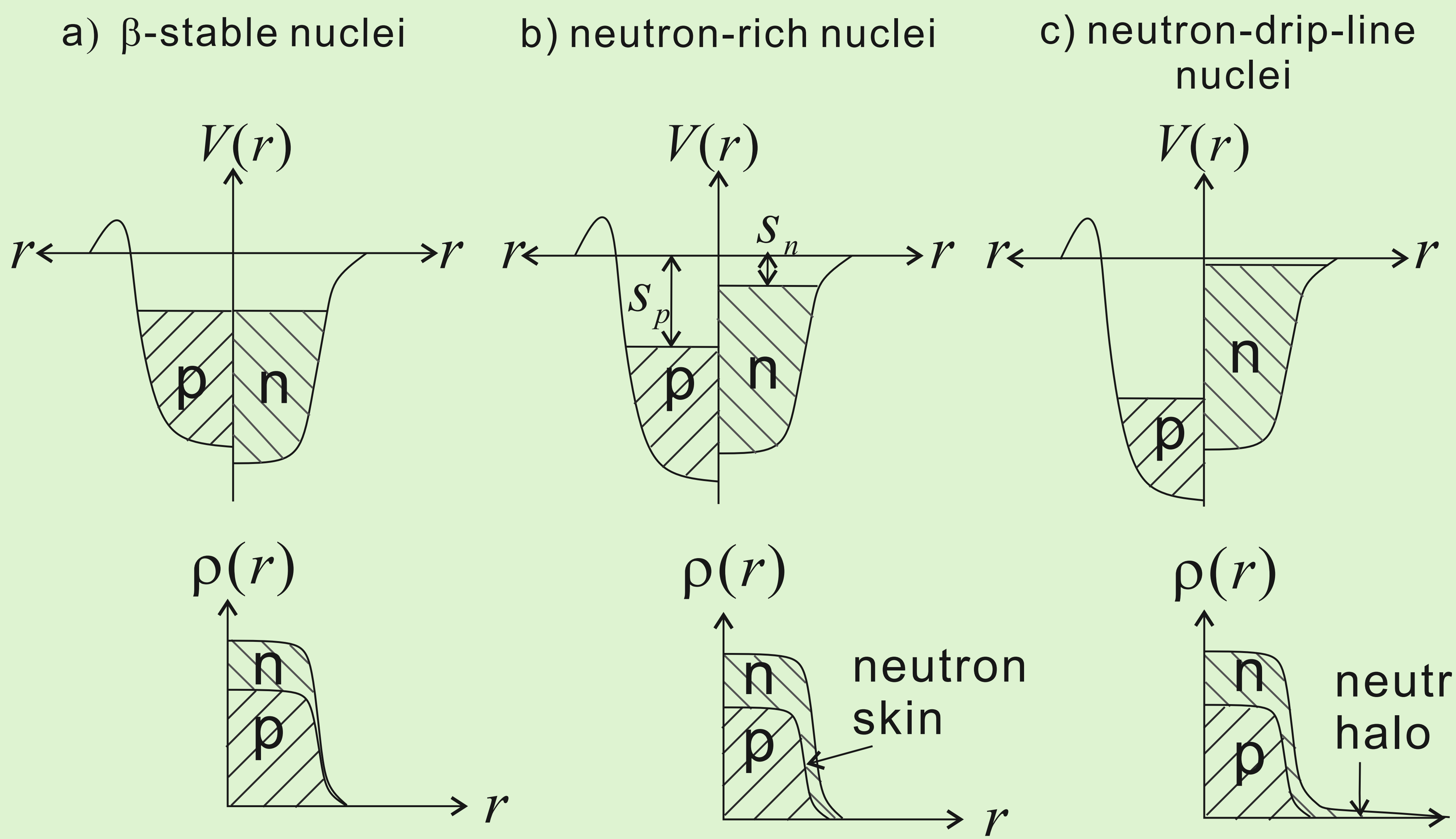

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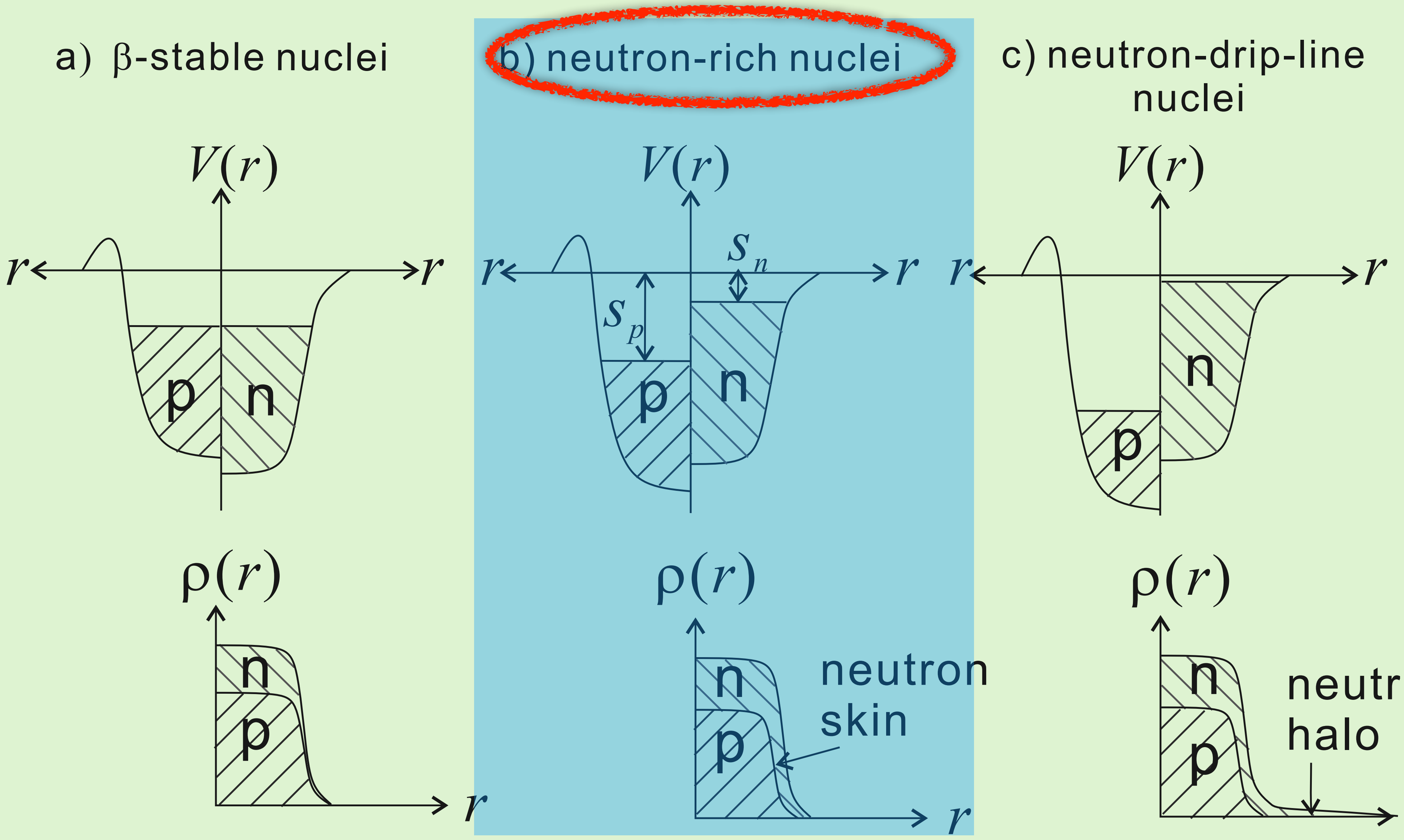

# Review papers

- 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

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- HF + RPA with Skyrme interaction
- Relativistic RPA and relativistic QRPA
- HFB + QRPA with Skyrme or Gogny interactions
- Second RPA (SRPA) and Subtracted SRPA (SSRPA)
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coupling to more complex configurations

Transition density for a state $\nu$ with an angular momentum $\lambda$ in the RPA approach

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

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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.

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

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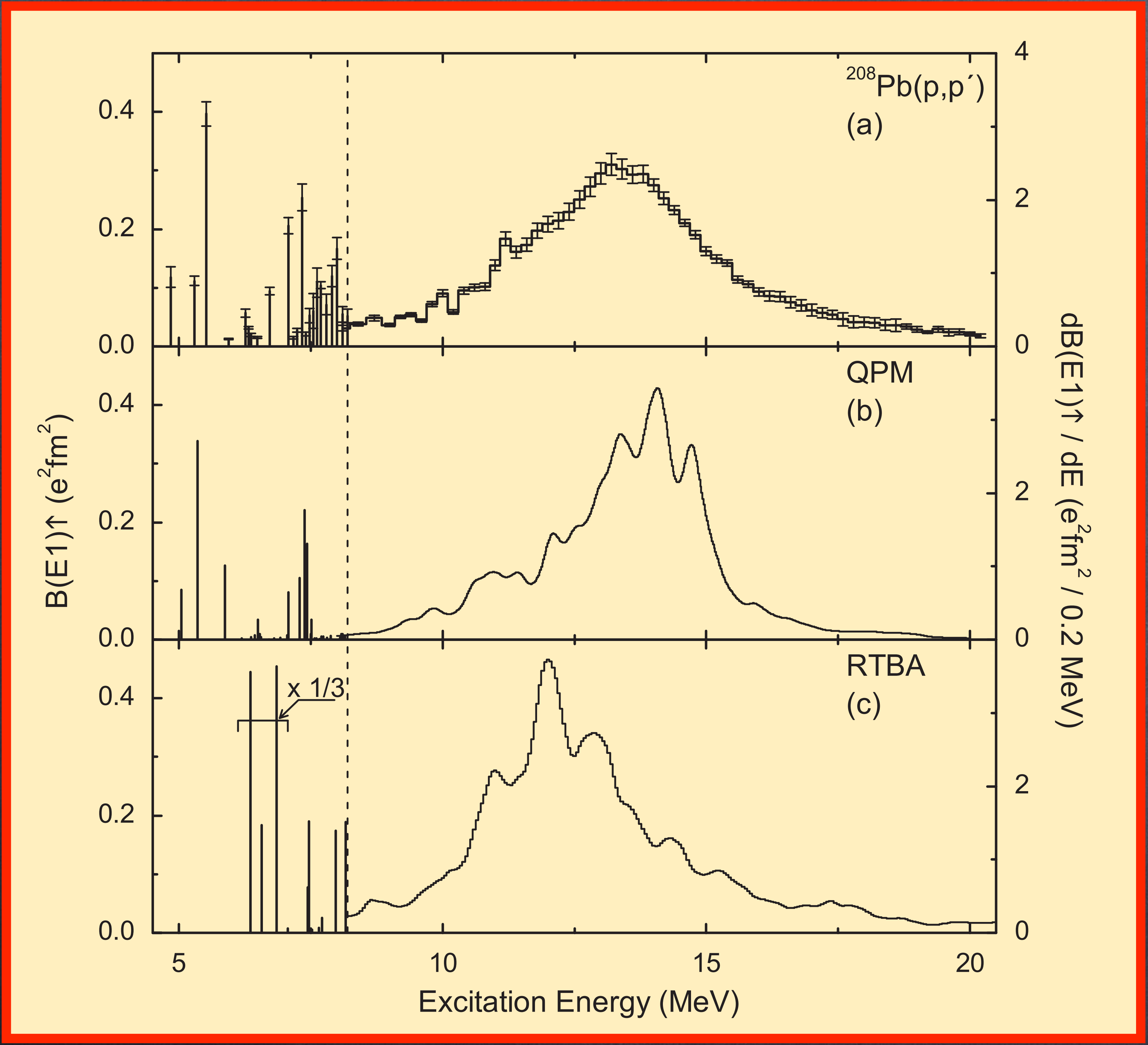

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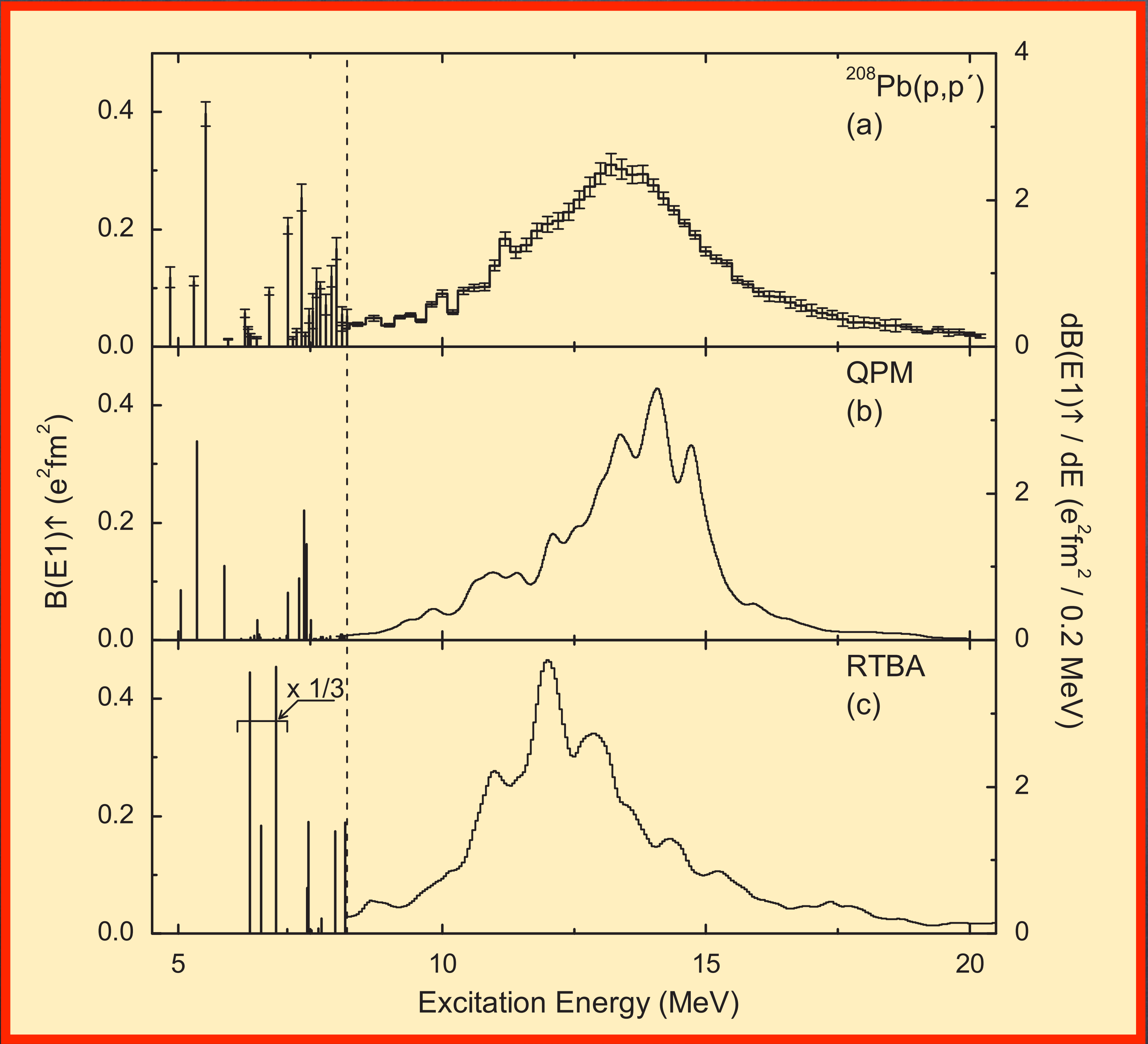


Quasiparticle-Phonon Model (QPM) calculations contain up to 3-phonon configurations at low energy

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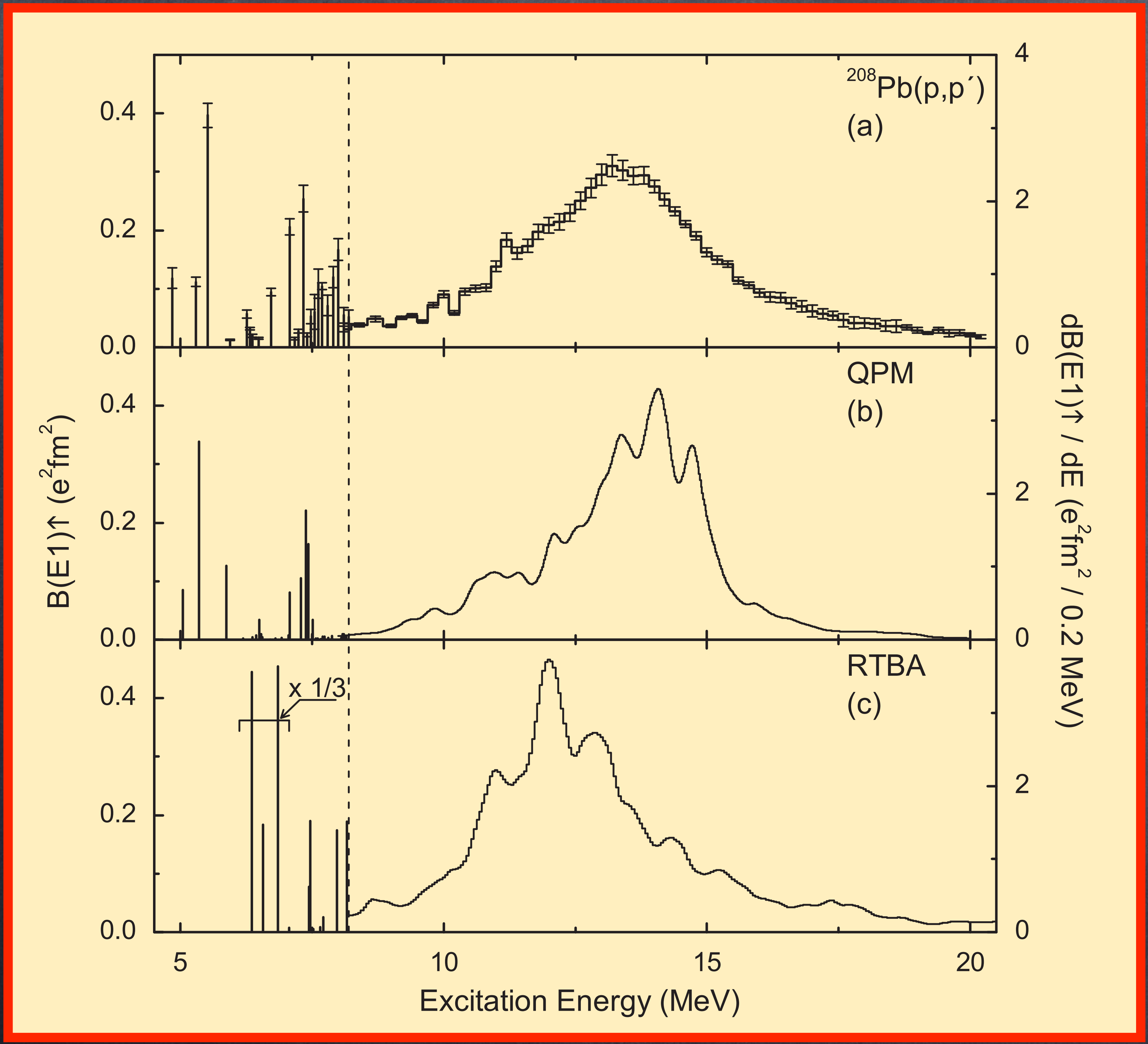


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Relativistic Time-Blocking Approximation (RTBA) based on a particle-hole ⊗ phonon model space

(by E. Litvinova)

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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: $(\gamma, \gamma')$ at Darmstadt
- Coulomb excitation by proton scattering: $(p, p')$ in Osaka and iThemba LABS

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- $(\alpha, \alpha' \gamma)$ At KVI
- $({}^{17}O, {}^{17}O' \gamma)$ on various target ${}^{208}Pb$, ${}^{90}Zr$, ${}^{140}Ce$ at Legnaro lab (LNL-INFN)
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For the Isoscalar probes, inelastic cross sections are also measured

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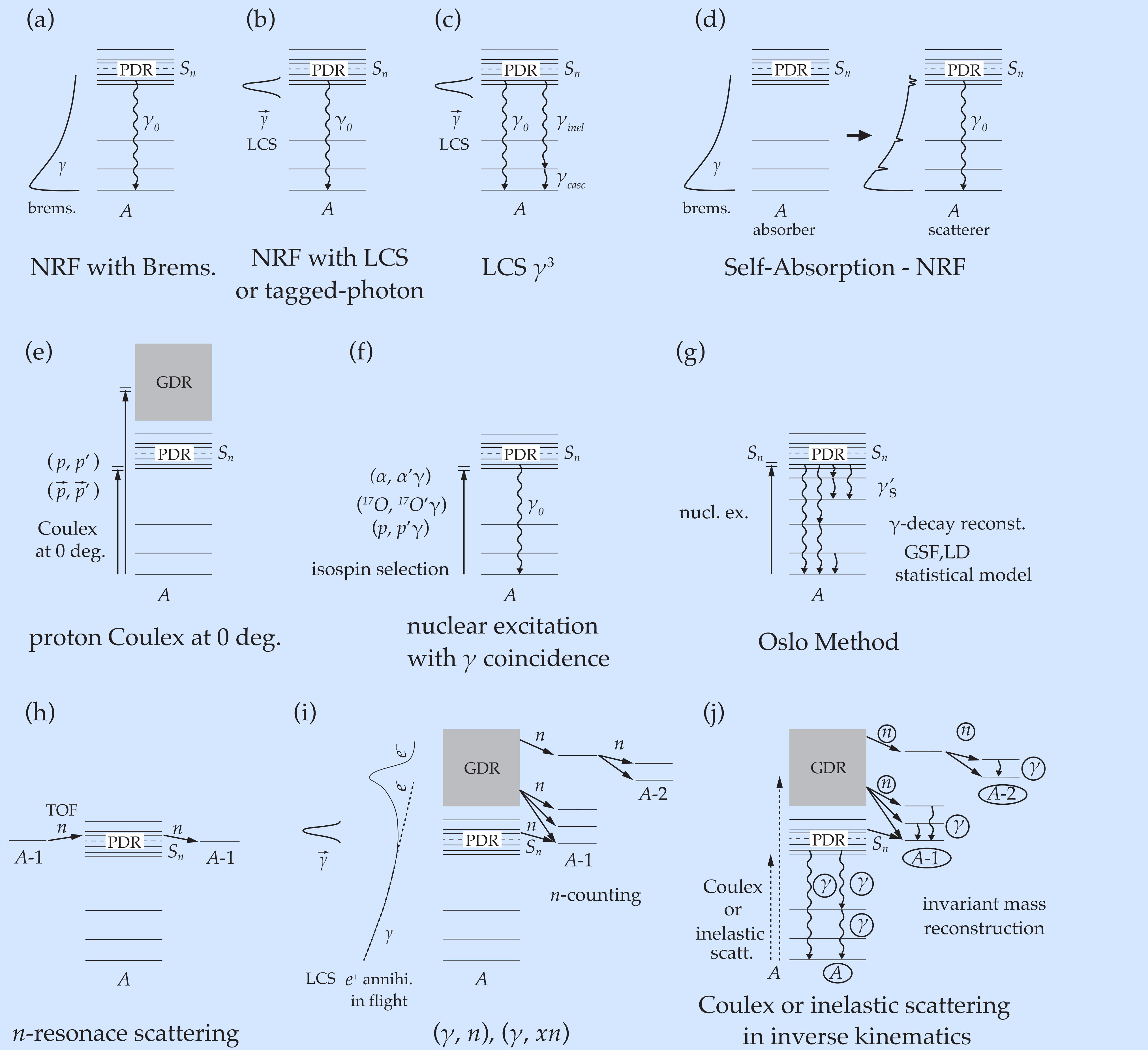

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The operators generating the toroidal and compressional modes are obtained as a second-order terms in a long wavelength limit of the electric multipole operator. They are of isoscalar nature.

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

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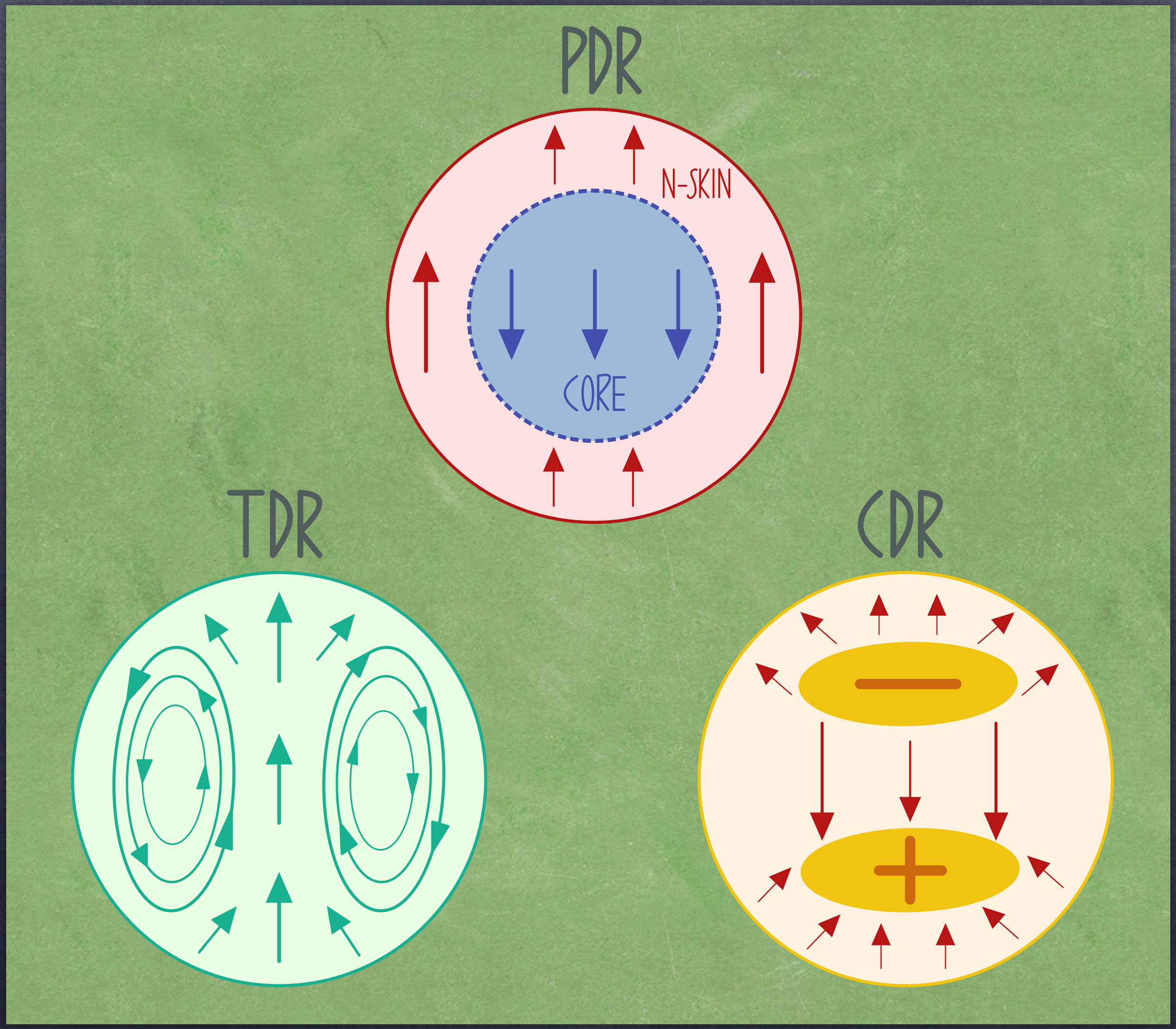

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In semiclassical models it is assumed that the motion of the two nuclei can be described according to the classical mechanics. This is true when the De Broglie wave length is small with respect to the distance of closest approach.

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

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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

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

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

The time dependent state is

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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

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$T(b)$: 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.

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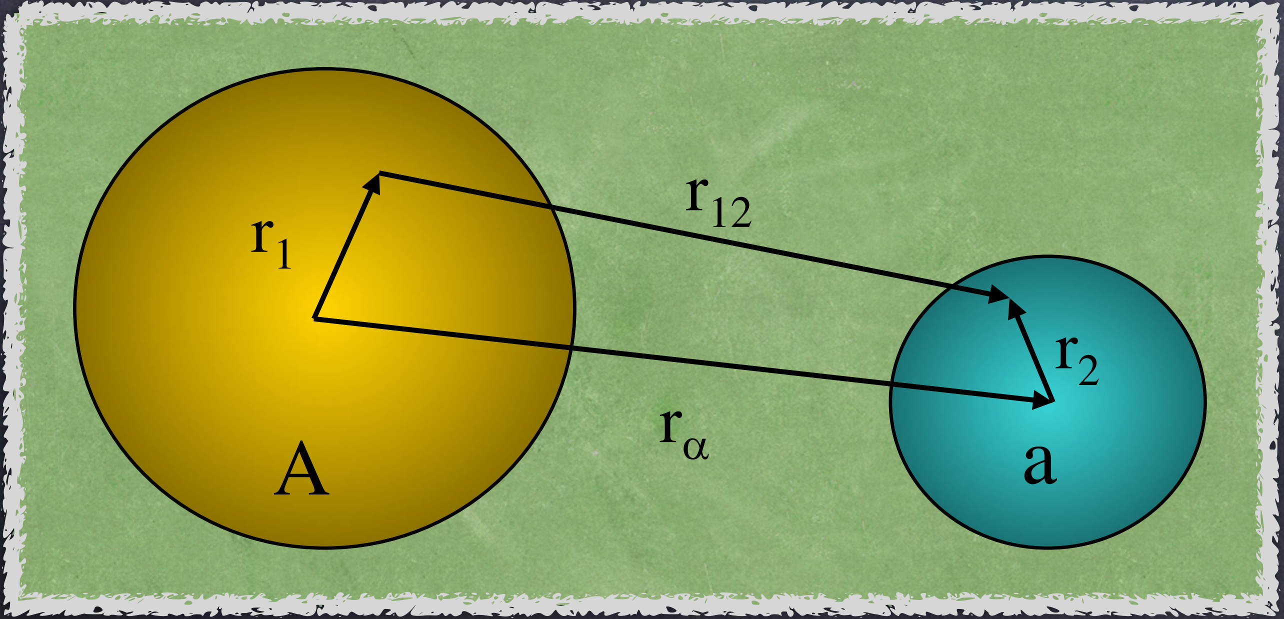

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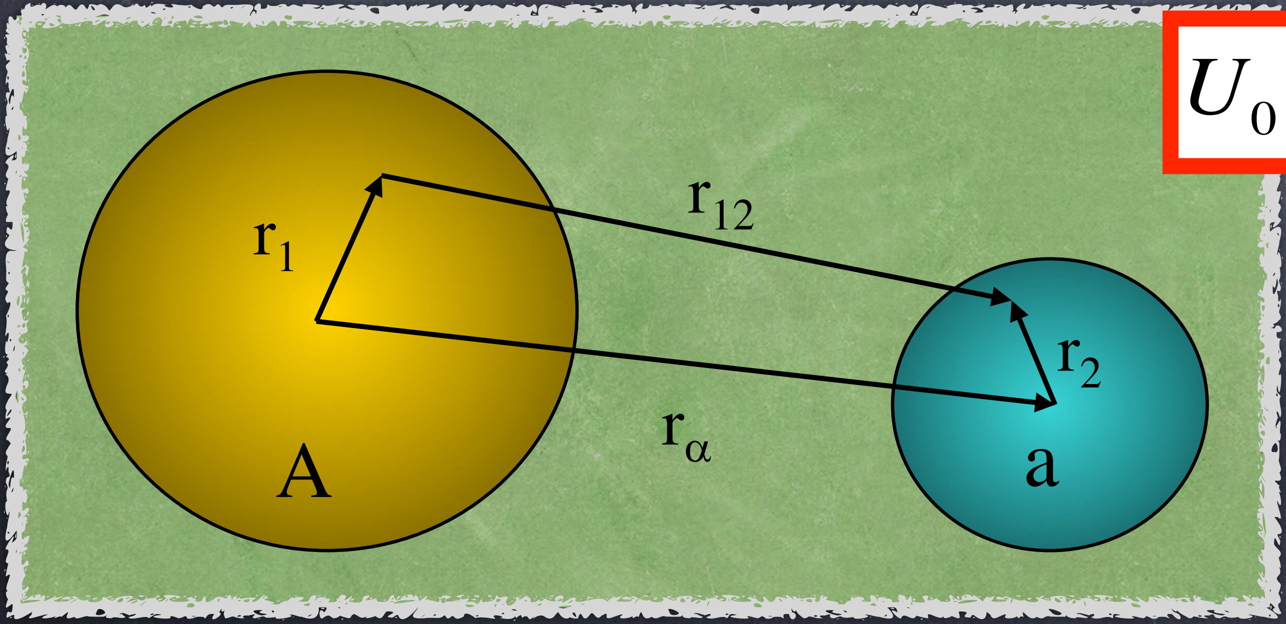


$$U_0(\vec{r}_\alpha) = \iint \rho_A(\vec{r}_1)\, v_0(r_{12})\, \rho_a(\vec{r}_2)\, d\vec{r}_1\, d\vec{r}_2$$

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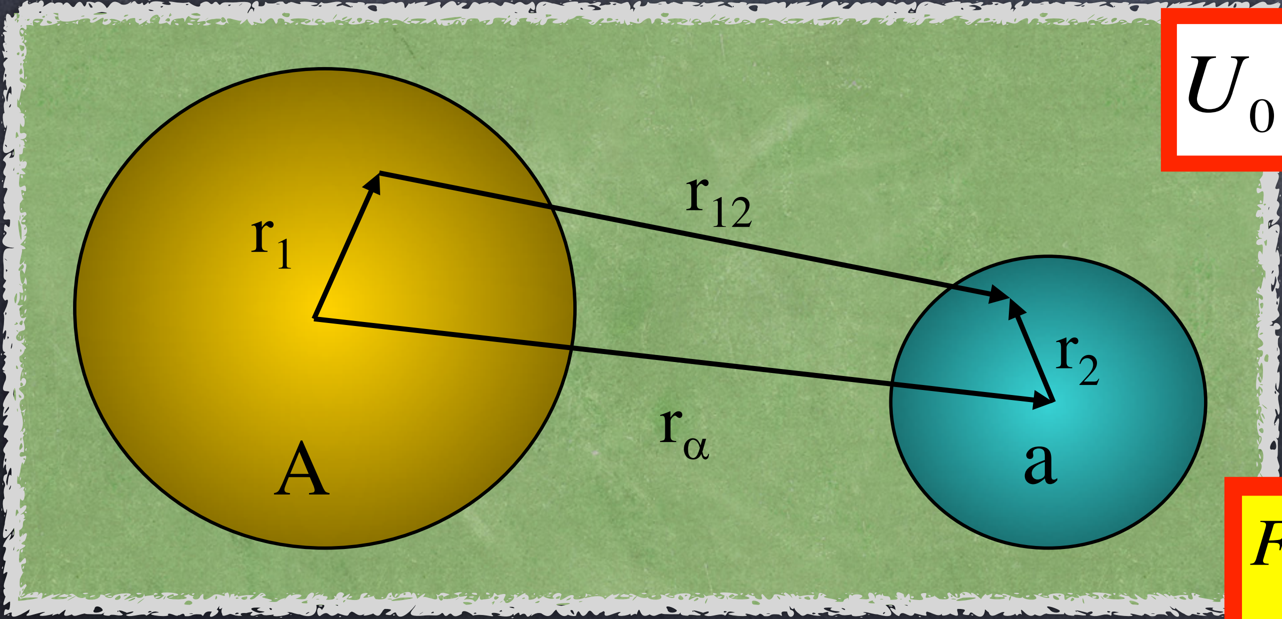


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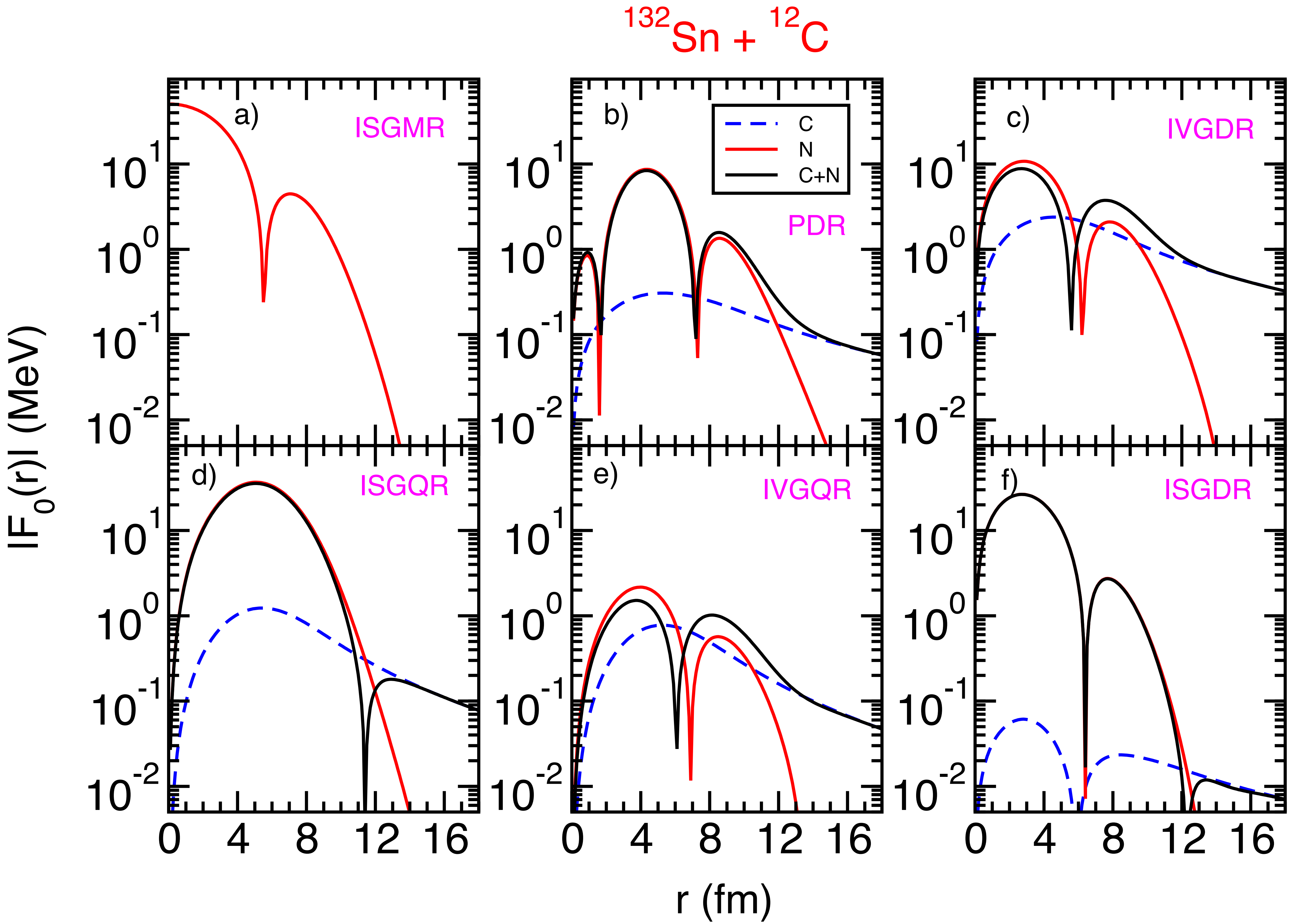
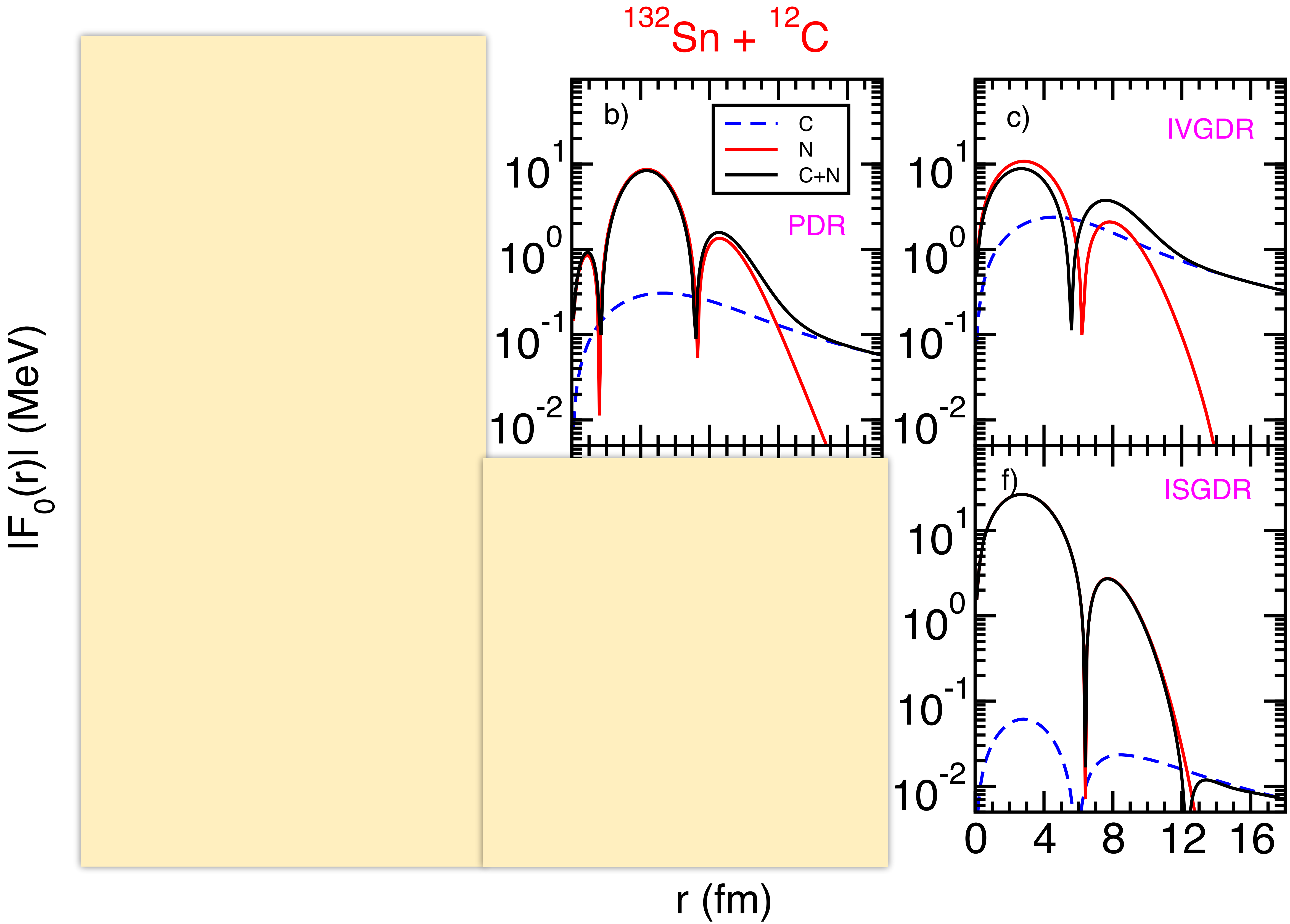
$$F_0(r_\alpha) = \iint \left[\delta\rho_{An}(\vec{r}_1) + \delta\rho_{Ap}(\vec{r}_1)\right] \times$$
$$\times\, v_0(r_{12}) \left[\rho_{an}(\vec{r}_2) + \rho_{ap}(\vec{r}_2)\right] r_1^2 dr_1 r_2^2 dr_2$$



132Sn + 12C
a) ISGMR
b) PDR
c) IVGDR
d) ISGQR
e) IVGQR
f) ISGDR
C
N
C+N
|F0(r)| (MeV)
r (fm)



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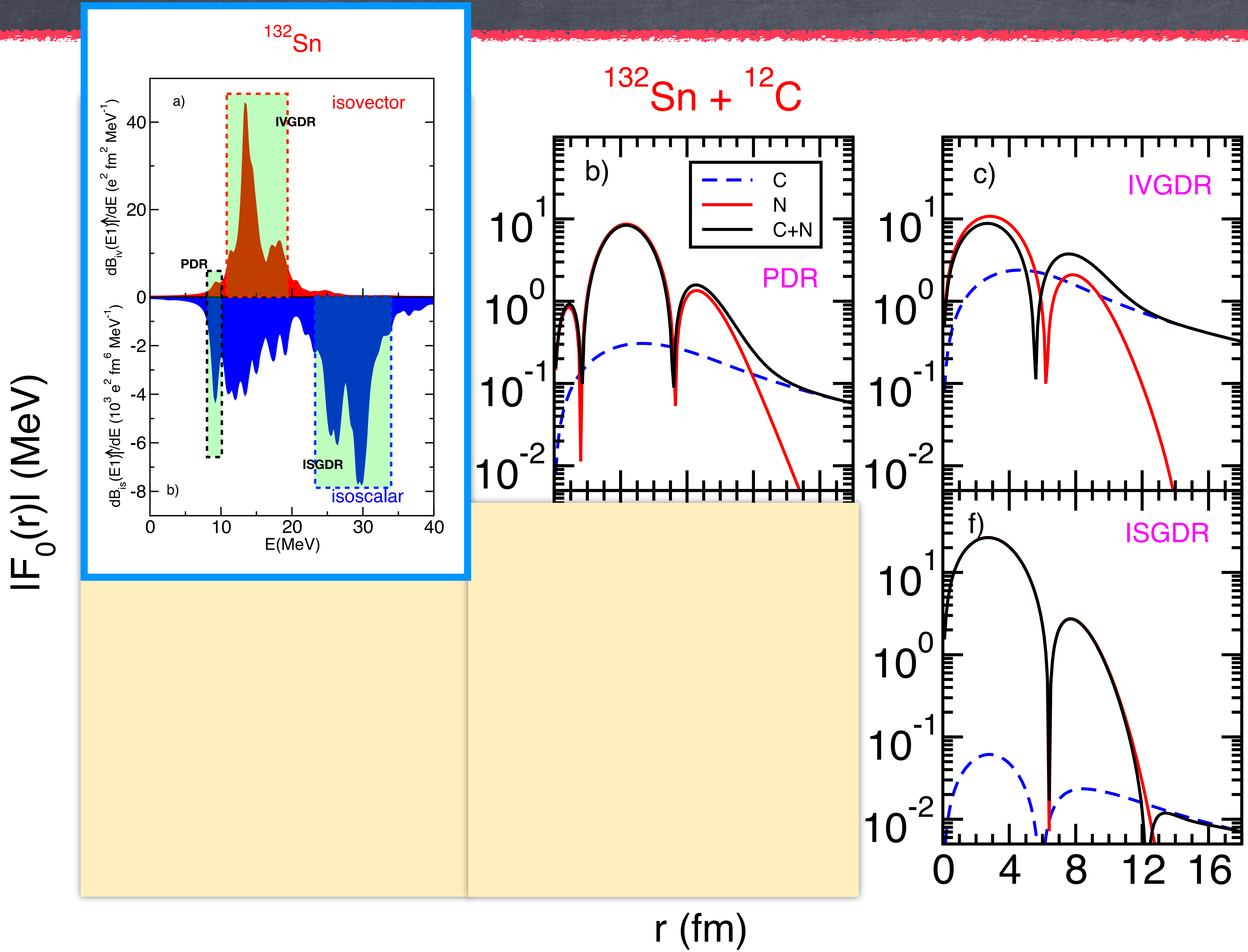

132Sn
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isovector
IVGDR
PDR
ISGDR
b)
isoscalar
E(MeV)
132Sn + 12C
b)
C
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C+N
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c)
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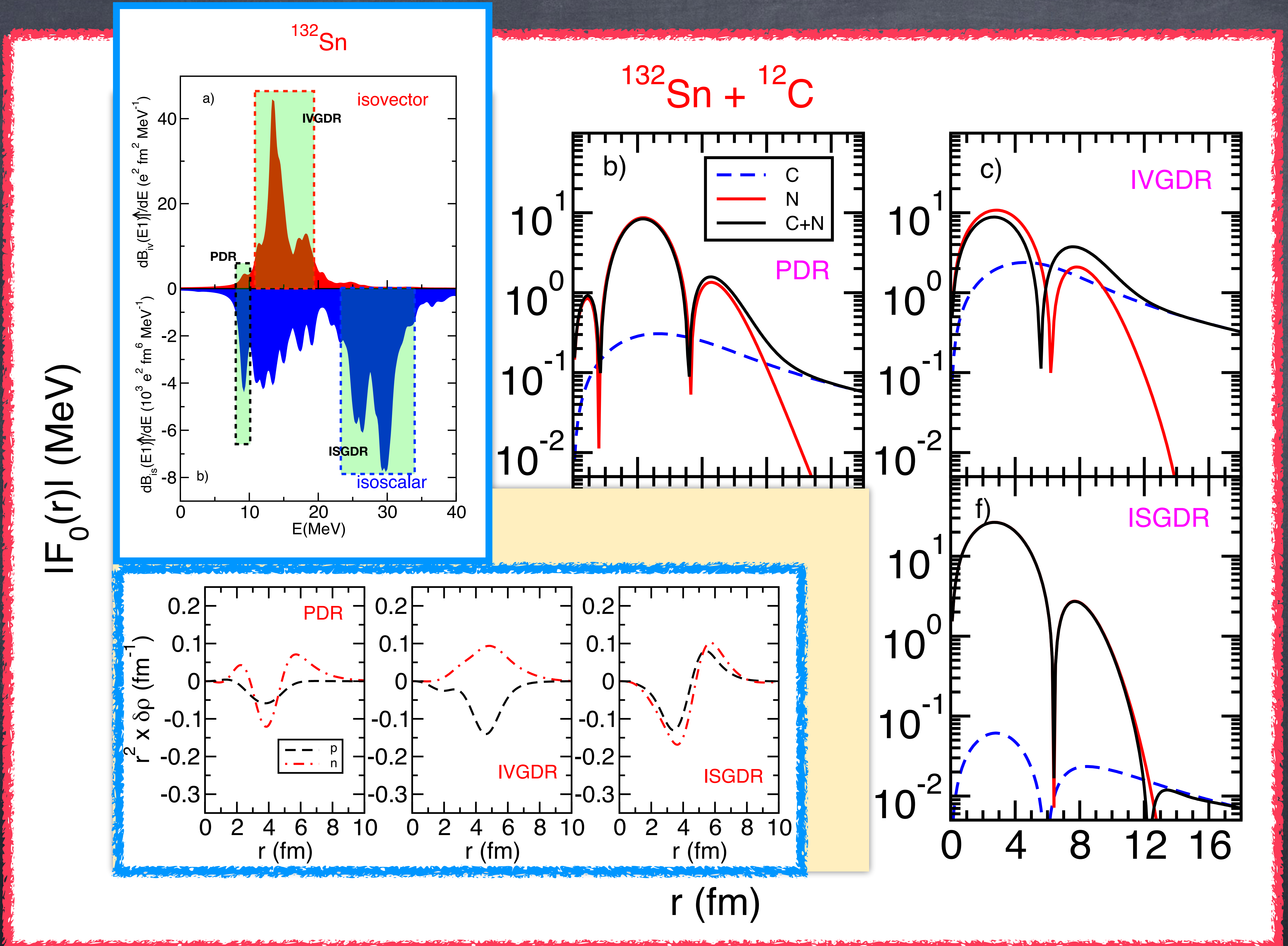

$^{132}Sn$
$^{132}Sn + ^{12}C$
a)
isovector
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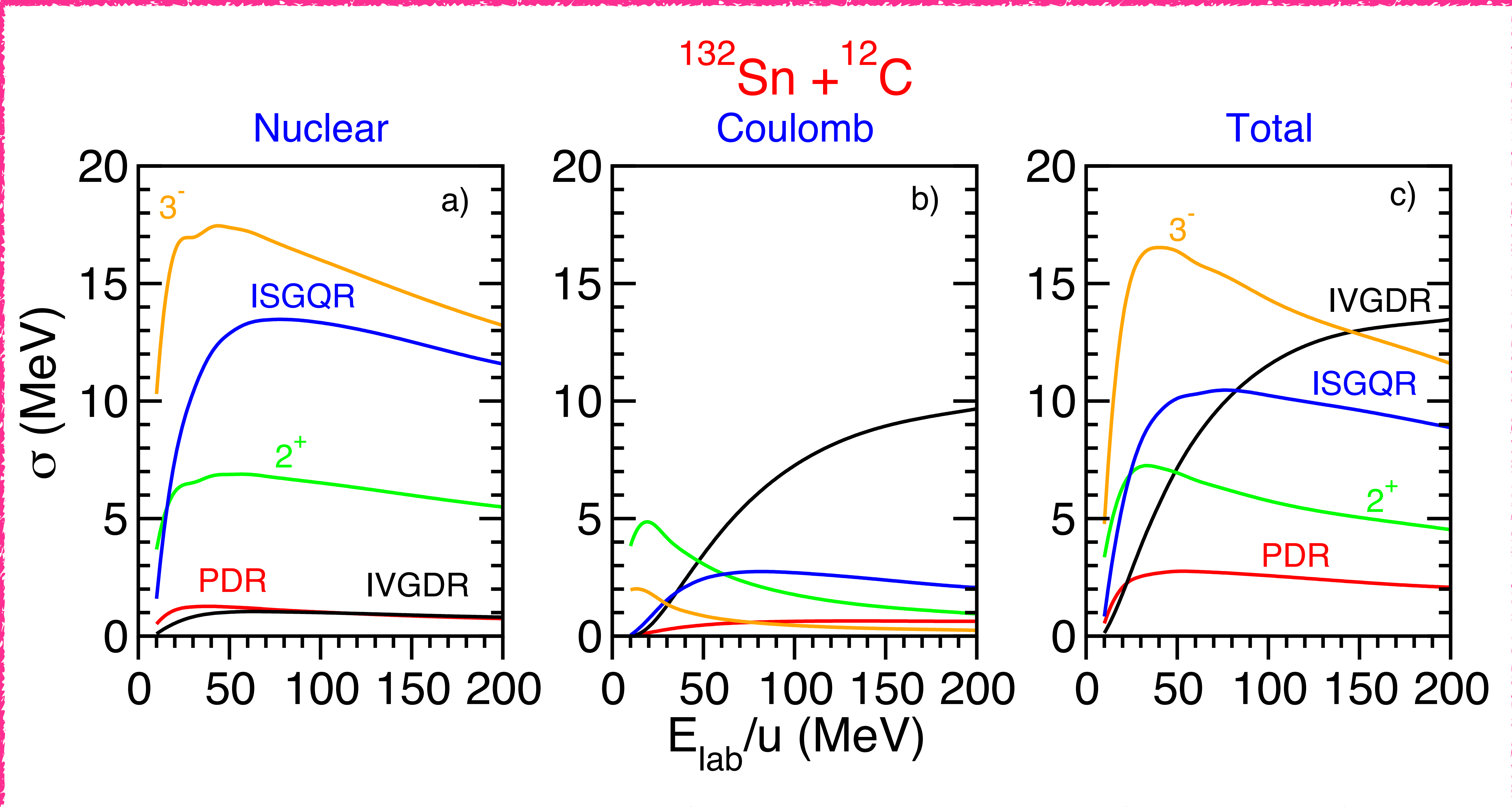
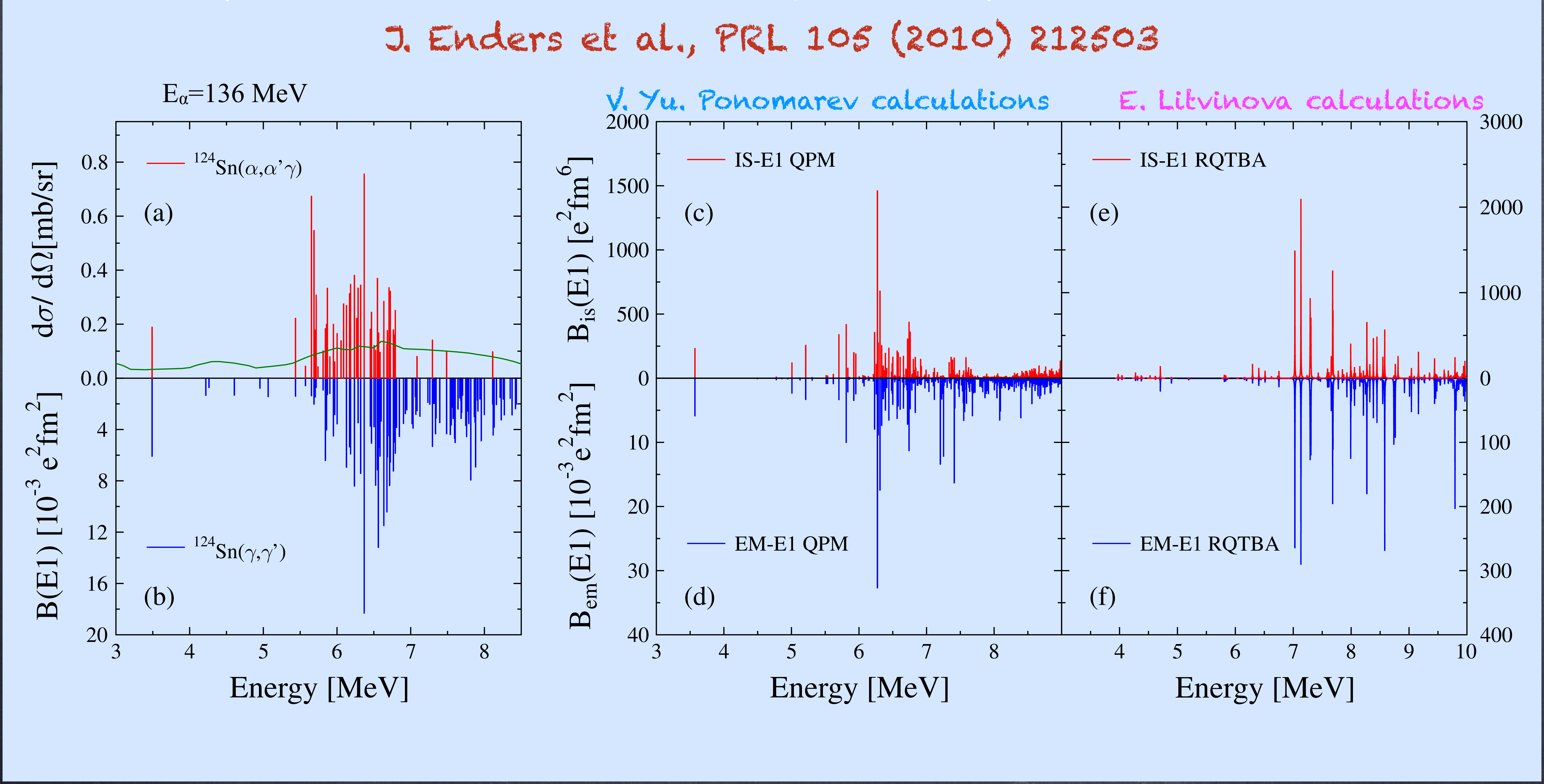
isoscalar
b)
E(MeV)
c)
f)
C
N
C+N
IVGDR
ISGDR
$|F_0(r)|$ (MeV)
r (fm)
$r^2 \times \delta\rho$ (fm$^{-1}$)
p
n

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

Total cross section



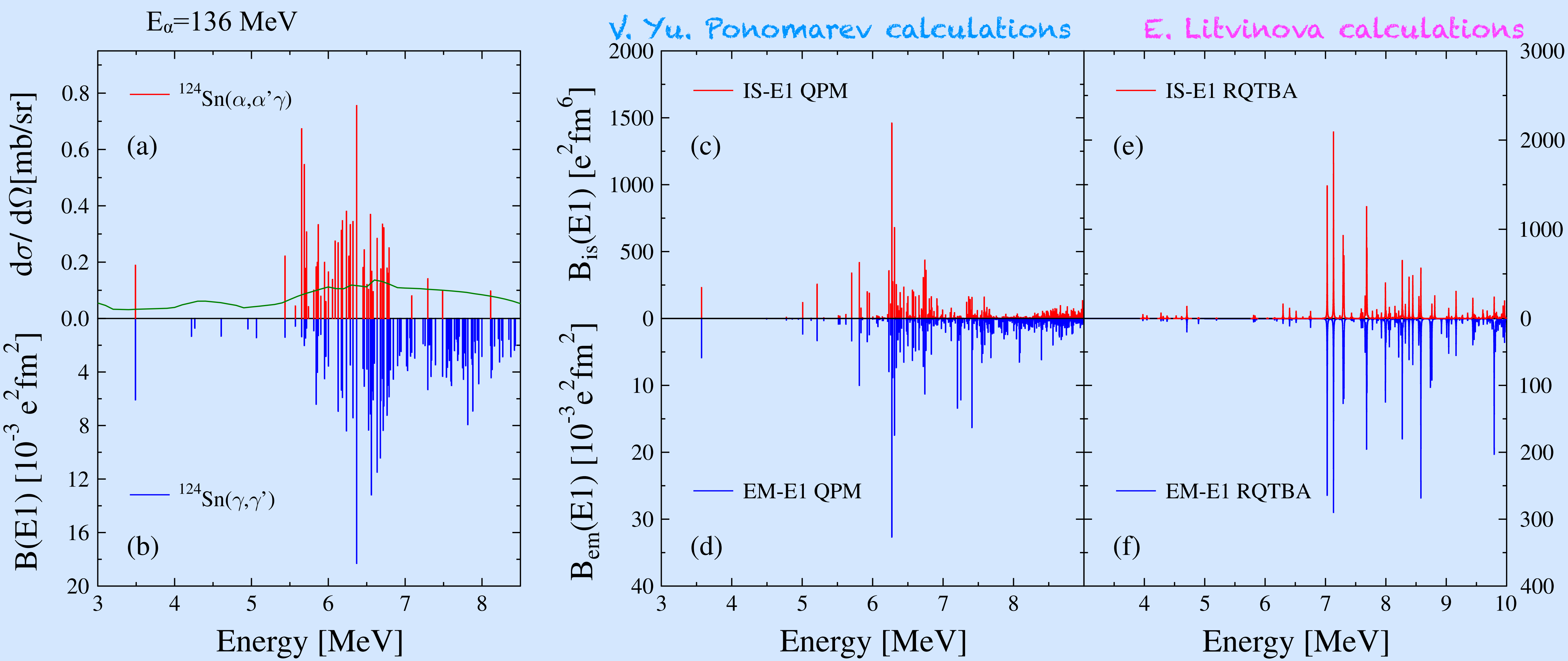
# Splitting of the low-lying dipole strength




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.

# Splitting of the low-lying dipole strength

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

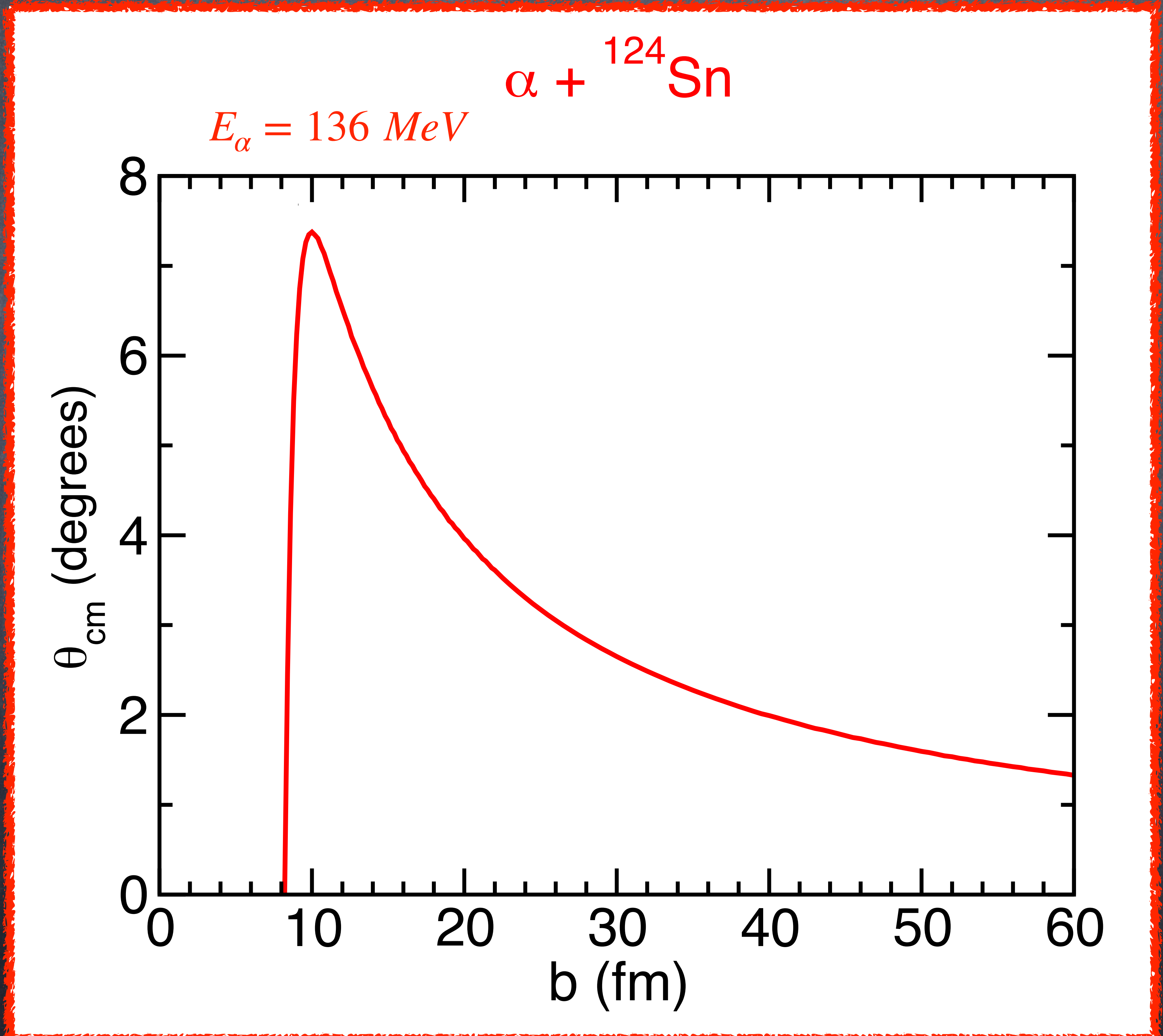



The lower lying group of states is excited by both isoscalar and isovector probes while the states at higher energy are excited by photons only.

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

Experimental data are usually taken at a finite angle range.

From the deflection function one can deduce the corresponding impact parameter range



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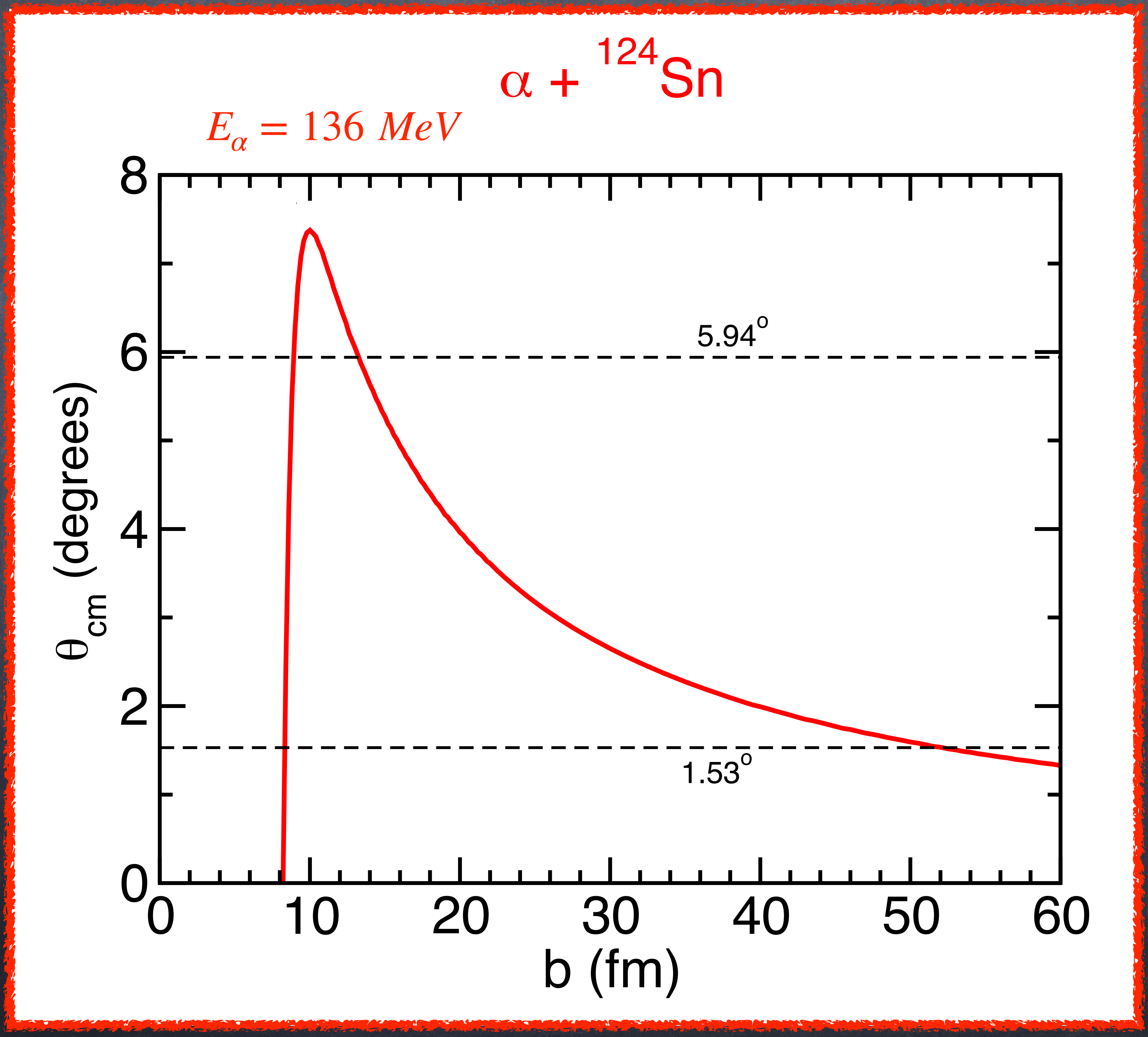
$^{124}Sn(\alpha,\alpha'\gamma)^{124}Sn$ @ 136 MeV



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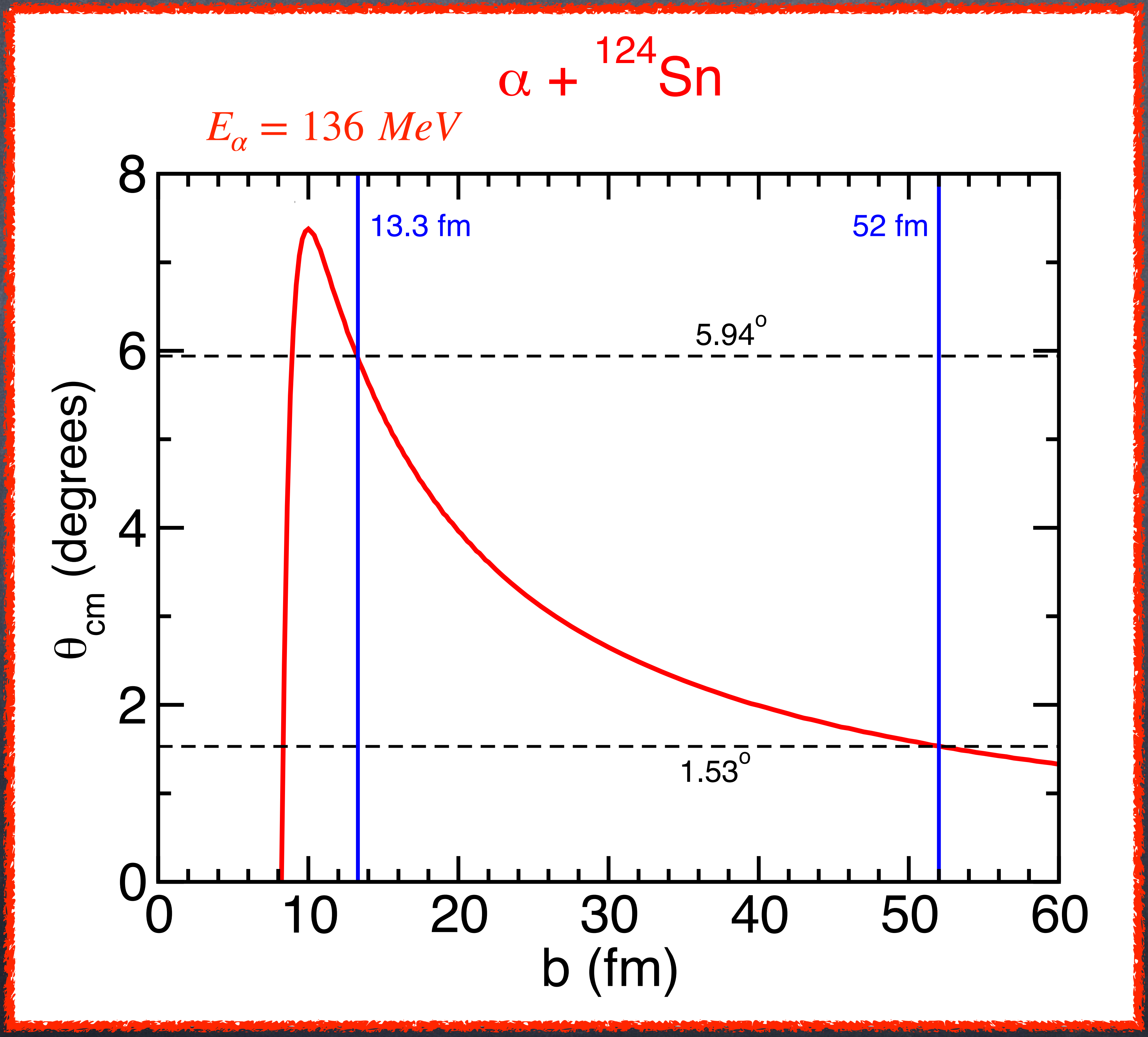

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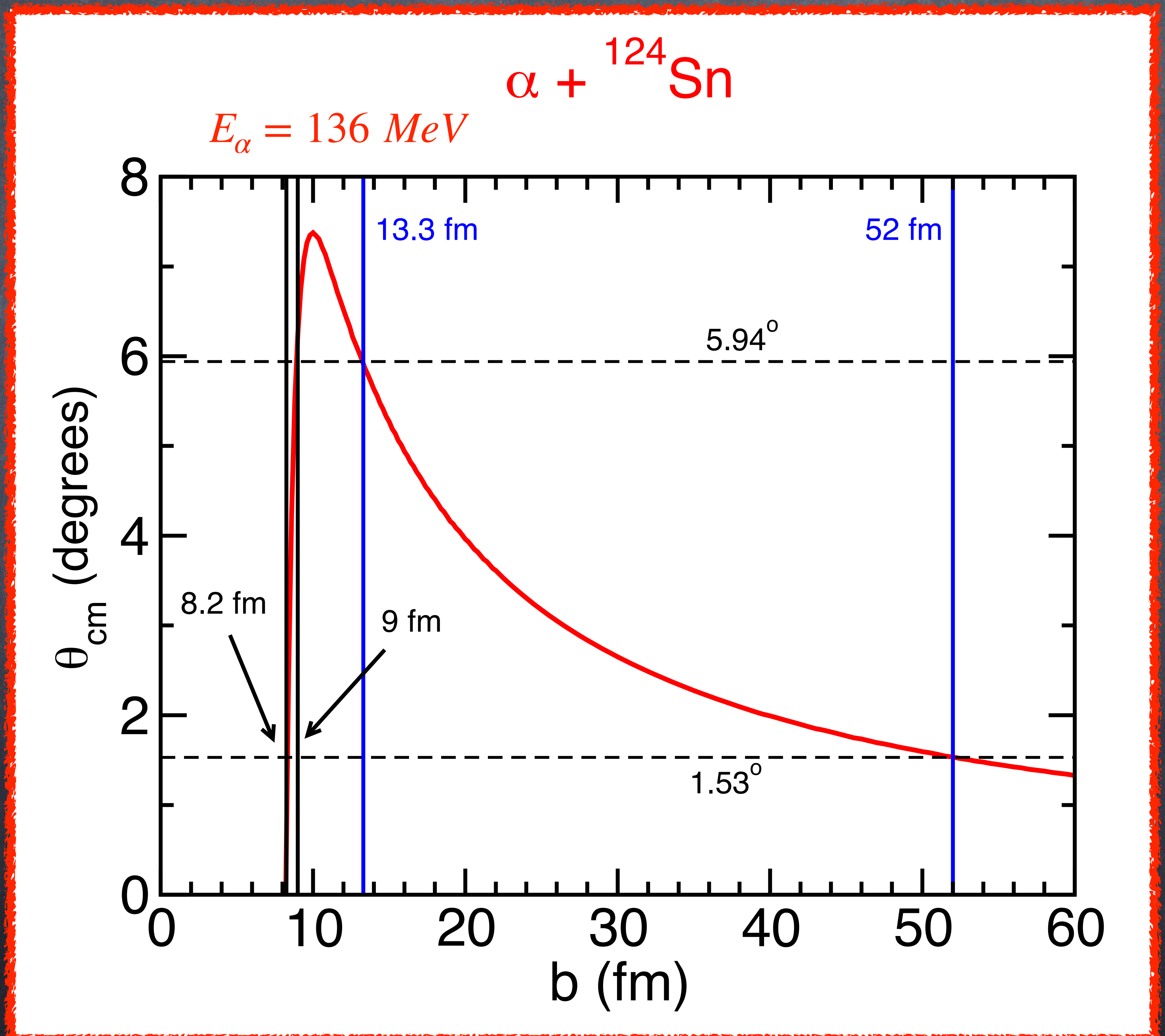
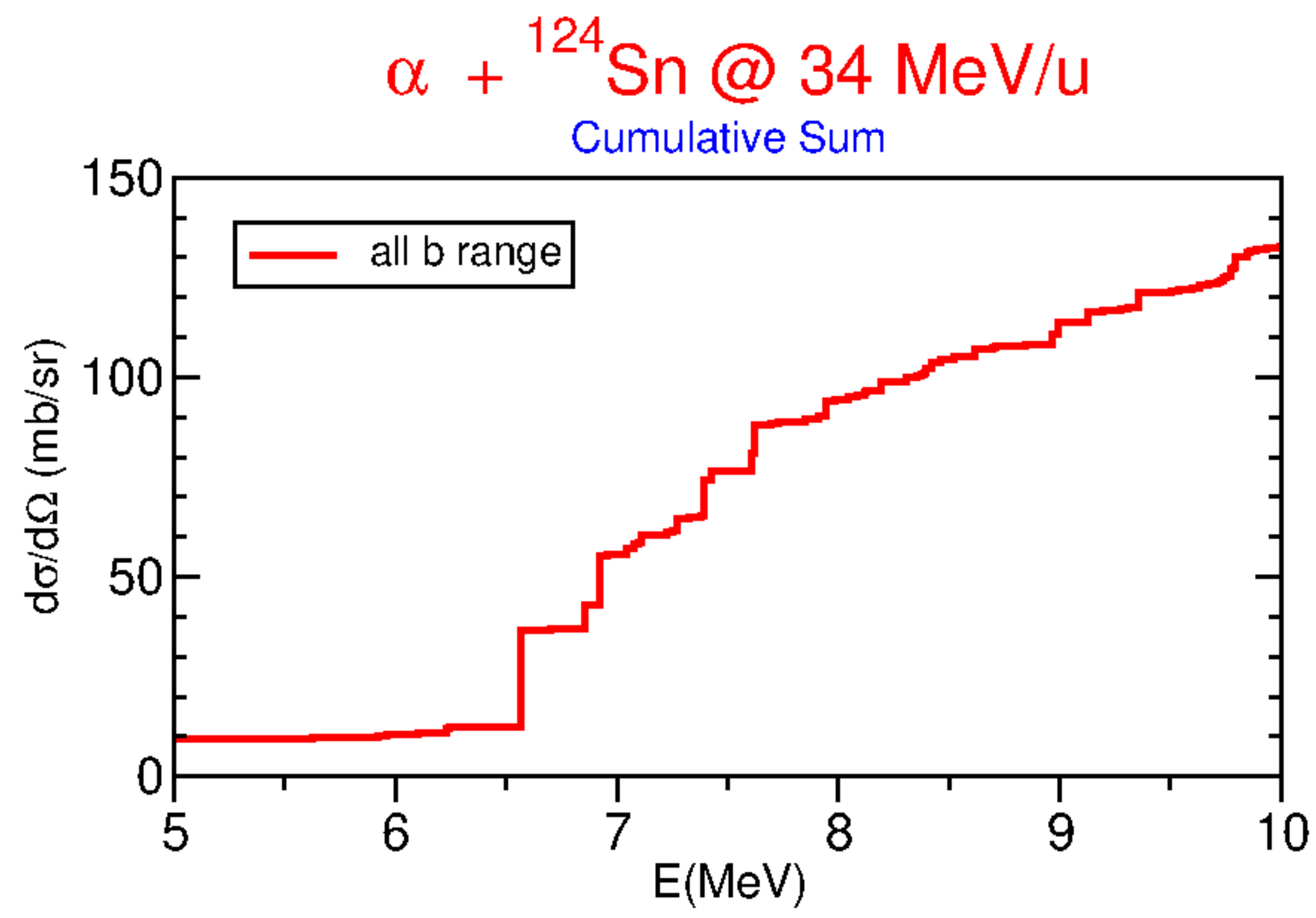


# Comparison with experimental data.

Cumulative Sum from 5 to 9 MeV. The theoretical calculations (by E. Litvinova with RQTBA) give a range which is higher in the excitation energy of about one MeV.



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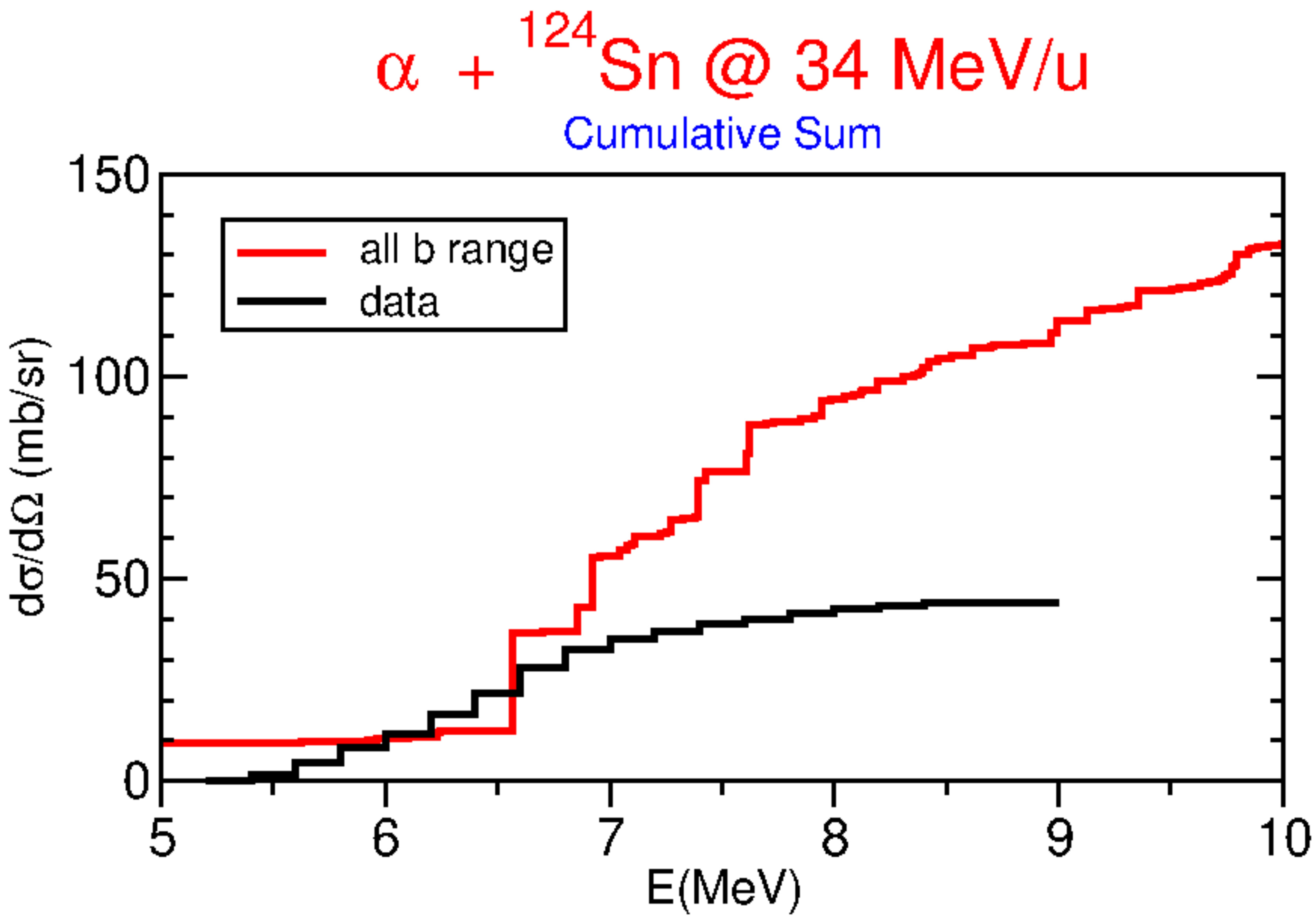

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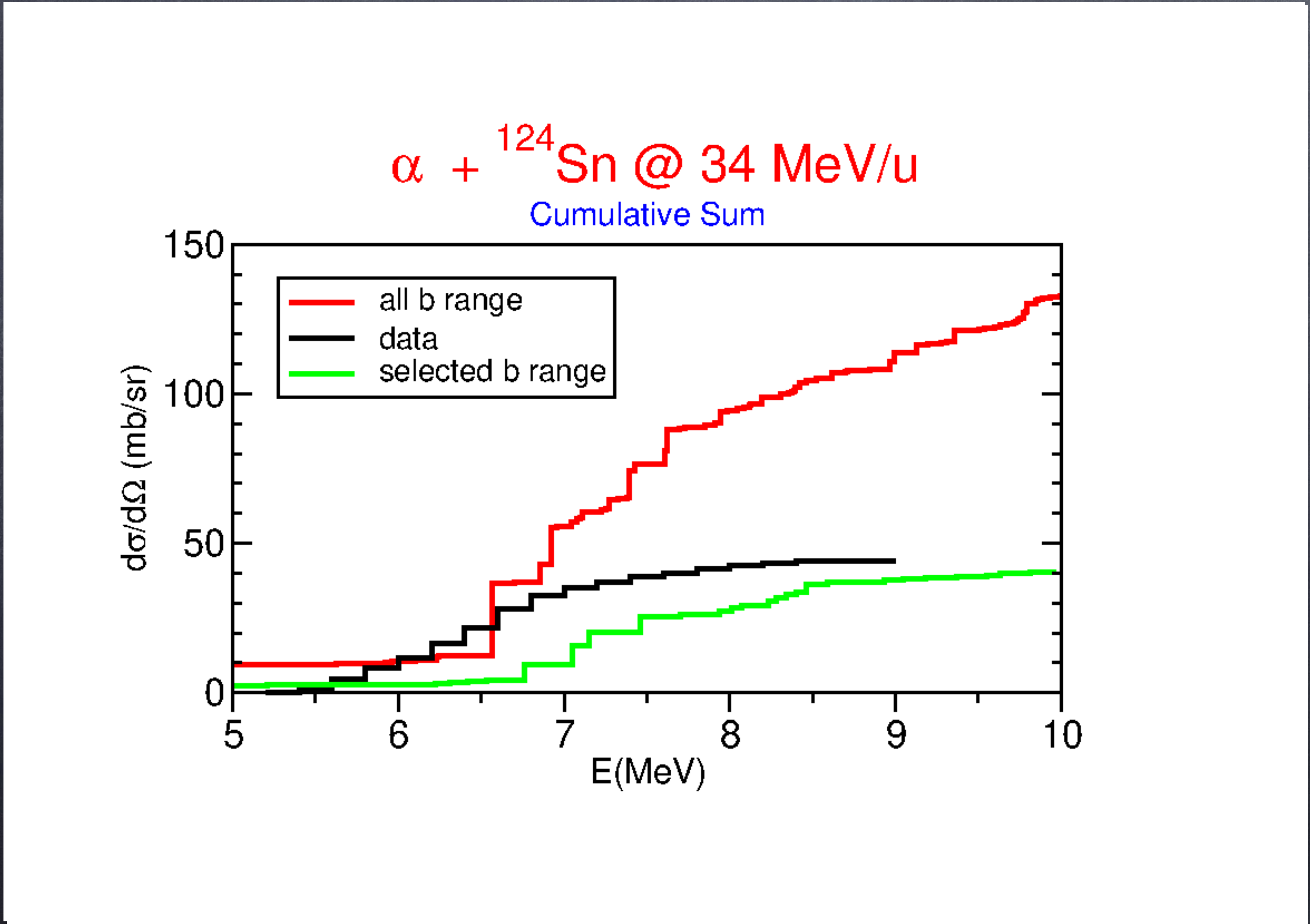

The model have been successfully employed in several physical problem involving heavy ion collisions.

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.

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- 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

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