Production of Superheavy Nuclei in Large Mass Transfer Reaction

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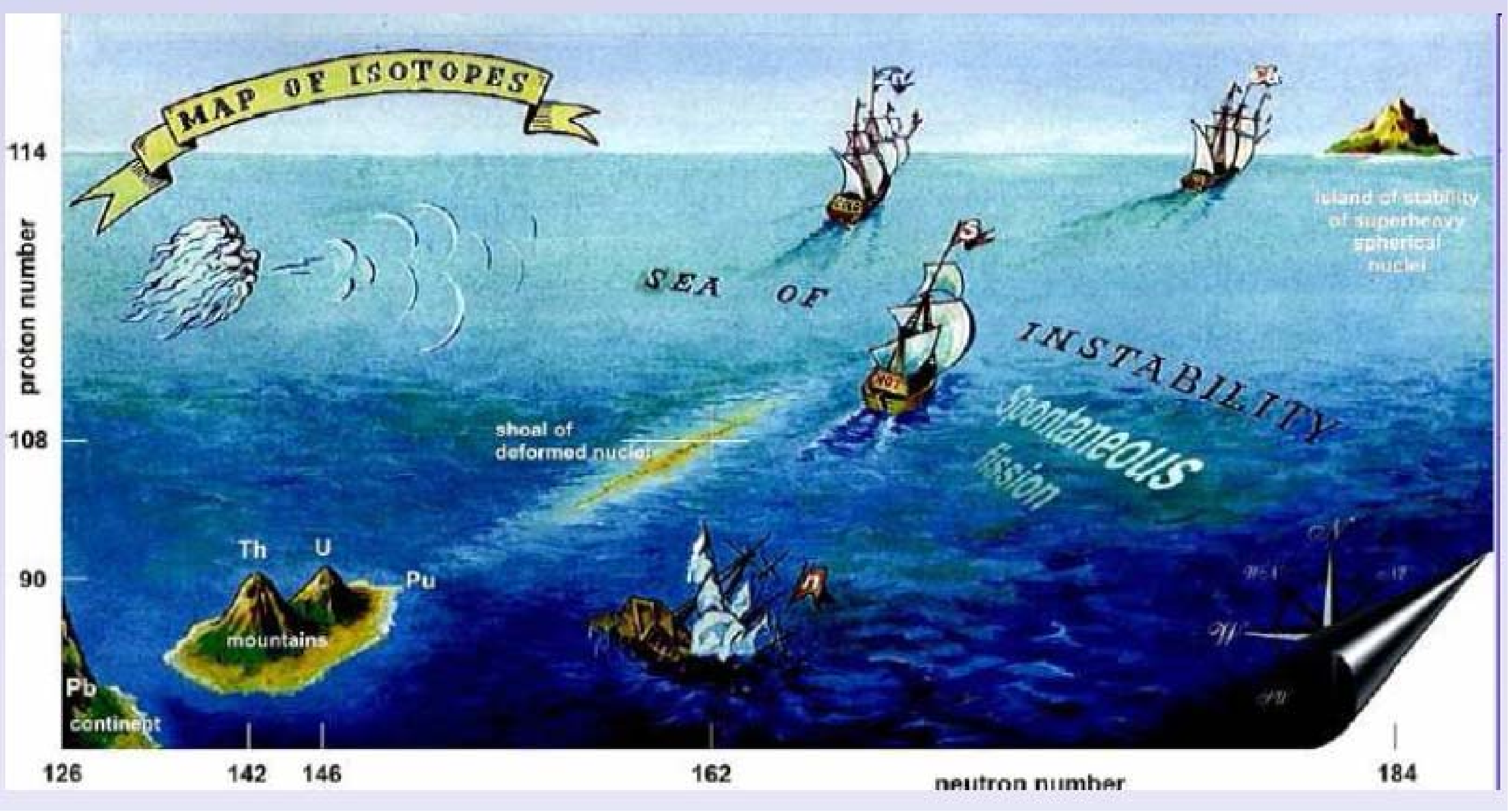
Outline

- **Introduction**
- **Theoretical Models**
- **Results and discussions**
- **Summary**

Sailing to the Superheavy Island



Experimental achievements

Super-heavy elements up to Z=118 have been synthesized experimentally.

Z up to 113: cold fusion, ^{208}Pb/^{209}Bi based reactions by evaporating 1 or 2 neutrons
(Rev.Mod.Phys.72(2000)733, Rep.Prog.Phys.61(1998)639)

Z=112-118: ^{48}Ca induced fusion reactions, ^{48}Ca bombarding actinide targets by evaporating 3-5 neutrons
(J.Phys.G34(2007)R165, NPA787(2007)343c, PRC 83, 054315 (2011))

IMP in Lanzhou: ^{259}Db, ^{265}Bh, ^{271}Ds

CHIN. PHYS. LETT. Vol. 29, No. 1 (2012) 012502

Observation of the Superheavy Nuclide ^{271}Ds *

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Theoretical models for SHN production

Macroscopic dynamical model

S. Bjornholm and W.J. Swiatecki

Fusion by diffusion model

Y. Abe, Y. Aritomo , C.W. Shen, Z.H. Liu, J.D. Bao, K. Siwek-Wilczynska et al

Nucleon collectivization model

V.I. Zagrebaev

Dinuclear system model

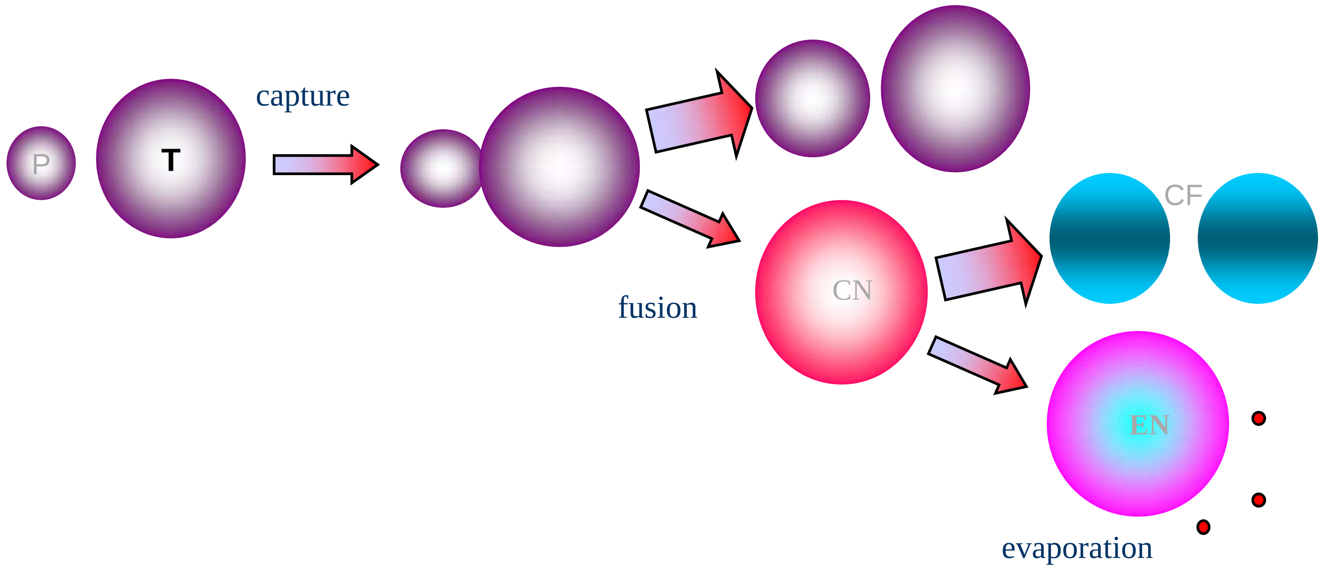
V.V Volkov, G.G. Adamian, N.V.Antonenko, A.K. Nasirov, G.Giardina, G. Mandaglio, W. Scheid, etal

J.Q.Li, E.G. Zhao, S.G. Zhou, Z.Q. Feng, M.H.Huang, Nan Wang et al

Other model

F S Zhang, Ning Wang

Schematic picture of the formation of SHN



Evaporation residue cross section:

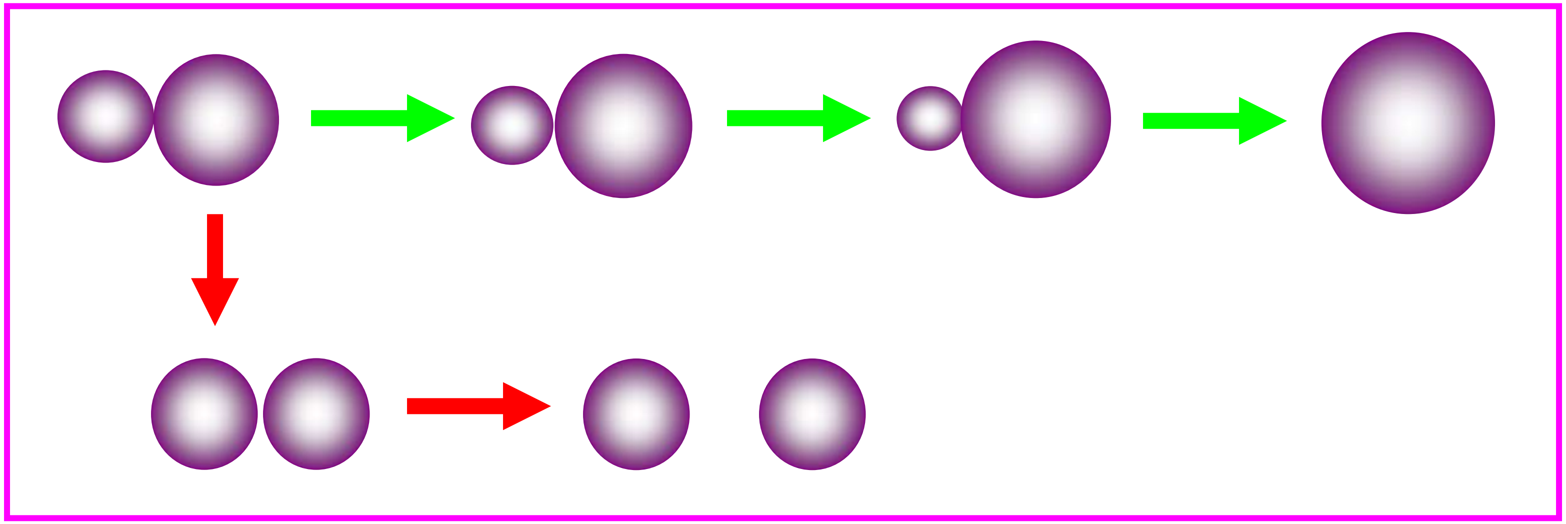
$$\sigma_{ER}(E_{c.m.}) = \frac{\pi\hbar^2}{2\mu E_{c.m.}} \sum_J (2J+1) T(E_{c.m.}, J) P_{CN}(E_{c.m.}, J) W_{sur}(E_{c.m.}, J)$$

Di-nuclear system concept

Dinuclear system concept (from the investigation of deep inelastic collisions)

V.V. Volkov, Phys. Rep. 44(1978) 93

The formation of compound nuclei is the fusion along the mass asymmetry degree of freedom.



Formation of compound nucleus - Master equation

$$\frac{dP(A_1,E_1,t)}{dt}=\sum_{A_1'}W_{A_1A_1'}(t)[d_{A_1}P(A_1',t)-d_{A_1'}P(A_1,t)]-\Lambda_{A_1}^{qf}(t)P(A_1,t)$$

$$P_{CN}=\sum_{i=0}^{A_{BG}}P(A_i)$$

Hamiltonian

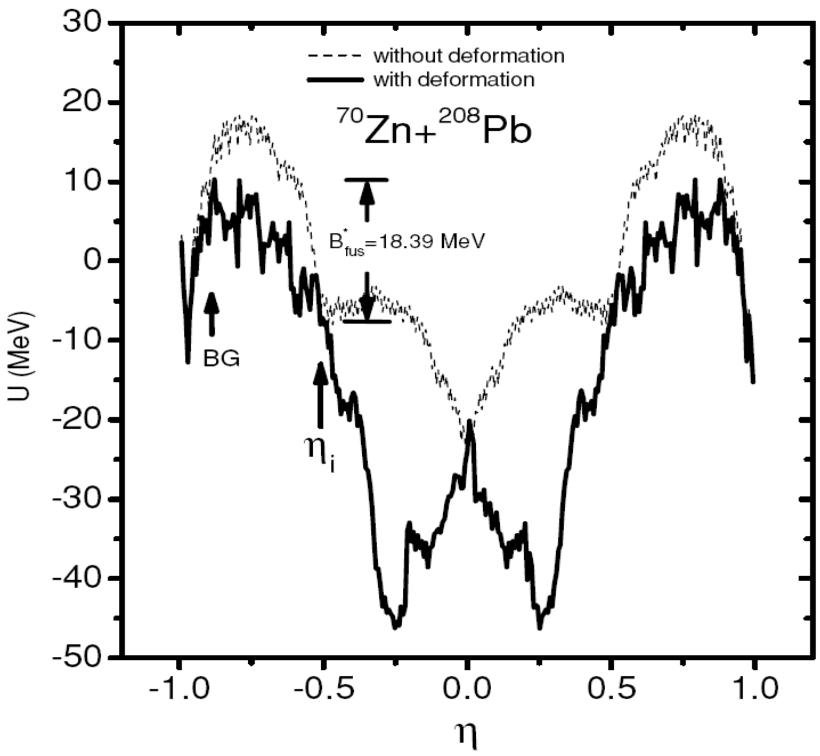
$$H(t)=H_0(t)+V(t)$$

$$H_0(t)=\sum_K\sum_\nu \varepsilon_{\nu_K}(t)a_{\nu_K}^+(t)a_{\nu_K}(t)$$

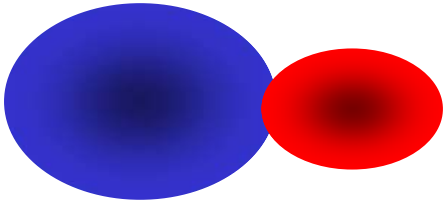
$$V(t)=\sum_{K,K'}\sum_{\alpha_K\beta_{K'}}u_{\alpha_K\beta_{K'}}(t)a_{\alpha_K}^+(t)a_{\beta_{K'}}(t)=\sum_{K,K'}V_{KK'}(t)$$

Influence of deformation on Super-heavy nuclei

PES in DNS model with static deformation



development of **dynamical** deformation



G. Wolschin, Phys.Lett.B 88 (1979) 35

C. Riedel, G.Wolschin, and W. Noerenberg, Z. Phys. A 290, 47(1979).

Li, Wang，Li et al., J.Phys. G 32(2006) 1143

Potential energy surface

Excitation energy of DNS

$$E^*_{DNS} = E_{total} - E^0_{DNS} - E^{rot}_{DNS}$$

$$E_{total} = E_{c.m.} + (M_T + M_P)c^2$$

$$E^0_{DNS} = V_C + V_N + (M_1 + M_2)c^2$$

Potential Energy Surface(PES)

$$V_{PES} = V_C + V_N + (M_1 + M_2 - M_T - M_P)c^2$$

Deformation dependent

Intrinsic energy

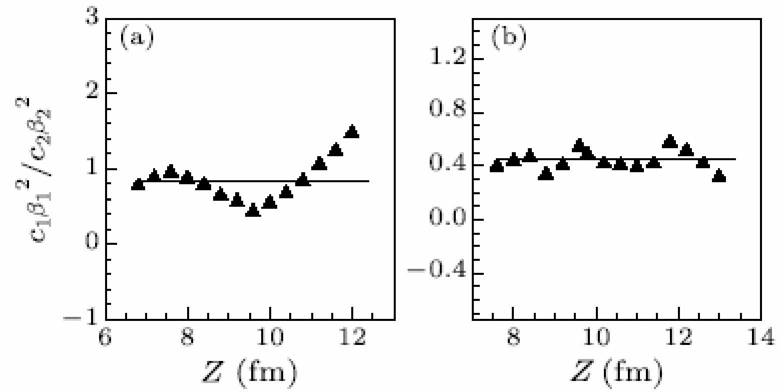
$$E_{\text{int}}(A_1, \delta\beta) = V_C(r, \beta_1, \beta_2) + V_N(r, \beta_1, \beta_2) + \sum_{i=1,2} \frac{1}{2} C_i \delta\beta_i^2$$

$$\delta\beta = \delta\beta_{\max}(1 - e^{-t/\tau})$$

$$\frac{C_1(\beta_1 - \beta_1^0)^2}{C_2(\beta_2 - \beta_2^0)^2} = \frac{A_1}{A_2}$$

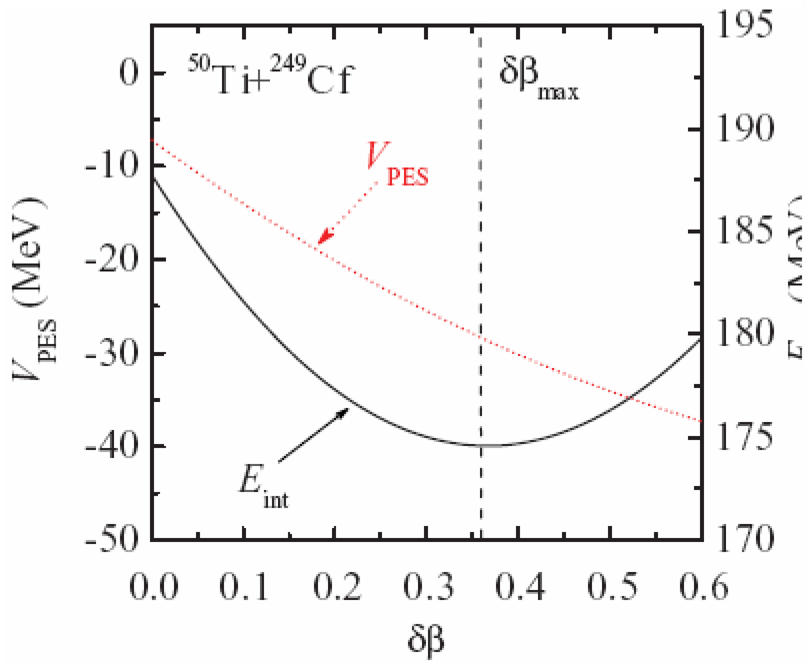
G. Wolschin, Phys.Lett.B 88 (1979) 35

V.I. Zagrebaev, Phys.Rev.C 64 (2001) 034606



L.Dou, Nan Wang, E.G.Zhao, Chin.Phys. Lett 28 (2011) 122401

Driving potential



Intrinsic energy and PES

for ^{50}Ti+^{249}Cf

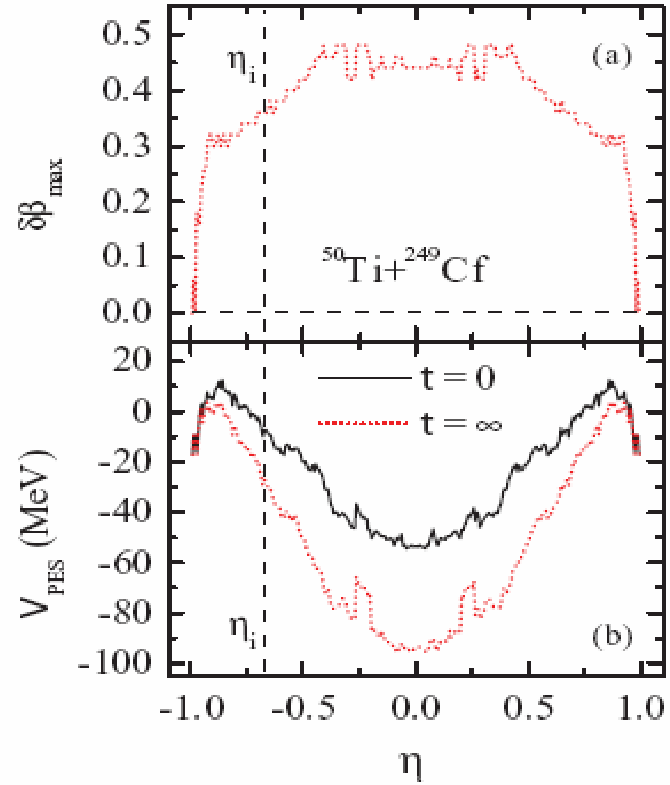
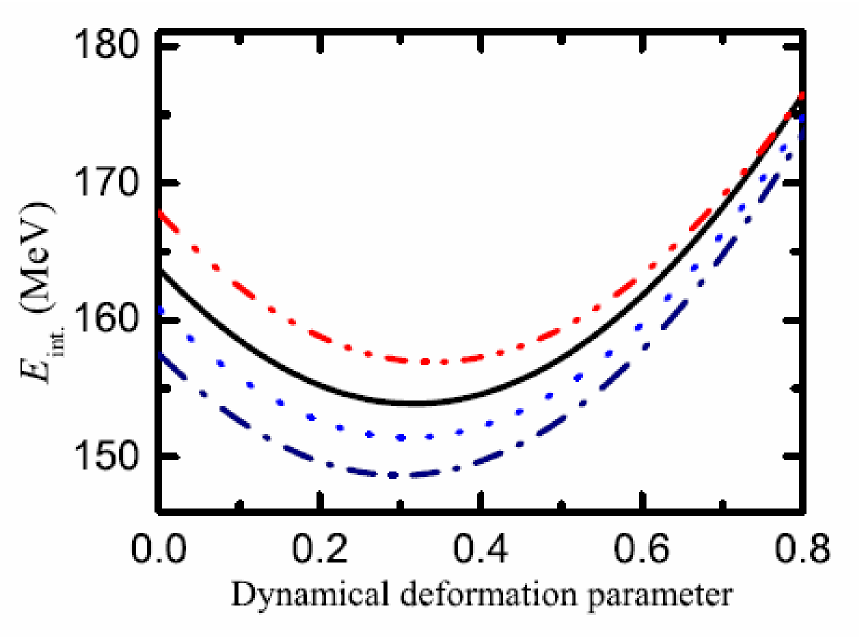


FIG. 2. (Color online) (a) The maximal dynamical deformation $\delta\beta_{max}$ and (b) the dynamical potential energy surface (DyPES) defined in Eq. (7) at $t = 0$ and $t = \infty$ as functions of the mass asymmetry coordinate η for the projectile-target combination ^{50}Ti + ^{249}Cf. The vertical dashed line shows the entrance channel.

Nan Wang, En-guang Zhao, Werner Scheid and Shan-gui Zhou, Phys.Rev.C 85 (2012) 041601(R)

Driving potential

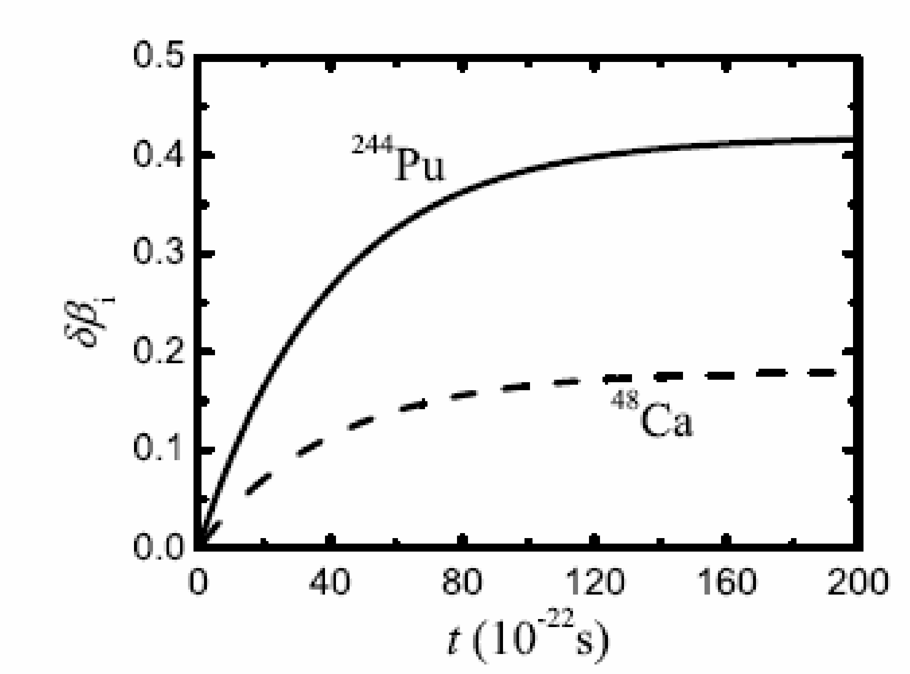


^{48}Ca + ^{238}U (dash dot line)

^{48}Ca + ^{242}Pu (dotted line)

^{48}Ca + ^{248}Cm (solid line)

^{48}Ca + ^{249}Cf (dash dot dot line)



Dynamical deformations for ^{48}Ca and ^{244}Pu

Survival probability of excited compound nucleus

The thermal compound nucleus will decay by evaporating γ-ray, light particles and fission. The survival probabilities can be written as

$$W_{sur}(E^*_{CN}, x, J) = P(E^*_{CN}, x, J) \prod_i^x \left(\frac{\Gamma_n(E_i^*, J)}{\Gamma_n(E_i^*, J) + \Gamma_f(E_i^*, J)} \right)_i$$

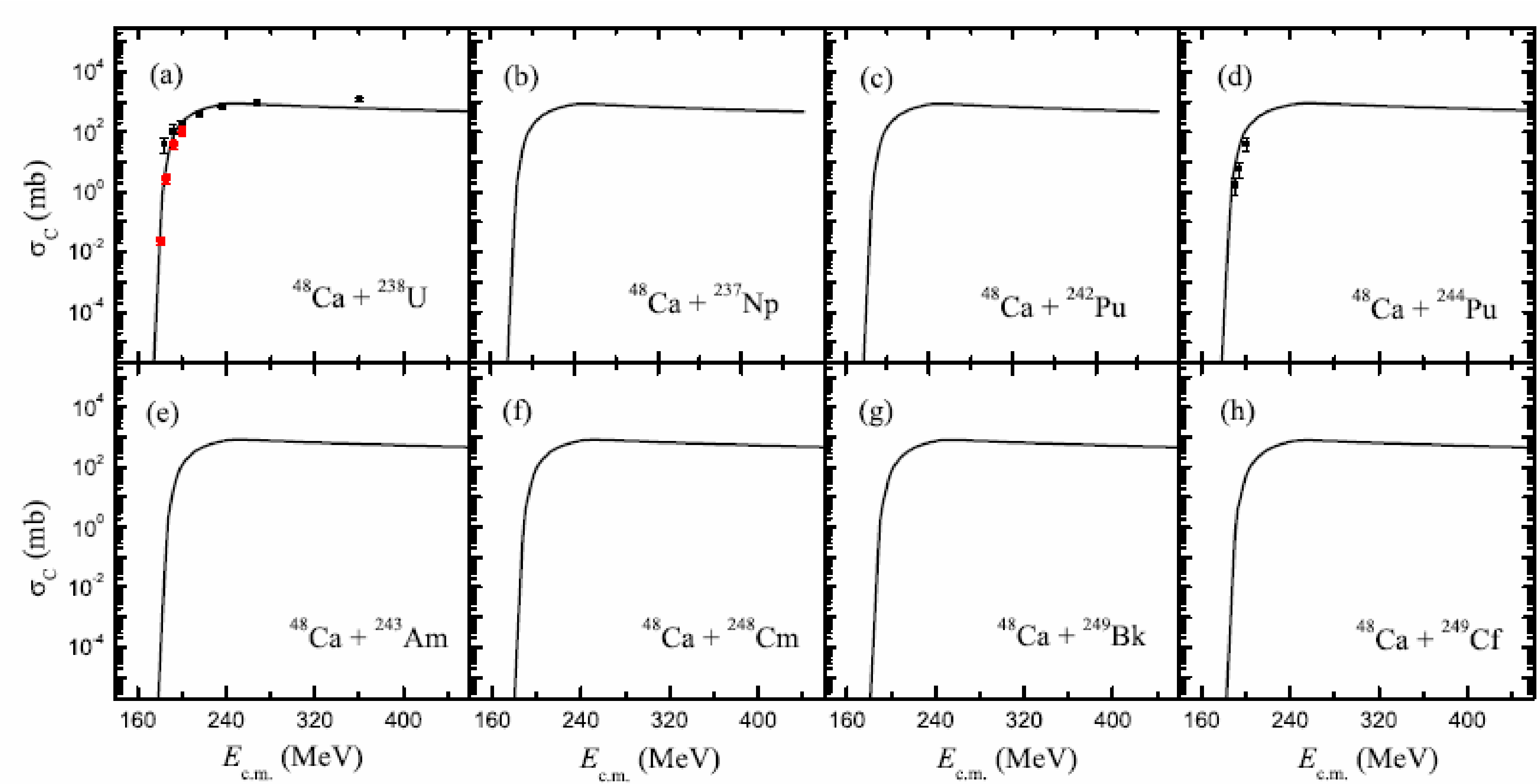
$$\Gamma_n(E^*, J) = (2s+1) \frac{m_\nu R^2}{\pi\hbar^2 \rho(E^*, J)} \int_0^{E^* - B_\nu - E_{rot} - \delta - \frac{1}{a}} \varepsilon \rho\left(E^* - B_\nu - E_{rot} - \varepsilon, J\right) d\varepsilon$$

$$\Gamma_f(E^*, J) = \frac{1}{2\pi\rho_f(E^*, J)} \int_0^{E^* - B_f - E_{rot} - \delta - \frac{1}{a_f}} \frac{\rho_f\left(E^* - B_f - E_{rot} - \varepsilon, J\right) d\varepsilon}{1 + \exp\left[-2\pi\left(E^* - B_f - E_{rot} - \varepsilon\right)/\hbar\omega\right]}$$

Fermi-gas level density is adopted

$$\rho(E^*, J) = \frac{2J+1}{24\sqrt{2}a^{1/4}\sigma^3(E^* - \delta)^{5/4}} \exp\left[2\sqrt{a(E^* - \delta)} - \frac{(J + 1/2)^2}{2\sigma^2}\right]$$

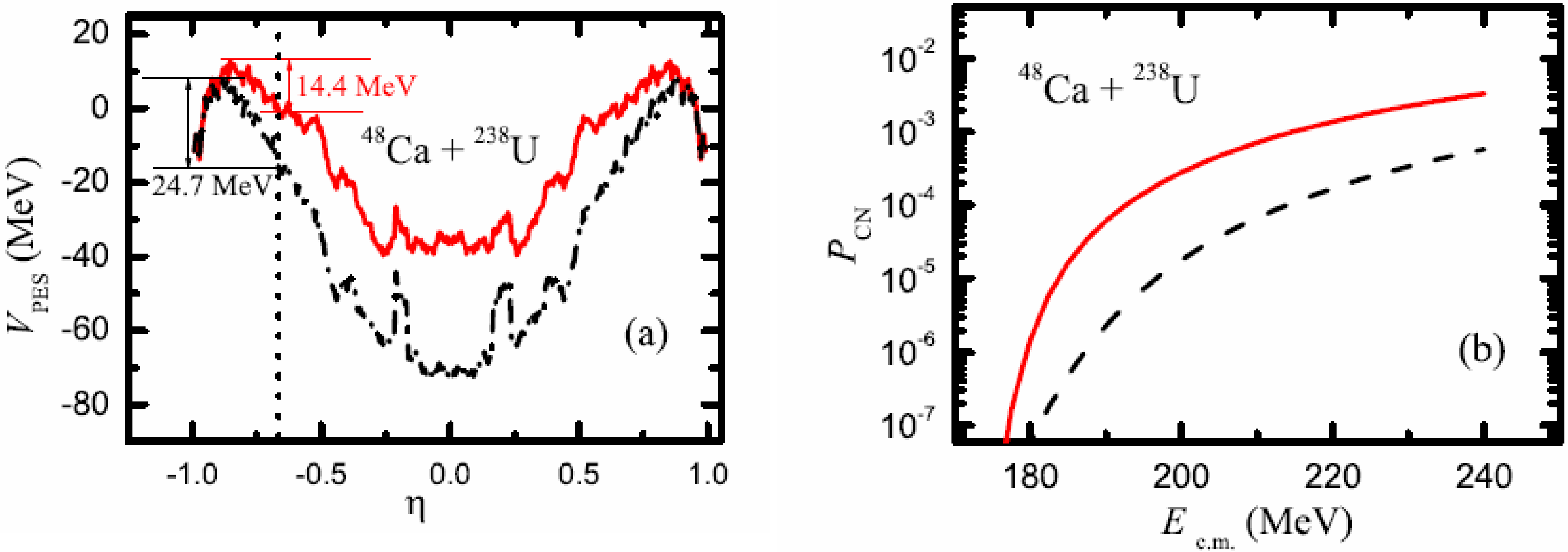
Results and discussions



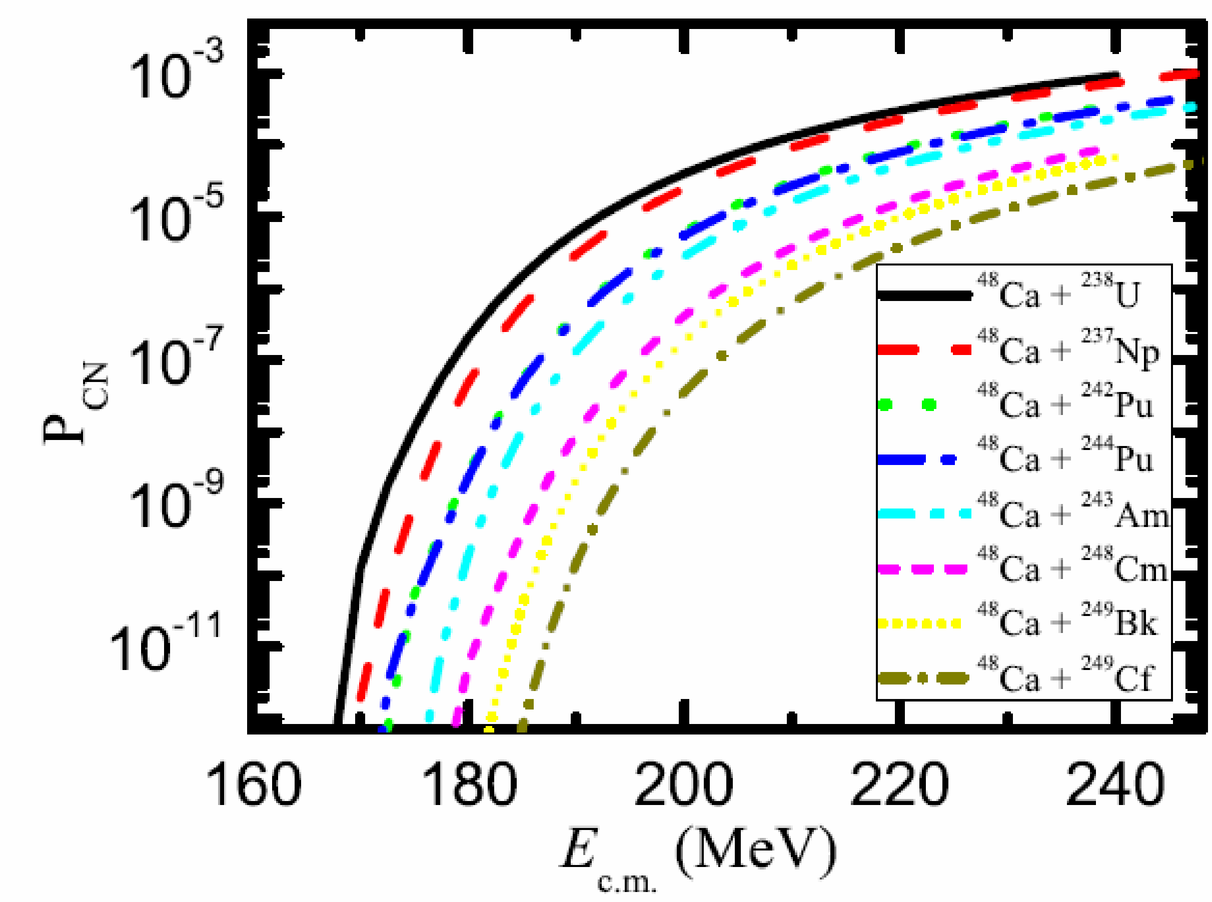
Capture cross sections for $^{48}Ca + ^{238}U$, ^{237}Np, ^{242}Pu, ^{244}Pu, ^{243}Am, ^{248}Cm, ^{249}Bk, ^{249}Cf

Exp.
Y. Oganessian, J. Phys. G 34(2007) R165
W.Q. Shen et al, PRC 36(1987) 115

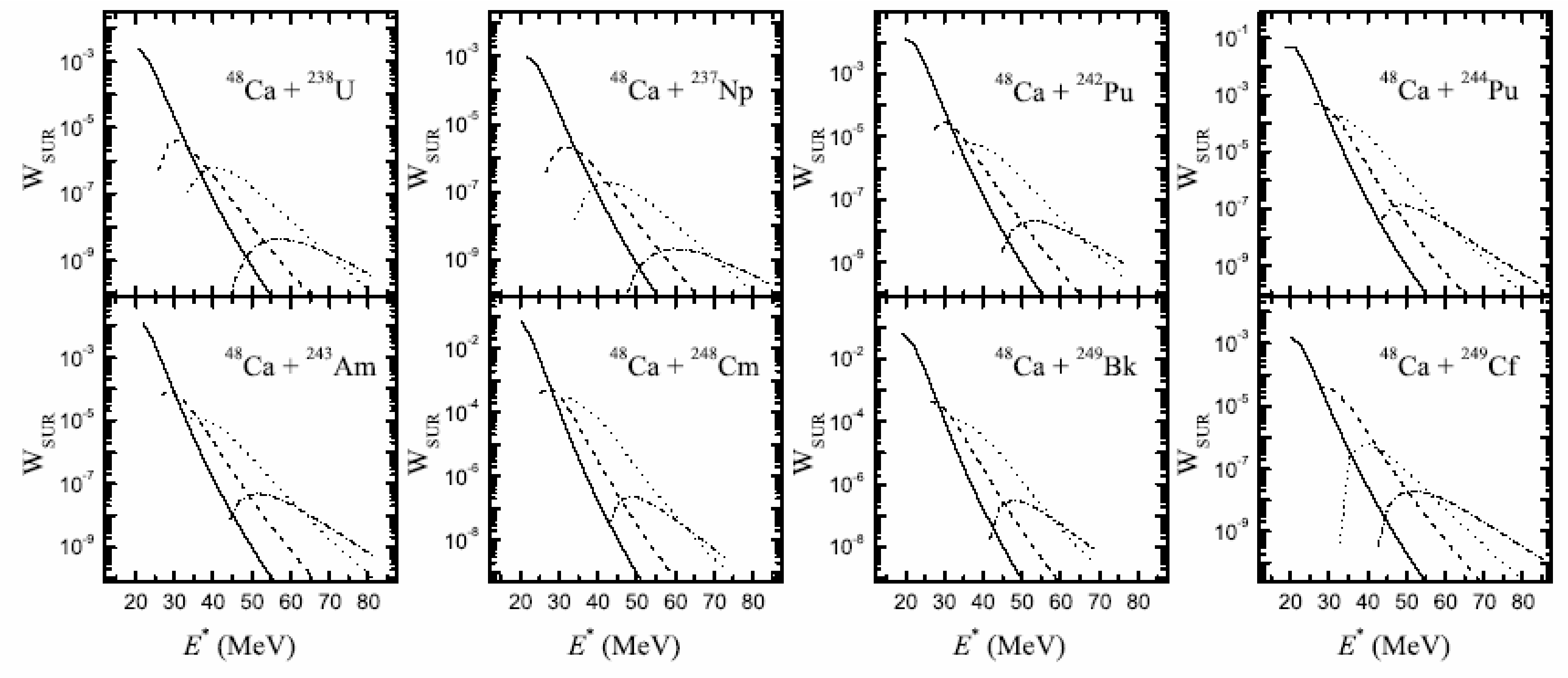
M. G. Itkis, et al, Proceedings of International Workshop on Fusion Dynamics at the Extremes, Dubna, Russia, 2000 , (2001).



Potential energy surface and Pcn for $^{48}Ca+^{238}U$

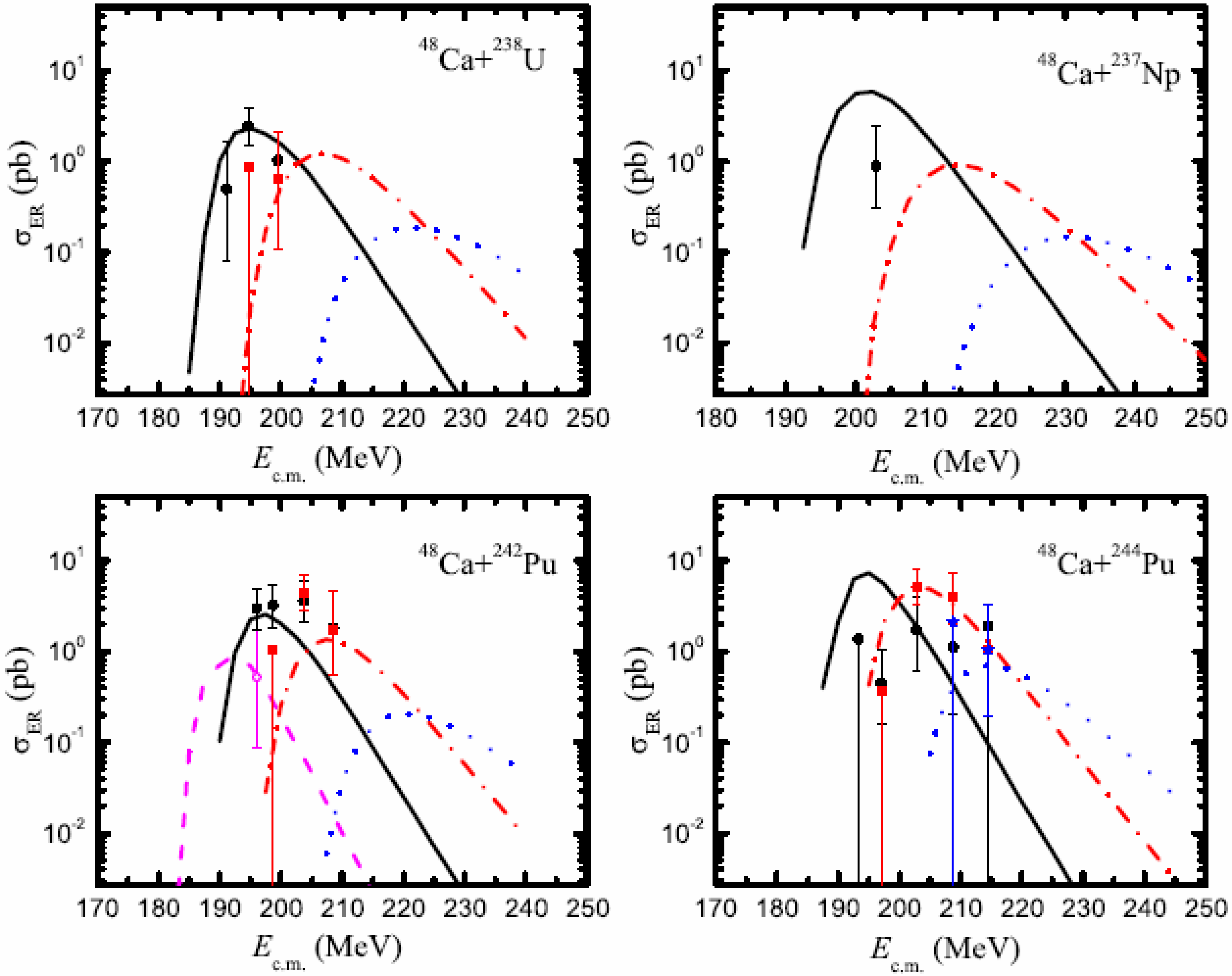


Fusion probabilities for some hot fusion reactions



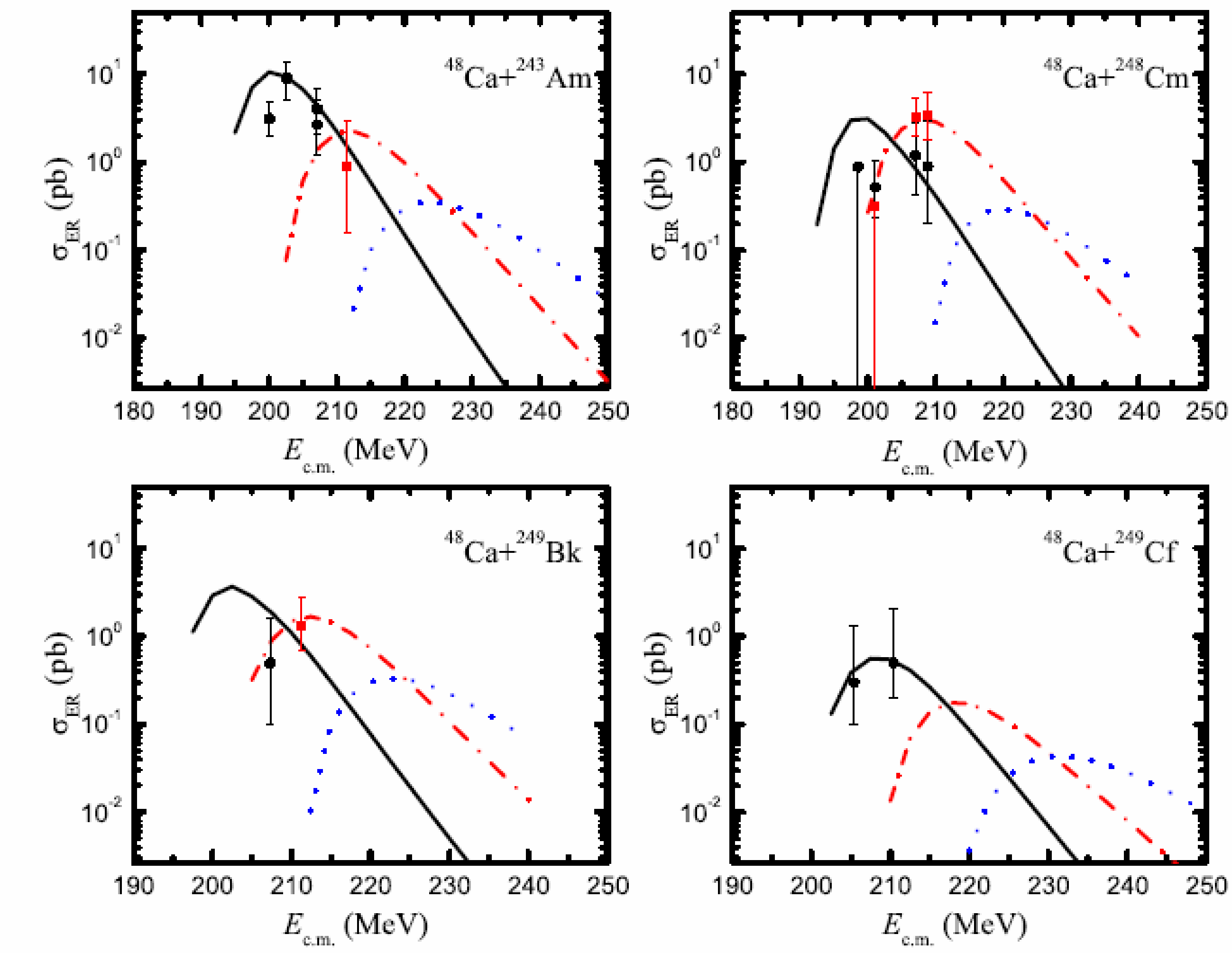
Survival probabilities for some compound nuclei produced in hot fusion reactions

P. Moller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).



Excitation functions for $^{48}Ca+^{238}U$, ^{237}Np, $^{242, 244}$ Pu

Exp. Yu.Ts. Oganessian, et al., PRC 70 (2004) 064609, P. A. Ellison, et al, PRL 105 (2010) 182701



Evaporation residue cross sections for ^{48}Ca+^{243}Am, ^{248}Cm, ^{249}Bk, ^{249}Cf

Exp. Yu.Ts. Oganessian et al., PRC 69 (2004) 021601(R) ,
70 (2004) 064609 , 74.044602(2006), 83, 054315 (2011)

S. Hofmann, S. Heinz, R. Mann, *et al.*, Euro. Phys. J. A 48, (2012) 1

Experiment about synthesis of elements 120

$^{58}Fe+^{244}Pu$

PHYSICAL REVIEW C 79, 024603 (2009)

Attempt to produce element 120 in the $^{244}Pu + ^{58}Fe$ reaction

Yu. Ts. Oganessian, V. K. Utyonkov, Yu. V. Lobanov, F. Sh. Abdullin, A. N. Polyakov, R. N. Sagaidak, I. V. Shirokovsky, Yu. S. Tsyganov, A. A. Voinov, A. N. Mezentsev, V. G. Subbotin, A. M. Sukhov, K. Subotic, V. I. Zagrebaev, and S. N. Dmitriev
Joint Institute for Nuclear Research, RU-141980 Dubna, Russian Federation

R. A. Henderson, K. J. Moody, J. M. Kenneally, J. H. Landrum, D. A. Shaughnessy, M. A. Stoyer, N. J. Stoyer, and P. A. Wilk
Lawrence Livermore National Laboratory, Livermore, California 94551, USA

(Received 24 October 2008; published 5 February 2009)

An experiment aimed at the synthesis of isotopes of element 120 has been performed using the ^{244}Pu(^{58}Fe,xn)$^{302-x}$120 reaction. No decay chains consistent with fusion-evaporation reaction products were observed during an irradiation with a beam dose of 7.1×10^{18} 330-MeV ^{58}Fe projectiles. The sensitivity of the experiment corresponds to a cross section of 0.4 pb for the detection of one decay.

DOI: 10.1103/PhysRevC.79.024603 PACS number(s): 25.70.Gh, 23.60.+e, 25.85.Ca, 27.90.+b

Yu.Ts. Oganessian, et al., PRC 79 (2009) 024603

$^{50}Ti+^{249}Cf$

C. E. Dullmann, “News from TASCA”, talk given at the 10thWorkshop on Recoil Separator for Superheavy Element Chemistry, October 14, 2011, GSI Darmstadt, Germany (unpublished)

Theoretical investigations of the production of SHN 119 - 120

DNS Model

A. K. Nasirov, G. Giardina, G. Mandaglio, M. Manganaro, F. Hanappe, S. Heinz, S. Hofmann, A. I. Muminov, and W. Scheid, PRC 79(2009) 02460

A. K. Nasirov, G. Mandaglio, G. Giardina, A. Sobiczewski, and A. I. Muminc PRC 84(2011) 044612

G.G.Adamian, G.A. Antonenko, W. Scheid. EJPA 41(2009) 235

Z.-G. Gan, et al ,Sci. China-Phys. Mech. Astron.54 (Suppl. 1), s61 (2011)

FBD model

Z.H.Liu, J.D.Bao. PRC 84(2011) 031602(R)

K. Siwek-Wilczynska, T. Cap, M. Kowal, A. Sobiczewski, and J. Wilczynski, PRC 78(2008) 034610

V. Zagrebaev, W. Greiner PRC 78(2008) 034610

Other model

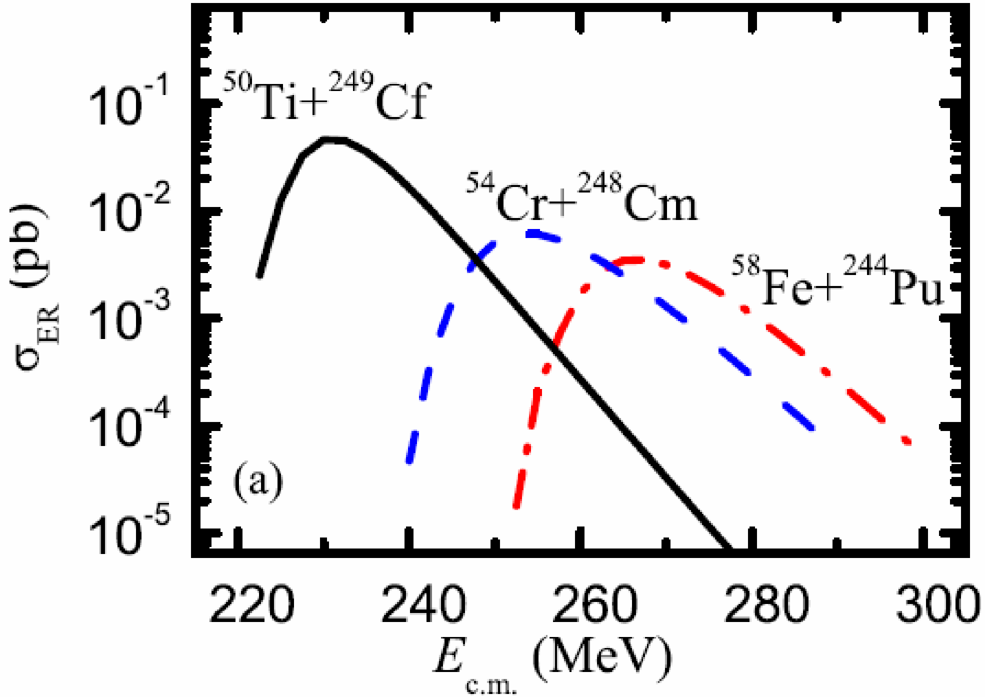
L Zhu, WJ Xie, and Feng-Shou Zhang PRC 89(2014) 024615

Ning Wang, J.L.Tian, W.Scheid PRC 84(2011) 061601(R)

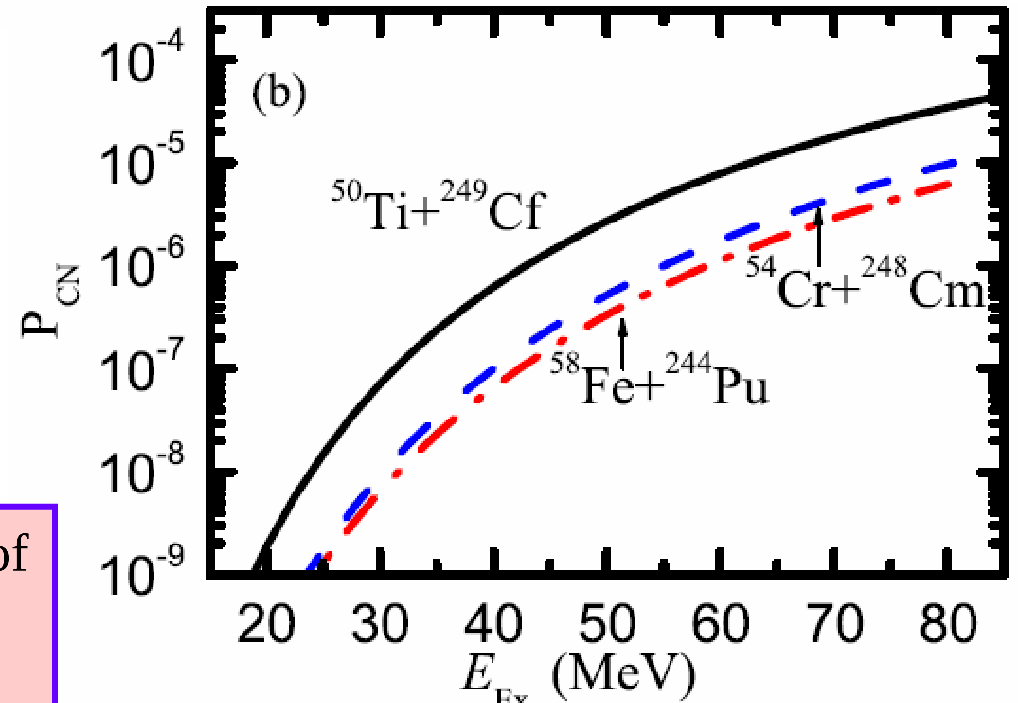
TABLE I. The predicted optimal evaporation residual cross section (in fb) for some reactions leading to elements 119 and 120.

Reference	$^{50}Ti + ^{249}Bk$	$^{50}Ti + ^{249}Cf$	$^{54}Cr + ^{248}Cm$	$^{58}Fe + ^{244}Pu$
Liu[10]	570	100		
Zagrebaev[12]	50	40	20	5
Ning Wang [16]	35	20	5	3
Siwek-Wilczyńska[8]	30	6	1	
This work	110	50	6	4

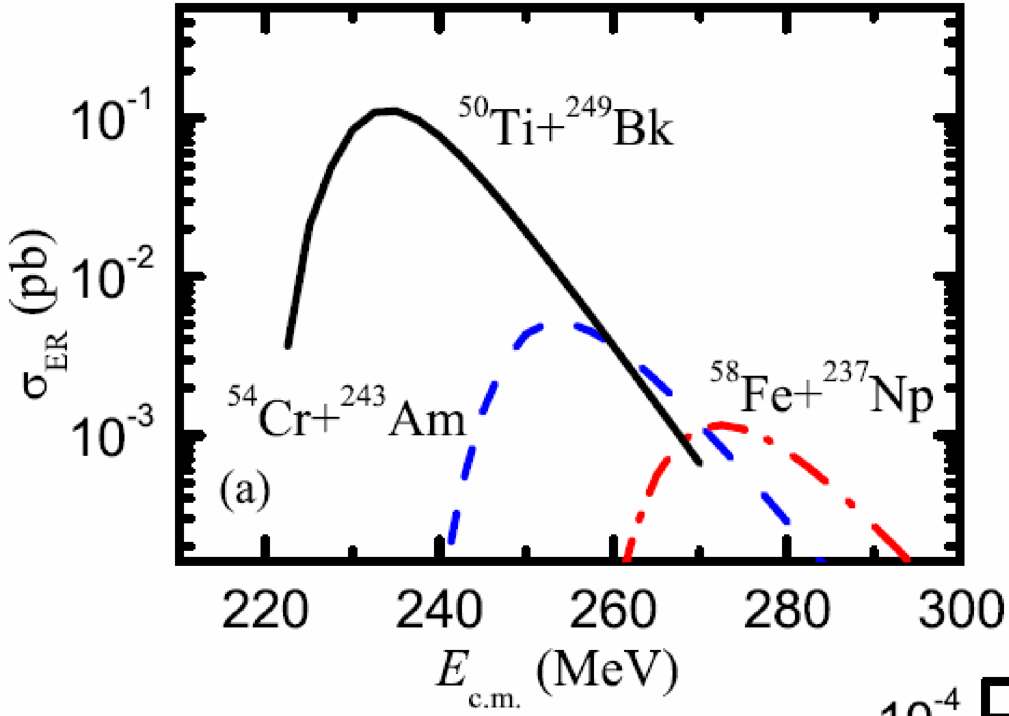
[8] K. Siwek-Wilczyńska, T. Cap, M. Kowal, A. Sobiczewski, and J. Wilczyński, Phys. Rev. C **86**, 014611 (2012).
[10] Z.-H. Liu and J.-D. Bao, Phys. Rev. C **84**, 031602(R) (2011)
[12] V. Zagrebaev and W. Greiner, Phys. Rev. C **78**, 034610 (2008)
[16] N. Wang, J. Tian, and W. Scheid, Phys. Rev. C **84**, 061601(R) (2011)



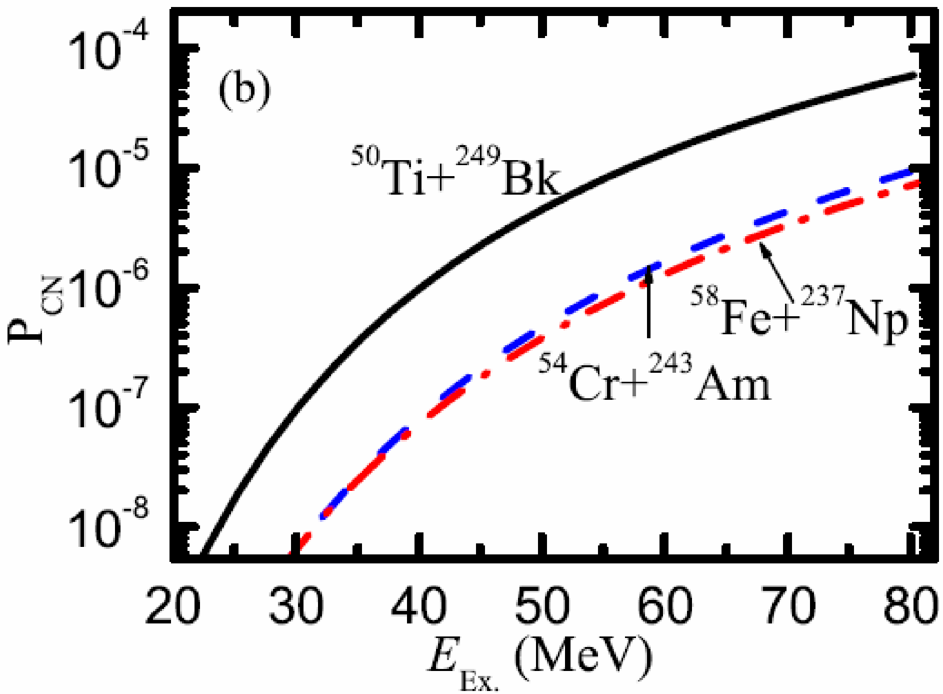
Excitation functions for producing nuclei Z=120



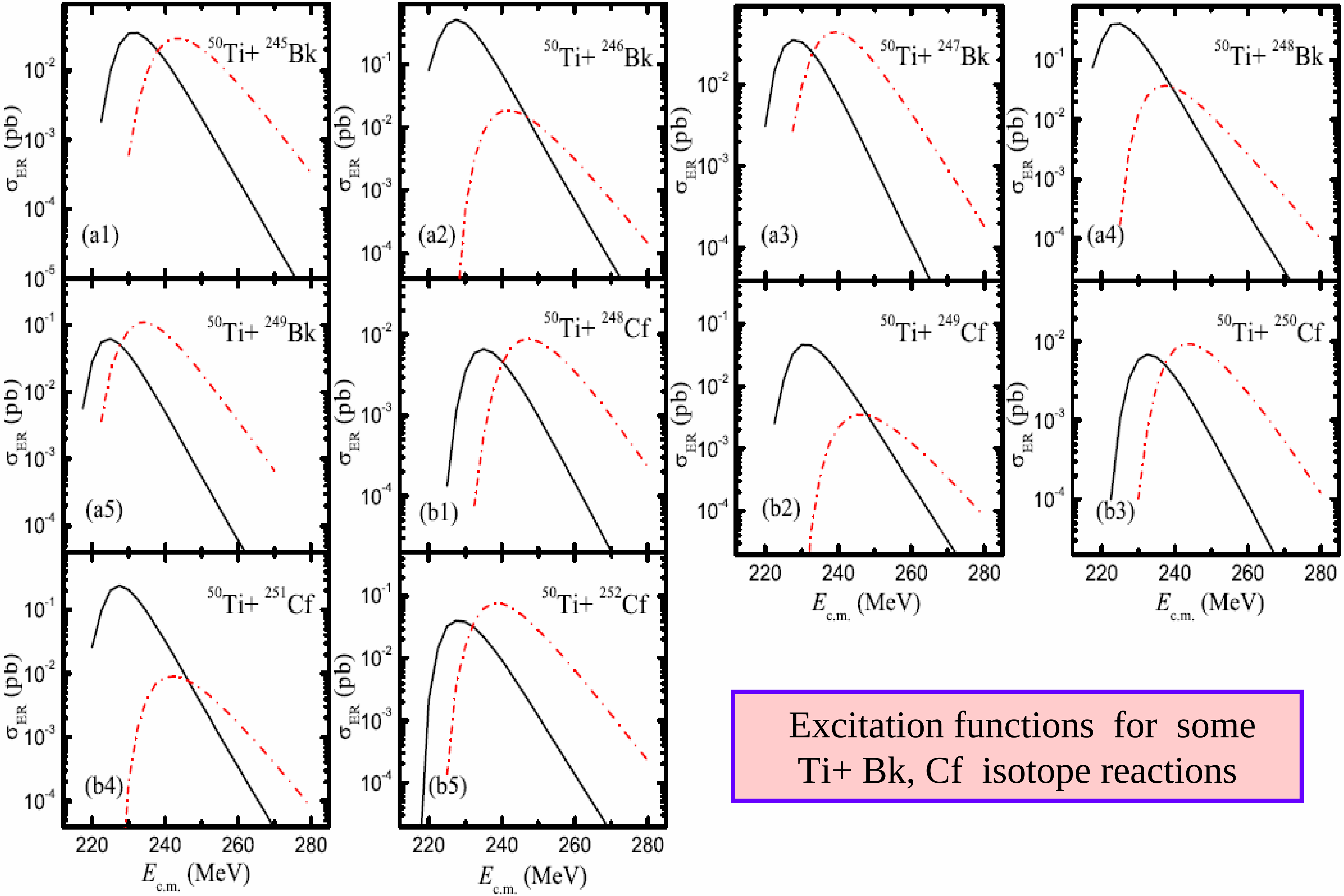
Fusion probabilities as a function of excitation energy for producing nuclei Z=120



Evp. Cross sections for ^{50}Ti+ ^{249}Bk, ^{54}Cr+ ^{243}Am and ^{58}Fe+^{237}Np reactions leading to nuclei with Z=119

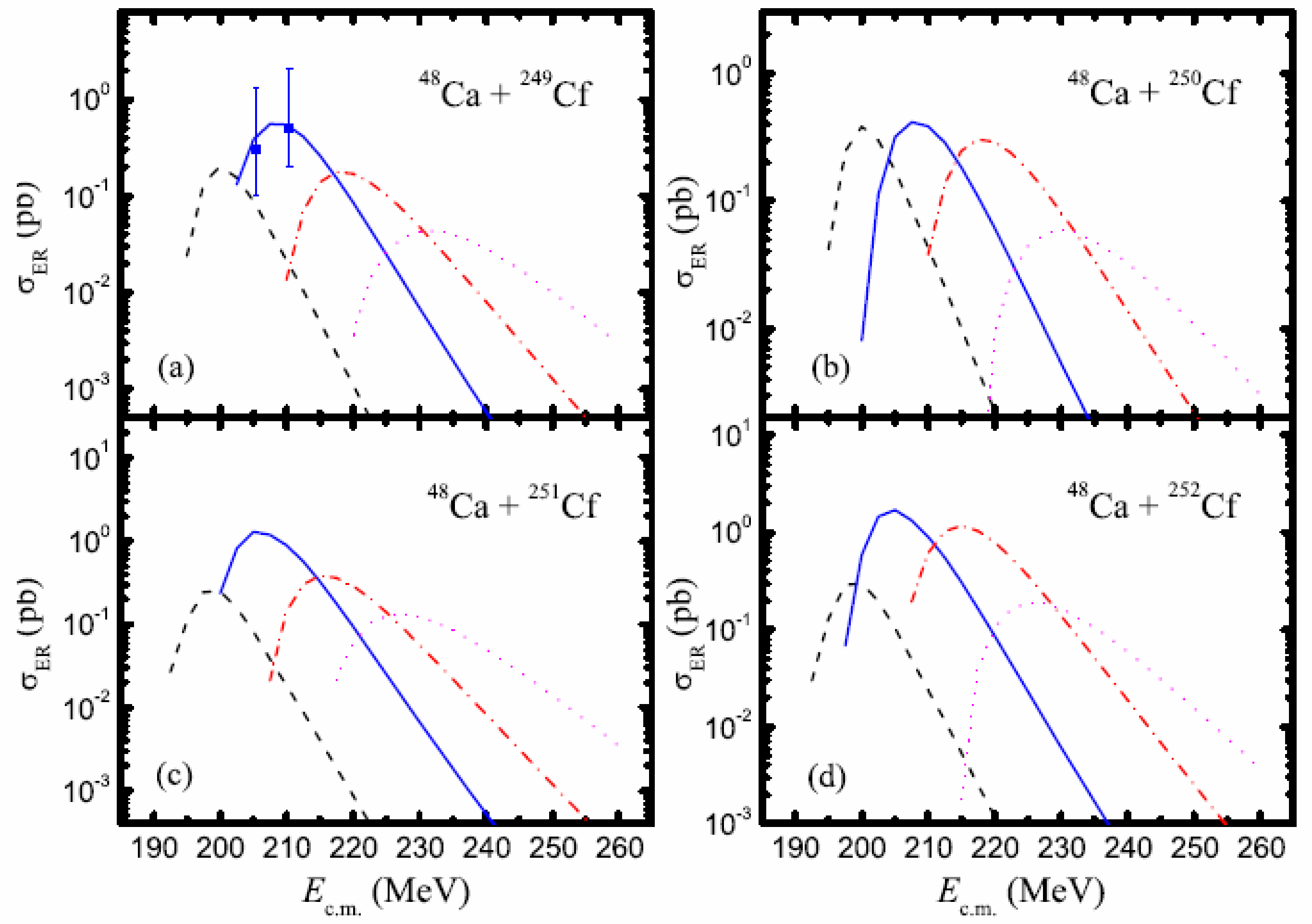


Fusion probabilities for ^{50}Ti + ^{249}Bk, ^{54}Cr+ ^{243}Am and ^{58}Fe+^{237}Np reactions leading to nuclei with Z=119

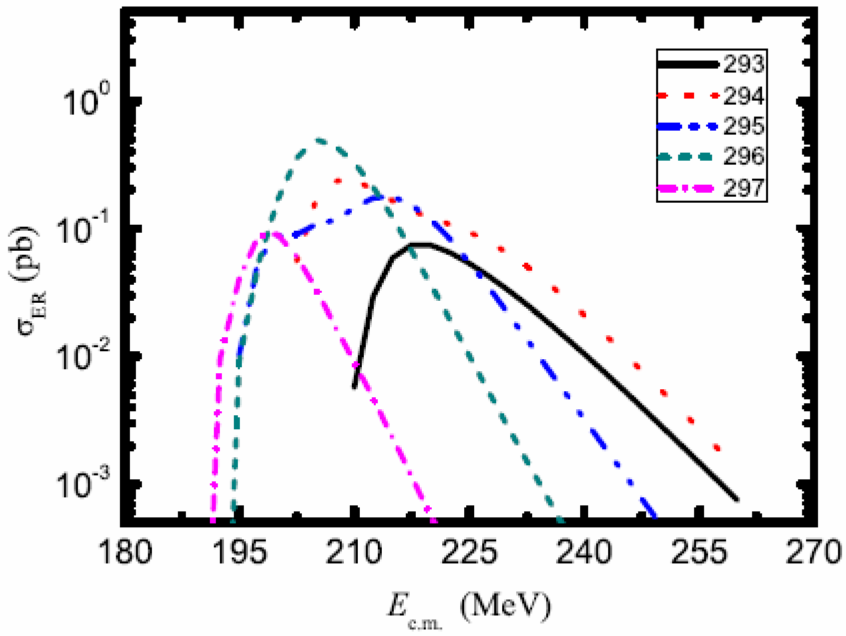


Excitation functions for some Ti+ Bk, Cf isotope reactions

Theoretical investigations of the production of SHN 118

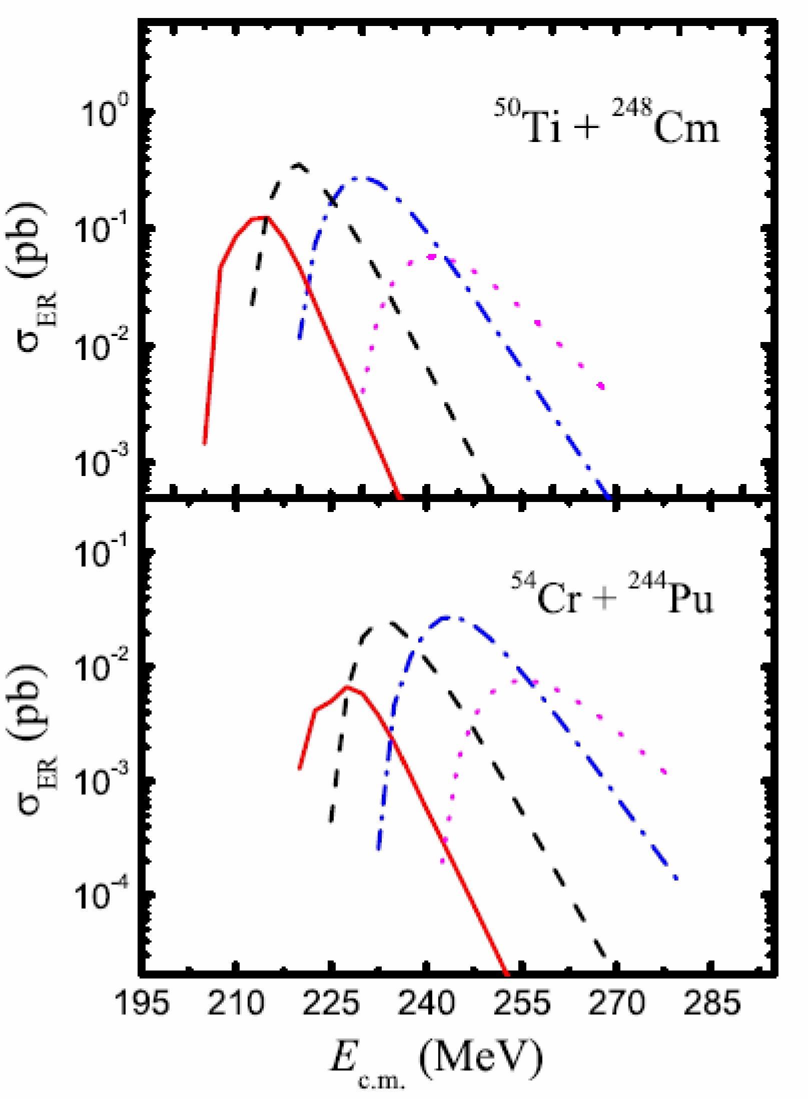


Nan Wang, En-guang Zhao, W. Scheid, Phys Rev C 89 (2014) 037601



Effective evaporation residue cross sections for 118 isotopes

Nan Wang, En-guang Zhao, W. Scheid, PRC 89 (2014) 037601



Excitation functions for synthesizing 118 in ^{50}Ti+^{248}Cm and ^{54}Cr+^{244}Pu reactions

Summary

- The dynamical deformation is introduced in the di-nuclear system model. The dynamical deformations, driving potentials and fusion are investigated in the DNS-DyPES model.

- By using the DNS-DyPES model, hot fusion reactions for synthesizing superheavy nuclei (SHN) with charge numbers Z = 112–118 are studied. Good agreement with experimental results is found.

- Several combinations producing elements Z=119, 120 with Fe, Cr and Ti as projectile are calculated and analyzed. It is shown that with increasing the mass asymmetry of the incidental channel, the fusion probabilities decrease significantly and so do the evaporation residue cross sections.

- The ER cross section for reaction ^{50}Ti bombarding ^{249}Bk and Cf isotopes are approximately found in the order of 0.1pb.

- Different combinations for synthesizing 118 are also investigated.

Thanks for your attention!
谢谢

祝大家工作顺利，
常来深圳大学！