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Fusion probability of massive nuclei in reactions leading to heavy composite nuclear systems

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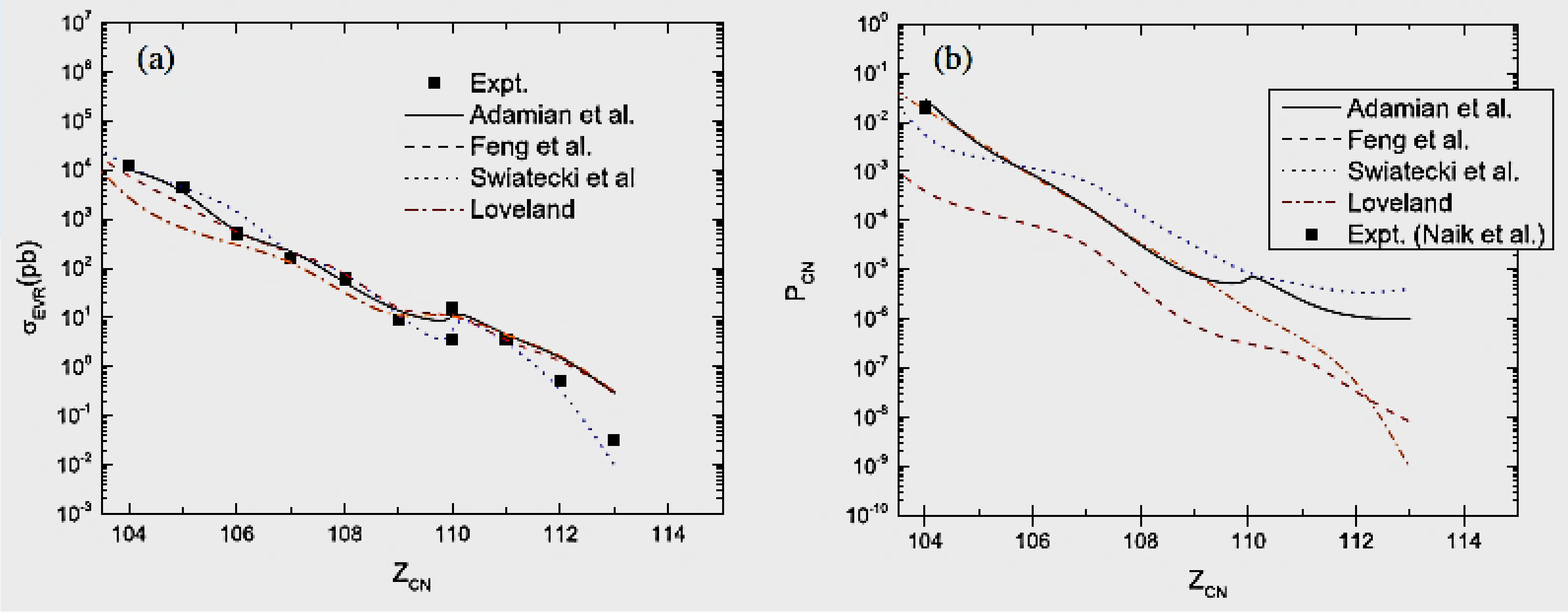
1. P_{CN} as a key value for the estimates of production cross sections for the heaviest nuclei
2. P_{CN} values and their scaling for the data obtained from fission study
3. P_{CN} values and their scaling as obtained with ER cross section data
4. Summary and conclusion

Theoretical and experimental estimates of P_{CN}

$$\sigma_{\mathrm{ER}} = \sum_{L=0}^{L_{max}} \sigma_{\mathrm{cap}}(E,L) \boldsymbol{P_{\mathrm{CN}}(E,L)} W_{\mathrm{sur}}(E^*_{\mathrm{CN}},L), \quad \sigma_{\mathrm{cap}} = \pi/k^2 \sum_{L=0}^{L_{max}} (2L+1) T_L(E,L).$$



W. Loveland, EPJ Web Conf. **131**, 04003 (2016)

Experiment

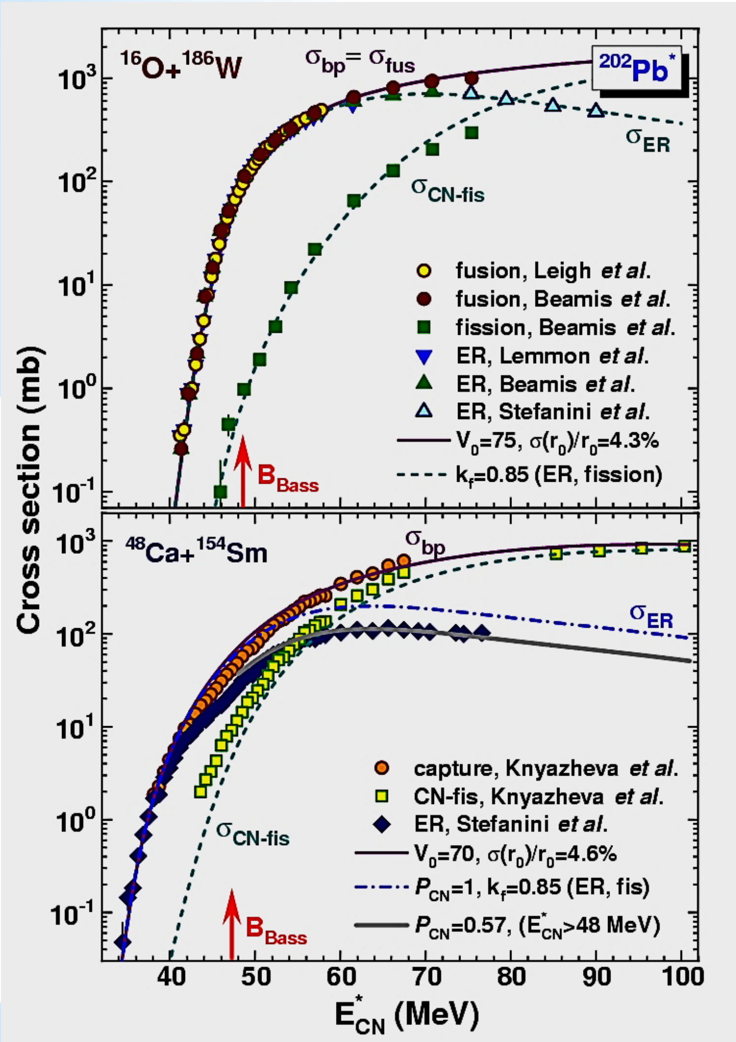
Fission study

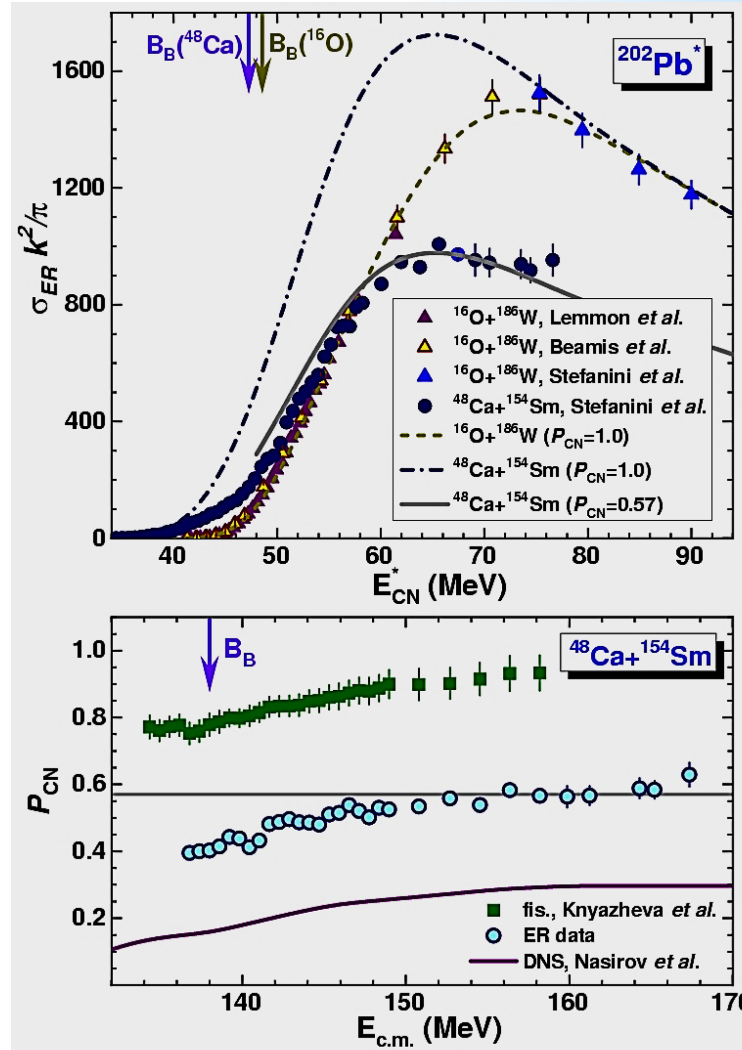
P_{CN} values are estimated by comparing the total yield of FF corresponding to the capture process and the FF yield attributed to true CN-fission. CN-fission events are usually extracted with proper decompositions of fission fragment TKE, mass and angular distributions

ER cross-section data

P_{CN} values are estimated by comparing production cross sections for a very asymmetric projectile-target combination, assuming $P_{\mathrm{CN}} \approx 1$, and those for a less asymmetric one, which is under study and leads to the came CN

Twofold estimates of P_{CN} in reactions leading to $^{202}Pb^*$ CN

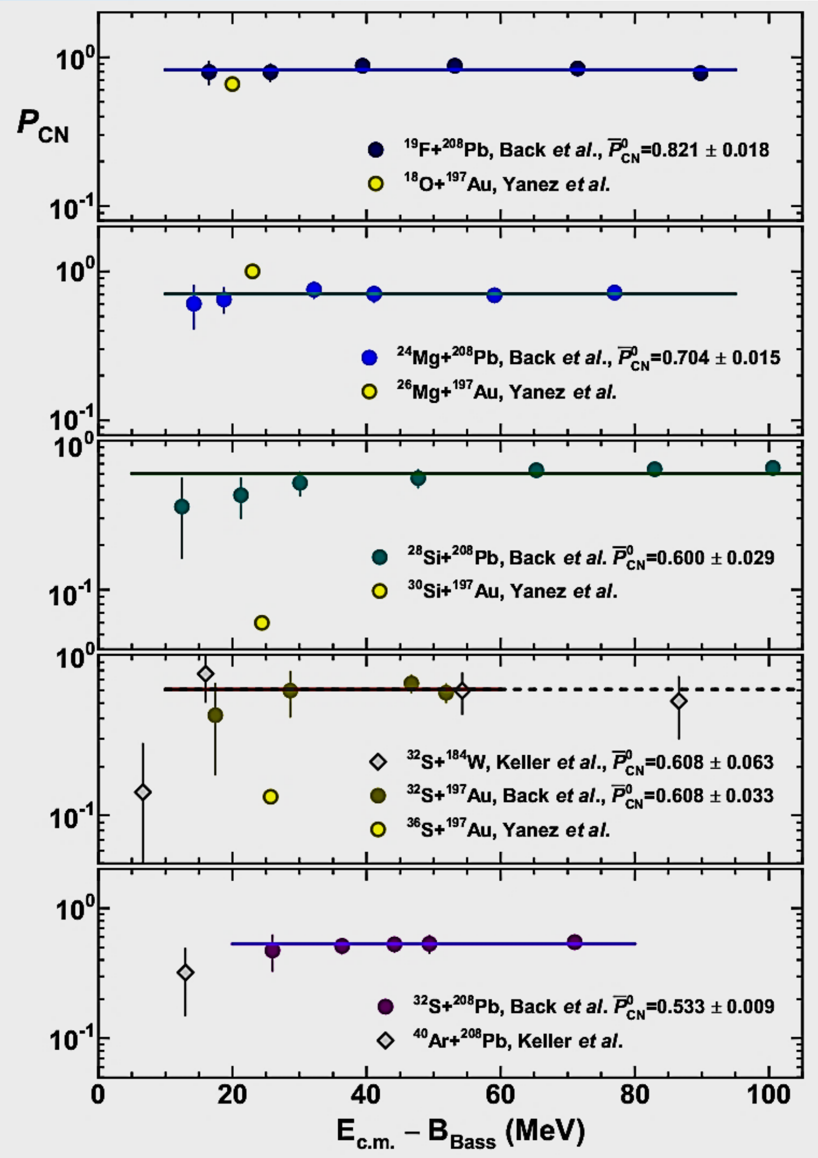


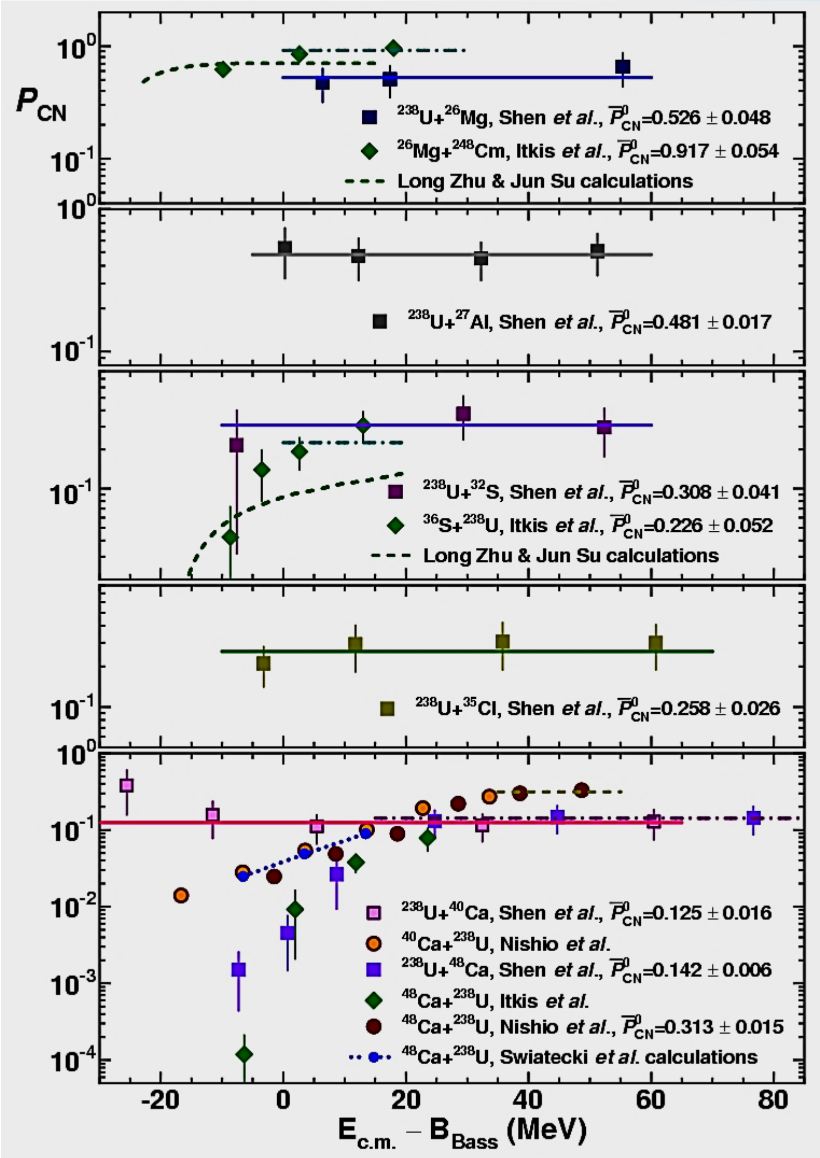


A.M. Stefanini *et al*., Eur. Phys. J. A **23**, 473 (2005)
G.N. Knyazheva *et al.*, Phys.Rev. C **76**, 054604 (2007)

P_{CN} in $^{48}Ca+^{154}Sm$ reaction was estimated by comparing ER cross sections obtained in $^{16}O+^{186}W$ and $^{48}Ca+^{154}Sm$ reactions and by decomposing fission fragment mass, angular and TKE distributions obtained in $^{48}Ca+^{154}Sm$

P_{CN} from fission reactions leading to strongly fissile compound nuclei





P_{CN} data scaling using extra-extra push model representation

Critical RLDM value $(Z_{CN}^2/A_{CN})_{cr}$=$50.883\{1-1.7826[(A_{CN}-2Z_{CN})/A_{CN}]^2\}$

CN fissility: $x_{CN} = Z_{CN}^2/A_{CN})/(Z_{CN}^2/A_{CN})_{cr}$

Effective equilibrated fissility: $x_{eff}^{eq} = \frac{(Z^2/A)_{eff}^{eq}}{(Z_{CN}^2/A_{CN})_{cr}},$ where

$$(Z^2/A)_{eff}^{eq} = 4A_pA_tZ_{CN}^2/[A_p^{\frac{1}{3}}A_t^{\frac{1}{3}}\left(A_p^{\frac{1}{3}}+A_t^{\frac{1}{3}}\right)A_{CN}^2]$$

H. Gägeller *et al.*, Z. Phys. A **316**, 291 (1984);
F.P. Heßberger, GSI-85-11;
HIVAP

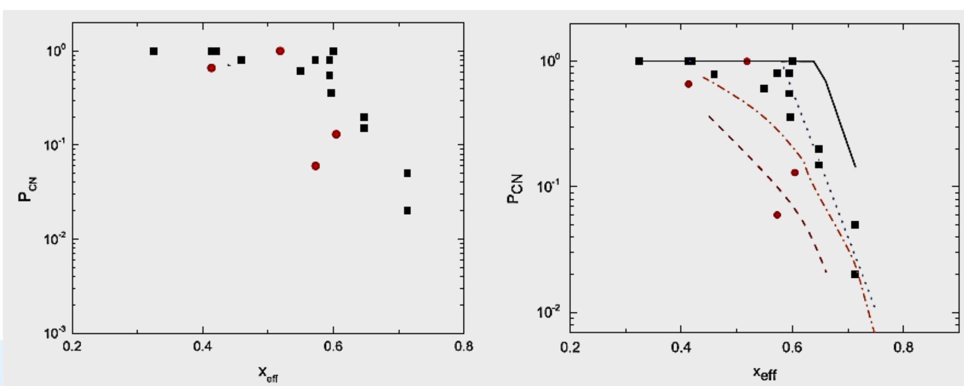
Equilibrated mean fissility: $x_{mean}^{eq} = \sqrt{(Z^2/A)_{eff}^{eq}\, x_{CN}}$

Effective fissility: x_{eff}=$4x_{CN}(k^2+k+k^{-1}+k^{-2})$, where $k = (A_p/A_t)^{-1/3}$

J.P. Blocki *et al.*, Nucl. Phys. **A459**,145 (1986)

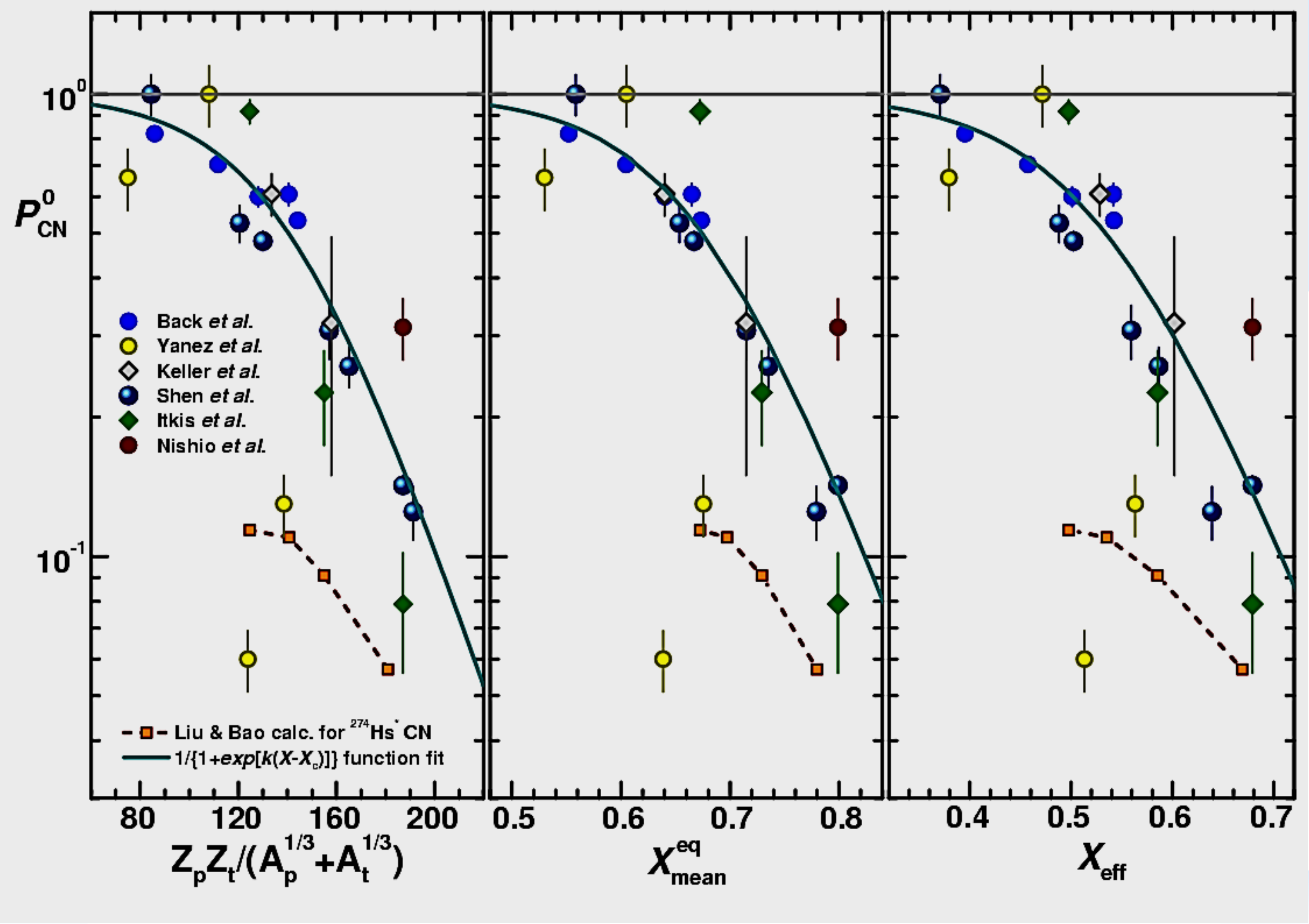
Characteristic ee – push energy: $E_{ch}^{xx} = 7.601\cdot 10^{-4}A_p^{\frac{1}{3}}A_t^{\frac{1}{3}}\left(A_p^{\frac{1}{3}}+A_t^{\frac{1}{3}}\right)^2(Z_{CN}^2/A_{CN})_{cr}/A_{CN}$

Fusion barrier shift $\Delta E = a_{push}^2E_{ch}^{xx}(x_{mean}^{eq}$- $x_{thr})^2$



R. Yanez *et al.*, Phys. Rev. C **88**, 014606 (2013)

Scaling of P^0_{CN} data obtained from fission studies



ER cross section data analysis for the extraction of P_{CN} values using barrier passing and statistical models (HIVAP)

$$\Sigma\sigma_{xn} = \sum_{L=0}^{L_{max}} \sigma_{cap}(E,L) P_{CN}(E,L) W_{sur}(E^*_{CN}, L),$$

Measured

Calculated with SM

Measured

$$\sigma_{cap} = \pi/k^2 \sum_{L=0}^{L_{max}} (2L+1) T_L(E,L).$$

Described in calculations with BPM

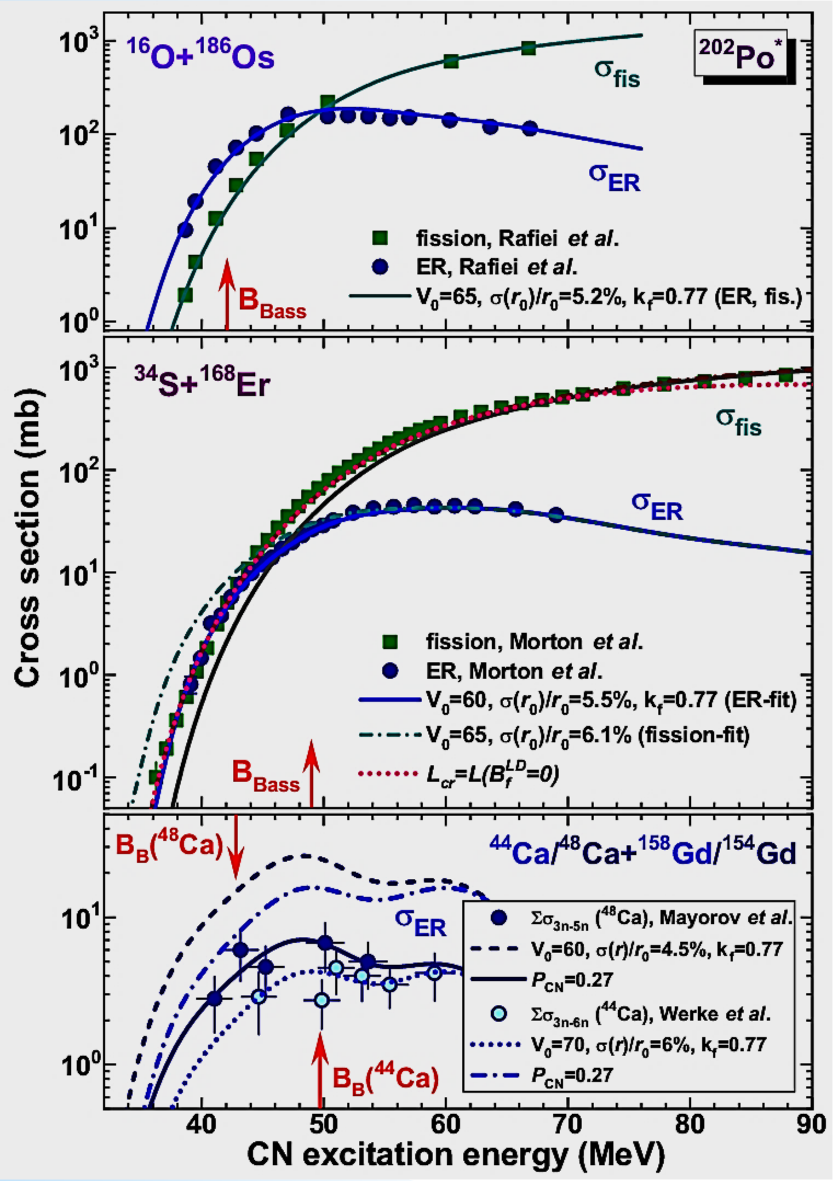
Barrier passing model (P_{CN} = 1 for very asymmetric projectile-target combinations)

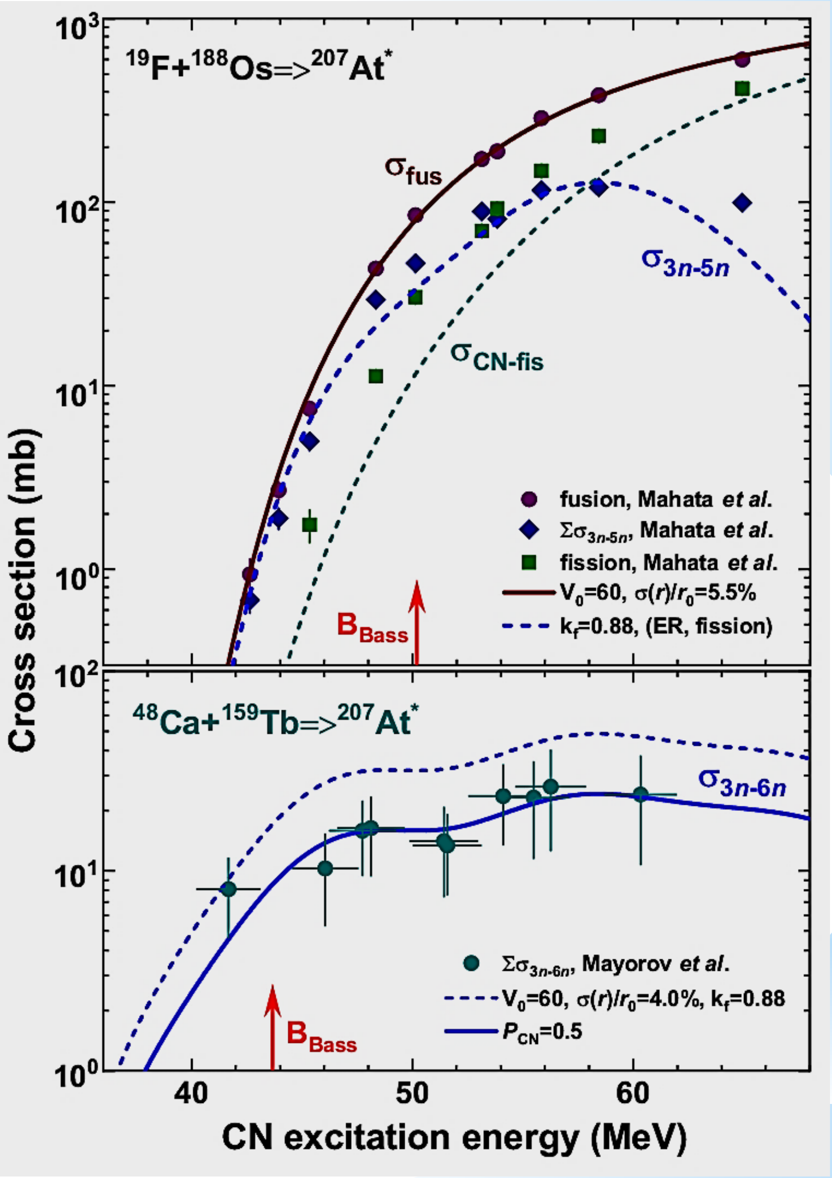
- Coupling to various entrance channels – via the radius (barrier) fluctuations $\sigma(r_0)/r_0$ generated using a Gaussian distribution with the mean value r_0 and width $\sigma(r_0)$
- The exponential nuclear potential with adjusting V_0 and $\sigma(r_0)/r_0$, fixed r_0=1.12 *fm* and *d*=0.75 *fm*
- The *WKB* approximation for transmission coefficients of partial waves penetrating the barrier

Statistical model approximations for description of W_{sur}

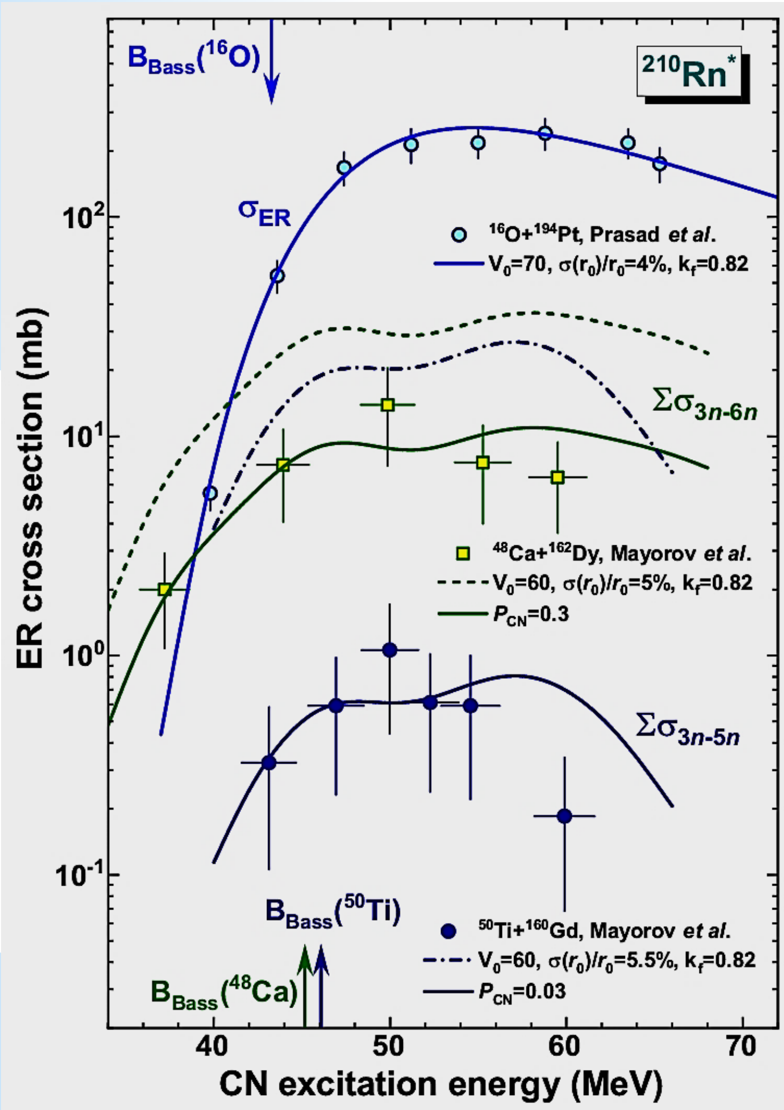
- Intrinsic level density only with the shell damping energy E_D = 18.5 MeV
- The expression of W. Reisdorf for the macroscopic level density parameters in the fission and evaporation channels of the CN decay $(\tilde{a}_f / \tilde{a}_v > 1)$
- ER and fission cross section calculations adjusted with the LD barrier scaling using a scaling parameter k_f as a main fitted parameter: $B_f(L) = k_f B_f^{LD}(L) - \Delta W_{gs}$
- Calculations of ground-state shell correction ΔW_{gs} (a difference between empirical and LD masses), excitation and separation energies with empirical masses

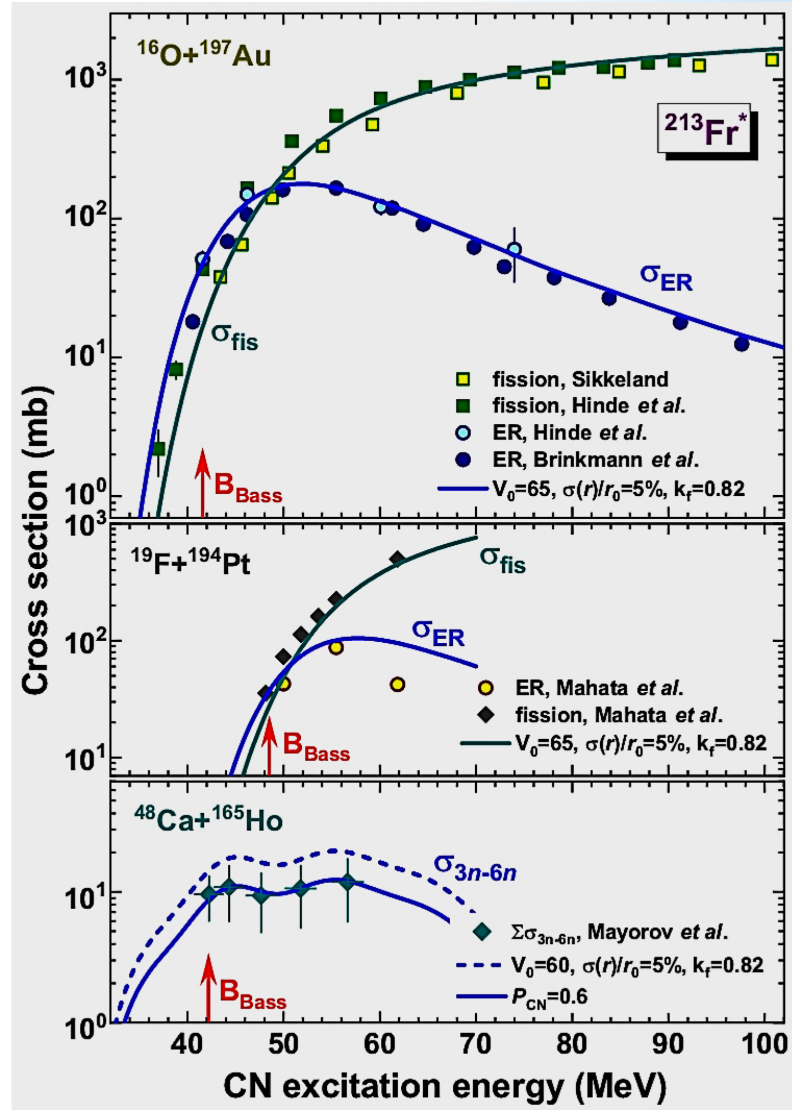
P_{CN} for reactions leading to $^{202}Po^{*}$ and $^{207}At^{*}$ compound nuclei



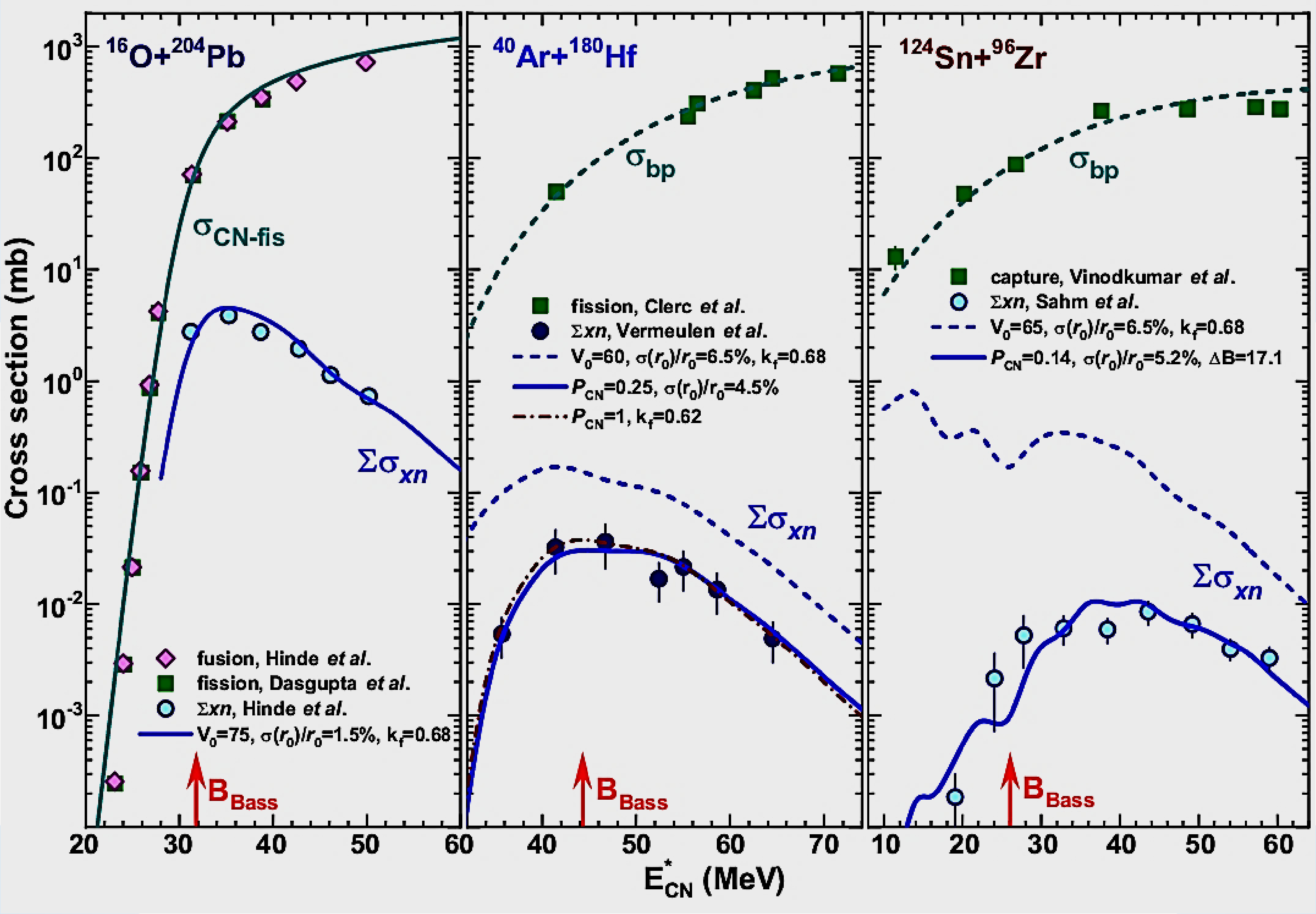


P_{CN} for reactions leading to $^{210}Rn^*$ and $^{213}Fr^*$ compound nuclei

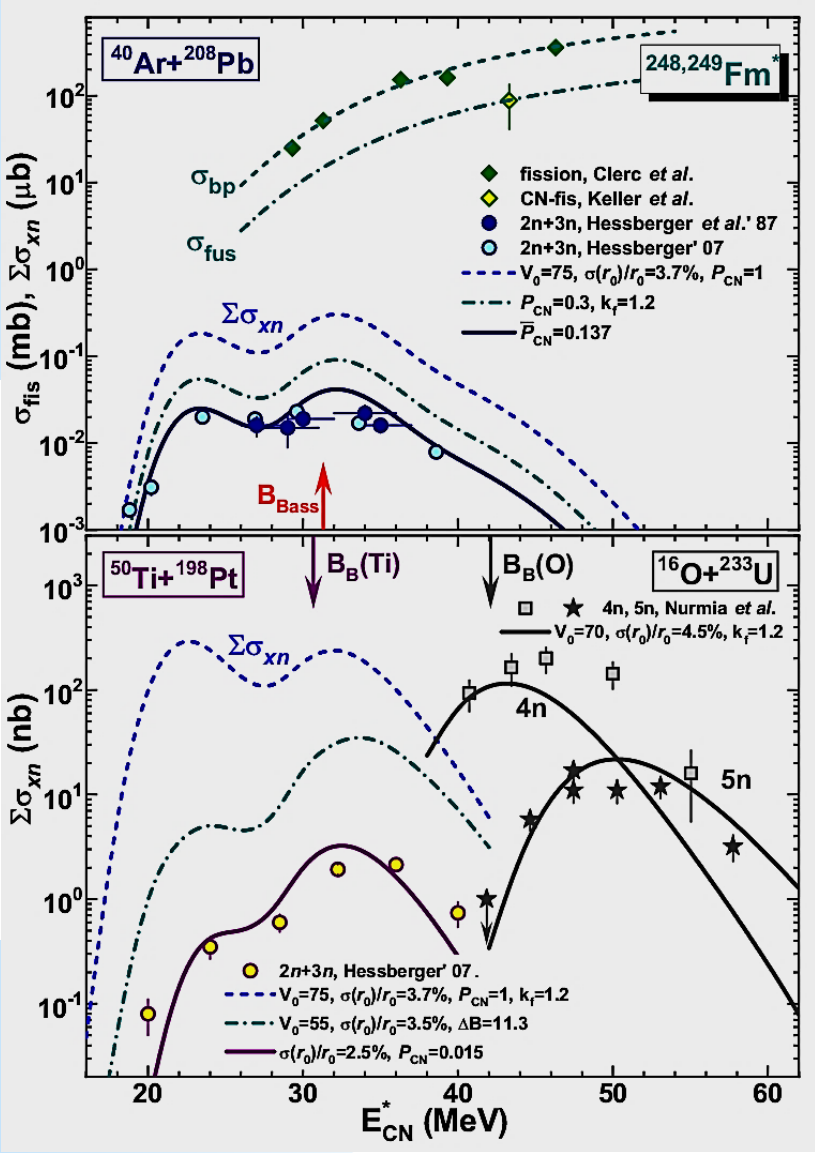


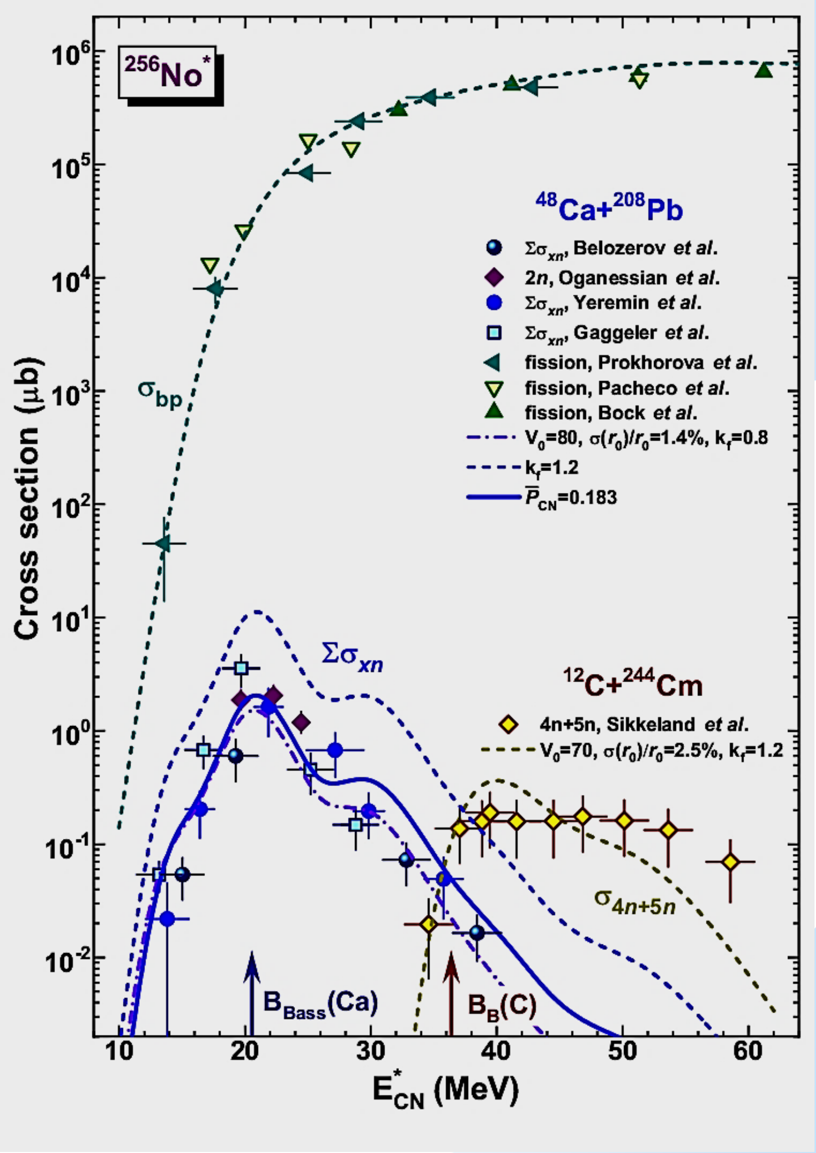


P_{CN} for reactions leading to $^{220}Th^*$ CN

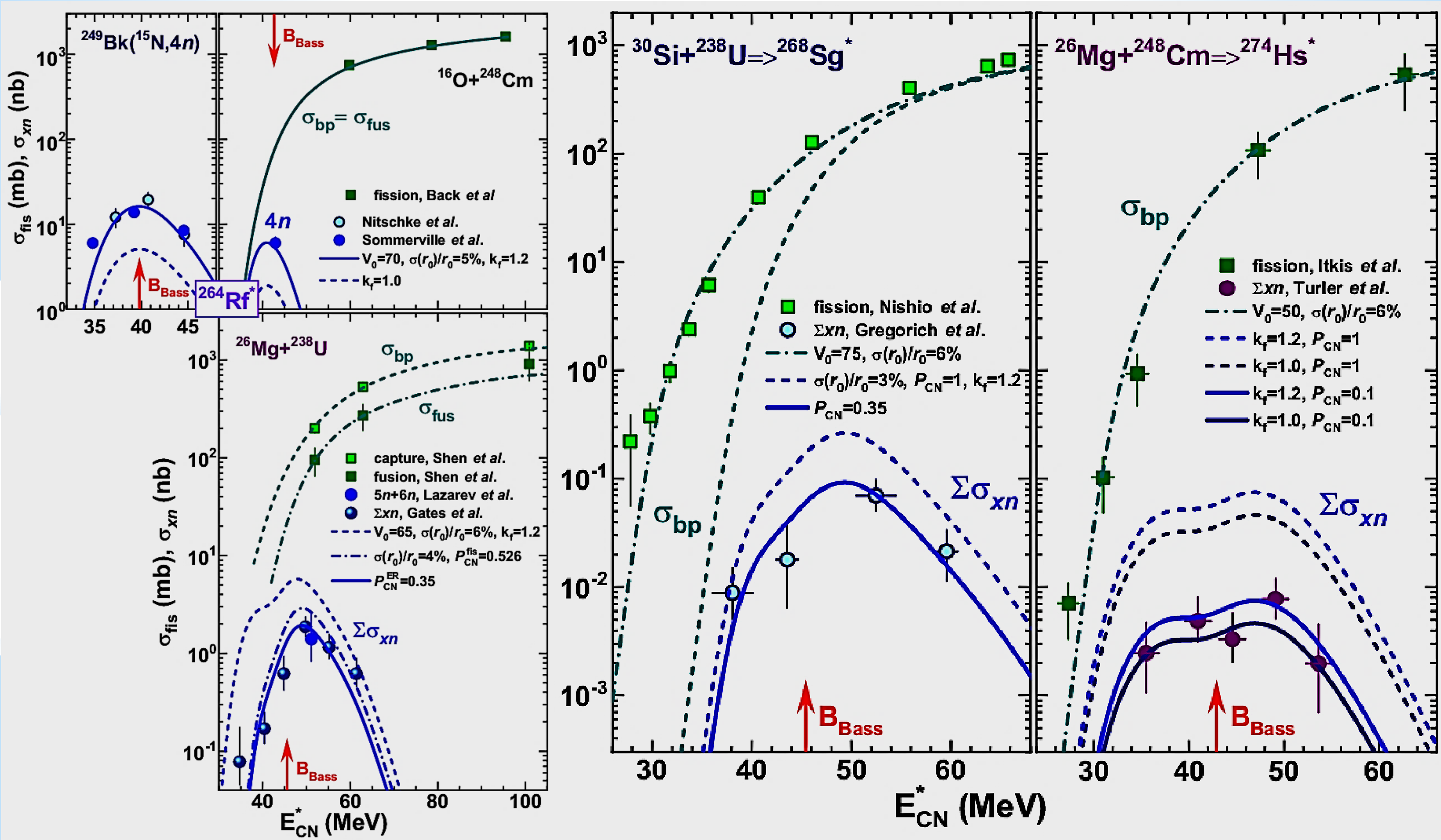


P_{CN} for reactions leading to $^{248}Fm^*$ and $^{256}No^*$ compound nuclei

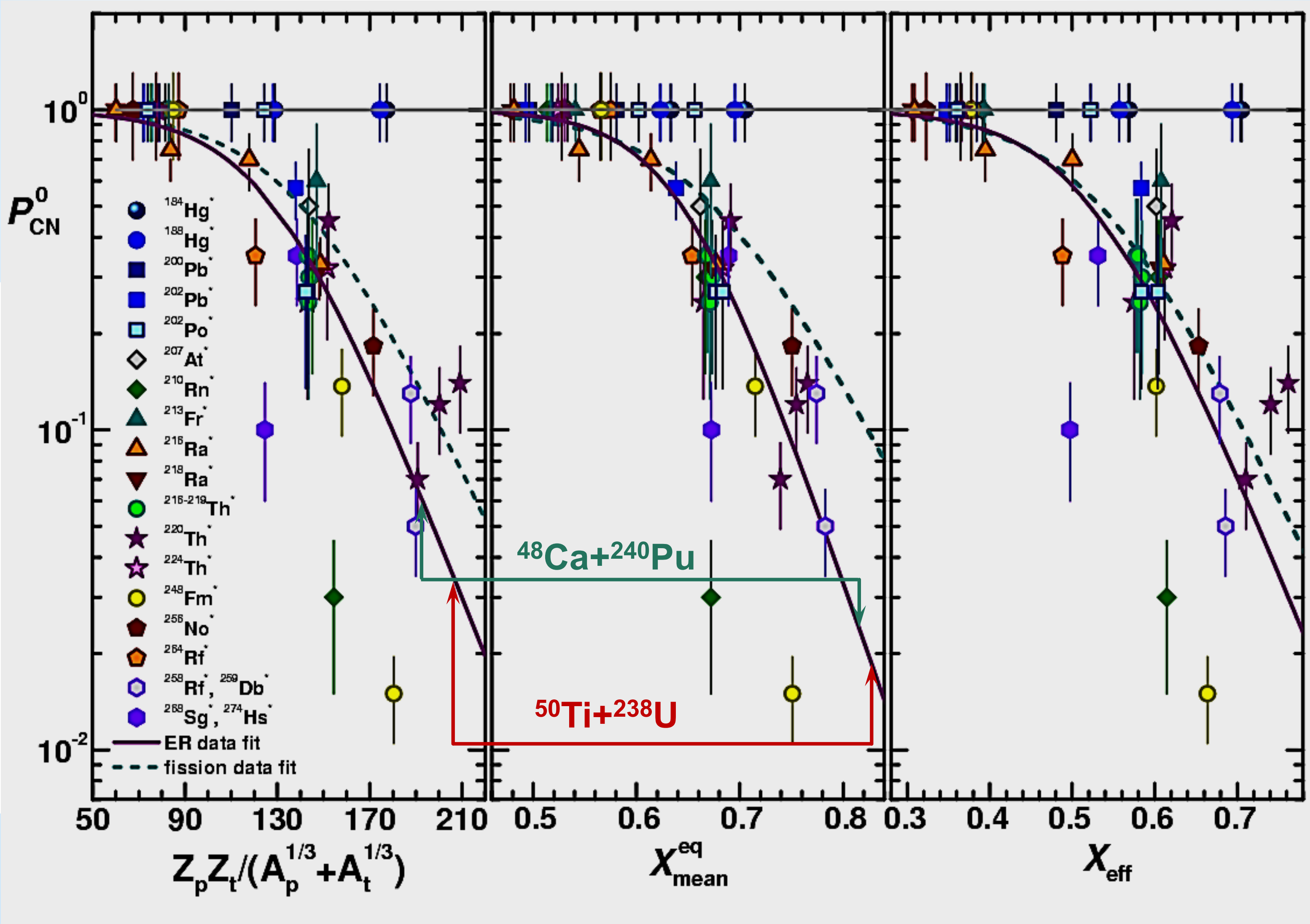




P_{CN} for reactions leading to the trans-actinide compound nuclei



P^{0}_{CN} data scaling using ER cross section data analysis



Summary and conclusion

- Being critical and correlating values in the estimates of ER cross sections, P_{CN} and survivability in CN-reactions leading to heavy and heaviest nuclei were considered using available experimental fission data and ER cross-section data. The latter could be described in the framework of the barrier passing model for a capture and the statistical model (SM) for a CN-decay using P_{CN} as an adjustable parameter.

- P_{CN} values obtained in fission reactions corresponding to the decay of heavy composite system formed in nucleus-nucleus collisions were scaled with the Coulomb factor and in the framework of the representation of the extra-extra-push model.

- P_{CN} values were also deduced by comparing ER production cross sections obtained in very asymmetric projectile-target combinations, assuming that P_{CN}=1 and those obtained in less asymmetric ones for which P_{CN} values have to be found. The survivability of heavy nuclei produced in very asymmetric projectile-target combinations can be reproduced by adjusting the liquid-drop component of fission barriers in the framework of SM approximations. These barriers were used for the empirical estimates of P_{CN} for more symmetric reactions leading to the same CN.

- P_{CN} values obtained with the ER production cross sections were also scaled with the Coulomb factor and in the framework of the representation of the extra-extra-push model, as in the case of fission data. A comparison of both dependencies shows that P_{CN} values deduced with the ER data as functions of the Coulomb factor and equilibrated mean fissility drop faster than of the similar values obtained from fission data.

Thank you for your attention