Fission at Intermediate Nucleon Energies

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Fission induced by intermediate energy nucleon

Fission induced by intermediate energy nucleons (200 MeV – 2.5 GeV) is usually considered as a two-stage process :

Fast intranuclear cascade, described as a succession of binary collisions, leading to the emission of fast nucleons, light fragments, pions … and leaving an excited residual nucleus, which decays by

Evaporation – fission,

described by evaporation, fission or other mechanism

Theoretical features for Fast Cascade (1/3)

Liège intranuclear cascade model:

INCL++ (C++ version)

(**A. Boudard, J. Cugnon, J.-C. David, S. Leray and D. Mancusi, Phys. Rev. C 87 , 2013**)

Main features of INCL++:

1) Target nucleus at the centre of a calculation volume (**CV**) of radius $\boldsymbol{R_{max} = R_0 + 8a}$, with $\boldsymbol{R_0}$ the radius and $\boldsymbol{a}$ the diffuseness of target nucleus density.

2) Incident nucleon located on the **CV** surface with its own impact parameter.

Theoretical features for Fast Cascade (2/3)

3) Particles move along straight-line trajectories between collisions inside the **CV**.

4) Binary collision model valid at **E_{proj} > 100 MeV**.

5) Potential well inside the **CV** is isospin dependent, so that neutron and proton Fermi levels have the same energy.

6) Potential well decreases with increasing nucleon energy and goes to zero at E $\approx$ 200 MeV.

7) Pauli blocking strictly applied in the first collision, stochastically applied in subsequent collisions on the basis of final-state blocking factors → depletion of the Fermi sphere during the cascade stage.

Theoretical features for Fast Cascade (3/3)

8) Coalescence model based on phase space considerations permits formation and **emission of light clusters (A <= 8)** in the cascade stage.

9)Possible excitation of nucleons to **Δ resonances** and subsequent production of **pions**, which can be reabsorbed or emitted through the **CV** → $\mathbf{E_{proj} < 2.5}$ **GeV**.

10) Duration of cascade connected with the target mass by the empirical law $t_{stop} = 29.8\, A_T^{0.16}$ fm/c (1 fm/c ≈ 3.3×10^{-24} sec).

Theoretical features for Evaporation (1/6)

Model for Evaporation-fission of residual nuclei:

1) GEMINI++ (C++ version)

(*D. Mancusi, R.J. Charity and J. Cugnon, Phys. Rev. C 82 (2010) 044610* and references therein)

2) ABLA07

(*A. Kelic, M.V. Ricciardi and K.-H. Schmidt, report INDC(NDS)-530, IAEA, Vienna, 2008, p. 181*).

Theoretical features for Evaporation (2/6)

Main features of GEMINI++:

Light particle evaporation described with the Hauser Feshbach formalism (conservation of angular momentum).

An important ingredient of the decay width is

1) the **level density formula:**

$\boldsymbol{\rho(E^*,J) \sim (2J+1)\exp[2\sqrt{a(U,J)U}]}$ (Fermi gas-like) ,

where $\boldsymbol{U = E^* - E_{rot}(J) + \delta P}$ (pairing correction)

and $\boldsymbol{a(U) = \tilde{a}(U)[1 + (\delta W/U)(1-\exp(-\eta U))]}$

(damping of shell correction $\boldsymbol{\delta W}$ according to Ignatyuk, but $\boldsymbol{\tilde{a}(U)}$ contains energy-dependent long-range correlations)

Theoretical features for Evaporation (3/6)

$\tilde{a}(U)$ admits the limits

$\tilde{a}(0) = A/k_0$, with $k_0 = 7.3$ MeV, from neutron resonance counting,

$\tilde{a}(\infty) = A/k_\infty$, with $k_\infty = 12$ MeV, from kinetic energy spectra of evaporated particles.

At intermediate energies it is taken of the form

$$\tilde{a}(U) = \frac{A}{k_\infty - (k_\infty - k_0)exp\left(-\frac{\gamma}{k_\infty - k_0}\frac{U}{A}\right)}$$

Here, $\gamma = 0.00493\ exp\ (0.0332\ A)$.

Theoretical features for Evaporation (4/6)

2) It is customary to assume that $\tilde{a}_f(0)$, the level density parameter at the saddle point, used in fission calculations, is larger than $\tilde{a}_n(0)$, the level density parameter used in neutron evaporation. The default value is $\tilde{a}_f(0)/\tilde{a}_n(0) = 1.036$.

3) Symmetric fission is described by Bohr-Wheeler decay Width $\Gamma_{BW} = \int d\varepsilon\, \rho_{sad}[E^* - B_f(J_{cn}) - \varepsilon] / [2\pi\, \rho_{cn}(E^*, J_{cn})]$

Binary decay (asymmetric fission) is described by Moretto's conditional decay width

$\Gamma_{ZA} = \int d\varepsilon\, \rho_{sad}[E^* - B_{ZA}(J_{cn}) - \varepsilon]/[2\pi\, \rho_{cn}(E^*, J_{cn})]$

where Z and A are charge and mass of one of the nascent fragments.

Theoretical features for Evaporation (5/6)

Main features of ABLA07:

1) Particle evaporation : Weisskopf-Ewing formalism with semiclassical approximation for degradation of intrinsic angular momentum.

2) Nuclear level density with collective enhancement factor :

$\rho(E) = \rho_{in}(E)\, K_{vib}(E)\, K_{rot}(E)$

$\rho_{in}(E)$: constant temperature formula at low energy combined with Bethe formula at high energy, with shell and pairing corrections and Ignatyuk asymptotic level density parameter

$\tilde{a} = 0.073\, A + 0.095\, B_s A^{2/3}$

with B_s the ratio of the surface of the deformed nucleus and a spherical one with same A.

Theoretical features for Evaporation (6/6)

3) High-energy fission : time-dependent fission width from approximate solution of one-dimensional Fokker-Planck equation in fission coordinate β :

$\Gamma_f\,(t) = K(\gamma)\;\Gamma_{BW}\,W(\beta = \beta_s\,;\,t\,,\,\gamma\,)\,/\,W(\beta = \beta_s\,;\,t \rightarrow \infty\,,\,\gamma\,)$ where :

$K(\gamma)$: Kramers factor depending on dissipation coefficient γ ;

Γ_{BW} : Bohr – Wheeler fission width ;

W *:* time-dependent distribution of fission coordinate β.

β_s : fission coordinate at the saddle point.

4) Low-energy fission : standard two-humped fission barrier in the limit of full damping of resonances in intermediate well :

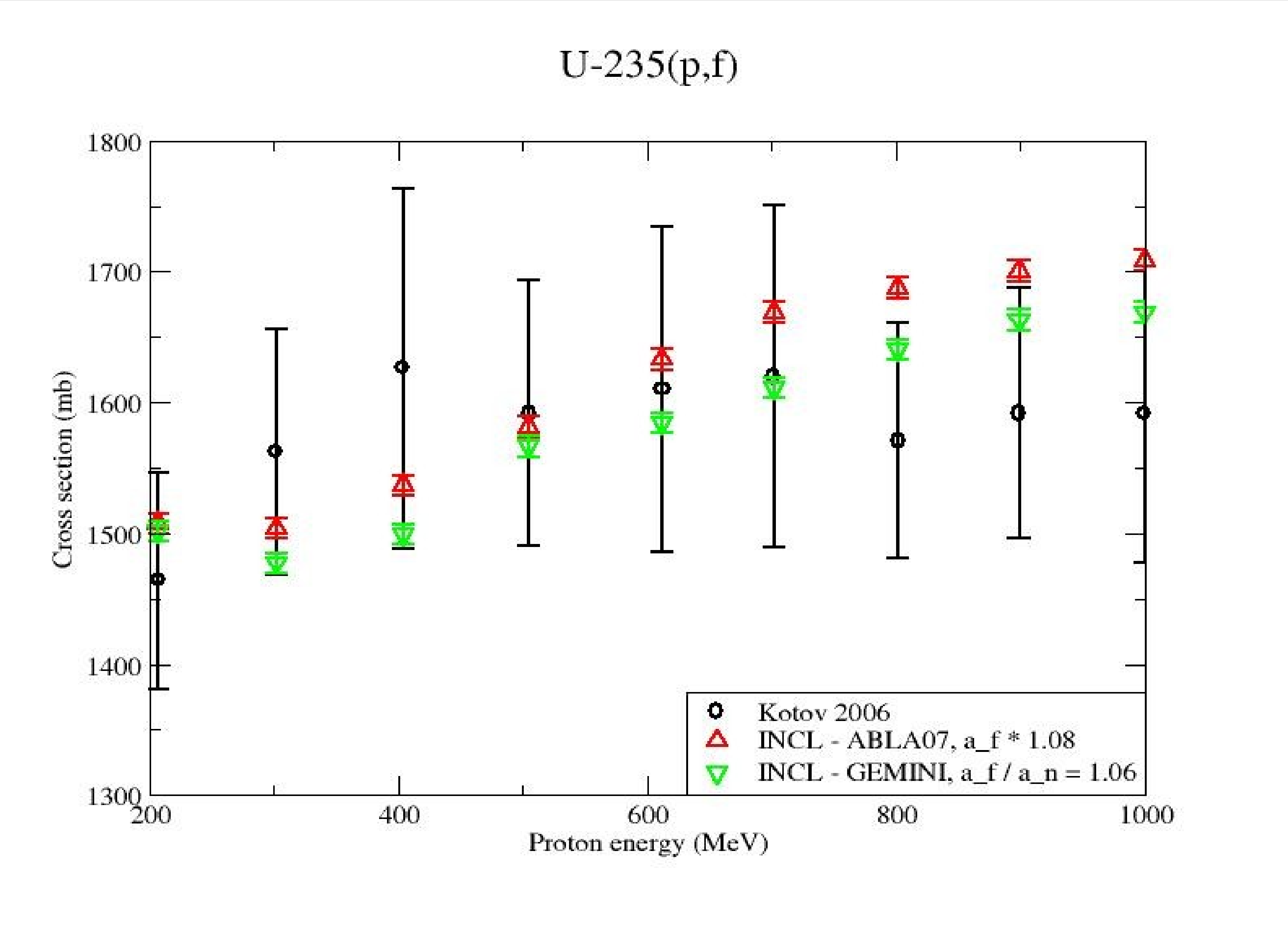
$\Gamma_f = \Gamma_A\,\Gamma_B\,/\,(\Gamma_A + \Gamma_B)$.

Computational strategy

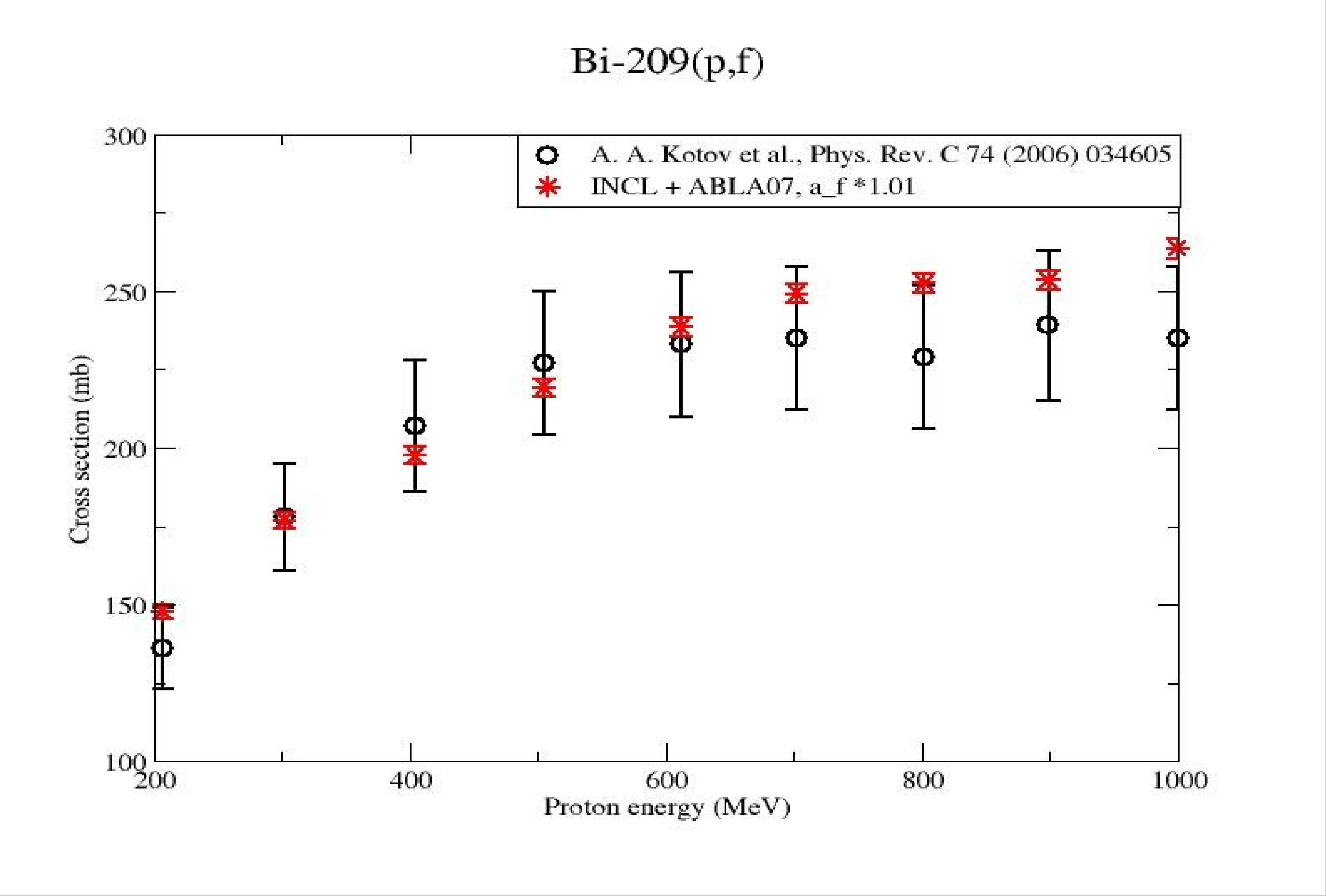
1) Parameters of fission models (basically $\tilde{a}_f / \tilde{a}_n$ in GEMINI and $\tilde{a}_f$ in ABLA) are calibrated on experimental **(p,f)** cross sections in the energy range 200 MeV – 1 GeV (**Kotov et al., Phys. Rev. C 74 (2006) 034605)** and are then applied to the calculation of **(n,f)** cross sections.

2) The theoretical ratios to the **^{235}U(n,f)** cross section are compared with the **n_TOF** (https://ntof-exp.web.cern.ch/ntof-exp/) ratios in the actinide region **(C. Paradela et al., Phys. Rev. C 82 (2010) 034601)** and in the Pb-Bi region (**D. Tarrío et al., Phys. Rev. C 83 (2011) 044620**).

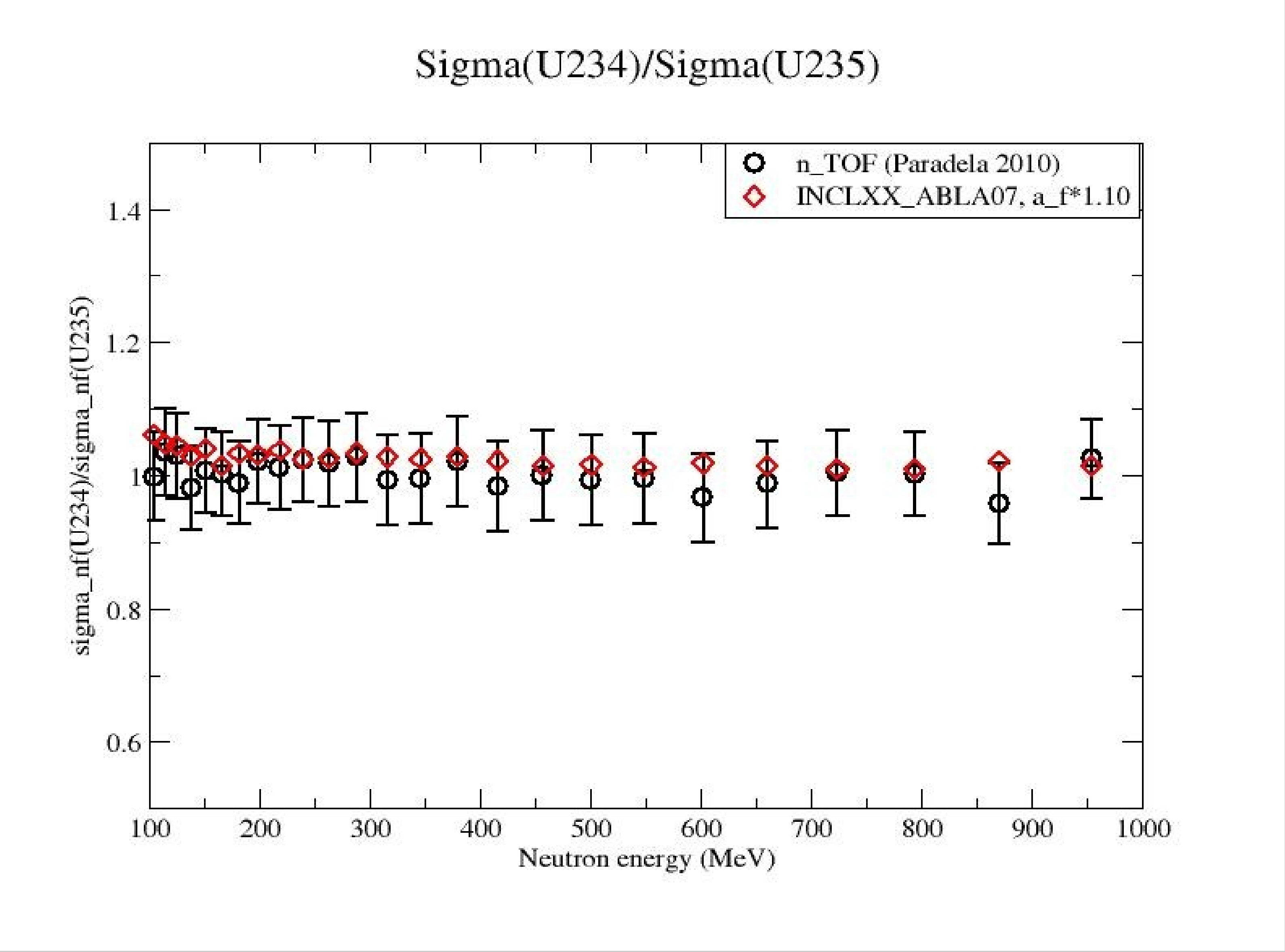
Computational results: $^{235}U(p,f)$



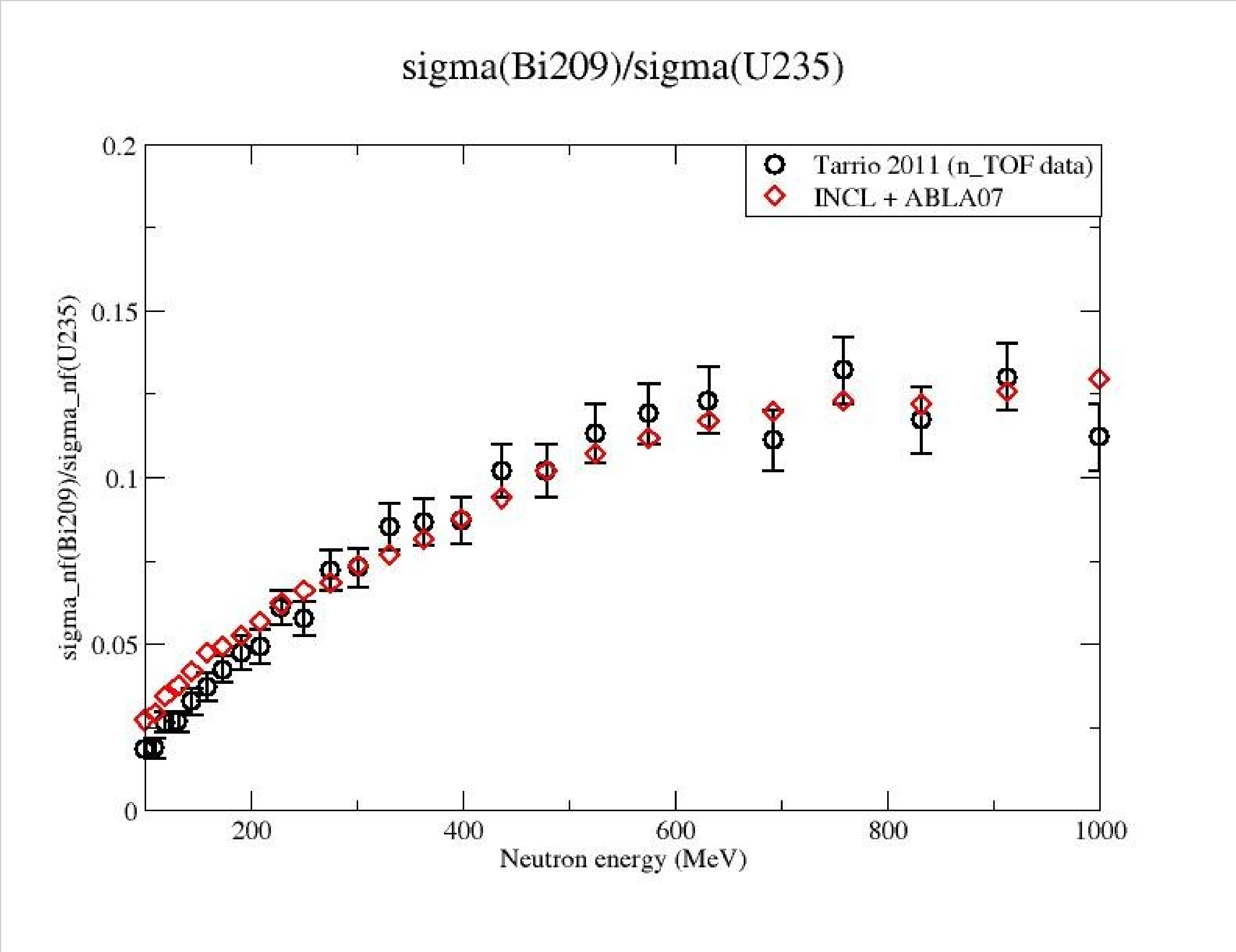
Computational results: ^{209}Bi(p,f)



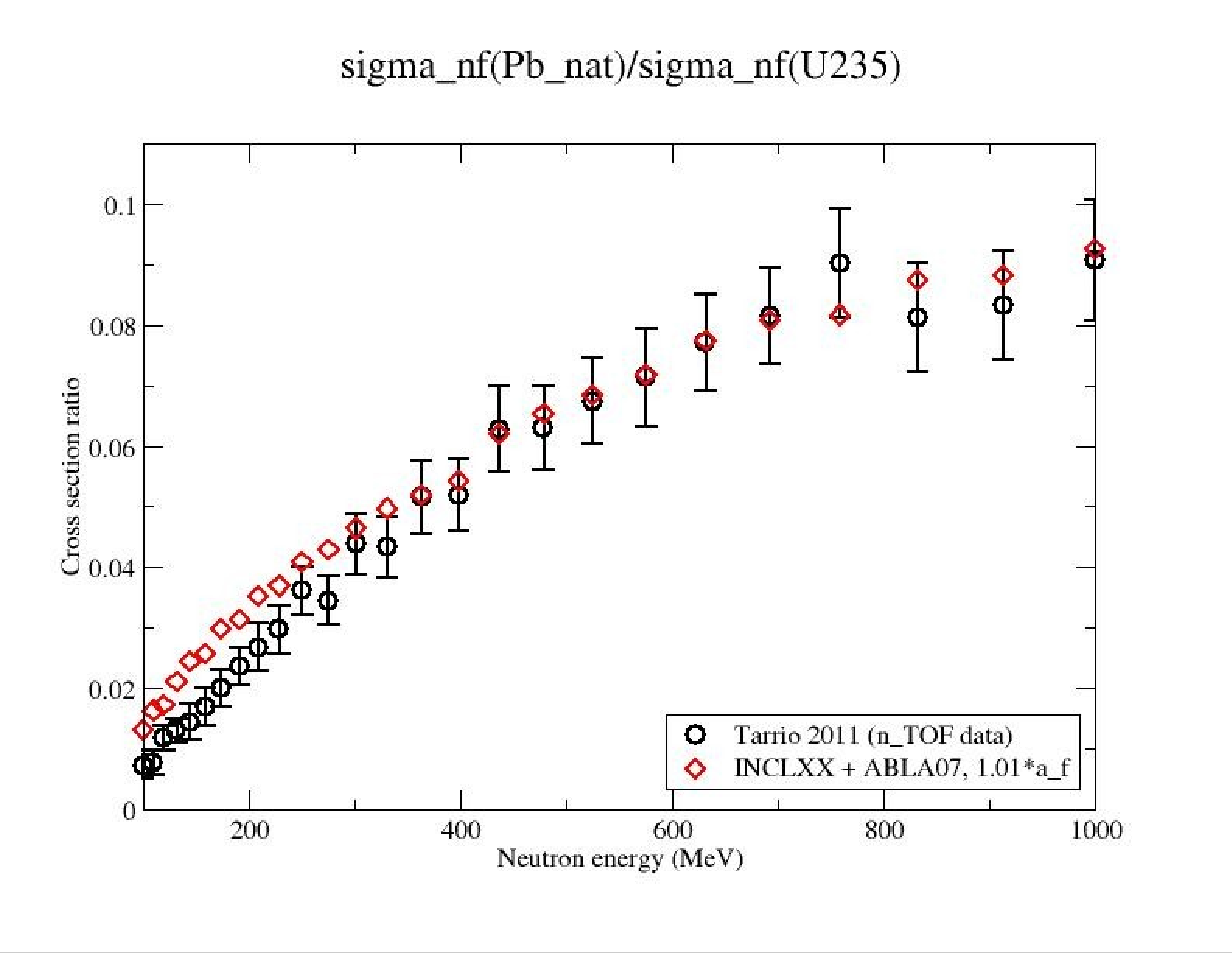
Computational results: $\sigma(^{234}U(n,f))/\sigma(^{235}U(n,f))$



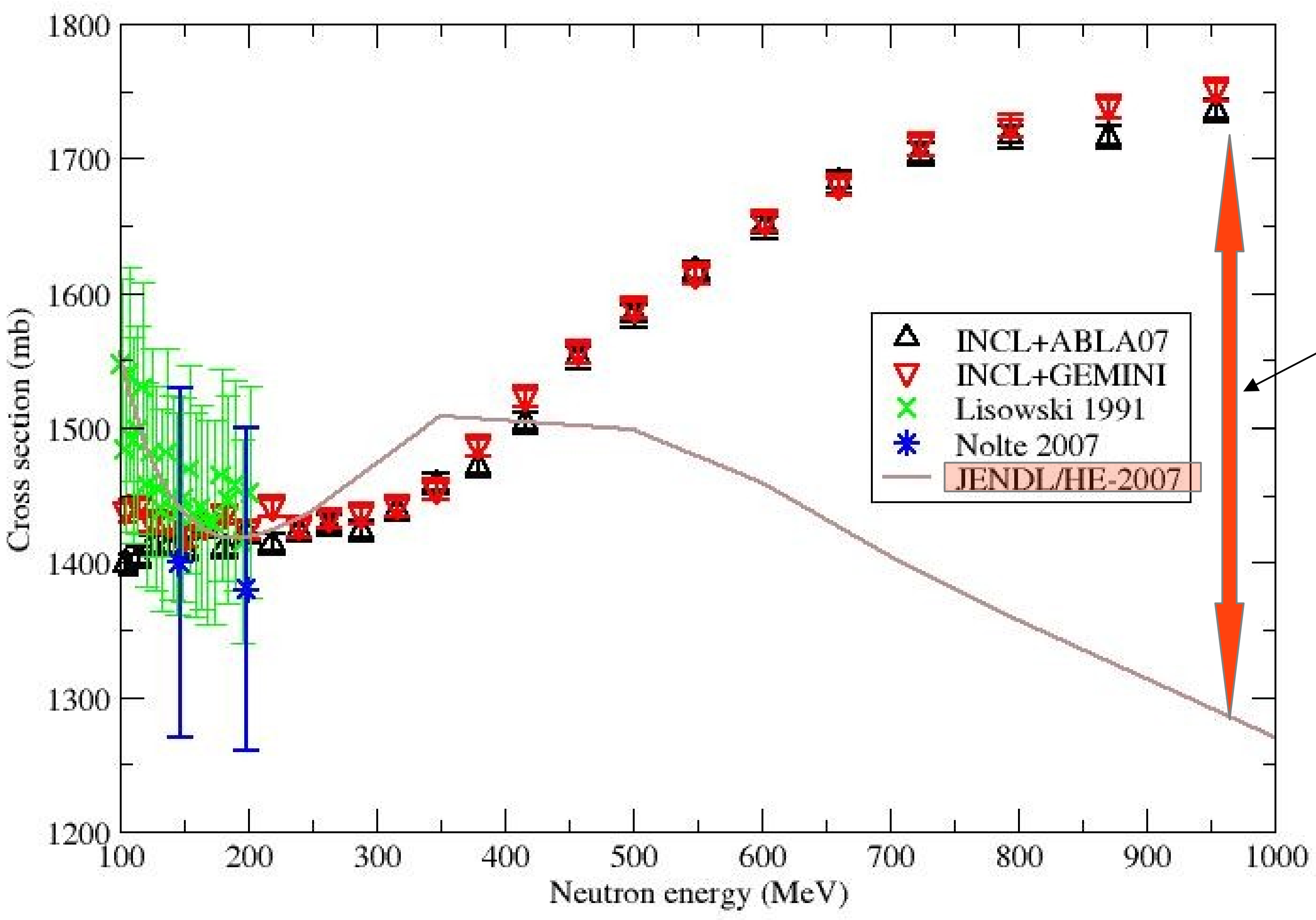
Computational results: $\sigma(^{209}Bi(n,f))/\sigma(^{235}U(n,f))$



Computational results: $\sigma(^{nat}Pb(n,f))/\sigma(^{235}U(n,f))$

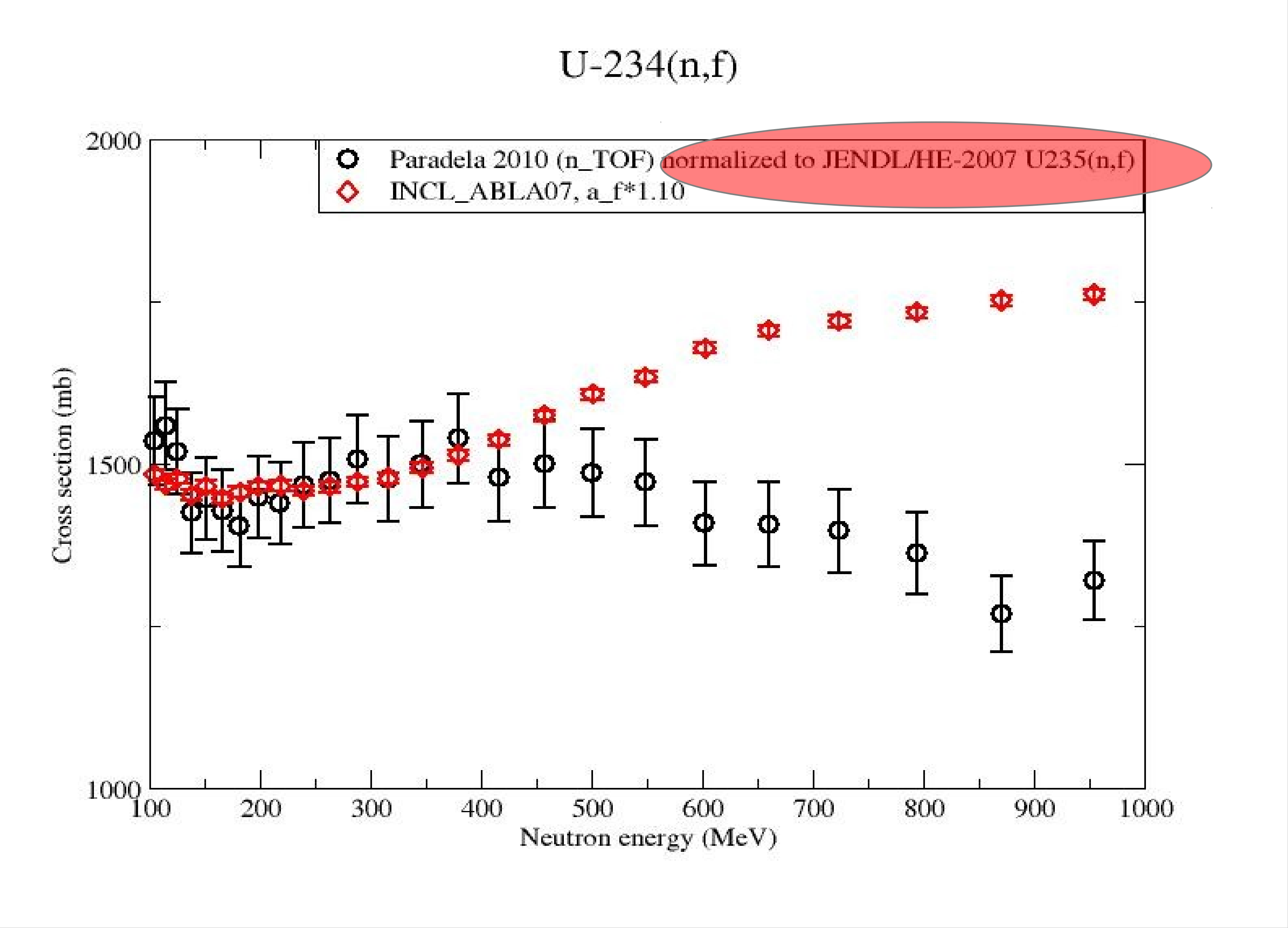


Computational results: $^{235}U(n,f)$

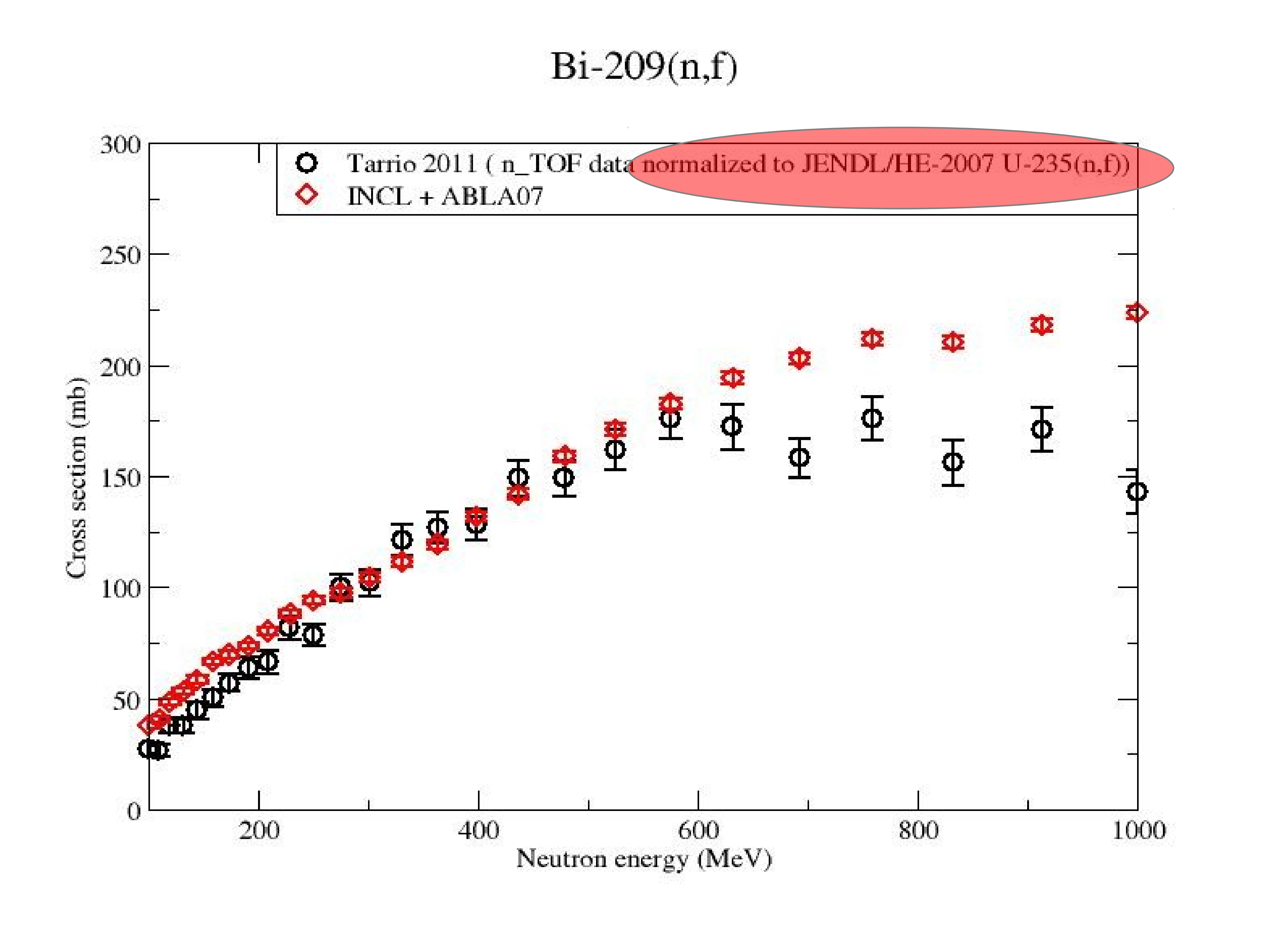


Big Difference!!

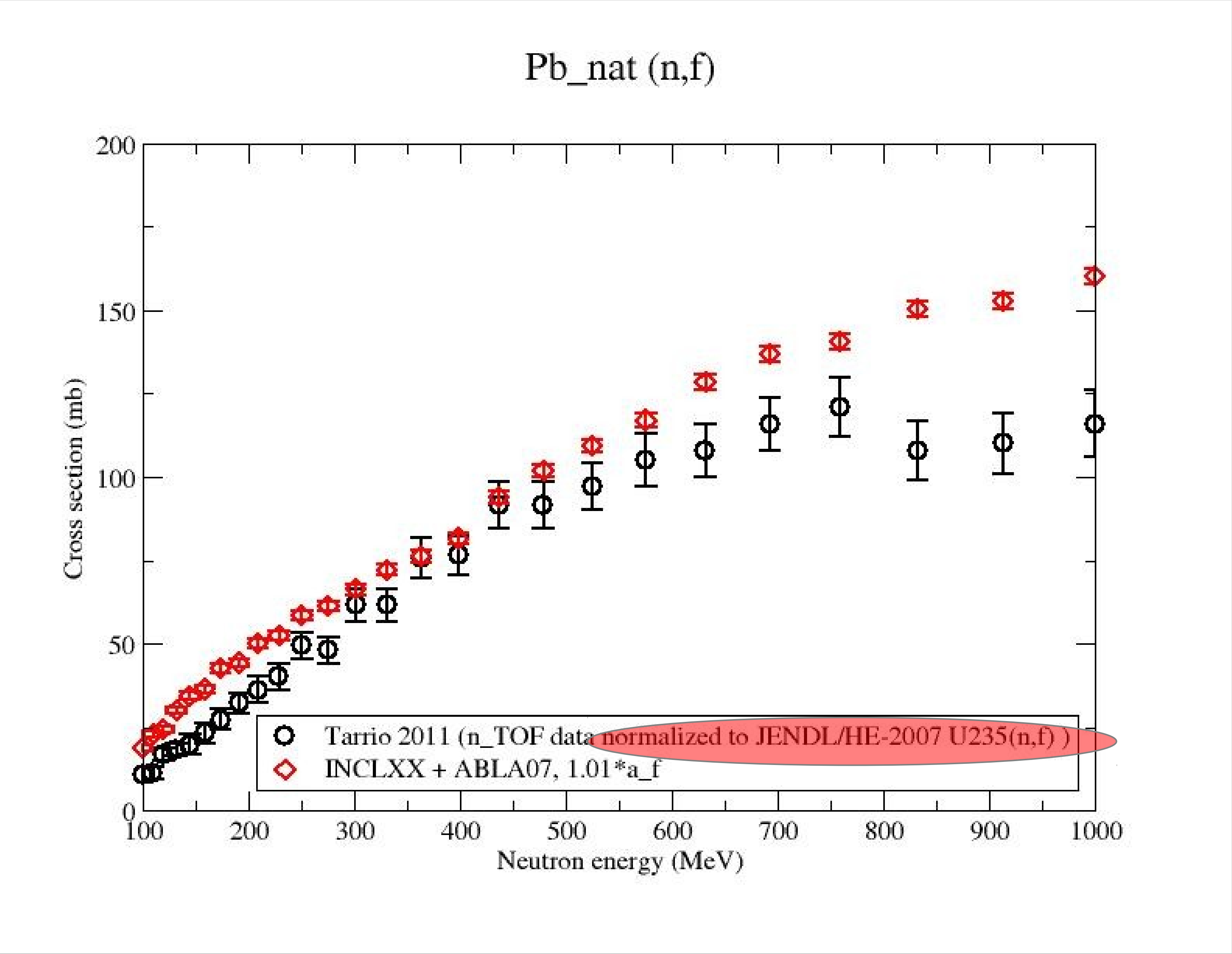
Computational results: $^{234}U(n,f)$



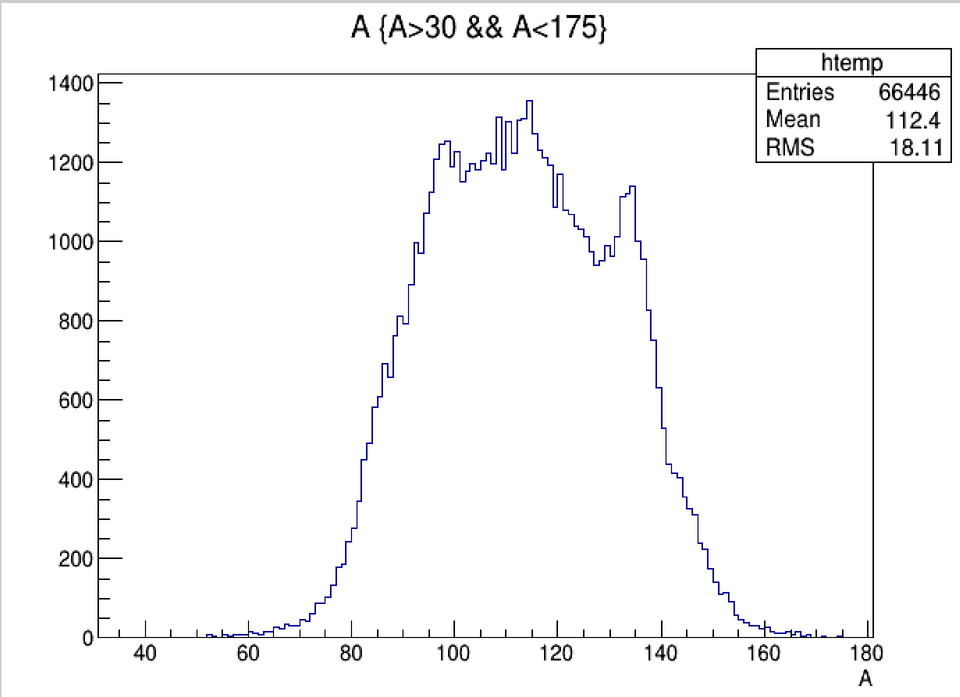
Computational results: ^{209}Bi(n,f)

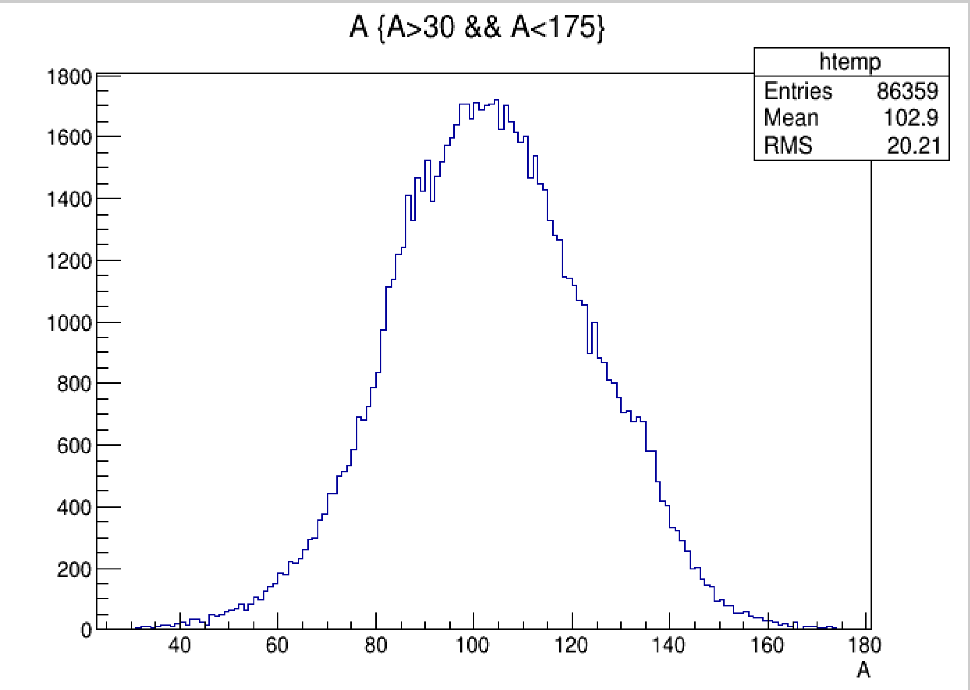


Computational results: $^{nat}Pb(n,f)$



Mass distribution of Fission Fragments $^{235}U(n,f)$





Mass distribution of fission fragments at E_n = 104.71 MeV (left panel) and E_n = 954.99 MeV (right panel) computed with INCL + ABLA07.

Conclusion

1) INCL + ABLA07 is able to reproduce experimental (p,f) cross sections (Kotov 2006) and experimental ratios of (n,f) cross sections to ^{235}U(n,f) (n_TOF data) in the Pb-Bi and actinide region.

2) Absolute (n,f) cross sections are larger than those published by n_TOF in the energy region from 500 MeV to 1 GeV because of different normalization. The JENDL evaluation of the ^{235}U (n, f) cross section does not seem to be consistent with the experimental (p, f) cross section in the same energy range.

3) INCL + GEMINI is equivalent to **INCL + ABLA07** in the actinide region, but less satisfactory in the Pb-Bi region.

Outlook

1) **Systematic analysis** of (p,f) and (n,f) cross sections above 100 MeV for determination of $\tilde{a}_f/\tilde{a}_n$ and other crucial parameters as a function of the fissility parameter and other characteristics of target nuclei.

2) **Prediction** of (n,f) cross sections to be measured by n_TOF, with particular reference to Pu isotopes.

3) **Calculation** of angular distributions of fission fragments for the isotopes of interest to n_TOF.

For further details:

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THANKS FOR ATTENTION!!