Hot fusion in recoil reparators - or - Understanding (super)heavy element formation cross sections

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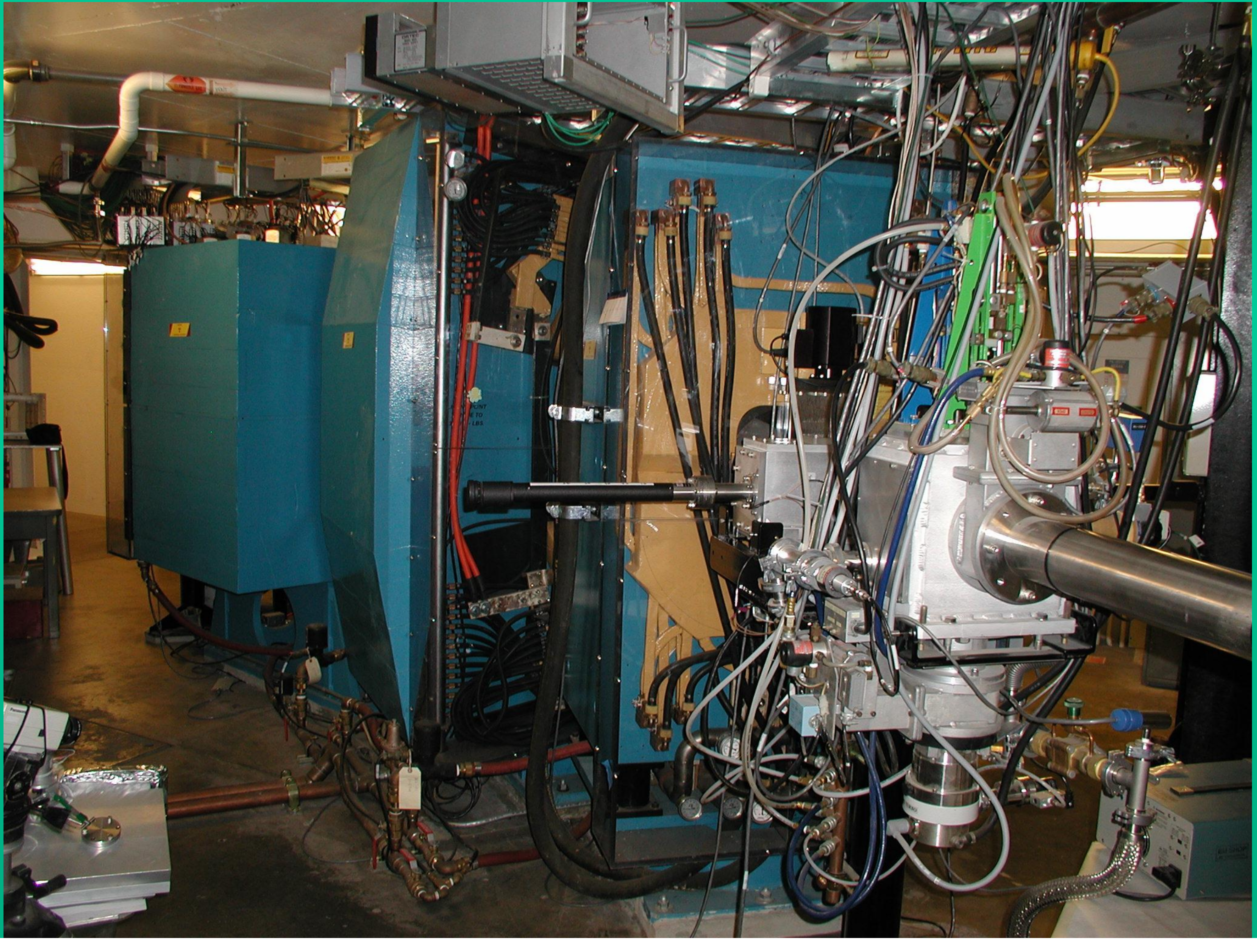

The Rest of the Participants

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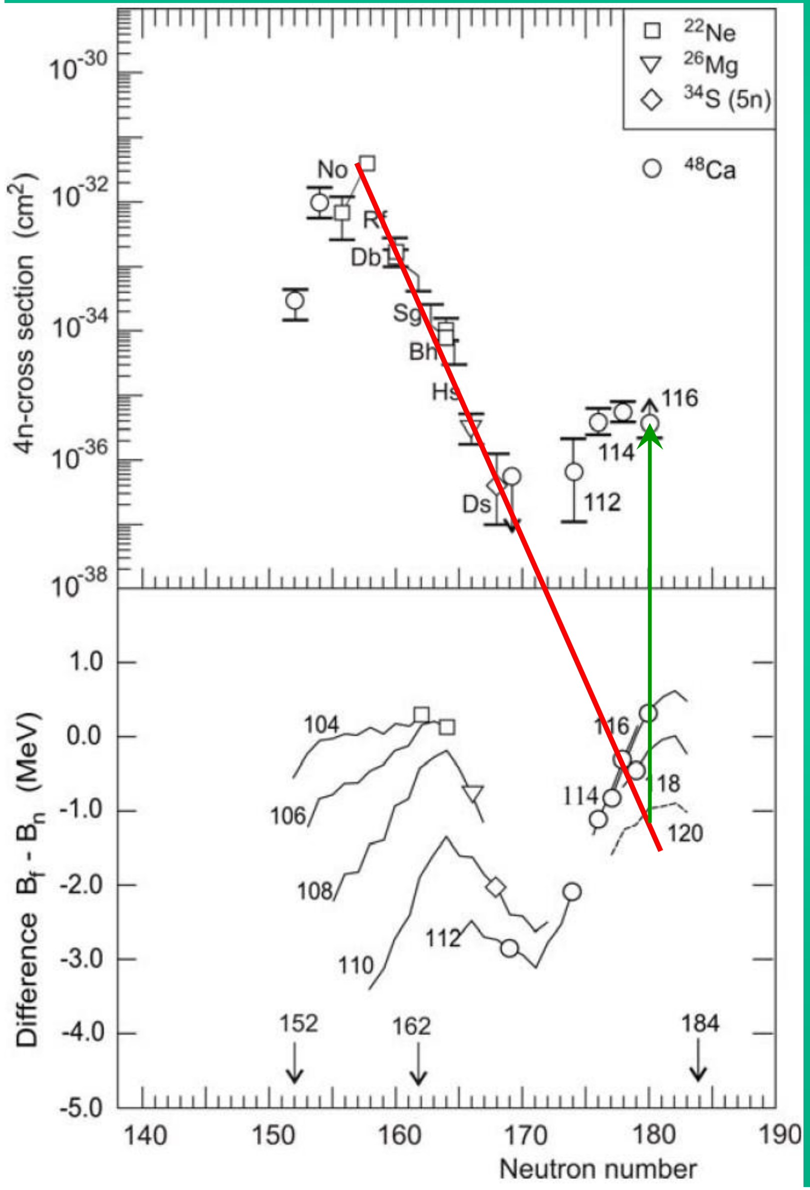
Hot fusion cross section trend

SHE cross sections “large” and constant



Plot from Y. Oganessian [review 2007] indicates that “large” SHE cross sections are due to shell effects near *Z*=114 and *N*=184. “ . . .*if predictions of the theoretical models (see above) about the existence of the next closed shell N=184 is justified, the fission barrier height will again increase when advancing to the region where* $N_{cn} \geq 174$ *and* $Z_{cn} \geq 112$*. In turn, the nuclear survivability will increase too and as a result, one can expect even a rise in the cross section* σ_{evr} *. . .”*

The exponential trend through the No-Ds cross sections indicates that as much as 6 orders of magnitude enhancement during evaporation of 4 neutrons.

Similar enhancement was NOT seen near the much stronger spherical *N*=126 shell. Schmidt and Maworek [Rep. Prog. Phys 54, 949 (1991)] state: “*Due to the extraordinary fragility of spherical shell effects in the nuclear level density (section 4.5) we expect an even steeper descent of the formation cross sections when the composite system approaches the N=184 shell, although shell effects are predicted to increase . . .”*

Improved understanding of P_{CN}, and Γ_n/Γ_{tot} is needed

Three-Step Model for Heavy Element Formation in Compound Nucleus Reactions

$$\sigma\,{}^{A}Z = \sigma_{cap}\cdot P_{CN}\cdot P_x\cdot\prod_{i=1}^{x}\left(\Gamma_n/\Gamma_{tot}\right)_i$$

Where the product over i stops when E^*
Becomes lower than B_f or S_n

A similar approach has been used in most modern calculations

Zagrabaev et al., Physics of Atomic Nuclei **66**, 1069 (2003)
Abe et al., Physics of Atomic Nuclei **66**, 1093 (2003)
Adamian et al., Phys. Rev. C **69**, 011601 (2004)
Adamian et al., Phys. Rev. C **69**, 11601(2004)
Adamian et al., Phys. Rev. C **69**, 14607 (2004)
Swiatecki et al., Phys. Rev. C **71**, 14602 (2005)
Feng et al., Nucl. Phys. **A771**, 50 (2006)
Feng et al., arXiv :0707.2588v2 (2007)
Aritomo, Phys. Rev. C **75** 024602 (2007)

Some of these models predict pb-level cross sections for SHE

σ_{cap} is relatively well understood

The product of P_{CN} and $\prod_{i=1}^{x}\left(\Gamma_n/\Gamma_{tot}\right)_i$ is modeled,

with little real knowledge of either separately.

Heavy Element Production with Pb and Bi Targets (Cold Fusion)

Excitation functions or cross sections measured for ~ 20 target-projectile combinations

Tests of general and *detailed* predictions of formation cross sections according to the Fusion by Diffusion model (Swiatecki, Siwek-Wilczynska, Wilczynski)

Several new isotopes have been produced:

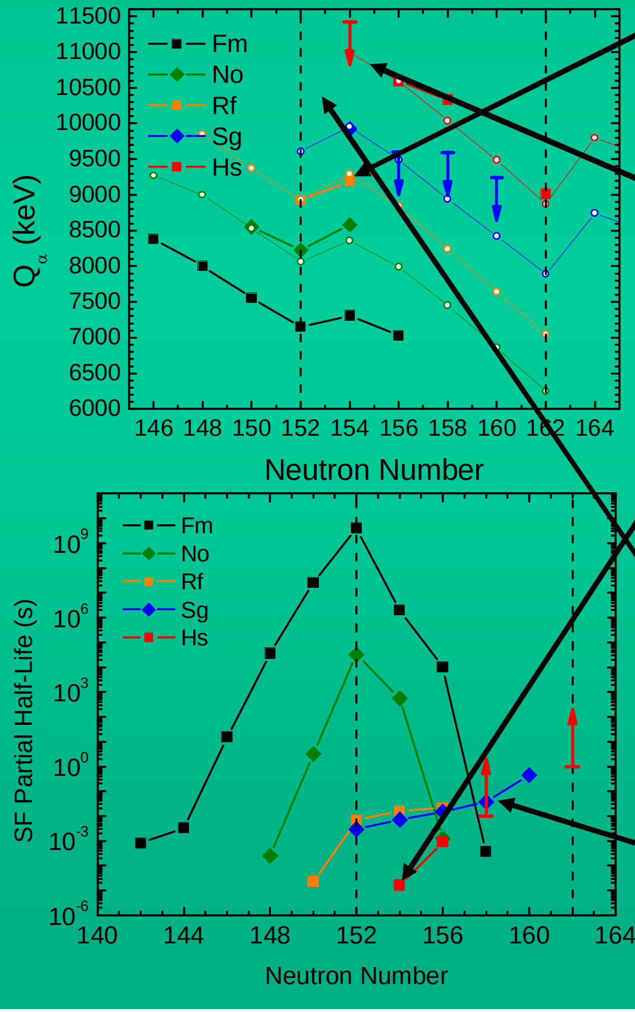
α-decay *Q*-values show that the deformed shell at *N*=152 persists up to *Z*=109

but

fission half-lives show *N*=152 weakening above *Z*=102. By *Z*=108 stabilization against fission seems to be gone

While the *Fusion by Diffusion* model gets the cross sections and excitation functions right for these "*cold fusion*" reactions right, it seems that

predicted Γ_n/Γ_{tot} is too small,
and therefore,
predicted P_{CN} is too large.



^{258}Rf
15ms
SF, α 9.05

^{263}Hs
0.74ms
10.6-10.9

^{262}Hs?
~10μs
SF, α?

^{260}Bh
35ms
10.16

^{264}Sg
37ms
SF

Systematic Study with ^{238}U Targets

and neutron-rich projectiles from ^{18}O to ^{40}Ar

^{238}U(^{18}O,xn)$^{256-x}$Fm (results from radiochemical experiments of Donets *et al*.)

^{238}U(^{19}F,xn)$^{257-x}$Md (results from radiochemical experiments of Donets *et al*.)

^{238}U(^{22}Ne,xn)$^{260-x}$No (0.158 mg/cm^2 UF_4 targets, six-point excitation function completed)

chopped beam, measured nobelium alpha singles during beam pause

^{238}U(^{23}Na,xn)$^{261-x}$Lr (0.158 mg/cm^2 UF_4 targets, three-point partial excitation function)

chopped beam, EVR-alpha correlations measured (EVR during beam pulse, alpha during pause)

^{238}U(^{26}Mg,xn)$^{264-x}$Rf (0.471 mg/cm^2 UF_4 targets, six-point excitation function completed)

DC beam short EVR-SF correlations for 20-ms ^{260}Rf and 12-ms ^{258}Rf.
chopped beam for 3.0-s ^{259}Rf, EVR during beam pulse, ^{259}Rf alpha during pause

^{238}U(^{27}Al,xn)$^{265-x}$Db (0.471 mg/cm^2 UF_4 targets, three-point partial excitation function)

DC beam, EVR-Db alpha shut off beam to search for Lr daughter alpha

^{238}U(^{30}Si,xn)$^{268-x}$Sg (0.471 mg/cm^2 UF_4 targets, four-point excitation function completed)

DC beam, EVR-Sg alpha shut off beam to search for Rf and No daughters

^{238}U(^{31}P,xn)$^{269-x}$Bh (0.471 mg/cm^2 UF_4 targets, search for ^{264}Bh via 5n exit channel)

DC beam, EVR-Bh alpha shut off beam to search for Db and Lr daughters

^{238}U(^{34}S,xn)$^{272-x}$Hs (^{267}Hs via 5*n* exit channel by Lazarev *et al*. ^{268}Hs via 4*n* exit channel by Nishio *et al*.)

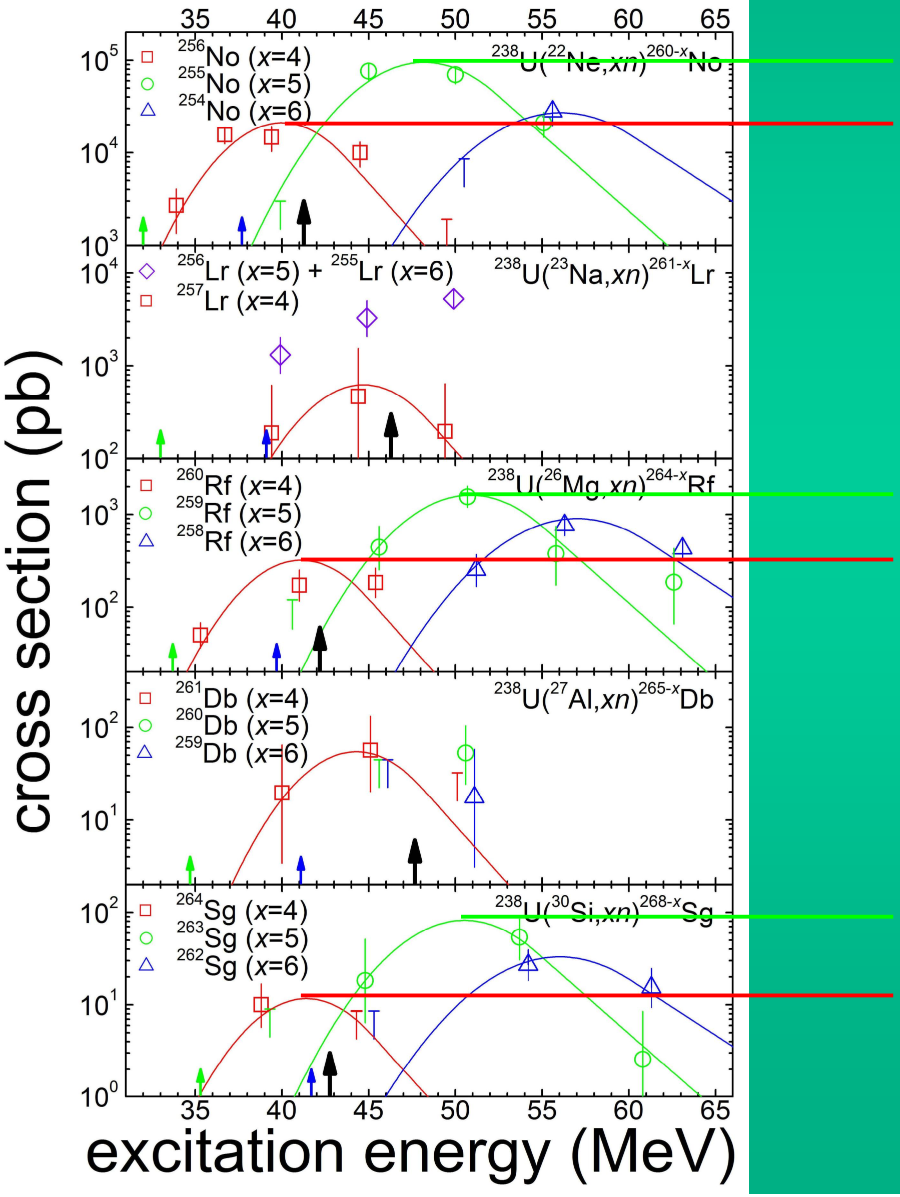
^{238}U(^{37}Cl,xn)$^{275-x}$Mt (~1.6 pb upper limit was not sensitive enough)

DC beam, EVR with MWPC signal, alpha w/o MWPC, beam shutoff to search for daughters

^{238}U(^{40}Ar,xn)$^{278-x}$Ds (0.7 pb upper limit from SHIP)

X+U Excitation Function Summary

Excitation functions with even-*Z* projectiles are complete



Peak of 5*n* cross section is always ~6x larger than the peak of the 4*n* cross section even though the 5*n* has an extra Γ_n/Γ_{tot} stage.

Larger capture cross sections, σ_{cap}, at 5*n* energies imply larger impact parameters, and therefore larger maximum angular momenta, l_{max}.

Conclusion:

Critical angular momentum for fusion, l_{crit}, does not limit fusion at the 5*n* energies.

Using σ_{cap} from Swiatecki, Siwek-Wilczynska, and Wilczynski [PRC **71**, 014602 (2005)] with a geometric (sharp cutoff) l_{max}:

$$l_{crit} > 33\,\hbar$$

Determination of first-stage Γ_n/Γ_{tot}

This is a modification of the method suggested by Vandenbosch and Huizenga.

[Vandenbosch and Huizenga, *Nuclear Fission*, p. 224, Academic Press, New York, (1973)].

First, insert a P_x term in the cross section equation.

$$\sigma\,{}^{A}Z = \sigma_{cap}\cdot P_{CN}\cdot P_x\cdot\prod_{i=1}^{x}\left(\Gamma_n/\Gamma_{tot}\right)_i$$

P_x is the probability that (in the absence of fission) exactly x neutrons will be emitted and after xth neutron, the residual nucleus will be below the fission barrier and the next neutron separation energy.

1) Write equations for adjacent exit channels from the same CN reaction (*near* peak energies)

2) Divide one by the other and solve for first stage Γ_n/Γ_{tot} from the larger x reaction

First stage Γ_n/Γ_{tot} is now the product of a series of ratios

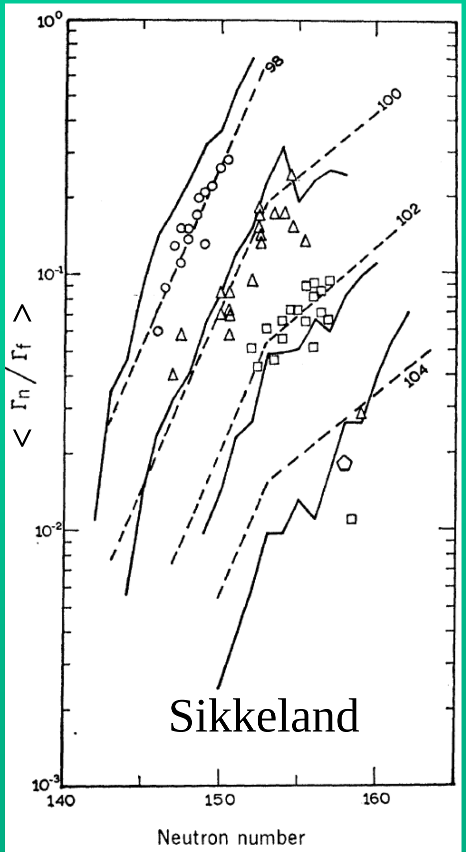
Each ratio is know to within much better than a factor of 2

First stage Γ_n/Γ_{tot} can be determined to within a factor of ~2

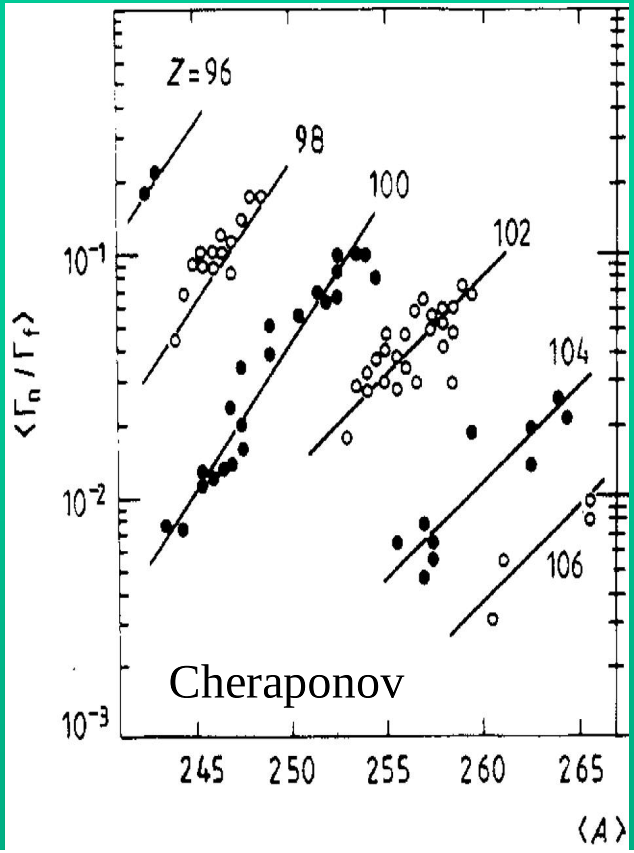
Geometric mean of all stages of Γ_n/Γ_{tot}, $< \Gamma_n/\Gamma_{tot} >$

Method used by several authors: Sikkeland Phys. Rev. **172**, 1232 (1968), Donets Sov. J. Nucl. Phys. **2**, 723 (1966), Cheraponov J. Phys. G **9**, 931 (1983)

1) Calculate compound nucleus formation cross section, $\sigma_{CN}(x)$: product of σ_{cap}, P_x, and assume $P_{CN} = 1$
2) $< \Gamma_n/\Gamma_{tot} >$ is the xth root of the ratio of $\sigma_{exp}(x)$ and $\sigma_{CN}(x)$



Sikkeland

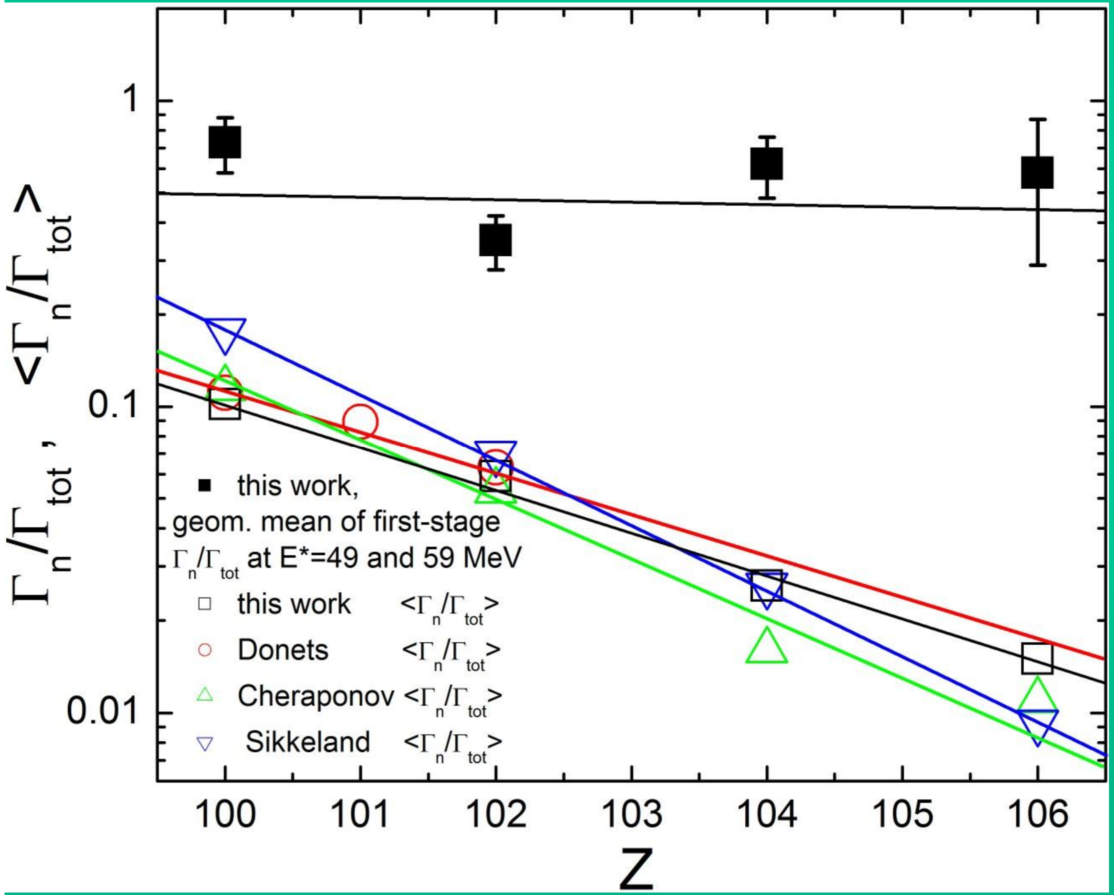


Cheraponov

Results of first stage Γ_n/Γ_f and $<\Gamma_n/\Gamma_f>$ calculations

Filled points are first-stage Γ_n/Γ_{tot} at 6*n* and 5*n* energies

Open points are $<\Gamma_n/\Gamma_{tot}>$, geometric mean of all stages of Γ_n/Γ_{tot}.



Four interesting conclusions:

1) $<\Gamma_n/\Gamma_{tot}>$ from this work agree with values from earlier work

2) First-stage Γ_n/Γ_{tot} is nearly independent of *Z*

3) First-stage Γ_n/Γ_{tot} is much larger than $<\Gamma_n/\Gamma_{tot}>$ . . .

This implies a large decrease in Γ_n/Γ_{tot} in later stages of *n* emission (at lower *E**)

4) The Γ_n/Γ_{tot} / $<\Gamma_n/\Gamma_{tot}>$ discrepancy increases with increasing Z . . .

This implies:
a strongly *Z*-dependent $P_{CN} << 1$
- or -
a catastrophic decrease of Γ_n/Γ_{tot} at low E* for higher Z

First-stage Γ_n/Γ_{tot} and l_{crit}

Table III. Calculation of first-stage Γ_n/Γ_{tot} and geometric mean $<\Gamma_n/\Gamma_{tot}>$.

x	E^* MeV	$\sigma_{expt, fit}$	σ_{cap} mb	P_x	geom. mean of all stages $<\Gamma_n/\Gamma_{tot}>^a$	first-stage $\Gamma_n/\Gamma_{tot}(A,E_1)^a$
^{238}U(^{18}O,xn)$^{256-x}$Fm [7]						
6	56.8	1664(333) nb	590	0.555	0.131	0.82(23)
5	48.0	2052(410) nb	319	0.594	0.102	0.65(18)
4	39.5	545(109) nb	36	0.571	0.072	
						<0.73(15)>^{b}
^{238}U(^{22}Ne,xn)$^{260-x}$No						
6	57.5	25(7) nb	489	0.570	0.067	0.23(7)
5	48.2	95(13) nb	228	0.600	0.059	0.53(10)
4	39.1	20(3) nb	16	0.618	0.038	
						<0.35(7)>^{b}
^{238}U(^{26}Mg,xn)$^{264-x}$Rf						
6	60.2	644(106) pb	473	0.518	0.037	0.40(11)
5	50.5	1520(350) pb	236	0.558	0.026	0.98(35)
4	41.1	320(87) pb	30	0.568	0.012	
						<0.62(14)>^{b}
^{238}U(^{30}Si,xn)$^{268-x}$Sg						
6	59.1	24(7) pb	393	0.565	0.022	0.26(16)
5	49.2	76(41) pb	169	0.623	0.015	1.3(10)
4	39.6	9.5(5.2) pb	16	0.683	0.005	
						<0.58(29)>^{b}

a. Error limits, from propagation of statistical errors in σ_{max} only, in the last digit(s) are given in parentheses.

b. Geometric mean of first stage Γ_n/Γ_{tot} from 6n and 5n excitation energies

Above Z=100, first-stage Γ_n/Γ_{tot} at 6n energies is smaller than first-stage Γ_n/Γ_{tot} at 5n energies.

This is not expected from transition-state theory.

Conclusion:

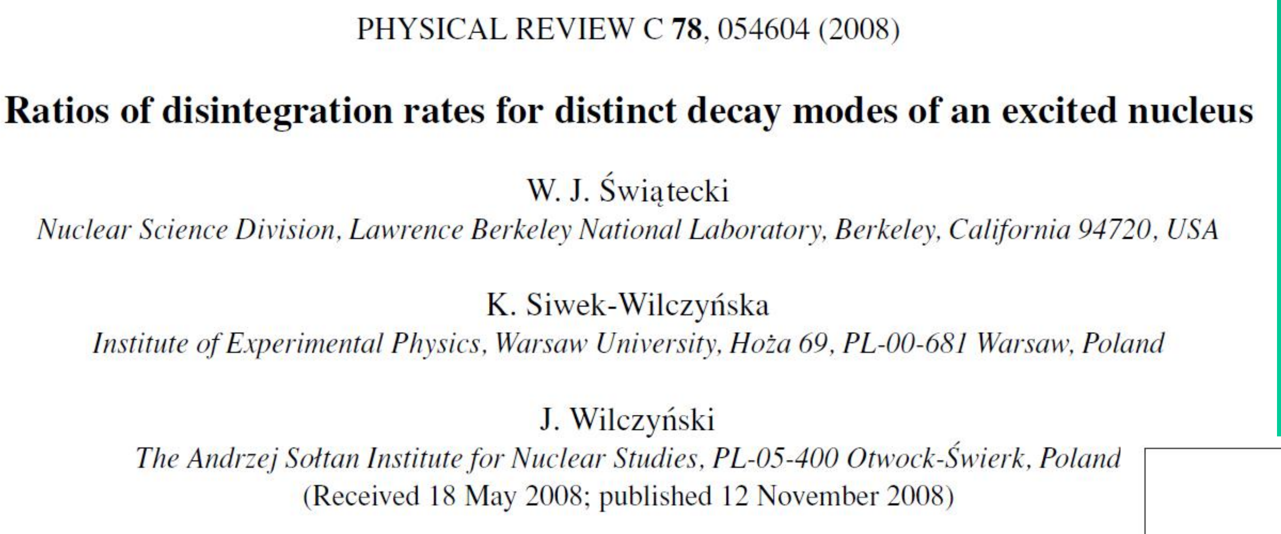
l_{crit} is limiting fusion at 6n energies for $Z > 100$

$$l_{crit} = 33\text{-}38\ \hbar$$

Point 3) from two slides ago: E^* dependence of Γ_n/Γ_{tot}

Lower E^* is where shell effects are important

A new treatment of Γ_n/Γ_{tot} based on transition state theory



PHYSICAL REVIEW C **78**, 054604 (2008)

Ratios of disintegration rates for distinct decay modes of an excited nucleus

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(Received 18 May 2008; published 12 November 2008)

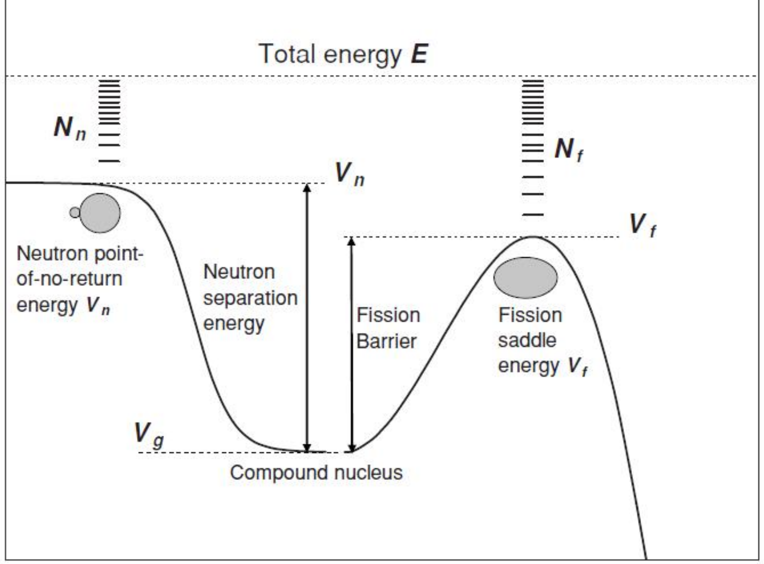
Got rid of the E^*-dependent ground-state energy used in integration of level densities in "standard" Γ_n/Γ_{tot} treatments.

Description of the problem(s) from the paper:

The disagreement actually concerns *two* features.

First, as explained in Sec. IV, an energy-dependent fission barrier arises from an unjustified assumption of an energy dependence of the ground-state energy of the compound nucleus, the bottom of the barrier. (And certainly the *top* of the barrier—the energy of the fission saddle—cannot depend on a shell effect in the level density of the compound nucleus.)

Second, the existence of a shell correction in the neutron emission rate, an integral part of the transition-state formula for Γ_n/Γ_f, is ignored altogether.



The difference

Correct treatment of E^* dependent level densities has a large effect on Γ_n/Γ_{tot} at low E^*

Small Γ_n/Γ_{tot} at low E^* in Z=100-110 region

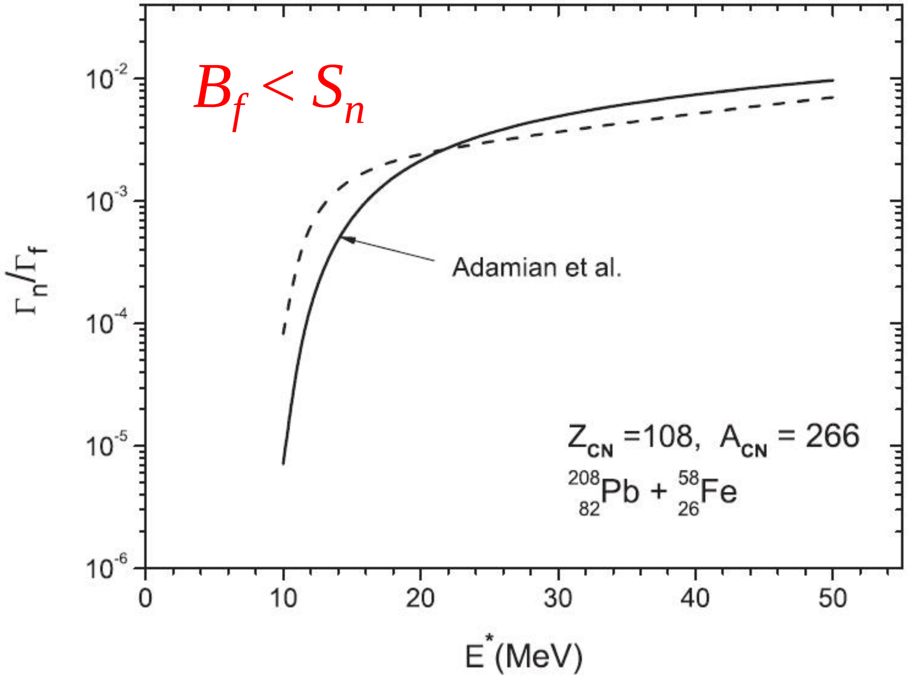


FIG. 3. The ratio Γ_n/Γ_f for the ^{266}Hs nucleus obtained by using the scheme and parameters of Refs. [2–11] with an excitation-energy-dependent fission barrier (solid curve) compared with the ratio Γ_n/Γ_f calculated with the transition state method [Eqs. (18) and (20)] with precise numerical integrations over level densities, for parameters as in Ref. [7], but for a standard value of the shell damping parameter $d = 18.5$ MeV (dashed curve).

Large Γ_n/Γ_{tot} at low E^* in SHE region

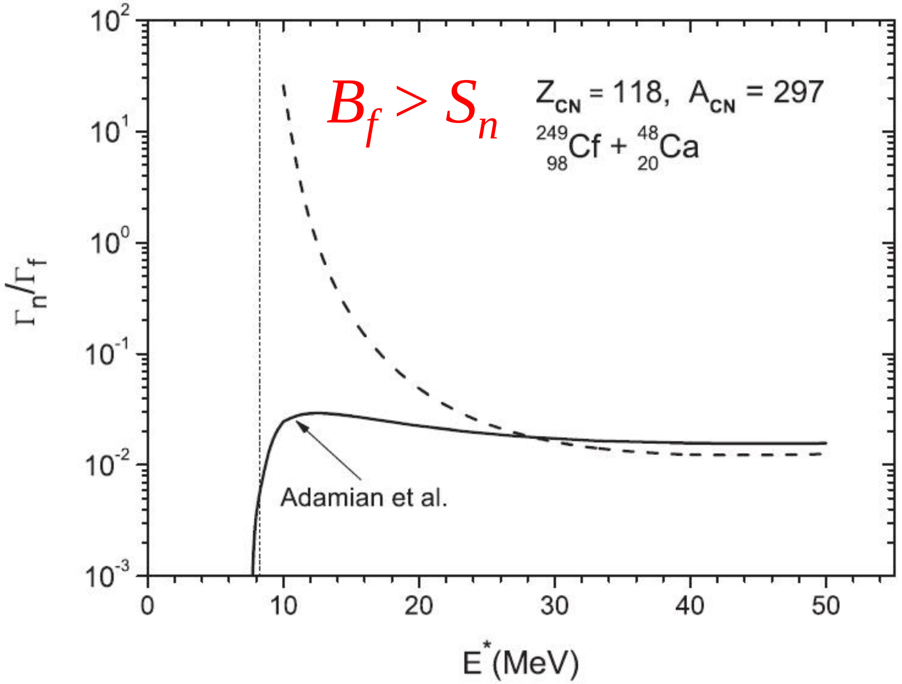
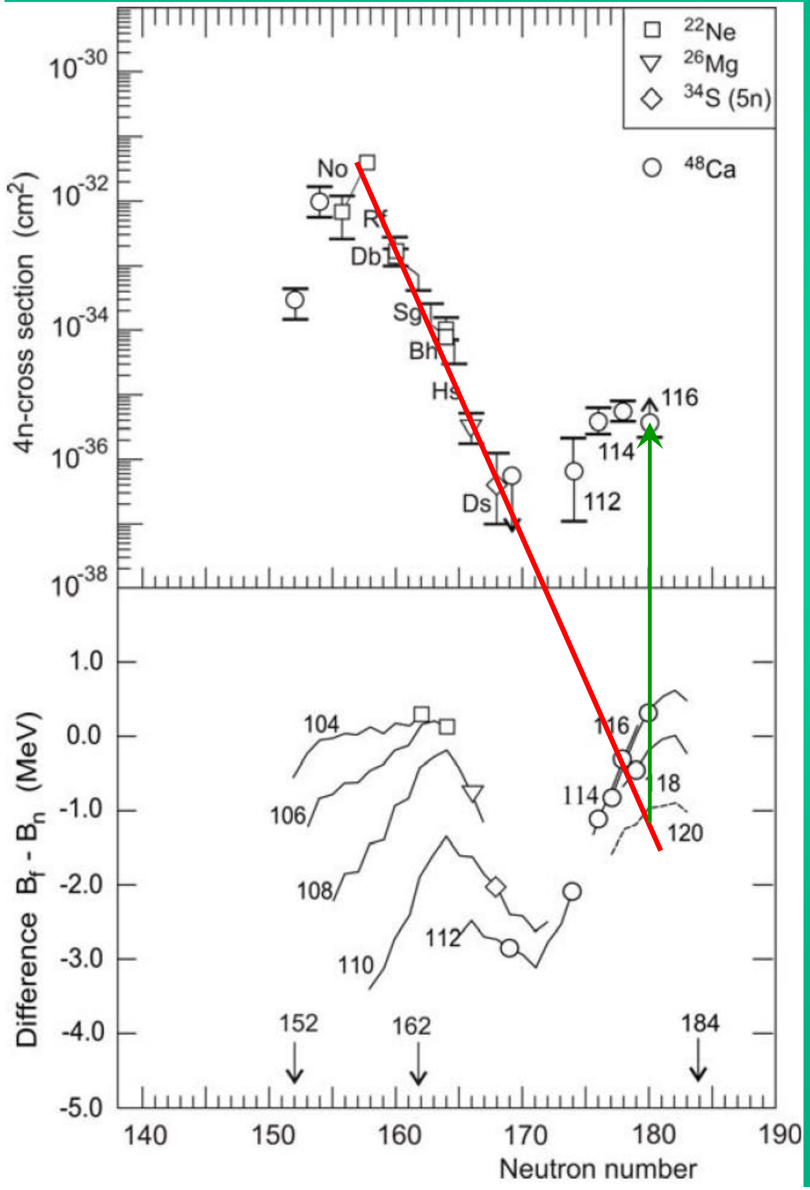


FIG. 4. Same as Fig. 3 but for a compound nucleus ^{297}118 formed in the ^{48}Ca + ^{249}Cf reaction. The excitation energy threshold $E^* = V_f - V_g = 8.27$ MeV is indicated by the vertical dashed line.

Hot fusion cross section trend

SHE cross sections “large” and constant



Plot from Y. Oganessian [review 2007] indicates that “large” SHE cross sections are due to shell effects near *Z*=114 and *N*=184. “ . . .*if predictions of the theoretical models (see above) about the existence of the next closed shell N=184 is justified, the fission barrier height will again increase when advancing to the region where* $N_{cn} \geq 174$ *and* $Z_{cn} \geq 112$. *In turn, the nuclear survivability will increase too and as a result, one can expect even a rise in the cross section* σ_{evr} *. . .”*

The exponential trend through the No-Ds cross sections indicates that as much as 6 orders of magnitude enhancement during evaporation of 4 neutrons.

Similar enhancement was NOT seen near the much stronger spherical *N*=126 shell. Schmidt and Maworek [Rep. Prog. Phys 54, 949 (1991)] state: “*Due to the extraordinary fragility of spherical shell effects in the nuclear level density (section 4.5) we expect an even steeper descent of the formation cross sections when the composite system approaches the N=184 shell, although shell effects are predicted to increase . . .”*

Improved understanding of P_{CN}, and Γ_n/Γ_{tot} is needed

Hot fusion heavy element experiments for the pre-GRETINA time frame (until fall 2011)

Systematics of Ds (Z=110) decay properties

^{242}Pu(^{34}S,x*n*)$^{276\text{-x}}$Ds, ^{244}Pu(^{34}S,x*n*)$^{278\text{-x}}$Ds, ^{244}Pu(^{36}S,x*n*)$^{280\text{-x}}$Ds

Bridging the gap between known isotopes and “the island of stability.”

Does the *N*=162 shell affect Γ_n/Γ_{tot}?

Extend X+^{238}U cross section systematics to X+^{242}Pu and X+^{244}Pu

Test cross section scaling with effective fissility of the fusing system

Measure the extent and strength of the *N*=162, *Z*=108 deformed shell

In addition to SHE and K-isomer experiments . . .