A quantitative picture of low-energy nuclear reactions derived from back-scattering measurements

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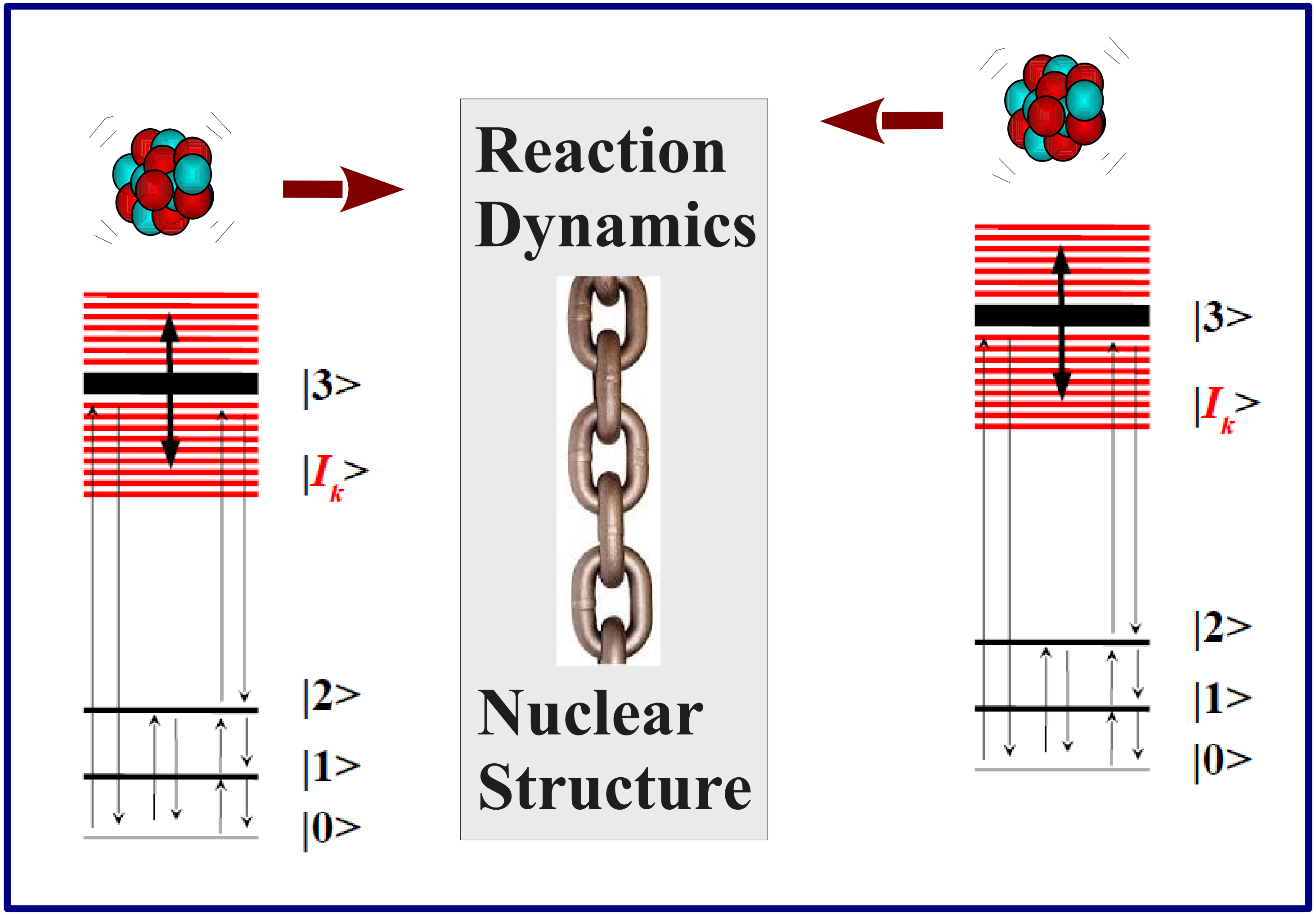
Outline

- Motivation & Some Important Concepts

- Deriving **reaction observables** from **back-scattering measurements of elastic & quasi-elastic excitation functions**
  - Energy-shifting formulae for probabilities
  - Formulae for some cross sections

- Summary & Outlook

Reactions between Complex Nuclei at Low Energy



The interplay between **nuclear structure** & **reaction dynamics** determines the reaction observables (**cross sections**)

Capture and Reaction Cross Sections

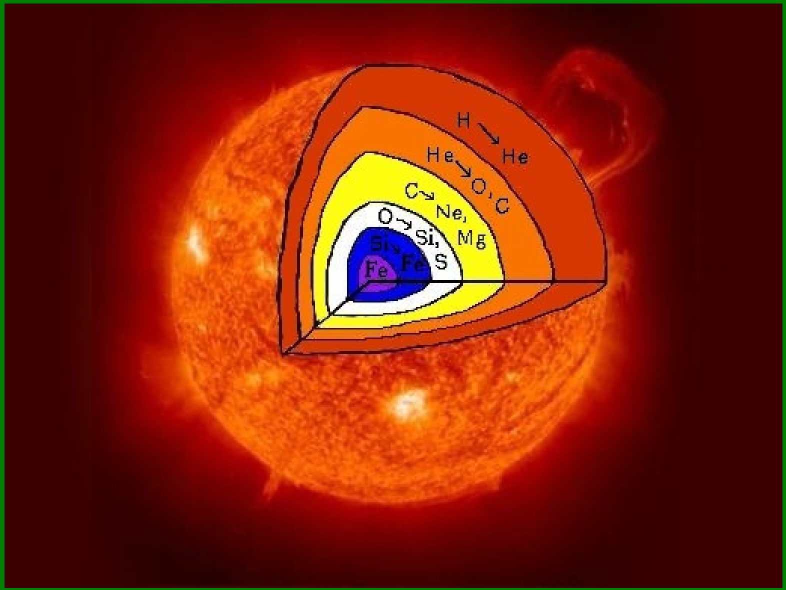
$$\underline{\sigma_{cap}} = \frac{\pi}{k^2} \sum_J (2J+1)\, \underline{P_{cap}(E,J)}$$

$$\underline{\sigma_{reac}} = \frac{\pi}{k^2} \sum_J (2J+1)\, \underline{P_{reac}(E,J)}$$

Some available coupled channels codes:

Thompson, Comp. Phys. Rep. **7** (1988) 167	**FRESCO**
Hagino, Rowley & Kruppa, CPC **123** (1999) 143	**CCFULL**

Alternative: Simplified method for predicting a number of cross sections using (as input) experimental information on elastic and quasi-elastic excitation functions at 180 degrees.

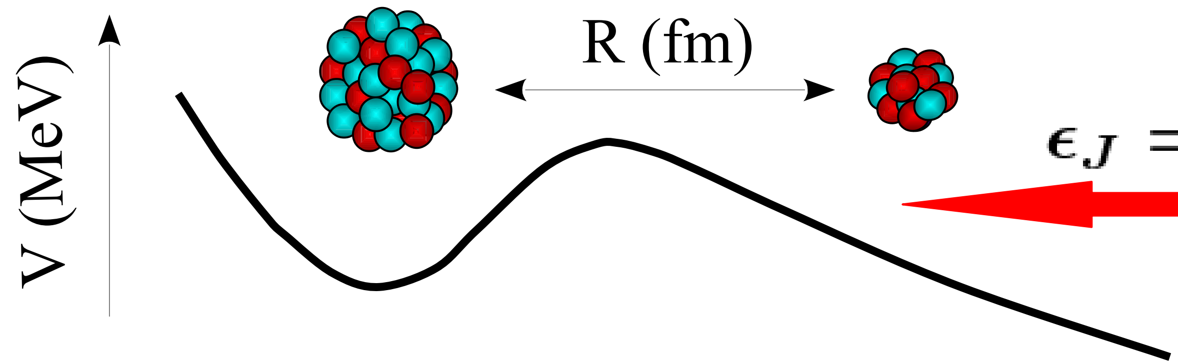


Energy-shifting formulae yield reliable capture and reaction probabilities

A.D-T, Adamian, Sargsyan & Antonenko, PLB **739** (2014) 348

Energy-Shifting Formulae

$$P_i(E, J) \approx P_i(\epsilon_J, J = 0)$$



$$\epsilon_J = E - E_{rot}(J)$$

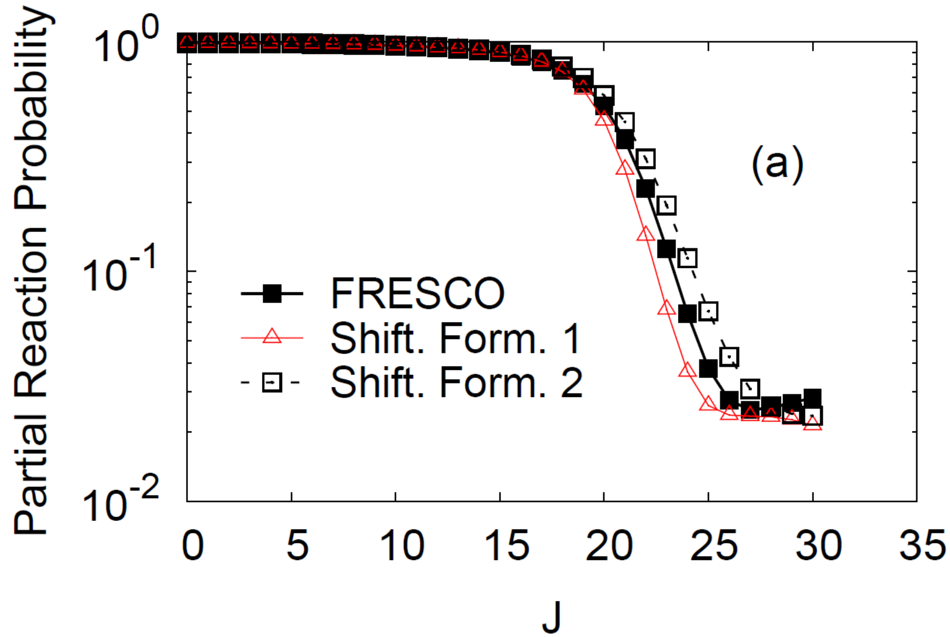
✯ Shifting Formula 1

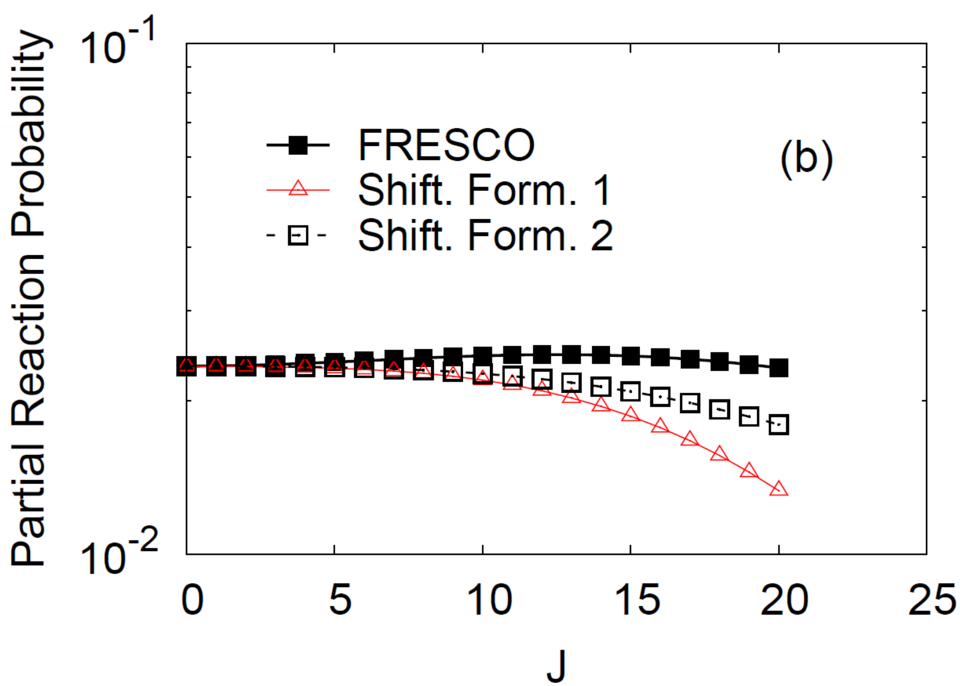
$$E_{rot}(J) = \frac{\hbar^2 \Lambda}{2\mu R_B^2} + \frac{\hbar^4 \Lambda^2}{2\mu^3 \omega_B^2 R_B^6} \qquad \Lambda = J(J+1)$$

✯ Shifting Formula 2

$$E_{rot}(J) = E\,\frac{(\eta'^2 + J^2)^{1/2} - \eta'}{(\eta'^2 + J^2)^{1/2} + \eta'} \qquad J = \eta' \cot(\theta/2)$$

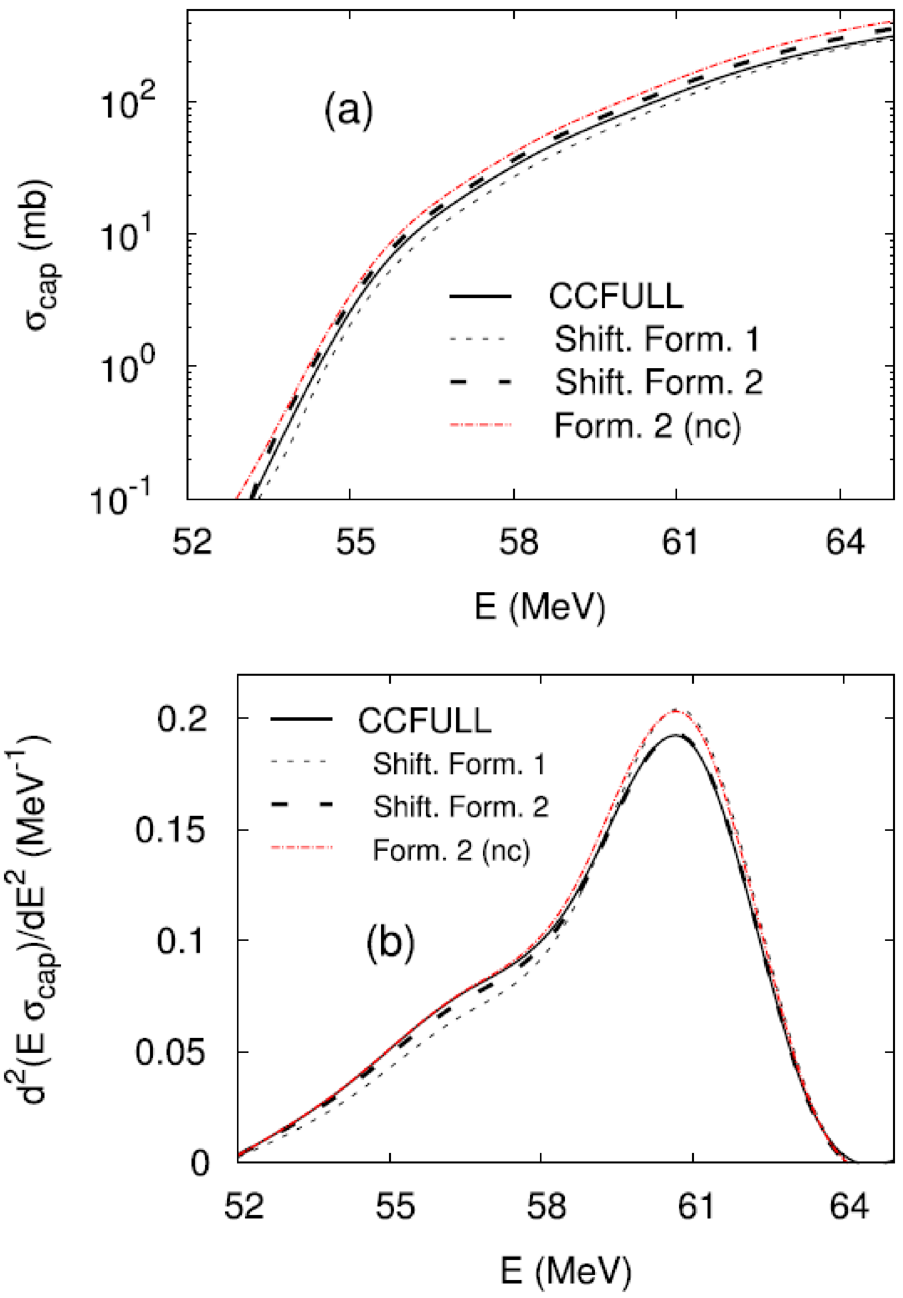
^{16}O + ^{120}Sn @ Ecm **above** and **below** the Coulomb barrier

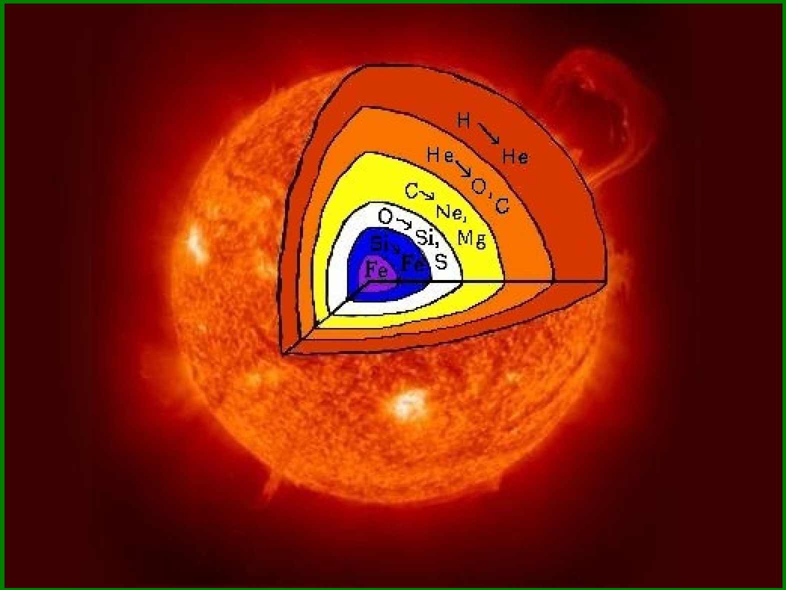




$$\mathbf{P(E,J) = 1 - |\underbrace{S(E,J)}_{\text{Elastic S-matrix}}|^2}$$

Capture excitation function for $^{16}O + ^{154}Sm$





Simplified formulae for integrated and differential cross sections

Feeding formulae with information from back-scattering measurements for making reliable predictions of x-sections

Sargsyan, Adamian, Antonenko, A.D-T, Gomes & Lenske,
PRC **90** (2014) 064601; EPJA **50** (2014) 168;
PRC **92** (2015) 054620; PRC **93** (2016) 054613

Simplified formulae for reaction and capture cross sections

Using the parameters of the J=0 Coulomb barrier and

- the Energy-Shifting Formula 1

$$\sigma_R(E) = \frac{\pi R_b^2}{E} \int_0^E d\epsilon \, \underline{P_R(\epsilon,0)} \left[1 - \frac{4(E-\epsilon)}{\mu\omega_b^2 R_b^2}\right]$$

$$\sigma_{cap}(E) = \frac{\pi R_b^2}{E} \int_{\epsilon_{cr}}^E d\epsilon \, \underline{P_{cap}(\epsilon,0)} \left[1 - \frac{4(E-\epsilon)}{\mu\omega_b^2 R_b^2}\right]$$

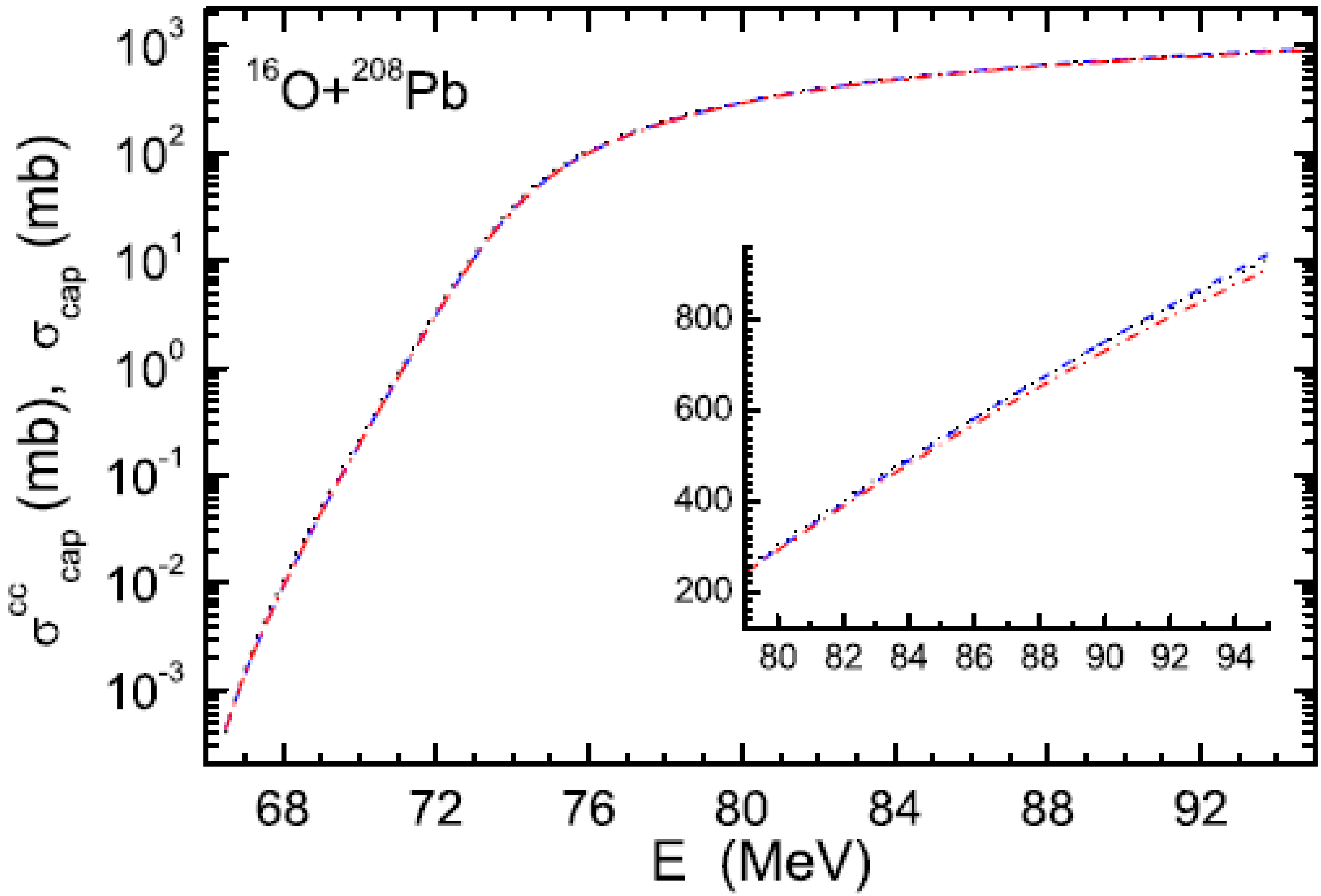
- the Energy-Shifting Formula 2

$$\sigma_R(E) = \frac{\pi Z'^2}{E} \int_0^E \mathrm{d}\epsilon \frac{2E-\epsilon}{\epsilon^3} \underline{P_R(\epsilon,0)}$$

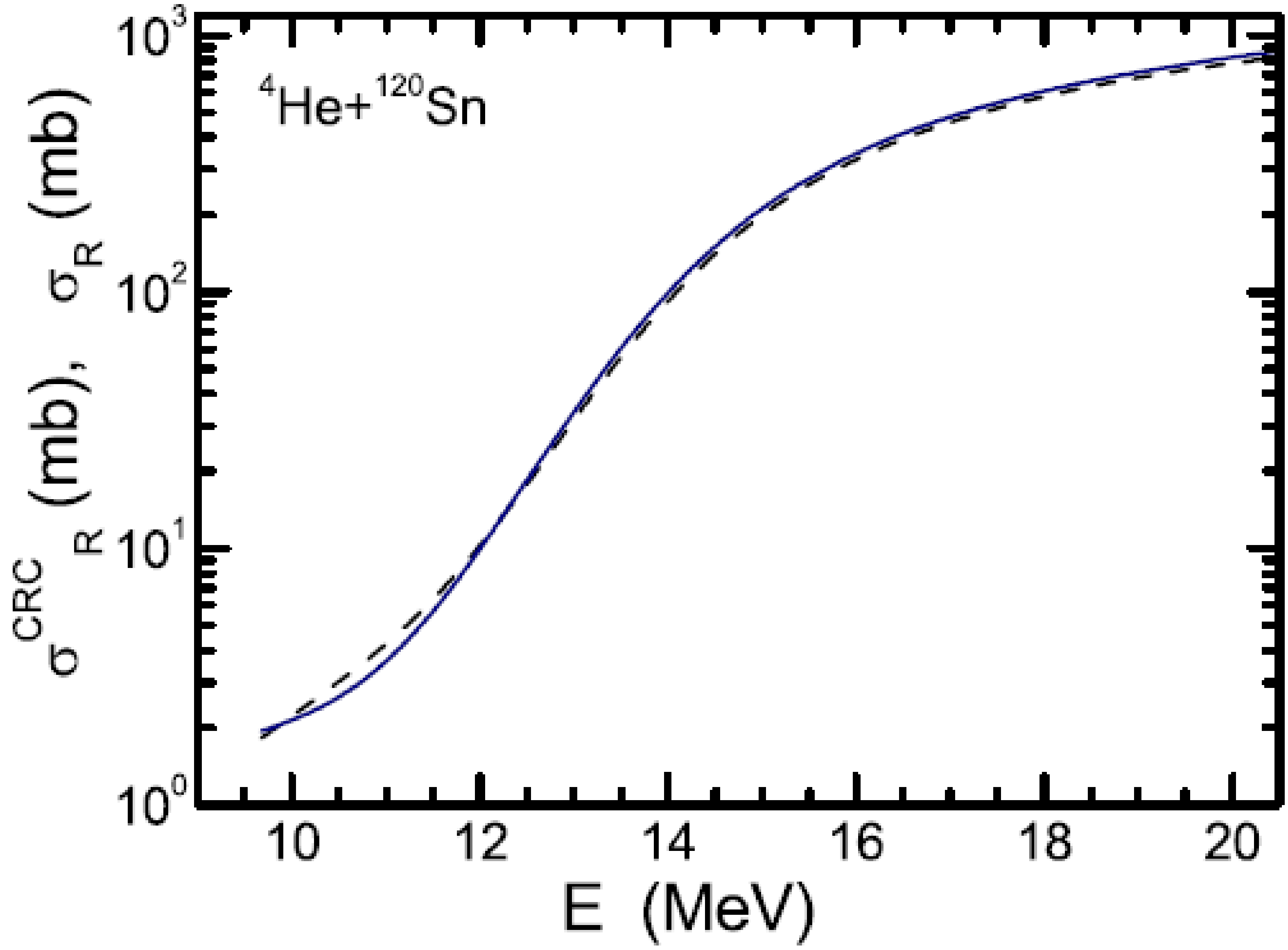
$$\sigma_{cap}(E) = \frac{\pi Z'^2}{E} \int_{\epsilon_{J_{cr}}}^E \mathrm{d}\epsilon \frac{2E-\epsilon}{\epsilon^3} \underline{P_{cap}(\epsilon,0)}$$

$$Z' = Z_1 Z_2 e^2 \left(1 - \frac{a_0}{R_b}\right)$$

Testing the simplified formula of the capture cross section against coupled channels calculations



Testing the simplified formula of the reaction cross section against coupled channels calculations



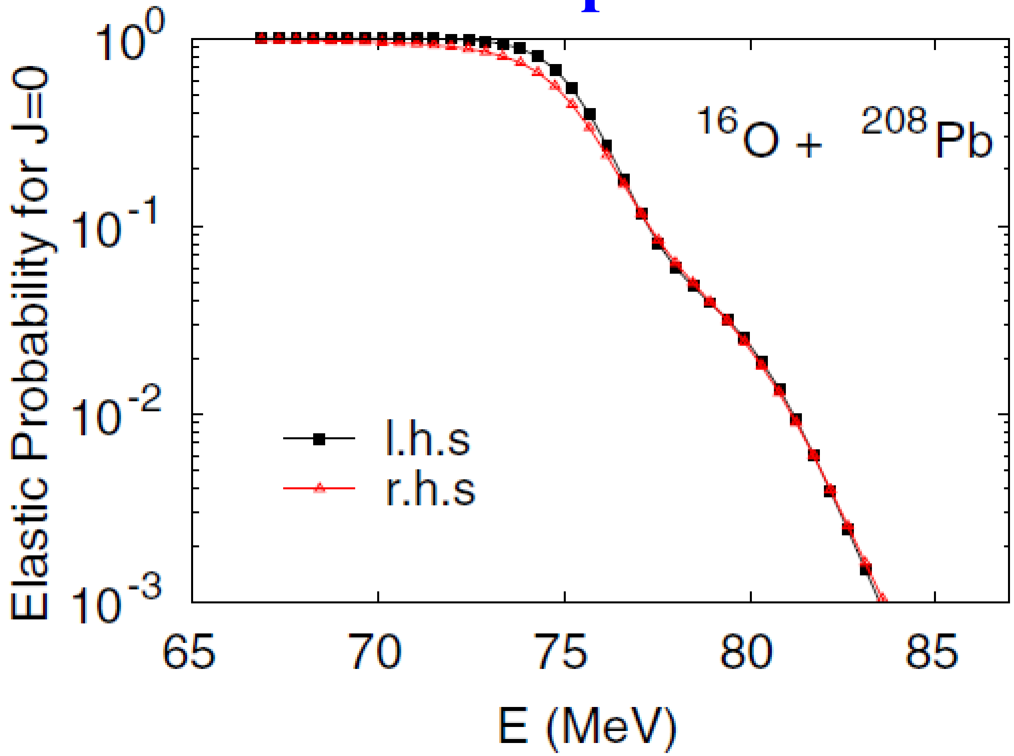
Linking formulae with back-scattering measurements

$$P_R^{ex}(E,0) = 1 - P_{el}^{ex}(E,0)$$

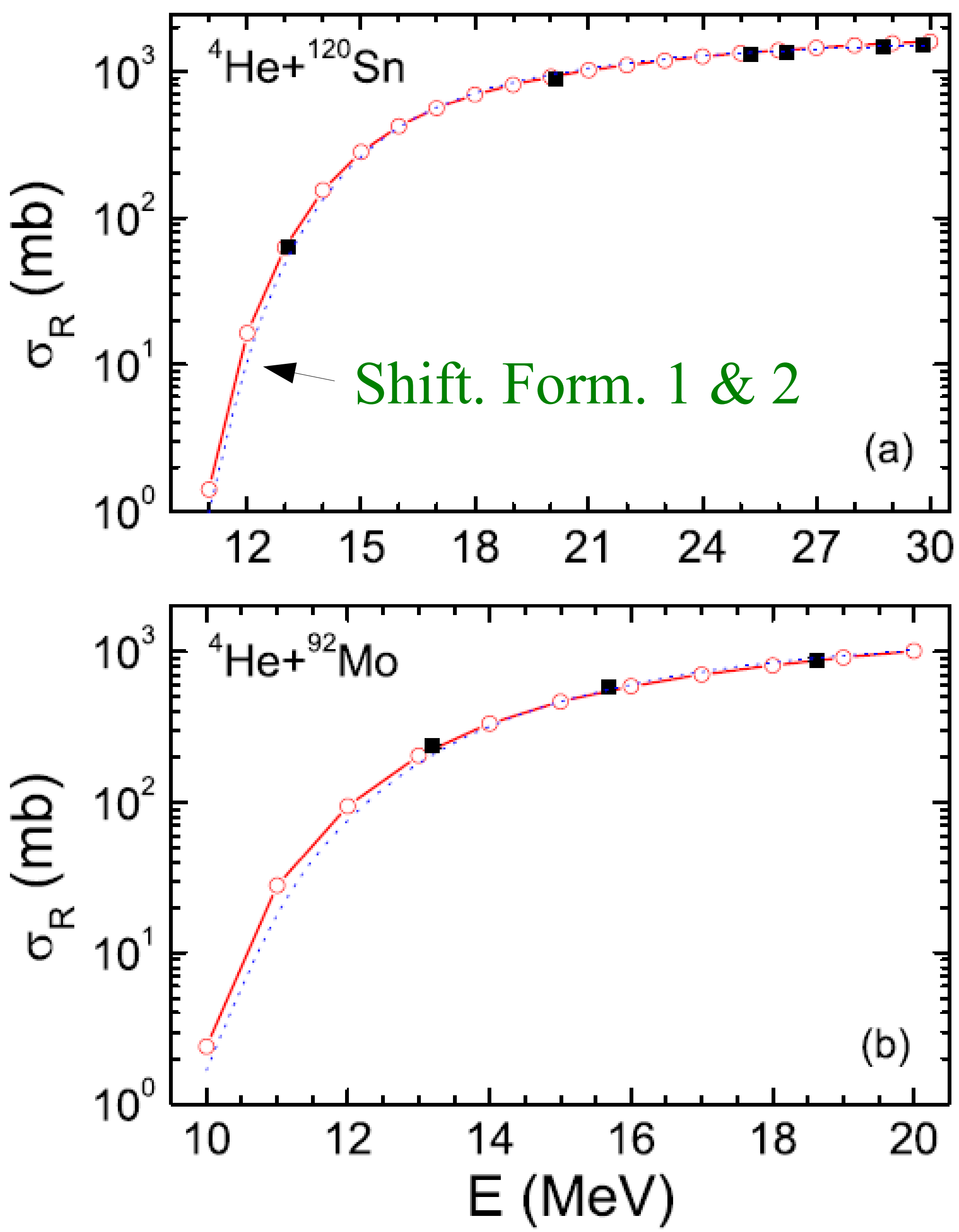
$$P_{cap}^{ex}(E,0) = 1 - \left[P_{qe}^{ex}(E,0) + P_{BU}^{ex}(E,0) + P_{DIC}^{ex}(E,0)\right]$$

$$P_{el,qe,BU}^{ex}(E,0) = \frac{\sigma_{el,qe,BU}(180^\circ)}{\sigma_C(180^\circ)}$$

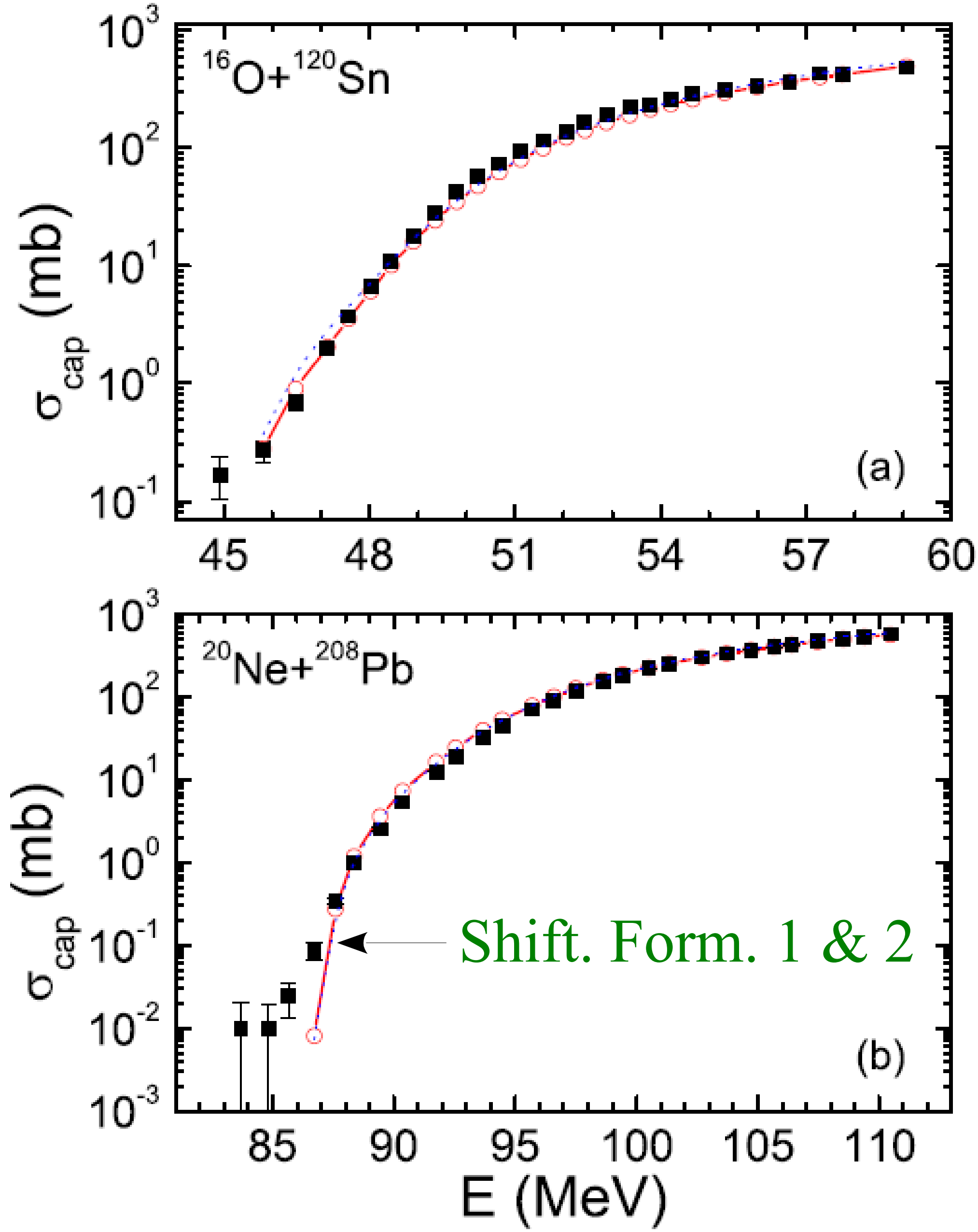
Example



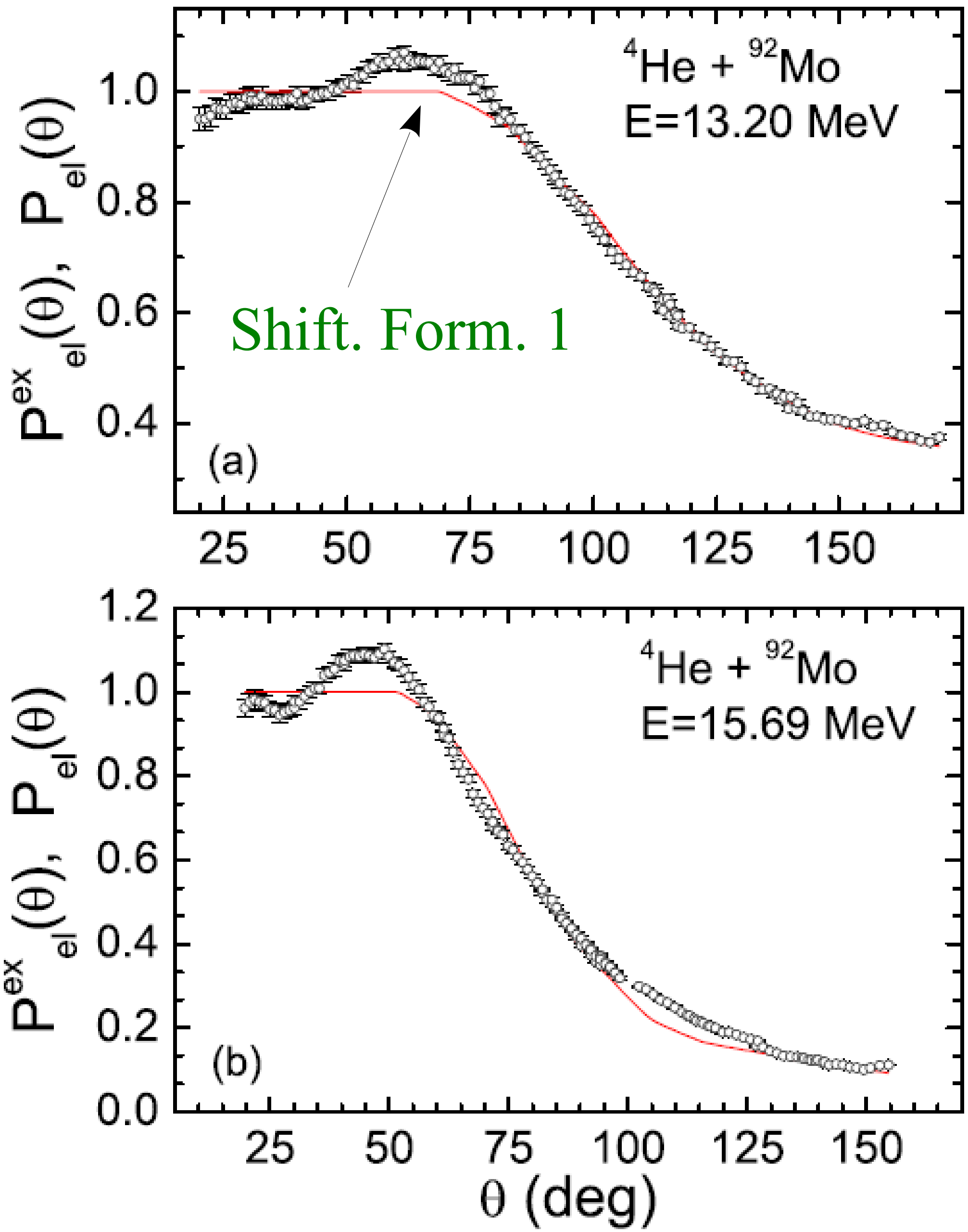
Reaction Excitation Function



Capture Excitation Function



Elastic-scattering differential cross sections



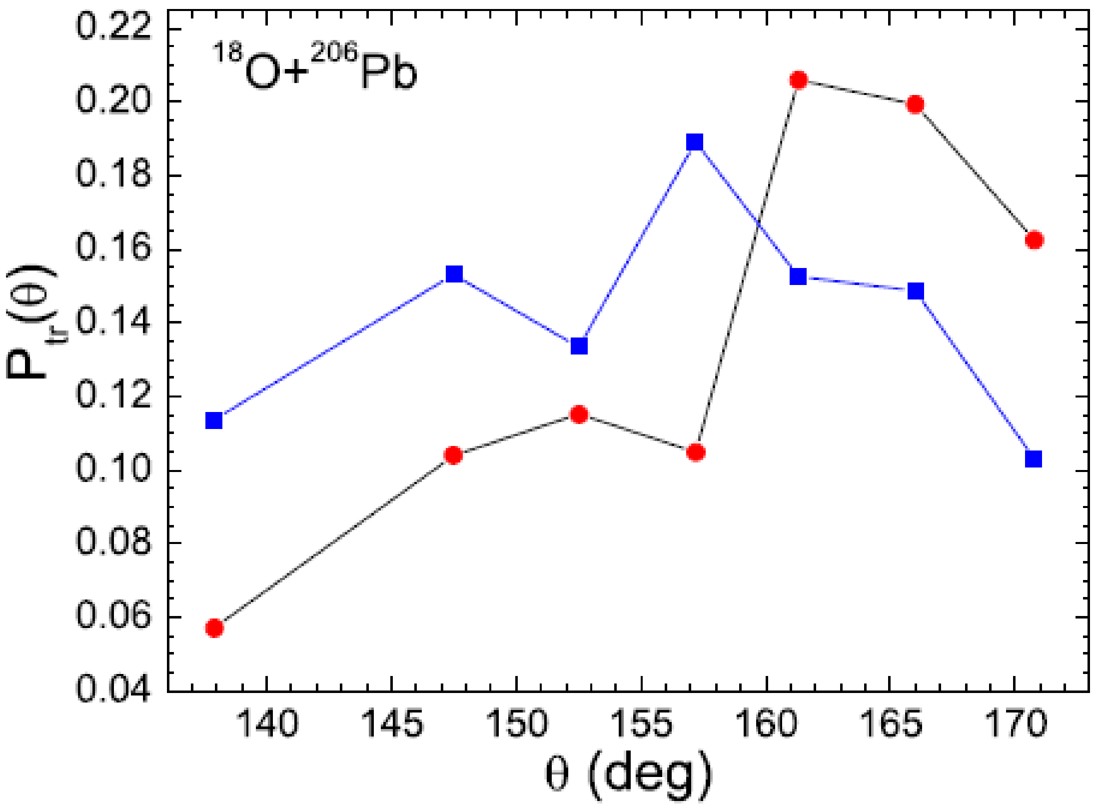
$$J = \eta' \cot\left[\frac{\theta}{2}\right],$$

$$P_{el}(\theta) \approx P_{el}(J) \approx P_{el}(\epsilon_J, J = 0).$$

Transfer probabilities

Sargsyan *et al.*, PRC **93** (2016) 054613

$$P_{\rm tr}(\theta) = 1 - \frac{P_{\rm el,qe}(\theta)[^{18}{\rm O} + {}^{A-2}{\rm X}]}{P_{\rm el,qe}(\theta)[^{16}{\rm O} + {}^{A}{\rm X}]}.$$



Formula

Experiment

Summary & Outlook

- Energy-shifting formulae for reaction & capture probabilities

PLB **739** (2014) 348

- Formulae for cross sections using experimental elastic & quasi-elastic excitation functions at 180 deg.

PRC **90** (2014) 064601; PRC **93** (2016) 054613

Simplicity

Reliability

Usefulness

Reaction Theory