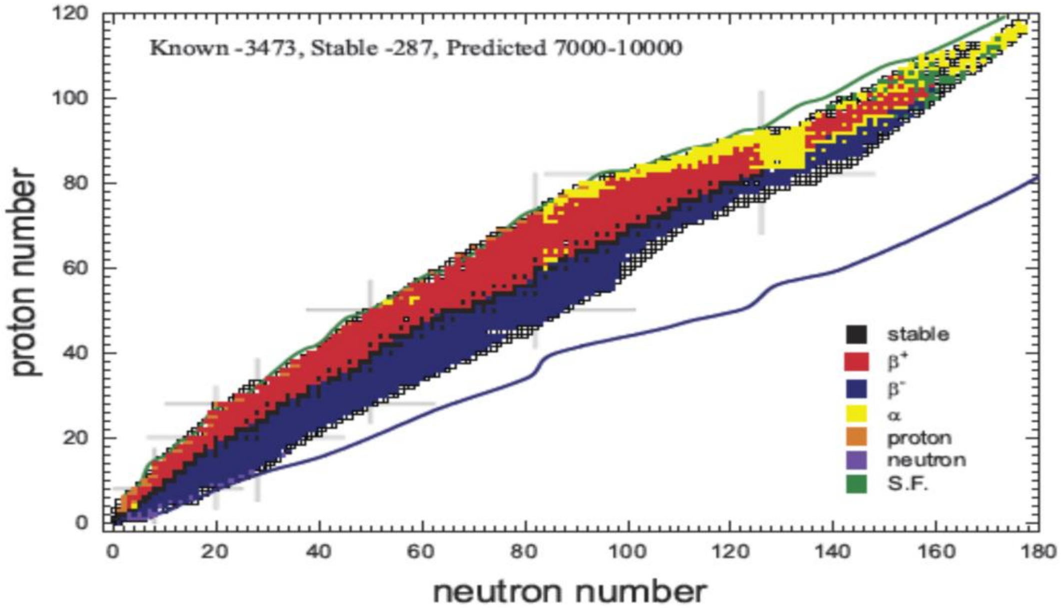
MNT2024

RIKEN, July 2-5, 2024



Cluster transfer and cluster emission in multinucleon transfer reactions

Zhao-Qing Feng

(School of Physics and Optoelectronics, South China University of Technology)

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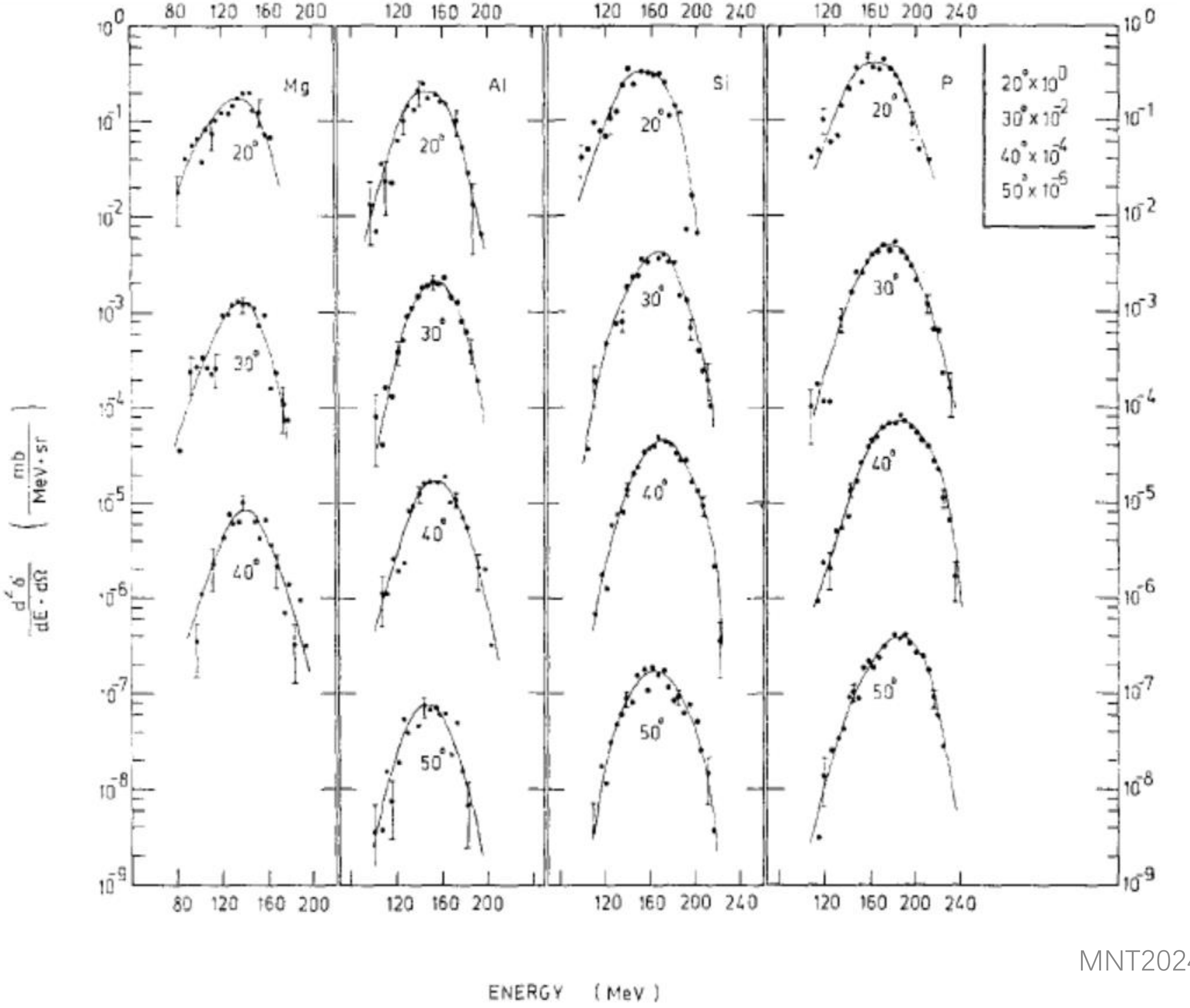
Outline

- Brief overview of MNT reactions
- Theoretical description of MNT reactions based on the dinuclear system model
- Results and discussion
- ✓ Fusion-evaporation reactions
- ✓ Yields, total kinetic energy spectra and angular distribution in MNT reactions
- ✓ Cluster transfer and cluster emission in MNT reactions
- Summary and perspective

Multinucleon transfer reactions-quasi-elastic scattering, quasifission, deep inelastic collisions

Dubna experiments, Nuclear Physics A 176 (1971) 284-288, A 211 (1973) 299-309, A 215 (1973) 91-108



MNT2024

2.N Nuclear Physics A176 (1971) 284—288; © North-Holland Publishing Co., Amsterdam

NEW ISOTOPES ^{29,30}Mg, ^{31,32,33}Al, ^{33,34,35,36}Si, ^{35,36,37,38}P, ^{39,40}S AND ^{41,42}Cl PRODUCED IN BOMBARDMENT OF A ^{232}Th TARGET WITH 290 MeV ^{40}Ar IONS

A. G. ARTUKH, V. V. AVDEICHIKOV †, G. F. GRIDNEV, V. L. MIKHEEV, V. V. VOLKOV and J. WILCZYŃSKI ††
Joint Institute for Nuclear Research, Dubna, USSR

MULTINUCLEON TRANSFER REACTIONS IN THE ^{232}Th + ^{22}Ne SYSTEM

A. G. ARTUKH, G. F. GRIDNEV, V. L. MIKHEEV, V. V. VOLKOV and J. WILCZYŃSKI †
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Received 18 December 1972
(Revised 14 May 1973)

TRANSFER REACTIONS IN THE INTERACTION OF ^{40}Ar WITH ^{232}Th

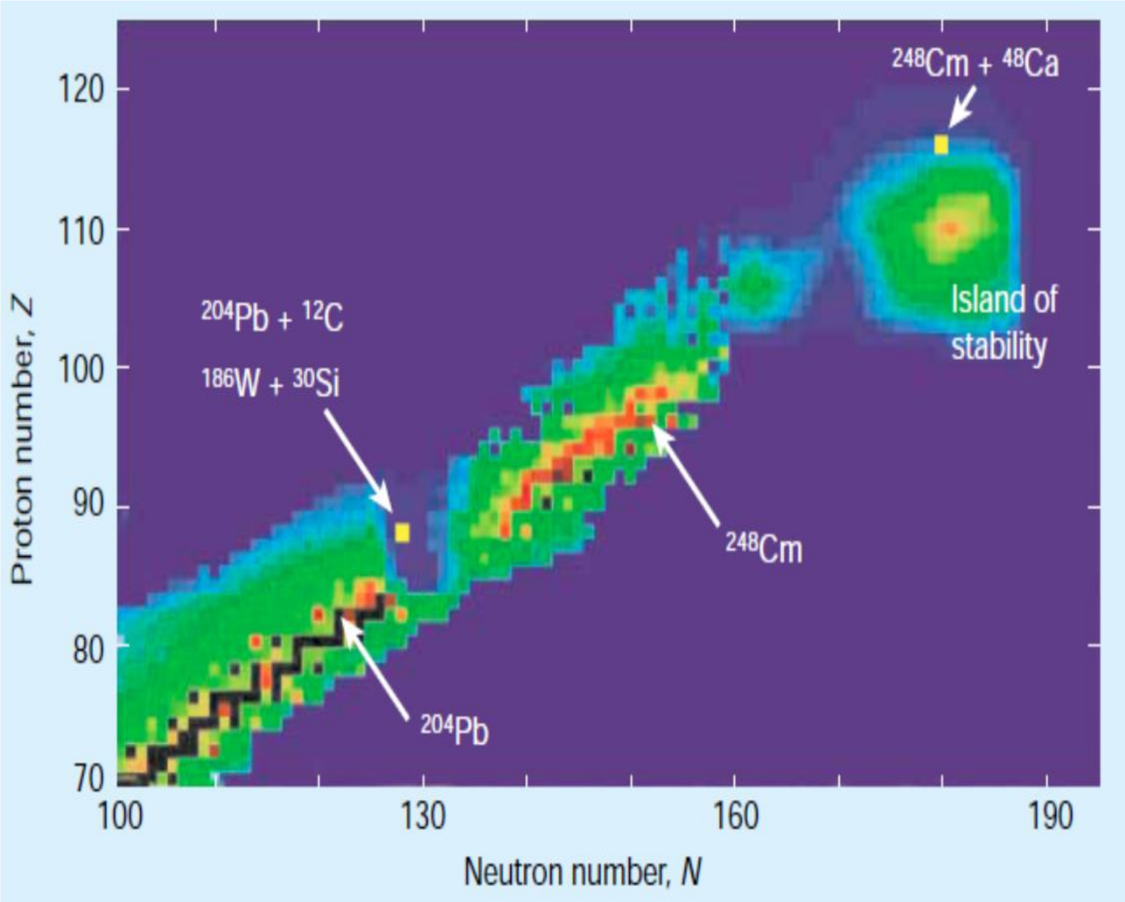
A. G. ARTUKH, G. F. GRIDNEV, V. L. MIKHEEV, V. V. VOLKOV and J. WILCZYNSKI†
Joint Institute for Nuclear Research, Dubna, USSR

Received 13 April 1973

Multi-nucleon transfer reactions (MNT), experiment progress

Lab.	Reaction system	References
Dubna	^{136}Xe + ^{208}Pb ^{156,160}Gd + ^{186}W	Phys. Rev. C 86, 044611 (2012); Phys. Rev. C 96, 064621 (2017)
GSI	^{238}U+^{238}U ^{48}Ca+^{248}Cm ^{48}Ca+^{238}U	Phys. Rev. Lett. 39, 385 (1977); Phys. Rev. Lett. 41, 469 (1978); Phys. Lett. B 748, 199 (2015); Eur. Phys. J. A 56, 224 (2020)
GANIL	^{238}U+^{238}U; ^{136}Xe+^{198}Pt	IJMPE 17, 2235-2239 (2008); Phys. Rev. Lett. 115, 172503 (2015)
Argonne	^{136}Xe+^{208}Pb ^{204}Hg+^{198}Pt	Phys. Rev. C 91, 064615 (2015); Physics Letters B 771, 119-124 (2017)
RIKEN-KISS	^{238}U+^{198}Pt→^{241}U	Phys. Rev. Lett. 130, 132502 (2023)

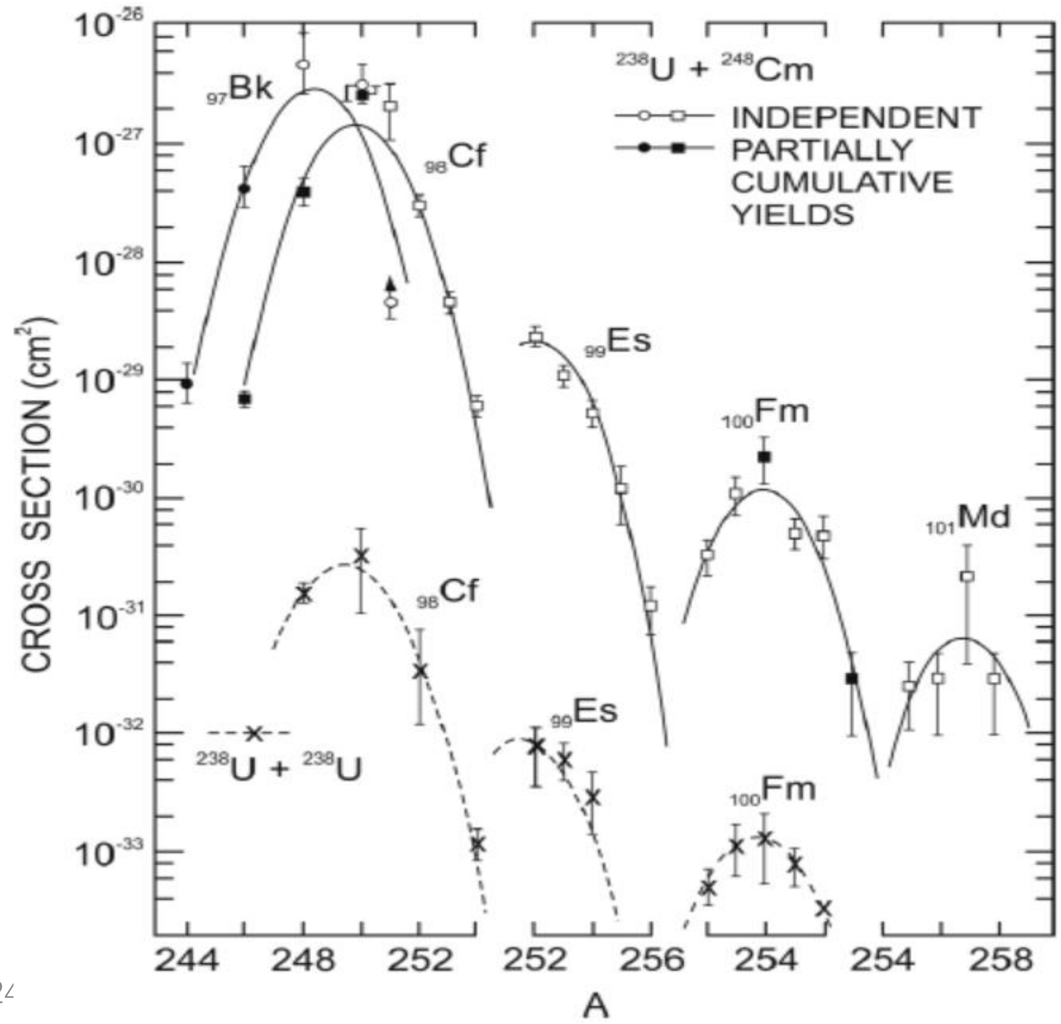
Slide from Yuri Oganessian in Lanzhou, 2005



Damped collisions of two actinide nuclei

PRL39(1977)1065, PRL41(1978)469, ZPA292(1979)171,

PRL43(1979)1483, PRC88(2013)054615



New isotope production around N=126

第 32 卷 第 2 期 原 子 核 物 理 评 论 Vol. 32, No. 2
2015 年 6 月 Nuclear Physics Review June, 2015
Article ID: 1007-4627(2015) 02-0137-09

Production of Exotic Nuclei in Low-Energy Multi-Nucleon Transfer Reactions

V.I. Zagrebaev[1], Walter Greiner[2]
(1. Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Moscow Region, Russia;
2. Frankfurt Institute for Advanced Studies, J.W. Goethe-Universität, Frankfurt, Germany)

PRL 101, 122701 (2008) PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2008

Production of New Heavy Isotopes in Low-Energy Multinucleon Transfer Reactions

Valery Zagrebaev[1] and Walter Greiner[2]
[1]Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Moscow Region, Russia
[2]Frankfurt Institute for Advanced Studies, J.W. Goethe-Universität, Frankfurt, Germany
(Received 8 July 2008; published 17 September 2008)

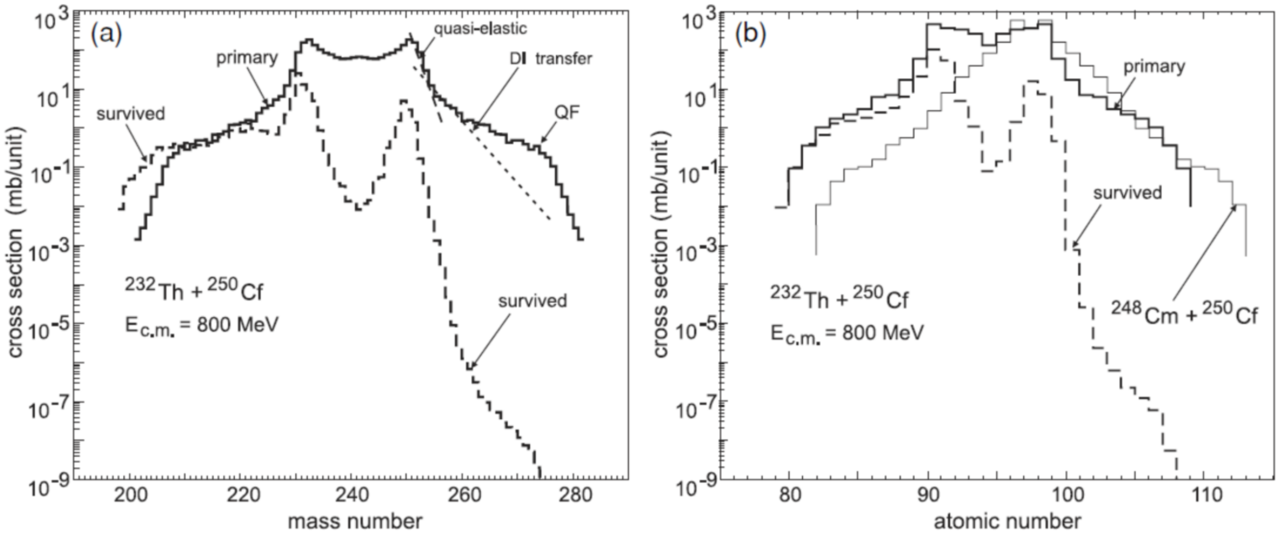
It is shown that the multinucleon transfer reactions in low-energy collisions of heavy ions may be used for production of new neutron-rich nuclei at the "northeast" part of the nuclear map along the neutron closed shell $N = 126$ which plays an important role in the r process of nucleosynthesis. More than 50 unknown nuclei might be produced in such reactions (in particular, in collision of ^{136}Xe with ^{208}Pb) with cross sections of not less than 1 μb.

DOI: 10.1103/PhysRevLett.101.122701 PACS numbers: 25.70.Jj, 25.70.Hi

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS
J. Phys. G: Nucl. Part. Phys. 34 (2007) 1–25 doi:10.1088/0954-3899/34/1/001

Low-energy collisions of heavy nuclei: dynamics of sticking, mass transfer and fusion

Valery Zagrebaev[1] and Walter Greiner[2]
[1] Flerov Laboratory of Nuclear Reaction, JINR, Dubna, Moscow Region, Russia
[2] Frankfurt Institute for Advanced Studies, JW Goethe-Universität, Frankfurt, Germany
E-mail: valeri.zagrebaev@jinr.ru



New isotope ^{241}U via MNT reactions and high-precision mass measurement

PHYSICAL REVIEW LETTERS 130, 132502 (2023)

Editors' Suggestion | Featured in Physics

Discovery of New Isotope ^{241}U and Systematic High-Precision Atomic Mass Measurements of Neutron-Rich Pa-Pu Nuclei Produced via Multinucleon Transfer Reactions

T. Niwase,[1,*] Y. X. Watanabe,[1] Y. Hirayama,[1] M. Mukai,[2] P. Schury,[1] A. N. Andreyev,[3] T. Hashimoto,[4] S. Iimura,[5] H. Ishiyama,[2] Y. Ito,[6] S. C. Jeong,[1] D. Kaji,[2] S. Kimura,[2] H. Miyatake,[1] K. Morimoto,[2] J.-Y. Moon,[4] M. Oyaizu,[1] M. Rosenbusch,[1] A. Taniguchi,[7] and M. Wada[1]

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[3]School of Physics, Engineering and Technology, University of York, York YO10 5DD, United Kingdom
[4]Institute for Basic Science, 70, Yuseong-daero 1689-gil, Yusung-gu, Daejeon 43000, Korea
[5]Department of Physics, Rikkyo University, Tokyo 171-8501, Japan
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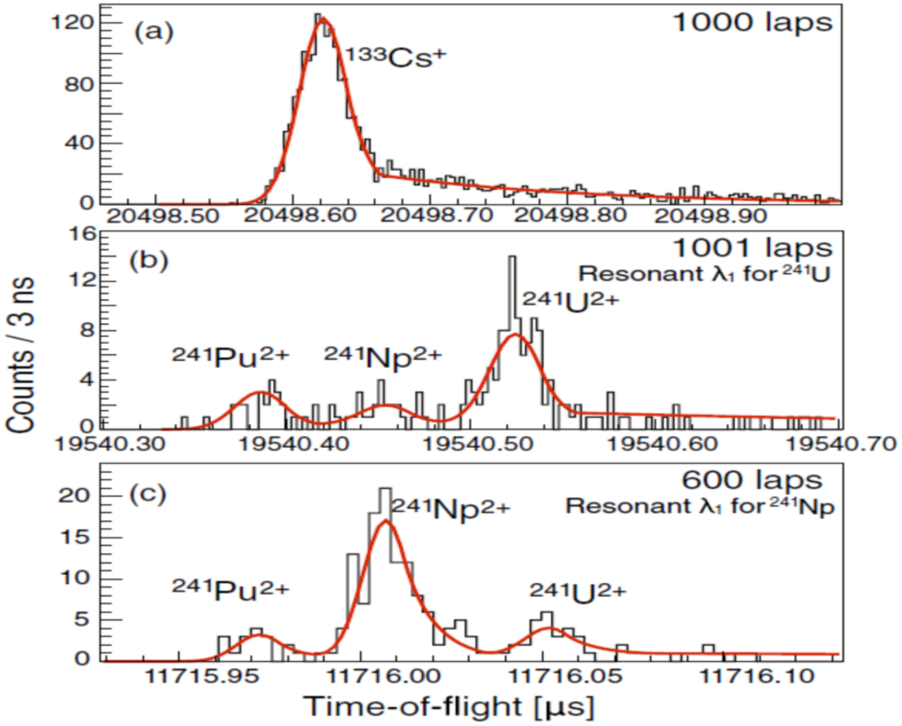
[7]Institute for Integrated Radiation and Nuclear Science, Kyoto University, Kumatori, Osaka 590-0494, Japan

(Received 21 November 2022; revised 26 January 2023; accepted 16 February 2023; published 31 March 2023)



PRL 115, 172503 (2015) PHYSICAL REVIEW LETTERS week ending 23 OCTOBER 2015

Pathway for the Production of Neutron-Rich Isotopes around the $N = 126$ Shell Closure

Y. X. Watanabe,[1,*] Y. H. Kim,[2,3,†] S. C. Jeong,[1,‡] Y. Hirayama,[1] N. Imai,[1,§] H. Ishiyama,[1,‡] H. S. Jung,[1] H. Miyatake,[1] S. Choi,[2,3] J. S. Song,[2,3,4] E. Clement,[5] G. de France,[5] A. Navin,[5,∥] M. Rejmund,[5] C. Schmitt,[5] G. Pollarolo,[6] L. Corradi,[7] E. Fioretto,[7] D. Montanari,[8] M. Niikura,[9,¶] D. Suzuki,[9,**] H. Nishibata,[10] and J. Takatsu[10]

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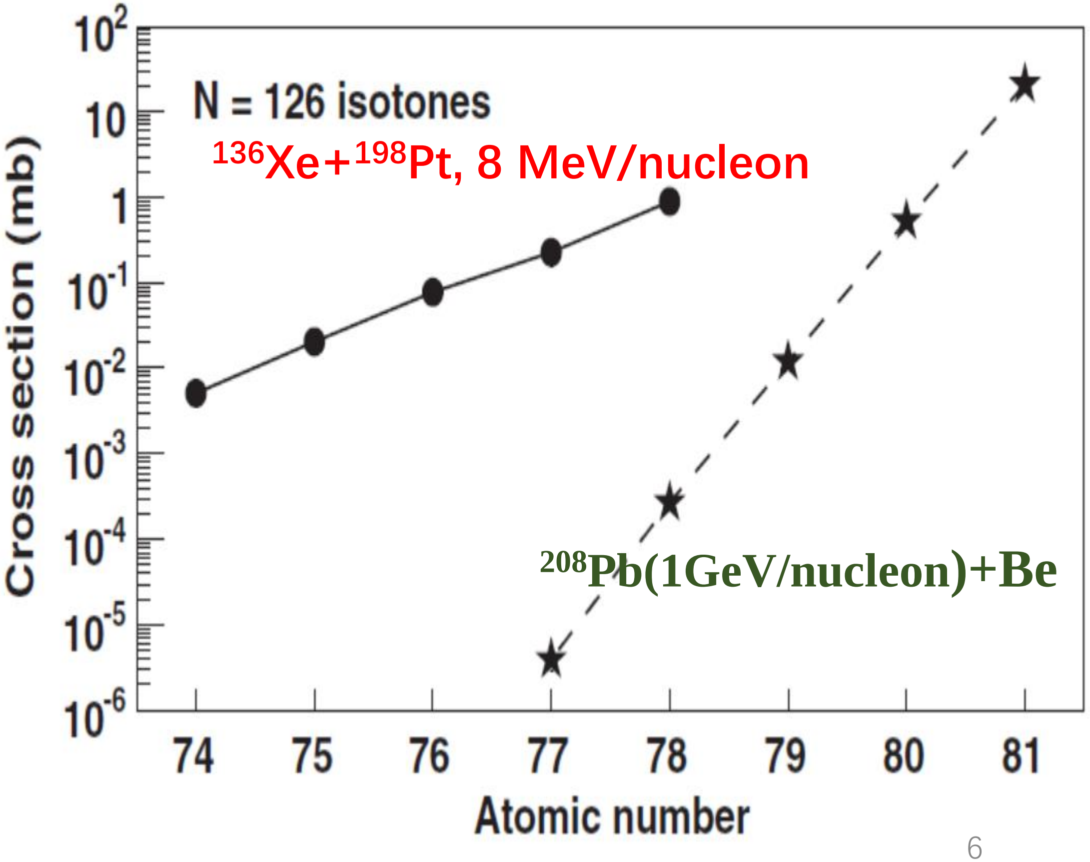
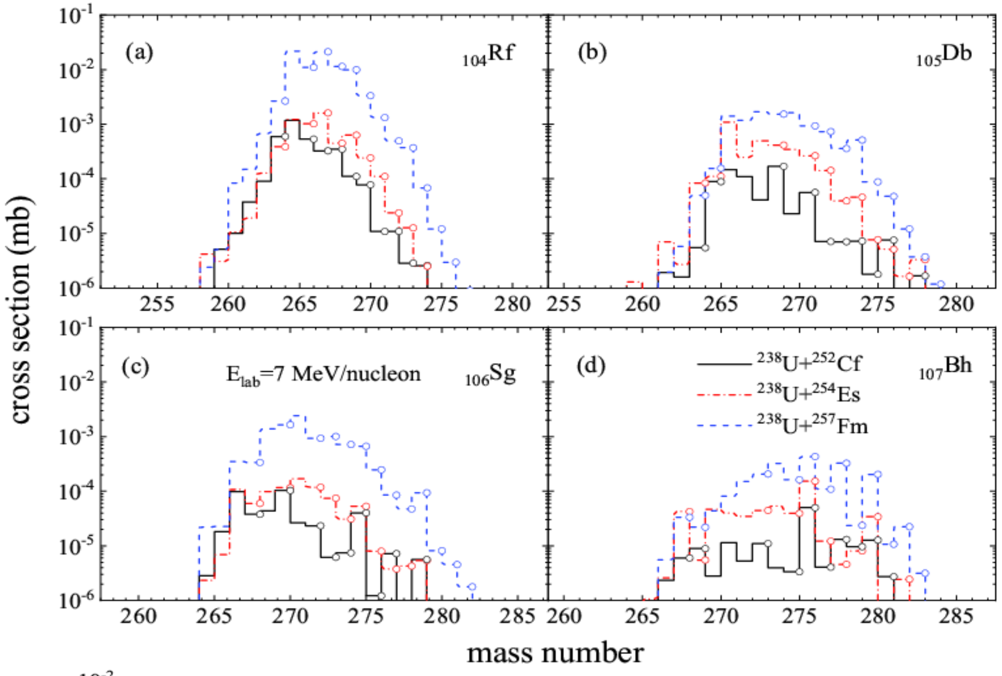
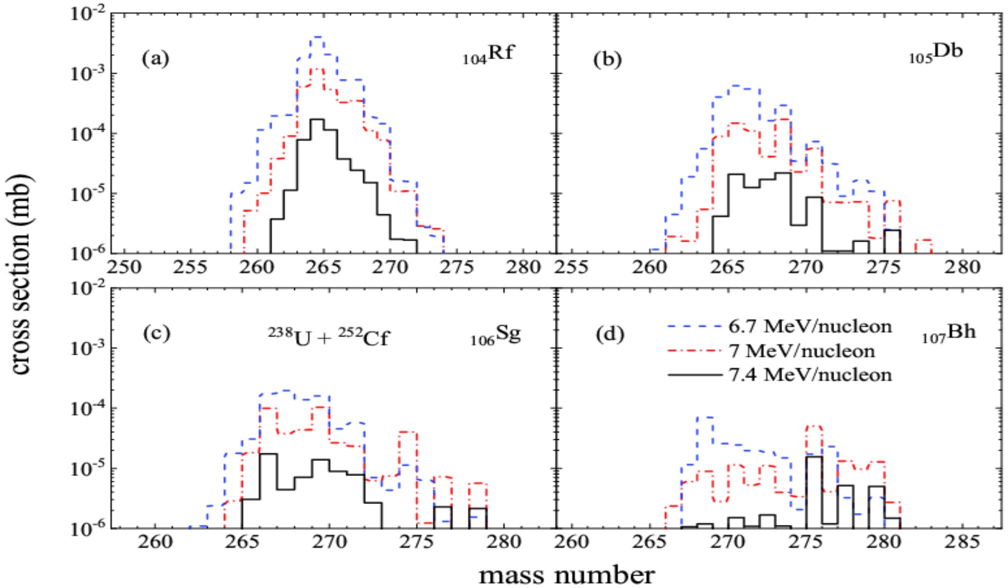
[7]Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy
[8]Dipartimento di Fisica, Università di Padova, and Istituto Nazionale di Fisica Nucleare, I-35131 Padova, Italy
[9]Institut de Physique Nucléaire (IPN), IN2P3-CNRS, F-91406 Orsay Cedex, France
[10]Department of Physics, Osaka University, Osaka 560-0043, Japan

(Received 26 June 2015; published 23 October 2015)



New isotope production around N= 162 in MNT reactions

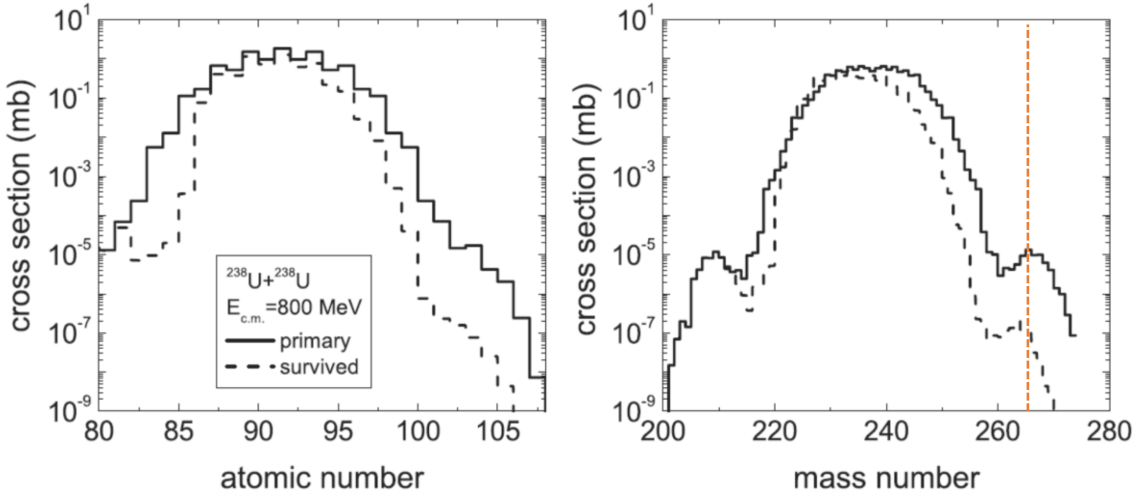




PHYSICAL REVIEW C **80**, 067601 (2009)

Production of heavy isotopes in transfer reactions by collisions of ^{238}U + ^{238}U

Zhao-Qing Feng,* Gen-Ming Jin, and Jun-Qing Li
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China
(Received 3 November 2009; published 7 December 2009)



Eur. Phys. J. A (2022) 58:162
https://doi.org/10.1140/epja/s10050-022-00819-2
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Theoretical Physics

Production of neutron-rich heavy nuclei around $N = 162$ in multinucleon transfer reactions

Cheng Peng[1], Zhao-Qing Feng[1,a]
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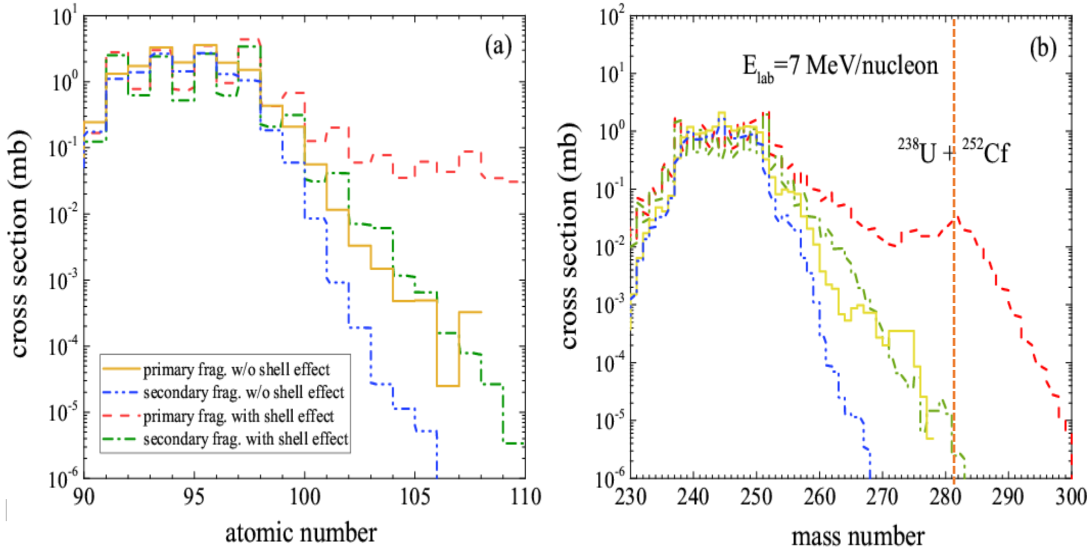


Cluster emission (α, ^{8}Be, etc) at IMP (Lanzhou) in the reaction of ^{12}C+^{209}Bi near barrier energy

第 1 卷 第 1 期 高 能 物 理 与 核 物 理 Vol. 1, No. 1
1977 年 11 月 PHYSICA ENERGIAE FORTIS ET PHYSICA NUCLEARIS November, 1977

^{12}C 轰击 ^{209}Bi 时发射的 α 粒子

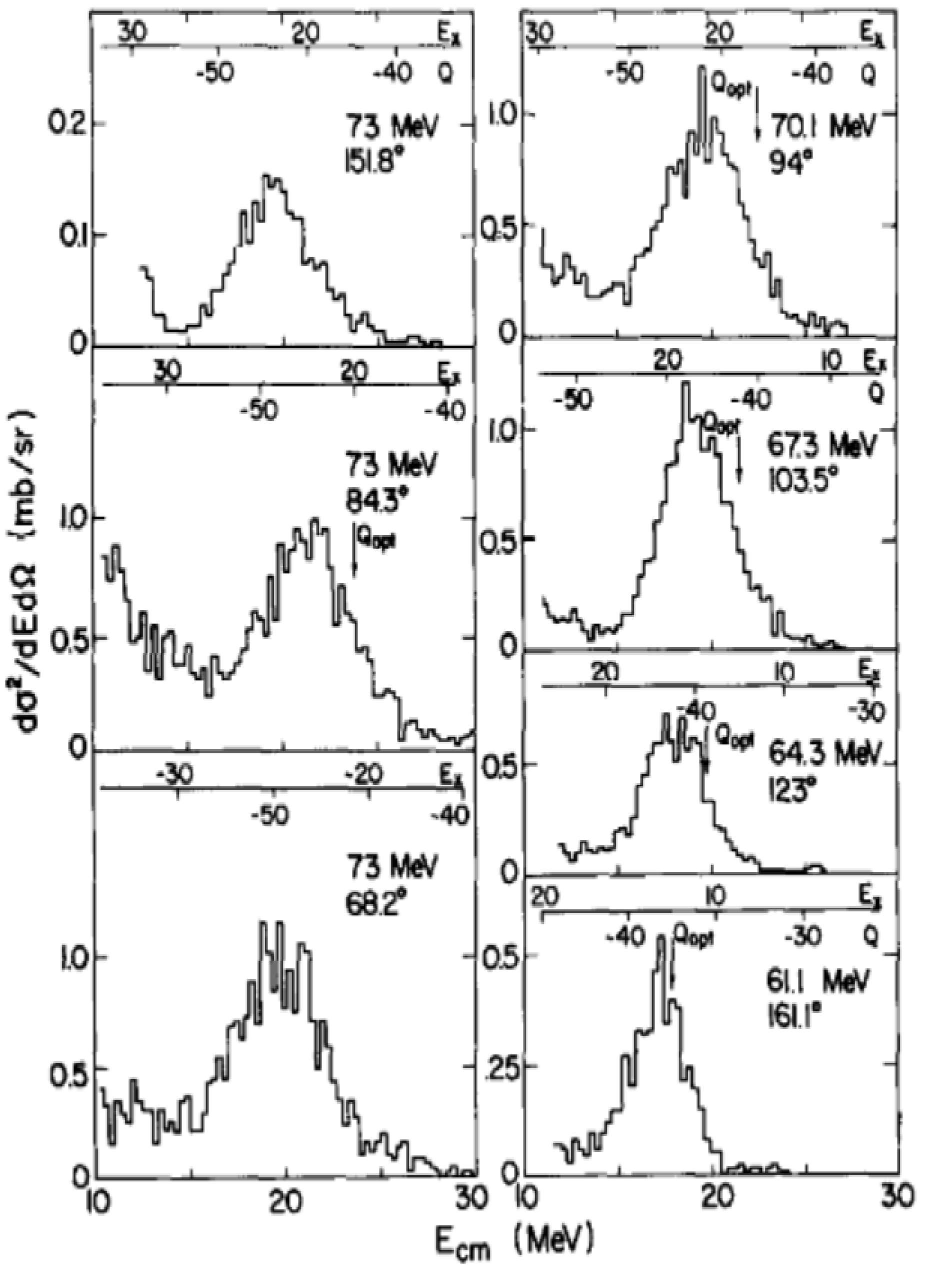
沈文庆 徐树威 王大延 谢元祥 郭中言 李祖玉
（中国科学院近代物理研究所）

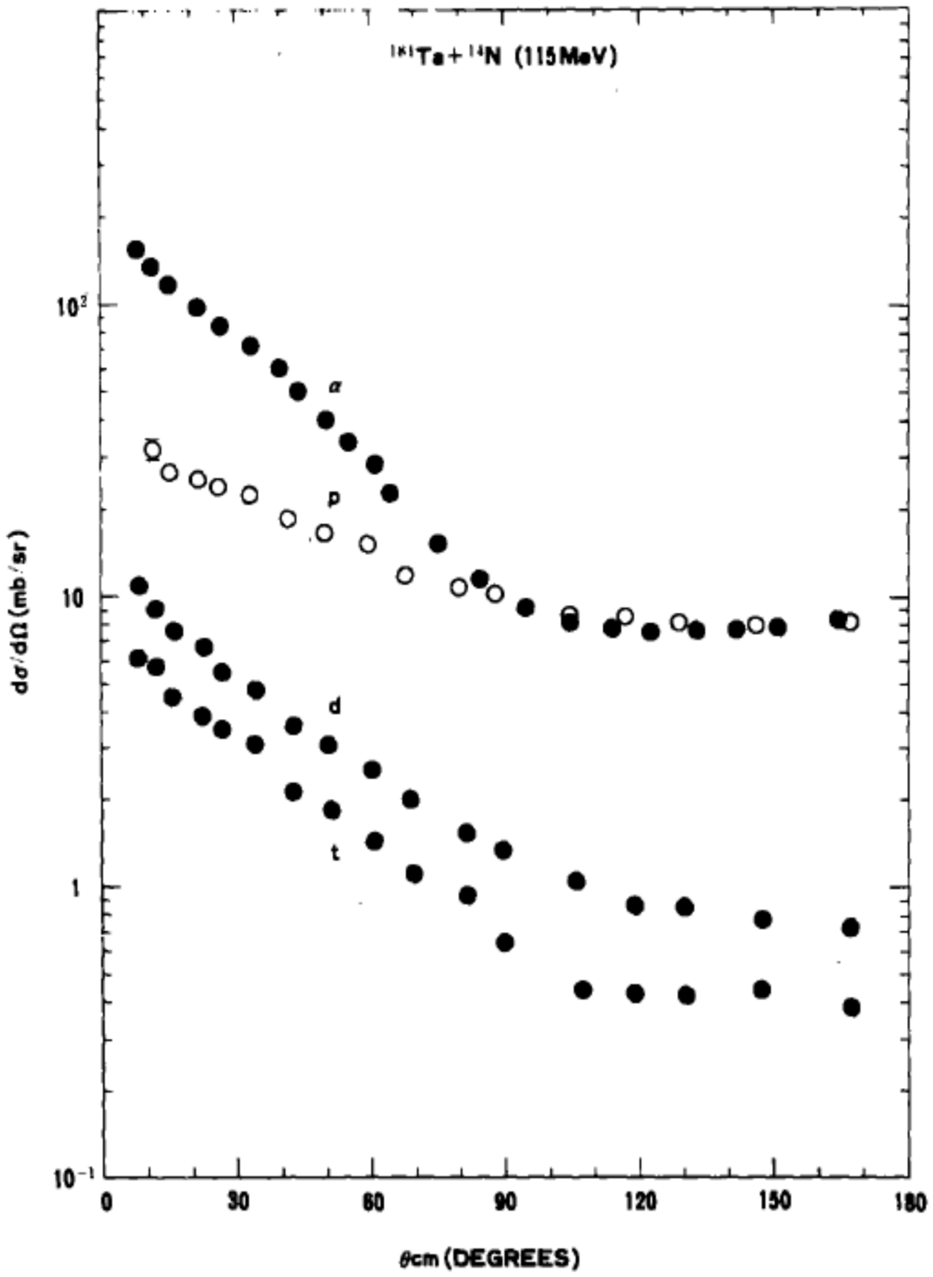
Nuclear Physics A
Volume 349, Issues 1–2, 3–10 November 1980, Pages 285–300

Product cross sections for the reaction of ^{12}C with ^{209}Bi ☆

Gen-Ming Jin[1, 2]
[1] Institute of Modern Physics, Academia Sinica, Lanzhou, People's Republic of China
[2] The Niels Bohr Institute, Copenhagen Ø, Denmark
Yuan-Xiang Xie, Yong-Tai Zhu, Wen-Ging Shen, Xi-Jun Sun, Jun-Sheng Guo, Guo-Xing Liu, Ju-Sheng Yu, Chi-Chang Sun
Institute of Modern Physics, Academia Sinica, Lanzhou, People's Republic of China
J.D. Garrett
The Niels Bohr Institute, Copenhagen Ø, Denmark

轰击能量低于73MeV的12C+209Bi反应研究	杨澄中，沈文庆，郭俊盛，邬恩九等	自然科学奖	三等奖	国务院	1982-11-12





2.B: 2.N

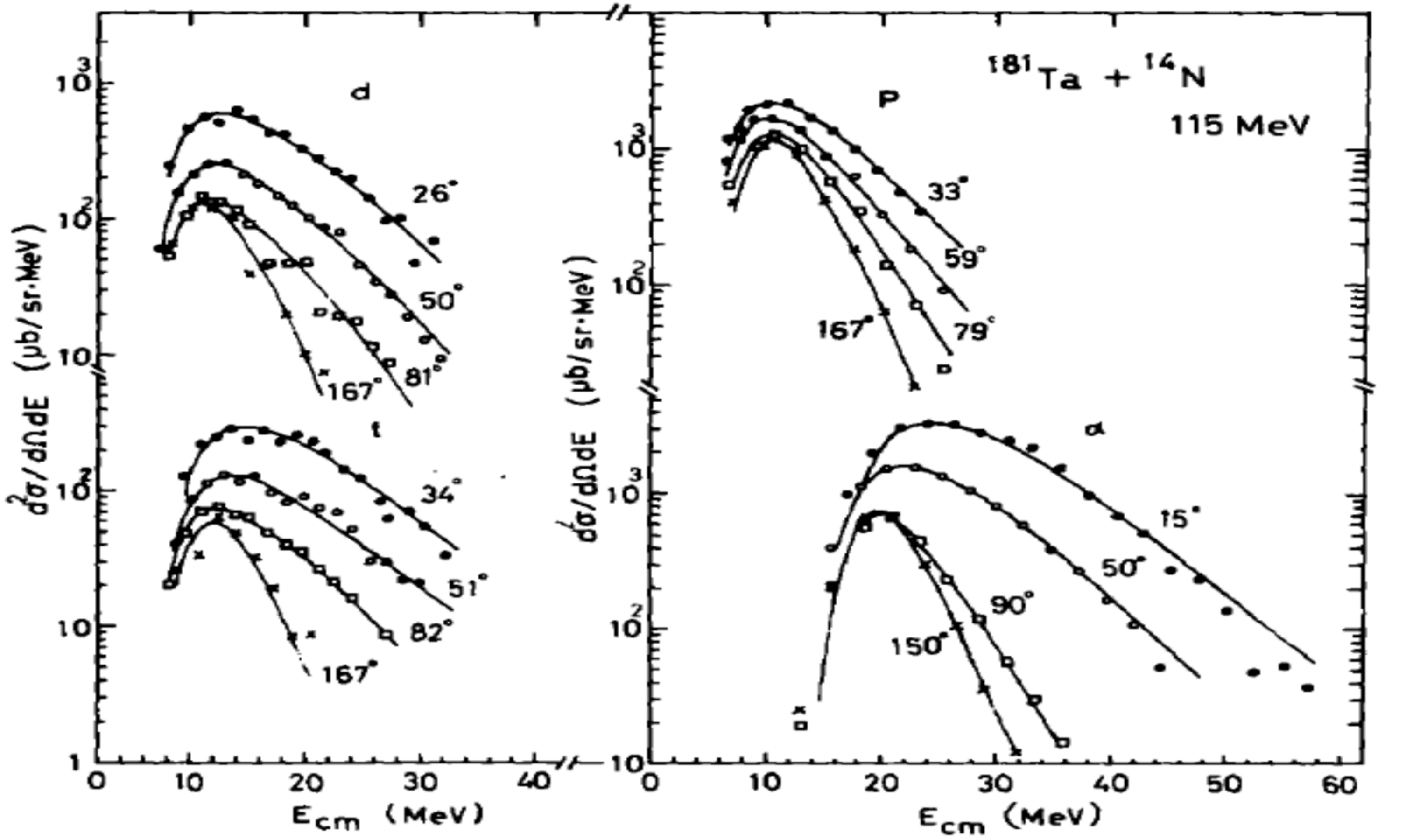
Nuclear Physics **A334** (1980) 127 – 143; © *North-Holland Publishing Co., Amsterdam*

PREEQUILIBRIUM α-PARTICLE EMISSION IN HEAVY-ION REACTIONS

H. UTSUNOMIYA †, T. NOMURA, T. INAMURA, T. SUGITATE †† and T. MOTOBAYASHI ‡

Cyclotron Laboratory, The Institute of Physical and Chemical Research, Wako-shi, Saitama, 351, Japan

Received 19 September 1979



II. Dinuclear system model

Quasifission fragments:

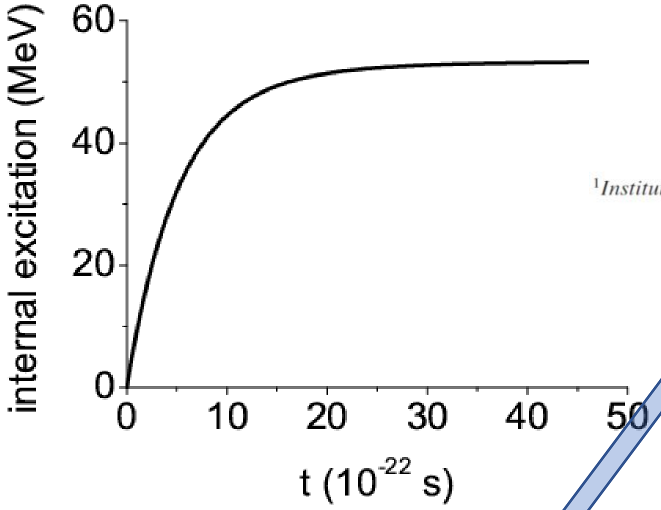
G. G. Adamian, N. V. Antonenko, and A. S. Zubov, Phys. Rev. C 71, 034603 (2005)

PHYSICS REPORTS (Review Section of Physics Letters) 44, No. 2 (1978) 93–157. North-Holland Publishing Company

DEEP INELASTIC TRANSFER REACTIONS – THE NEW TYPE OF REACTIONS BETWEEN COMPLEX NUCLEI

V.V. VOLKOV
Joint Institute for Nuclear Research, Dubna, USSR

Received October 1977



PHYSICAL REVIEW C **76**, 044606 (2007)

Formation of superheavy nuclei in cold fusion reactions

Zhao-Qing Feng,[1,2] Gen-Ming Jin,[1] Jun-Qing Li,[1] and Werner Scheid[3]
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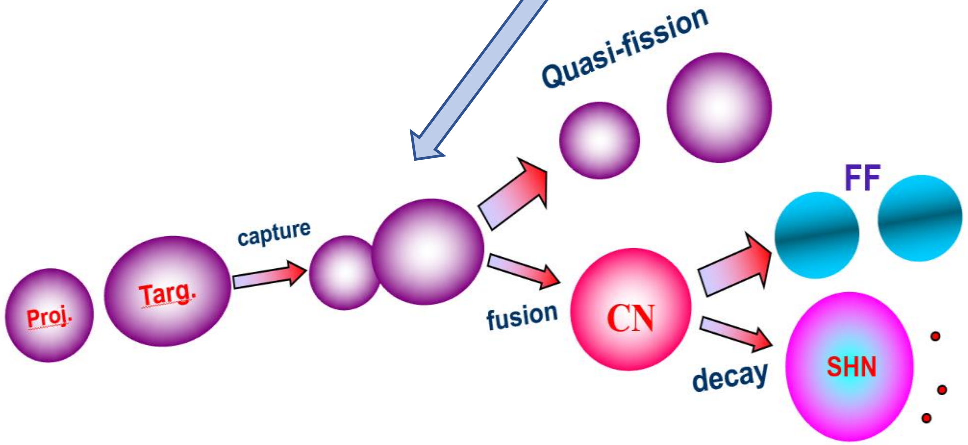
(Received 19 July 2007; published 16 October 2007)

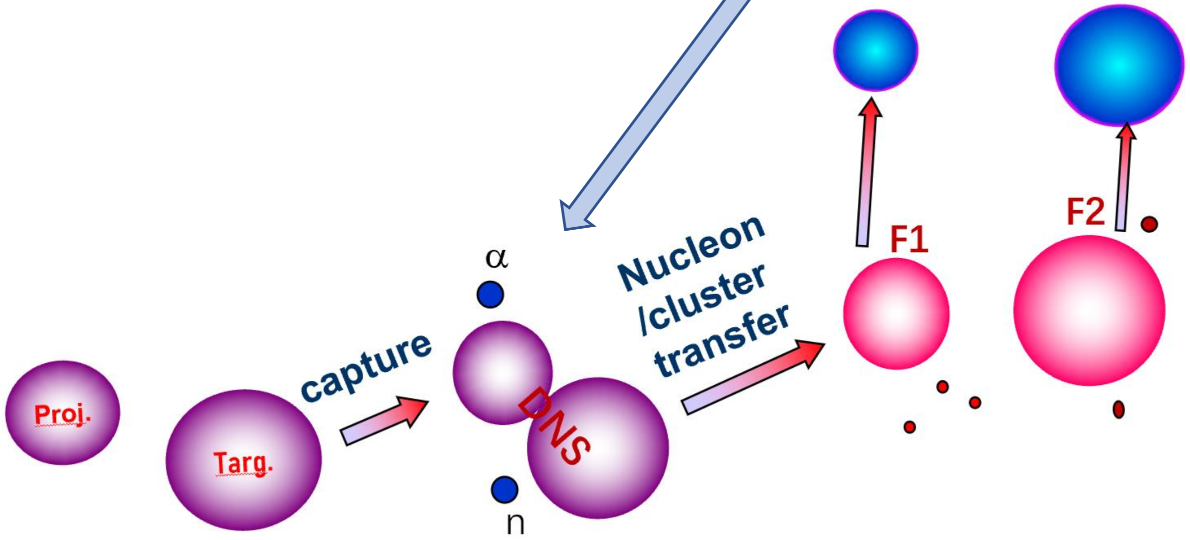
PHYSICAL REVIEW C **80**, 067601 (2009)

Production of heavy isotopes in transfer reactions by collisions of $^{238}U + ^{238}U$

Zhao-Qing Feng,* Gen-Ming Jin, and Jun-Qing Li
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China
(Received 3 November 2009; published 7 December 2009)

Diffusion dynamics within the concept of dinuclear system





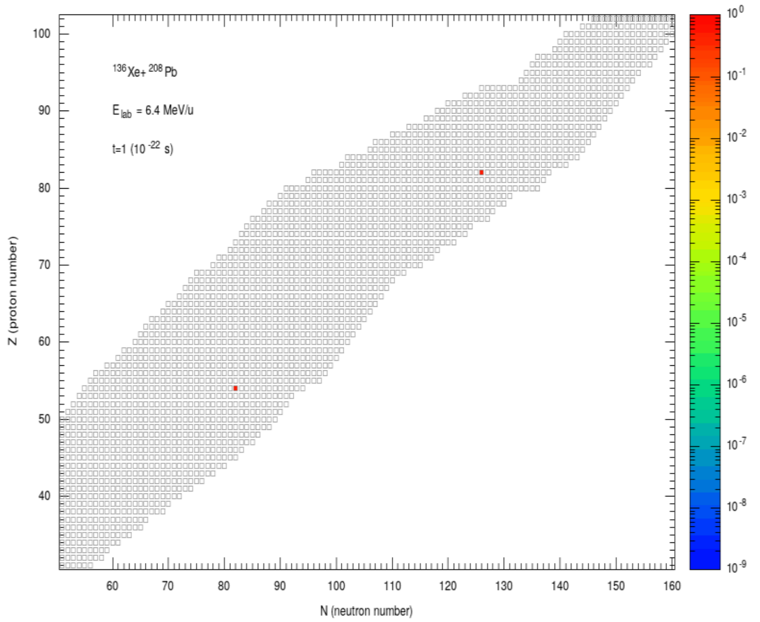
CSs in the fusion-evaporation and MNT reactions

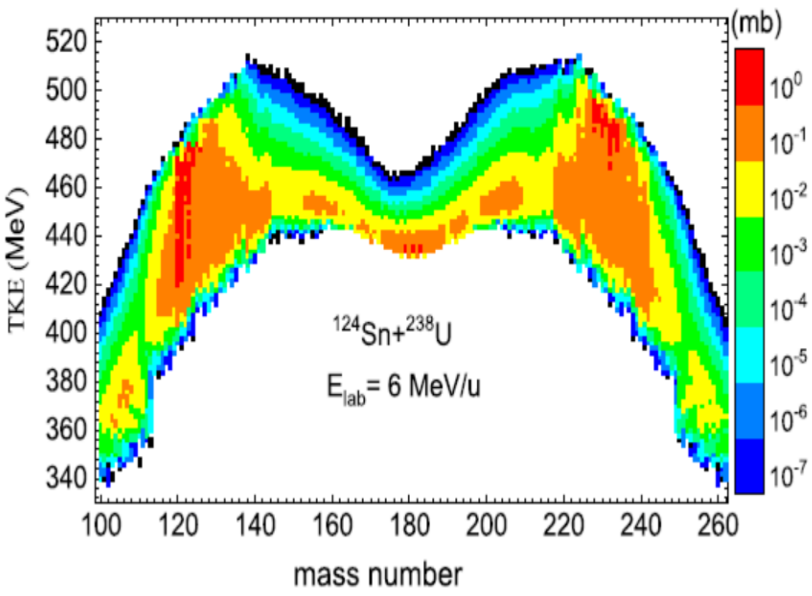
Peng-Hui Chen et al., Physical Review C 101, 024610 (2020); 102, 014621 (2020)

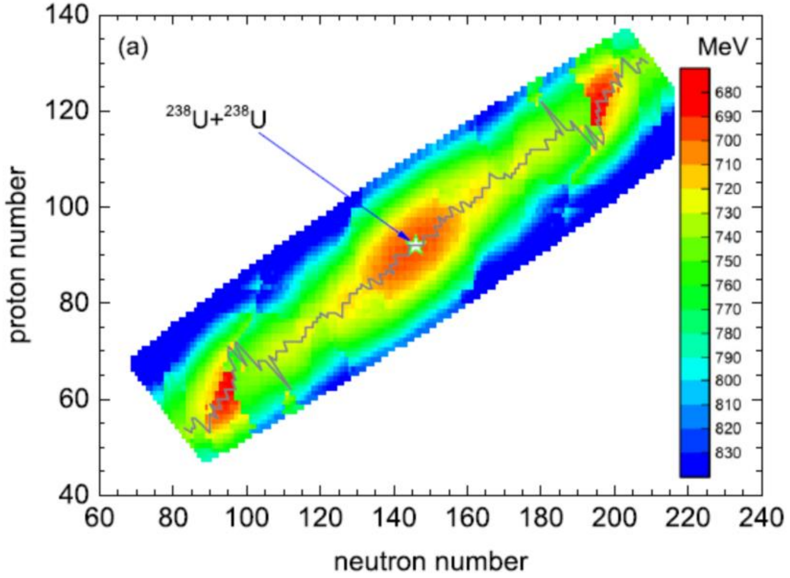
$$\sigma_{ER}(E_{c.m.}) = \frac{\pi\hbar^2}{2\mu E_{c.m.}} \sum_J (2J+1) T(E_{c.m.}, J) P_{CN}(E_{c.m.}, J) W_{sur}(E_{c.m.}, J)$$

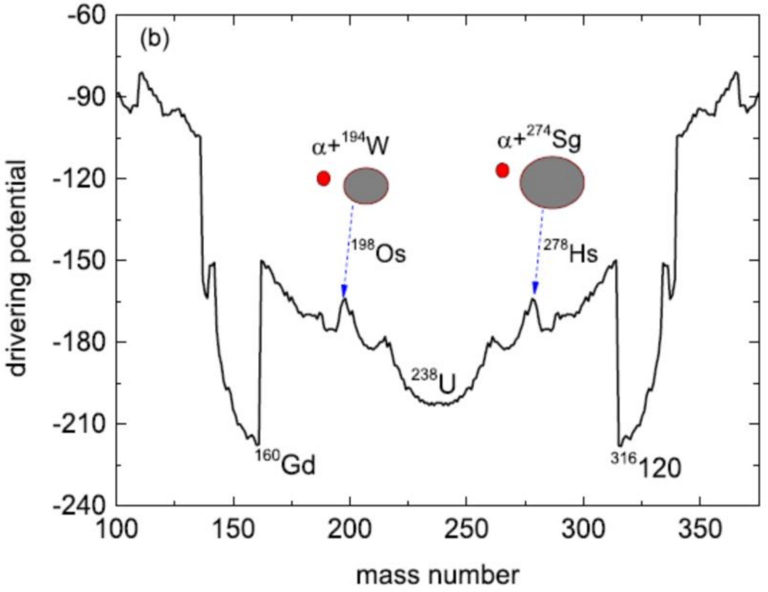
$$\sigma_{\rm pr}(Z_1, N_1, E_{\rm c.m.}) = \sum_{J=0}^{J_{\rm max}} \sigma_{\rm cap}(E_{\rm c.m.}, J) \int f(B) \times P(Z_1, N_1, E_1, J_1, B) dB.$$

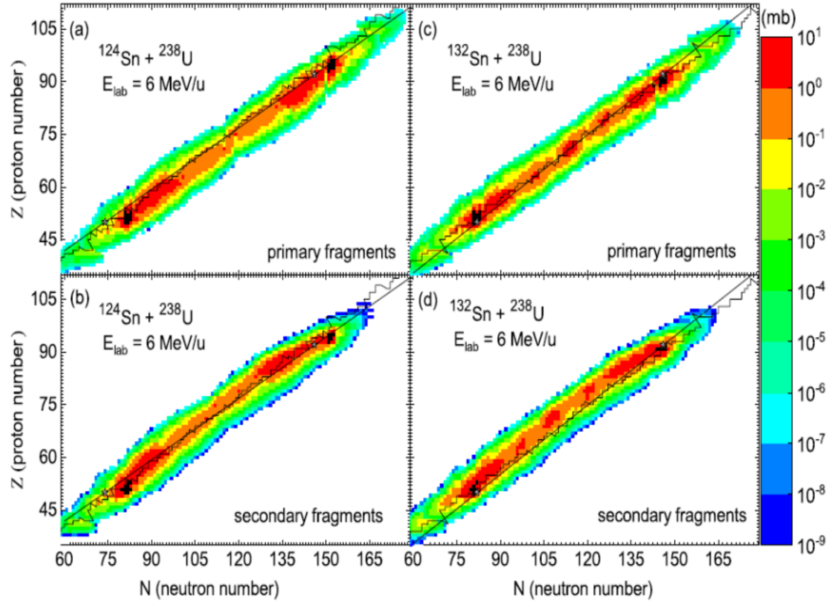
$$\sigma_{\rm sur}(Z_1, N_1, E_{\rm c.m.}) = \sum_{J=0}^{J_{\rm max}} \sigma_{\rm cap}(E_{\rm c.m.}, J) \int f(B) \times P(Z_1, N_1, E_1, J_1, B) W_{\rm sur}(E_1, J_1, s) dB,$$











The distribution probability with pure nucleon transfer

W. Li et al., Europhys. Lett. 64 (2003) 750; Z.-Q. Feng et al., NPA 771 (2006) 50, PRC 76 (2007) 044606, NPA 816 (2009) 33

$$\frac{dP(Z_1,N_1,E_1,t)}{dt} = \sum_{Z_1'} W_{Z_1,N_1;Z_1',N_1}(t)[d_{Z_1,N_1}P(Z_1',N_1,E_1',t) - d_{Z_1',N_1}P(Z_1,N_1,E_1,t)] + \sum_{N_1'} W_{Z_1,N_1;Z_1,N_1'}(t) \times [d_{Z_1,N_1}P(Z_1,N_1',E_1',t) - d_{Z_1,N_1'}P(Z_1,N_1,E_1,t)]$$

Transition probability

$$W_{Z_1,N_1;Z_1',N_1} = \frac{\tau_{mem}(Z_1,N_1,E_1;Z_1',N_1,E_1')}{d_{Z_1,N_1}d_{Z_1',N_1}\hbar^2} \times \sum_{ii'} |\langle Z_1',N_1,E_1',i'|V|Z_1,N_1,E_1,i\rangle|^2$$

The distribution probability with cluster transfer (neutron, proton, deuteron, triton, ^{3}He and α)

$$\begin{aligned}
\frac{dP(Z_1,N_1,E_1,\beta_1,B,t)}{dt} = & \sum_{Z_1'=Z_1\pm1} W_{Z_1,N_1,\beta_1;Z_1',N_1,\beta_1'}(t)[d_{Z_1,N_1}P(Z_1',N_1,E_1',\beta_1',B,t) - d_{Z_1',N_1}P(Z_1,N_1,E_1,\beta_1,B,t)] \\
& + \sum_{N_1'=N_1\pm1} W_{Z_1,N_1,\beta_1;Z_1,N_1',\beta_1'}(t)[d_{Z_1,N_1}P(Z_1,N_1',E_1',\beta_1',B,t) - d_{Z_1,N_1'}P(Z_1,N_1,E_1,\beta_1,B,t)] \\
& + \sum_{Z_1'=\pm1,N_1'=N_1\pm1} W^d_{Z_1,N_1,\beta_1;Z_1',N_1',\beta_1'}(t)[d_{Z_1,N_1}P(Z_1',N_1',E_1',\beta_1',B,t) - d_{Z_1',N_1'}P(Z_1,N_1,E_1,\beta_1,B,t)] \\
& + \sum_{Z_1'=\pm1,N_1'=N_1\pm2} W^t_{Z_1,N_1,\beta_1;Z_1',N_1',\beta_1'}(t)[d_{Z_1,N_1}P(Z_1',N_1',E_1',\beta_1',B,t) - d_{Z_1',N_1'}P(Z_1,N_1,E_1,\beta_1,B,t)] \\
& + \sum_{Z_1'=\pm2,N_1'=N_1\pm1} W^{^3He}_{Z_1,N_1,\beta_1;Z_1',N_1',\beta_1'}(t)[d_{Z_1,N_1}P(Z_1',N_1',E_1',\beta_1',B,t) - d_{Z_1',N_1'}P(Z_1,N_1,E_1,\beta_1,B,t)] \\
& + \sum_{Z_1'=\pm2,N_1'=N_1\pm2} W^\alpha_{Z_1,N_1,\beta_1;Z_1',N_1',\beta_1'}(t)[d_{Z_1,N_1}P(Z_1',N_1',E_1',\beta_1',B,t) - d_{Z_1',N_1'}P(Z_1,N_1,E_1,\beta_1,B,t)].
\end{aligned}$$

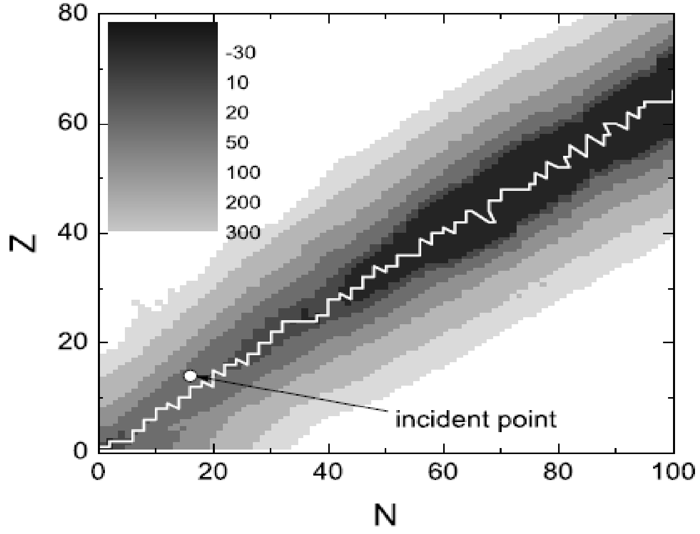
$$W^\nu_{Z_1,N_1;Z_1',N_1'} = G_\nu \frac{\tau_{mem}(Z_1,N_1,E_1;Z_1',N_1',E_1')}{d_{Z_1,N_1}d_{Z_1',N_1'}\hbar^2} \sum_{ii'} |\langle i'|V|i\rangle|^2$$

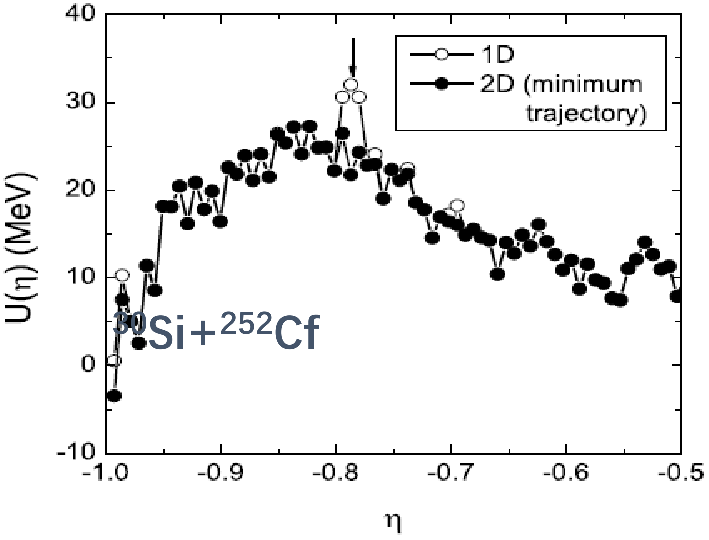
$$\sum_{Z_1=0,N_1=0}^{Z_1=Z_p+Z_t,\ N_1=N_p+N_t} P(Z_1,N_1,E_1,t) = 1$$

Potential energy surface

$$U(\{\alpha\}) = B(Z_1,N_1) + B(Z_2,N_2) - [B(Z,N) + V_{rot}^{CN}(J)] + V(\{\alpha\})$$

With {α} being $Z_1, N_1, Z_2, N_2;\ J, R;\ \beta_1, \beta_2, \theta_1, \theta_2$





$$V(A_1, A_2, J, \mathbf{R}; \beta_1, \beta_2, \theta_1, \theta_2) = V_N(A_1, A_2, \mathbf{R}; \beta_1, \beta_2, \theta_1, \theta_2) + V_C(A_1, A_2, \mathbf{R}; \beta_1, \beta_2, \theta_1, \theta_2) + \frac{J(J+1)\hbar^2}{2\mu \mathbf{R}^2},$$

$$V_N = C_0 \left\{ \frac{F_{in} - F_{ex}}{\rho_0} \left[\int \rho_1^2(\mathbf{r}) \rho_2(\mathbf{r} - \mathbf{R}) d\mathbf{r} + \int \rho_1(\mathbf{r}) \rho_2^2(\mathbf{r} - \mathbf{R}) d\mathbf{r} \right] + F_{ex} \int \rho_1(\mathbf{r}) \rho_2(\mathbf{r} - \mathbf{R}) d\mathbf{r} \right\},$$

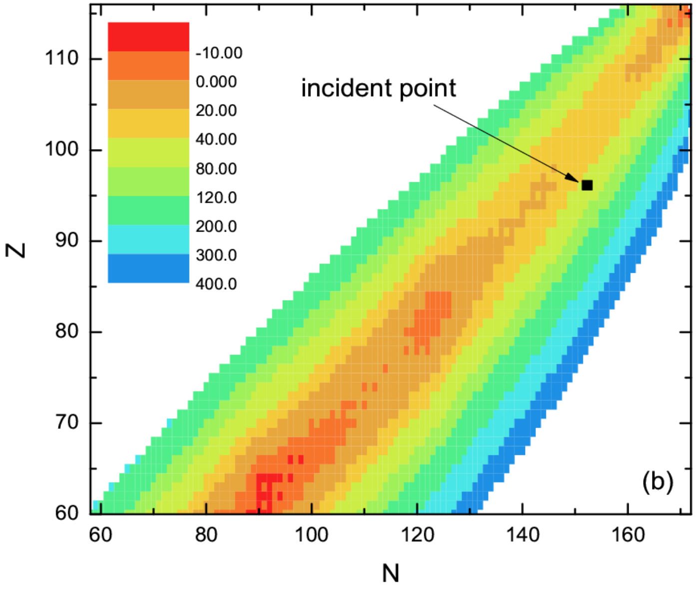
with

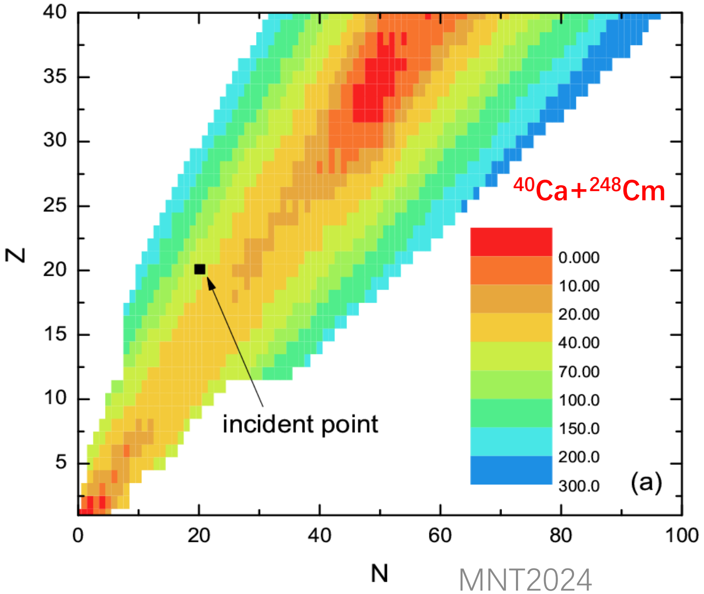
$$F_{in,ex} = f_{in,ex} + f'_{in,ex} \frac{N_1 - Z_1}{A_1} \frac{N_2 - Z_2}{A_2},$$

$$\rho_1(\mathbf{r}) = \frac{\rho_0}{1 + \exp[(\mathbf{r} - \Re_1(\theta_1))/a_1]}$$

and

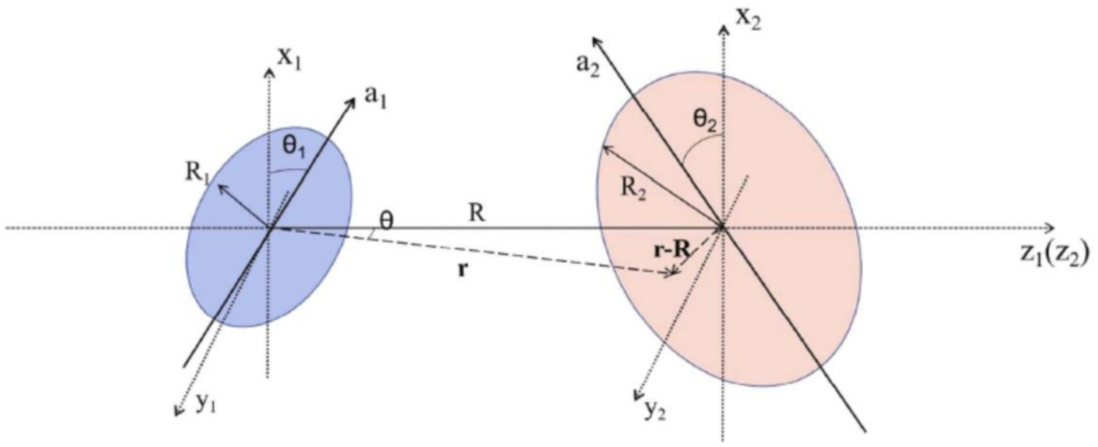
$$\rho_2(\mathbf{r} - \mathbf{R}) = \frac{\rho_0}{1 + \exp[(|\mathbf{r} - \mathbf{R}| - \Re_2(\theta_2))/a_2]}.$$





Nucleus-nucleus potential from the Skyrme energy-density functional

Commun. Theor. Phys. 74 (2022) 055302 C Peng and Z-Q Feng



Bartel J and Bencheikh K 2002 Eur. Phys. J. A 14 179
Denisov V Y and Nörenberg W 2002 Eur. Phys. J. A 15 375

$$V_{\mathrm{nucl}}(R, \{\alpha\}_{\mathrm{P}}, \{\alpha\}_{\mathrm{T}}) = E_{\mathrm{sys}}(R, \{\alpha\}_{\mathrm{P}}, \{\alpha\}_{\mathrm{T}}) - E_{\mathrm{P}}(\{\alpha\}_{\mathrm{P}}) - E_{\mathrm{T}}(\{\alpha\}_{\mathrm{T}}).$$

$$E_{\mathrm{sys}}(R, \{\alpha\}_{\mathrm{P}}, \{\alpha\}_{\mathrm{T}}) = \int \varepsilon[\rho_{1p}(\boldsymbol{r}) + \rho_{2p}(\boldsymbol{R}-\boldsymbol{r}), \rho_{1n}(\boldsymbol{r}) + \rho_{2n}(\boldsymbol{R}-\boldsymbol{r})]\mathrm{d}\boldsymbol{r},$$

$$E_{\mathrm{P}}(\{\alpha\}_{\mathrm{P}}) = \int \varepsilon[\rho_{1p}(\boldsymbol{r}), \rho_{1n}(\boldsymbol{r})]\mathrm{d}\boldsymbol{r}$$

and

$$E_{\mathrm{T}}(\{\alpha\}_{\mathrm{T}}) = \int \varepsilon[\rho_{2p}(\boldsymbol{R}-\boldsymbol{r}), \rho_{2n}(\boldsymbol{R}-\boldsymbol{r})]\mathrm{d}\boldsymbol{r},$$

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Potential energy surface and formation of superheavy nuclei with the Skyrme energy-density functional

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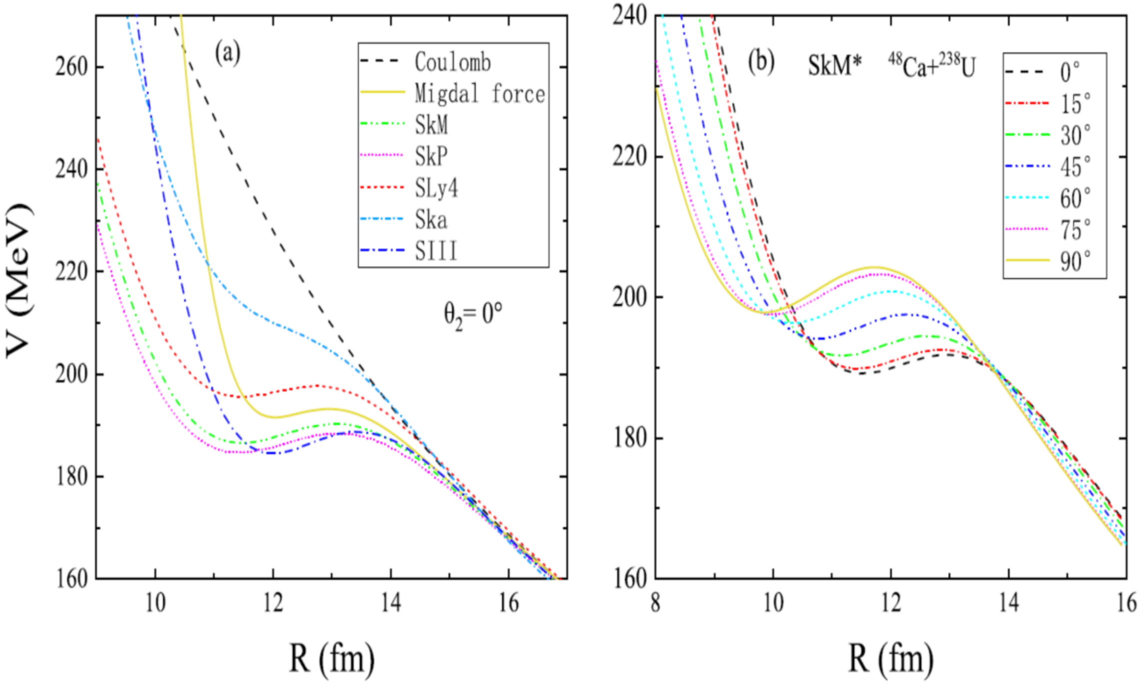
$$\begin{aligned}\hat{V}_{\mathrm{eff}}(\boldsymbol{r}_1, \boldsymbol{r}_2) &= t_0(1 + x_0\hat{P}_\sigma)\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)\\ &+ \frac{t_3}{6}(1 + x_3\hat{P}_\sigma)\delta\left(\frac{1}{2}(\boldsymbol{r}_1 + \boldsymbol{r}_2)\right)\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)\\ &- \frac{t_1}{2}(1 + x_1\hat{P}_\sigma)((\nabla_1 - \nabla_2)^2\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2) + h.c.)\\ &- t_2(1 + x_2\hat{P}_\sigma)((\nabla_1 - \nabla_2)\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)(\nabla_1 - \nabla_2))\\ &+ \mathrm{i}W_0(\hat{\sigma}_1 + \hat{\sigma}_2)\cdot\hat{\boldsymbol{k}}' \times \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)\hat{\boldsymbol{k}}\end{aligned}$$

$$\begin{aligned}\nu_{sk}(\boldsymbol{r}) &= \frac{t_0}{2}\left[\left(1 + \frac{1}{2}x_0\right)\rho^2 - \left(x_0 + \frac{1}{2}\right)(\rho_p^2 + \rho_n^2)\right]\\ &+ \frac{1}{12}t_3\rho^\alpha\left[\left(1 + \frac{1}{2}x_3\right)\rho^2 - \left(x_3 + \frac{1}{2}\right)(\rho_p^2 + \rho_n^2)\right]\\ &+ \frac{1}{4}\left[t_1\left(1 + \frac{1}{2}x_1\right) + t_2\left(1 + \frac{1}{2}x_2\right)\right]\tau\rho\\ &+ \frac{1}{4}\left[t_2\left(x_2 + \frac{1}{2}\right) - t_1\left(x_1 + \frac{1}{2}\right)\right](\tau_p\rho_p + \tau_n\rho_n)\\ &+ \frac{1}{16}\left[3t_1\left(1 + \frac{1}{2}x_1\right) - t_2\left(1 + \frac{1}{2}x_2\right)\right](\nabla\rho)^2\\ &- \frac{1}{16}\left[3t_1\left(x_1 + \frac{1}{2}\right) + t_2\left(x_2 + \frac{1}{2}\right)\right]((\nabla\rho_n)^2 + (\nabla\rho_p)^2)\end{aligned}$$

$$-\frac{mW_0^2}{2\hbar^2}\left[\frac{\rho_p}{f_p}(2\nabla\rho_p + \nabla\rho_n)^2 + \frac{\rho_n}{f_n}(2\nabla\rho_n + \nabla\rho_p)^2\right]$$

Table 1. Parameters of the Skyrme forces used in the calculation.

Parameter	SkP	SkM	SkM*	SLy4	Ska	SIII
t_0 (MeV fm^3)	−2931.7	−2645	−2645	−2488.91	−1602.78	−1128.75
t_1 (MeV fm^5)	320.6	385	410	486.82	570.88	395.0
t_2 (MeV fm^5)	−337.4	−120	−135	−546.39	−67.70	−95
t_3 (MeV fm$^{3+3\alpha}$)	18 709	15 595	15 595	13 777	8000	14 000
x_0	0.292	0.09	0.09	0.834	−0.02	0.45
x_1	0.653	0	0	−0.344	0	0
x_2	−0.537	0	0	−1.0	0	0
x_3	0.181	0	0	1.354	−0.286	1
W_0 (MeV fm^5)	100	130	130	123	125	120
α	1/6	1/6	1/6	1/6	1/3	1
K_∞ (MeV)	199	217	217	230	261	352



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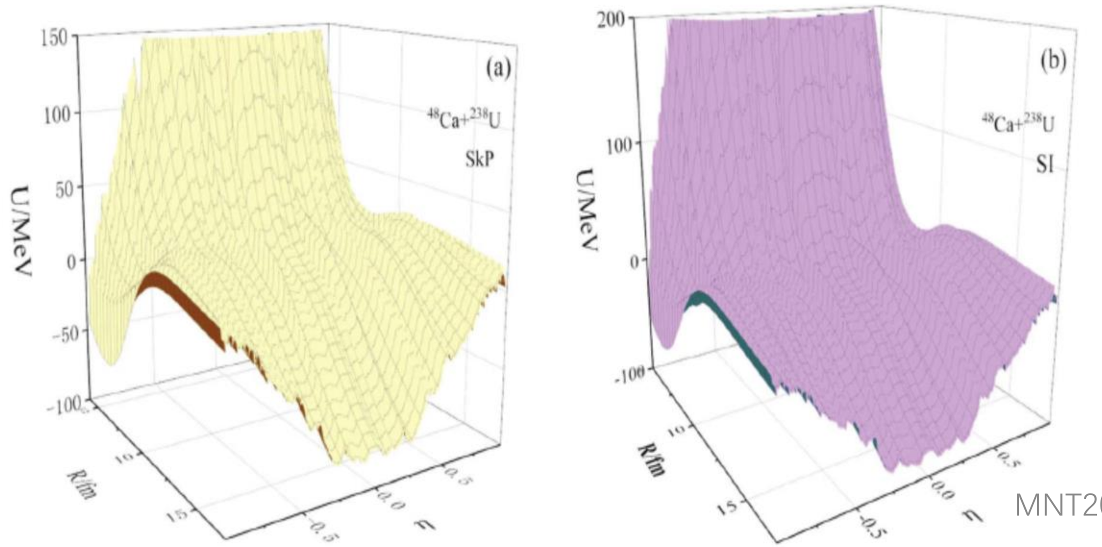
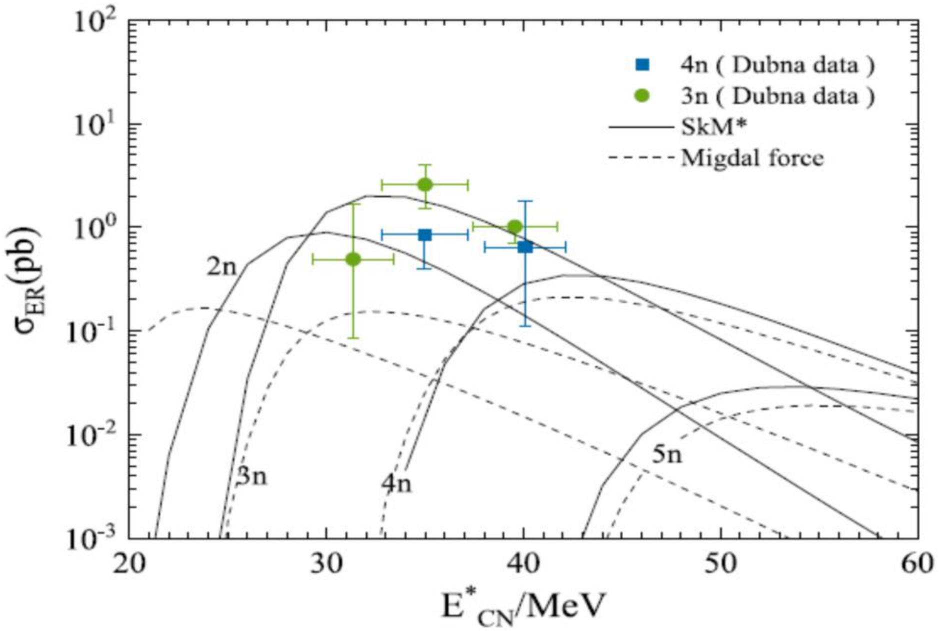
C Peng and Z-Q Feng



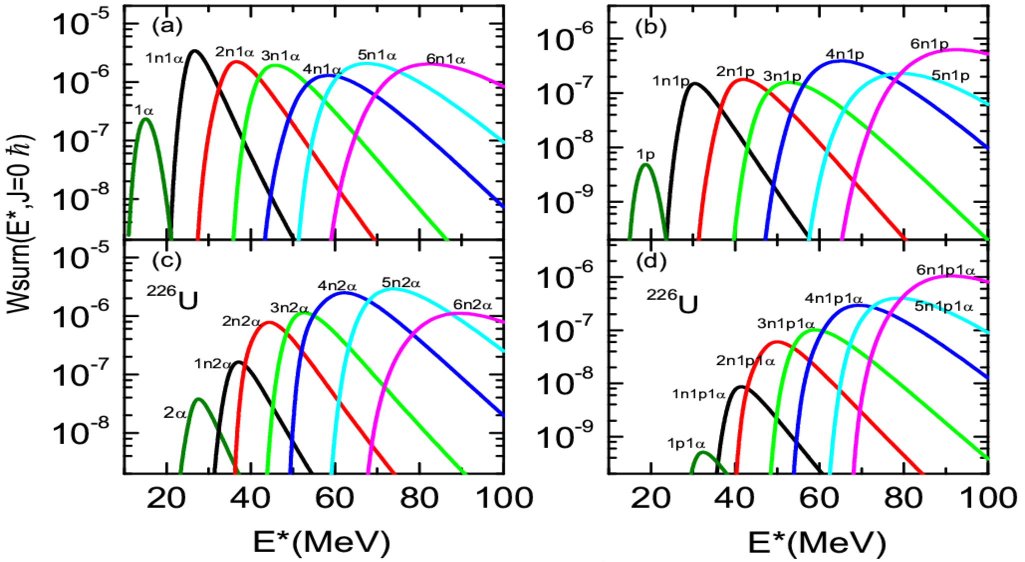


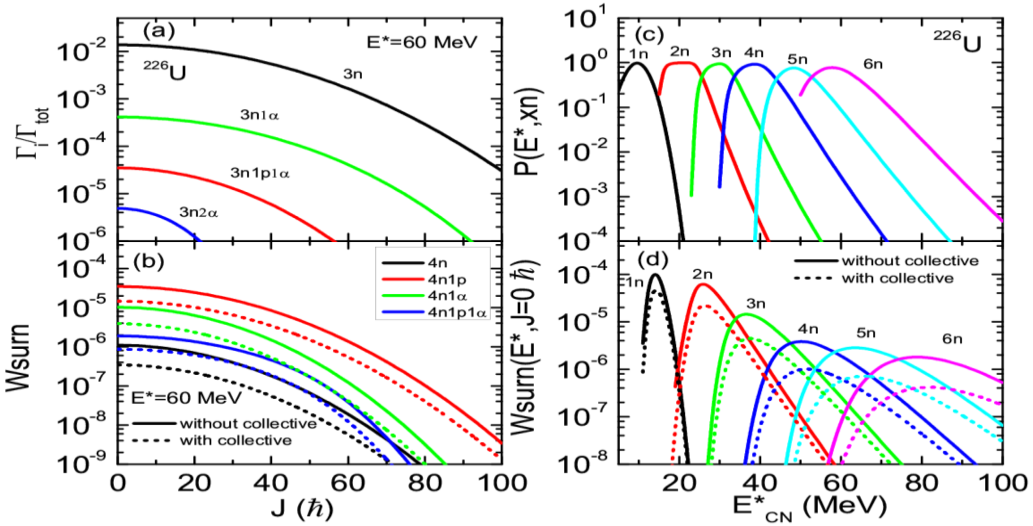
MNT2024

Survival probability and fusion-evaporation CSs

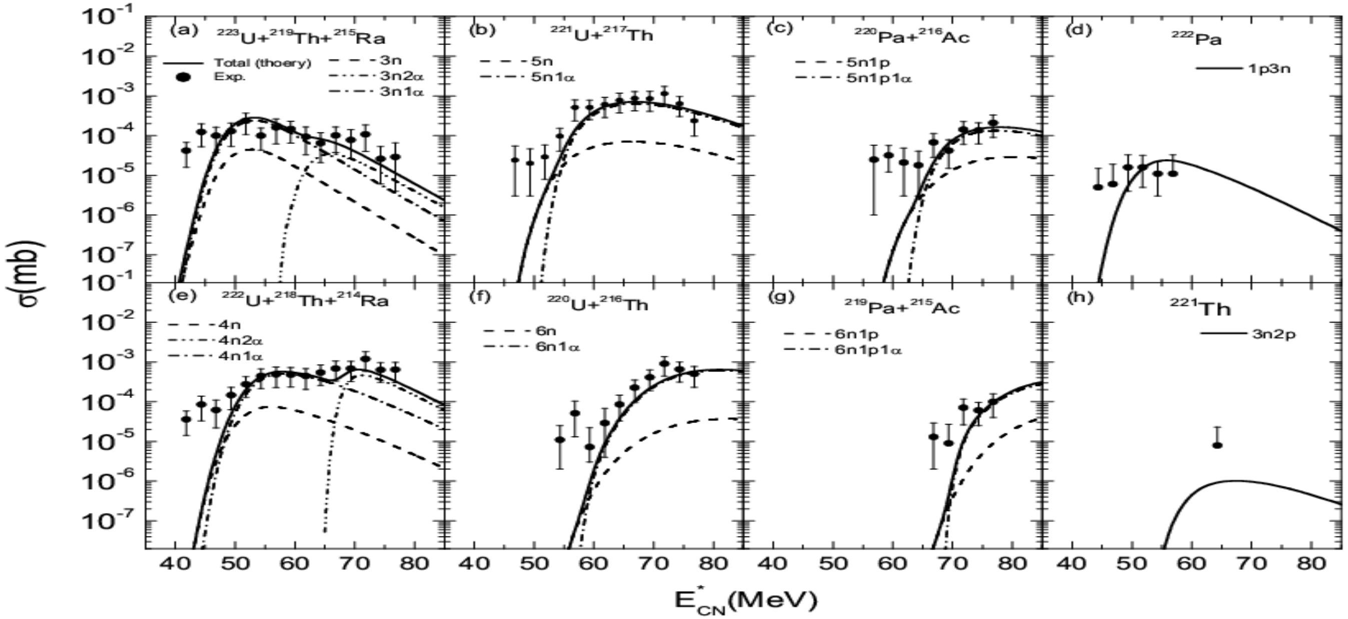
P. H. Chen, Z. Q. Feng* et al., Chinese Physics C 40, 091002 (2016) (highlight CPC in 2016)

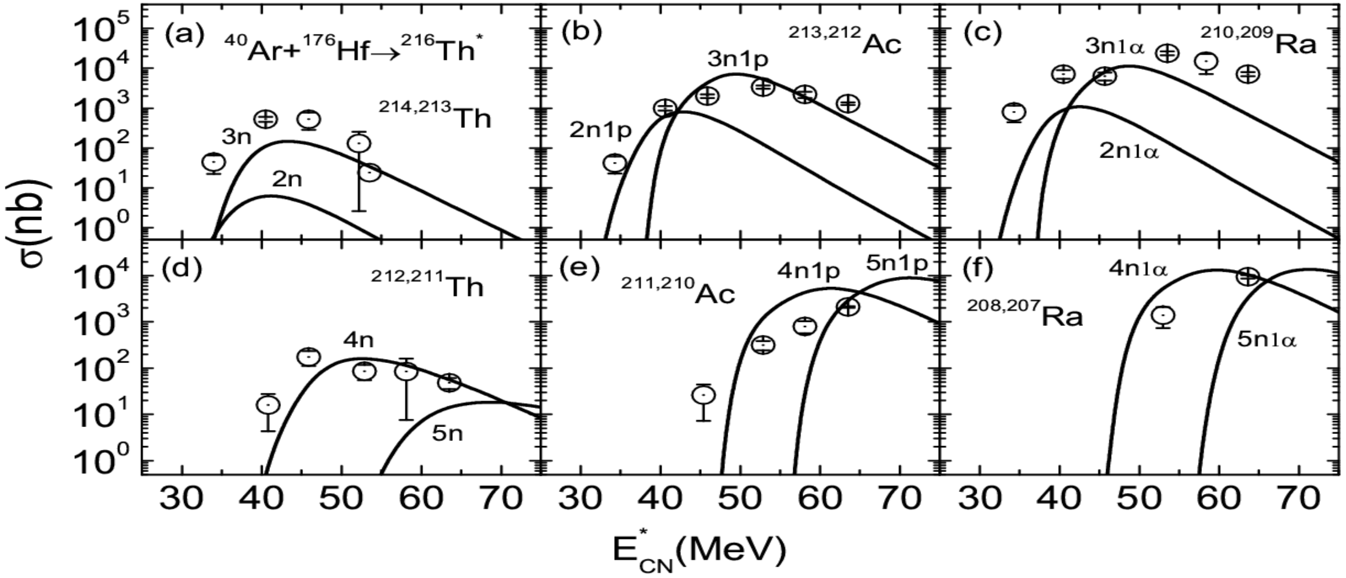
Peng-Hui Chen, Zhao-Qing Feng*, et al., Eur. Phys. J. A 53, 95 (2017)





Data from RIKEN (K. Nishio, H. Ikezoe, S. Mitsuoka et al, Phys. Rev. C 62, 014602 (2000))

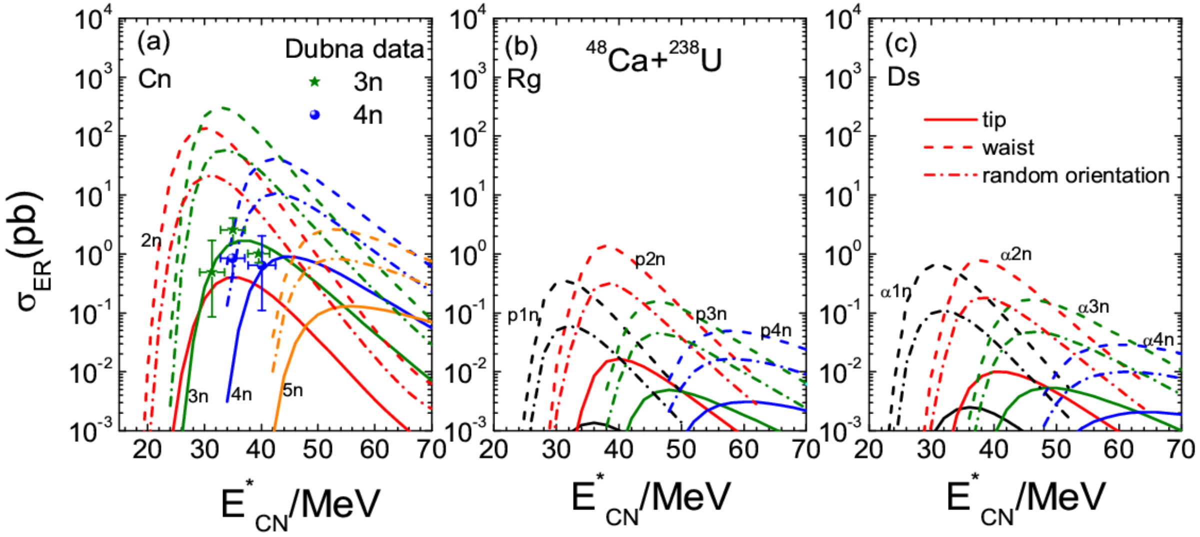


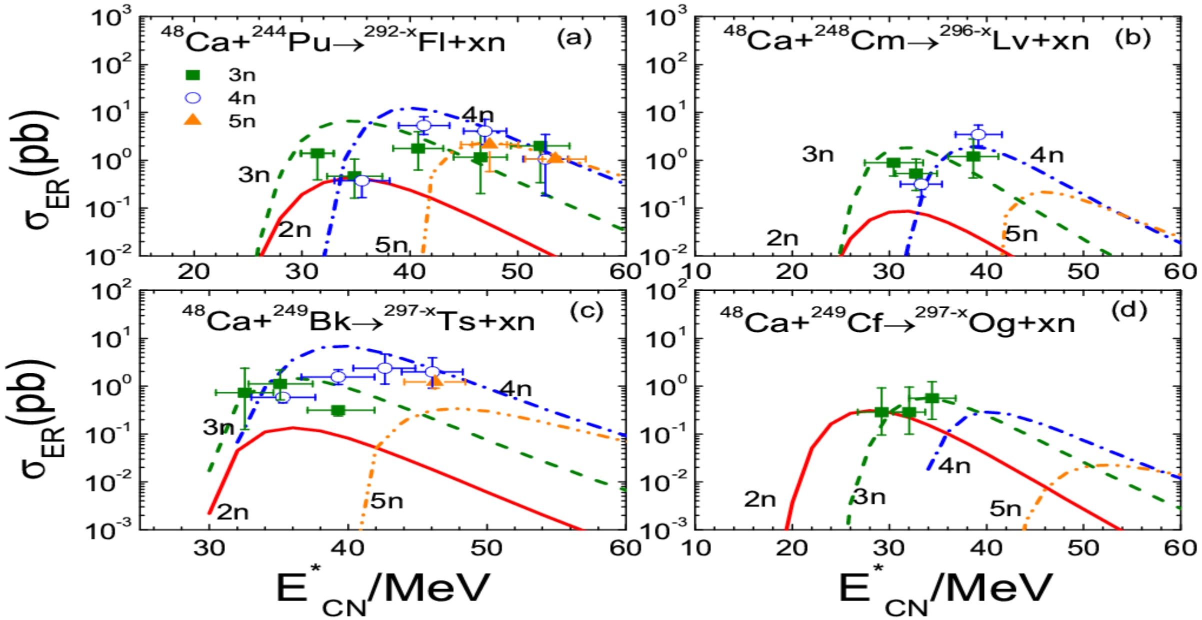


III. Results and discussion

1. Fusion-evaporation reactions for synthesizing 119 and 120

Fei Niu, Peng-Hui Chen, Zhao-Qing Feng, Nuclear Science and Techniques 32 (2021) 103





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2022 年 10 月 Nuclear Physics Review Oct., 2022
Article ID: 1007-4627(2022)03-0001-15

Production cross-sections of new superheavy elements with Z = 119-120 in fusion-evaporation reactions

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4. School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510641, China)

Table 2 The same as in Table 1; for the production of SHE $Z = 120$

Reaction systems	σ_{ER} (pb)	E^*_{CN} (MeV)	References
^{249}Cf(^{50}Ti,4n)^{295}120	0.006	43	[61]
^{251}Cf(^{50}Ti,4n)^{297}120	0.003	42	
^{248}Cm(^{54}Cr,4n)^{298}120	0.001	35	
^{244}Pu(^{58}Fe,3n)^{299}120	0.01	36	[63]
^{238}U(^{64}Ni,3n)^{299}120	0.007	36	
^{248}Cm(^{54}Cr,3n)^{299}120	0.076	36	
^{249}Cf(^{50}Ti,3n)^{296}120	0.76	33	
^{249}Cf(^{50}Ti,3n)^{296}120	0.1	29	[64]
^{248}Cm(^{54}Cr,3n)^{299}120	0.055	30	
^{249}Cf(^{50}Ti,4n)^{295}120	0.046	43	[59]
^{248}Cm(^{54}Cr,4n)^{298}120	0.028	43	
^{249}Cf(^{50}Ti,3n)^{296}120	0.06	36	[29]
^{248}Cf(^{46}Ti,2n)^{292}120	0.17	34	
^{249}Cf(^{46}Ti,3n)^{292}120	0.24	39	
^{250}Cf(^{46}Ti,2n)^{294}120	0.13	36	
^{251}Cf(^{46}Ti,3n)^{294}120	0.37	39	
^{251}Cf(^{50}Ti,3n)^{298}120	0.11	33	This work
^{251}Cf(^{48}Ti,2n)^{297}120	0.25	25	
^{244}Pu(^{58}Fe,3n)^{299}120	0.004	33	
^{244}Pu(^{62}Fe,3n)^{303}120	0.0004	31	
^{248}Cm(^{54}Cr,3n)^{299}120	0.004	33	
^{248}Cm(^{52}Cr,2n)^{300}120	0.37	25	
^{238}U(^{64}Ni,3n)^{299}120	0.001	31	
^{238}U(^{62}Ni,2n)^{300}120	0.001	27	
^{252}Es(^{44}Sc,3n)^{293}120	3.18	35	
^{252}Es(^{45}Sc,3n)^{293}120	0.59	35	
^{249}Bk(^{49}V,2n)^{296}120	0.18	27	
^{249}Bk(^{51}V,2n)^{298}120	0.1	27	

Q(^{54}Cr+^{248}Cm) = –207.77 MeV

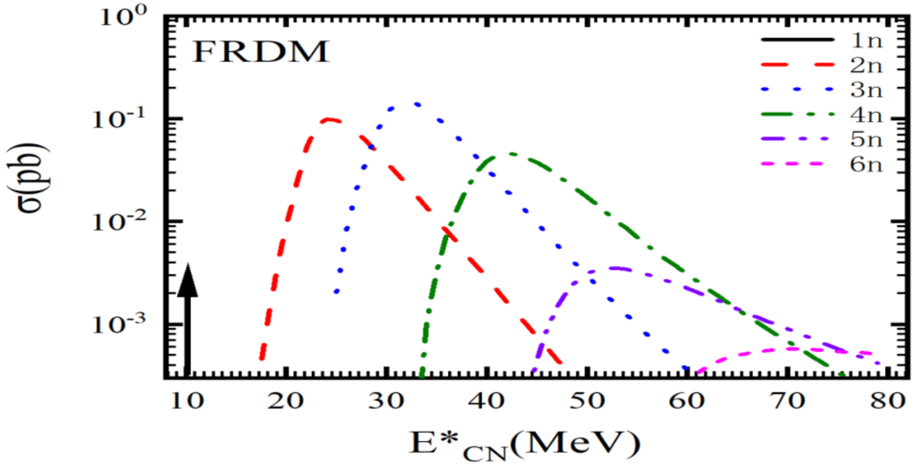
σ_{3n}=**4 fb**, E^*_{CN}=33 MeV,

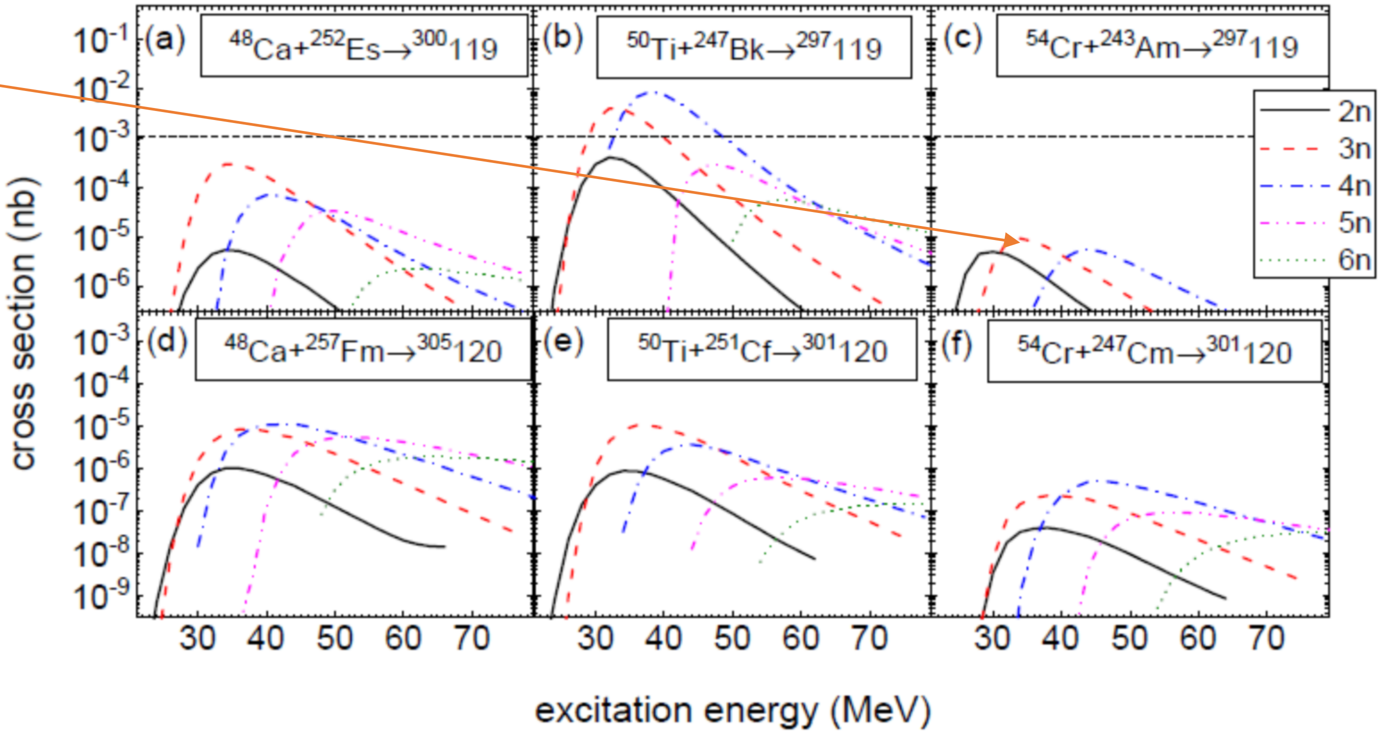
$E_{c.m.}$=240.77 MeV,

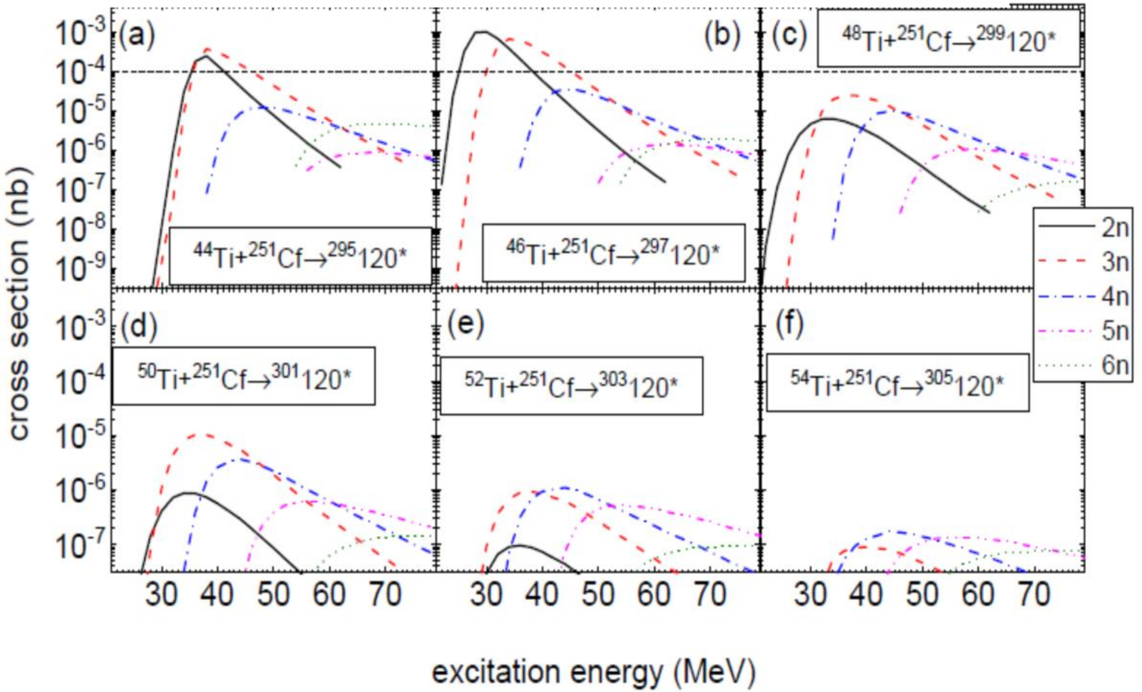
E_{lab}=5.43 MeV/nucleon

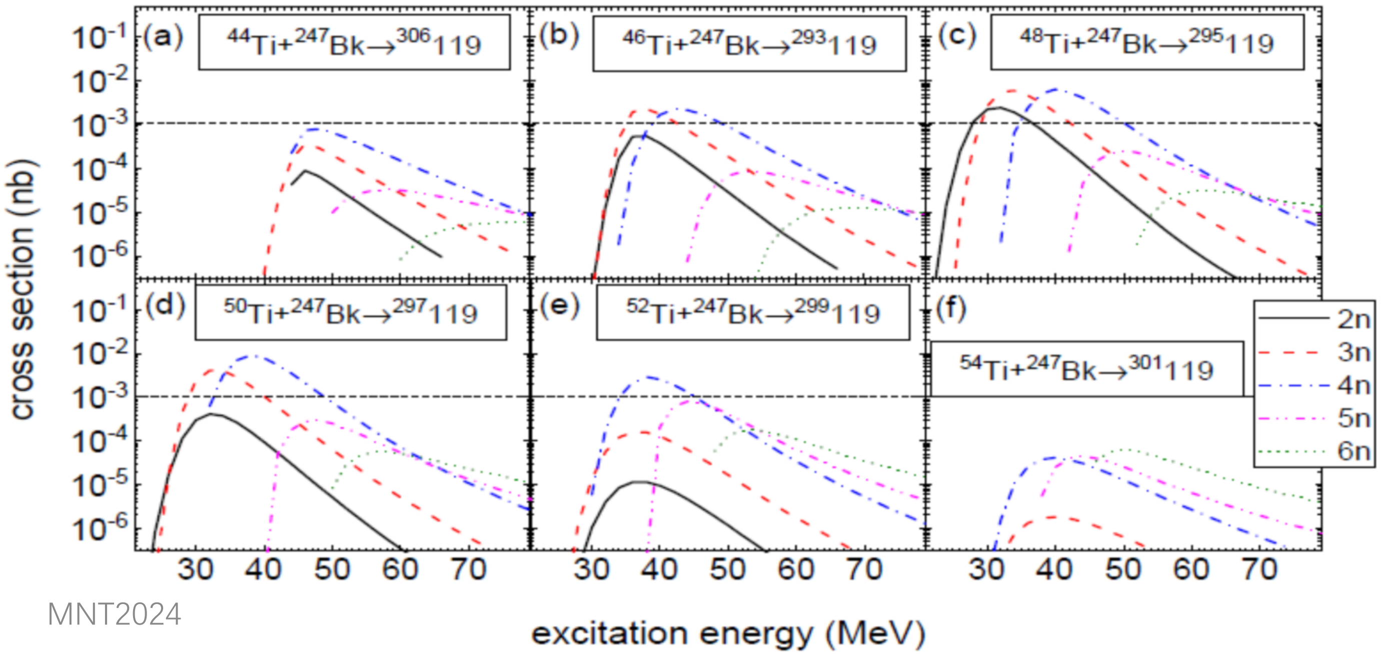
10 fb in the reactions ^{54}Cr(^{243}Am, 3n)^{294}119 at the excitation energy 34 MeV, Q=-205.43 MeV, $E_{c.m.}$=239.43 MeV, E_{lab}=5.42 MeV/nucleon

mass table: P. Möller et al., PRC 91, 024310 (2015)

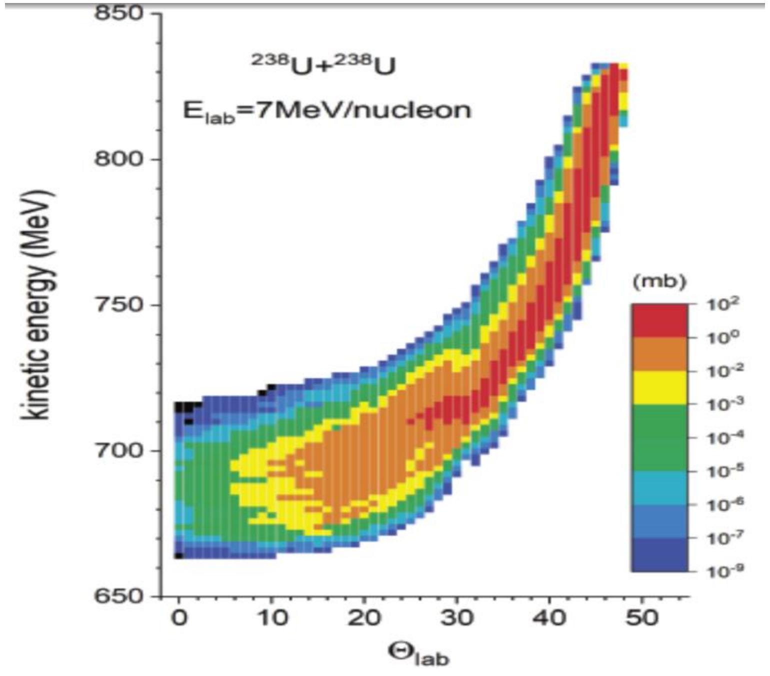


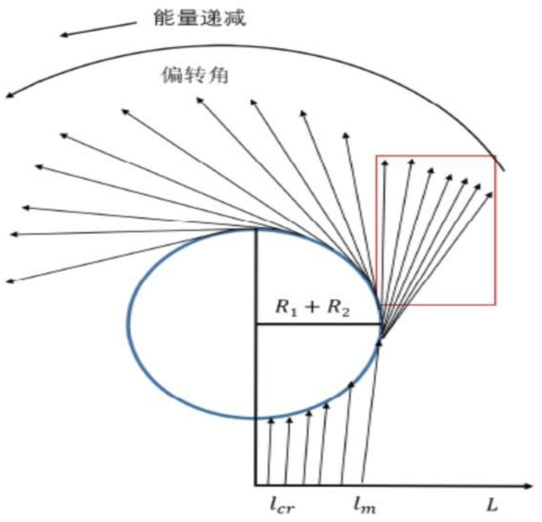






2. Yields, total kinetic energy spectra and angular distribution in MNT reactions





PHYSICAL REVIEW C 95, 024615 (2017)

Production of neutron-rich isotopes around $N = 126$ in multinucleon transfer reactions

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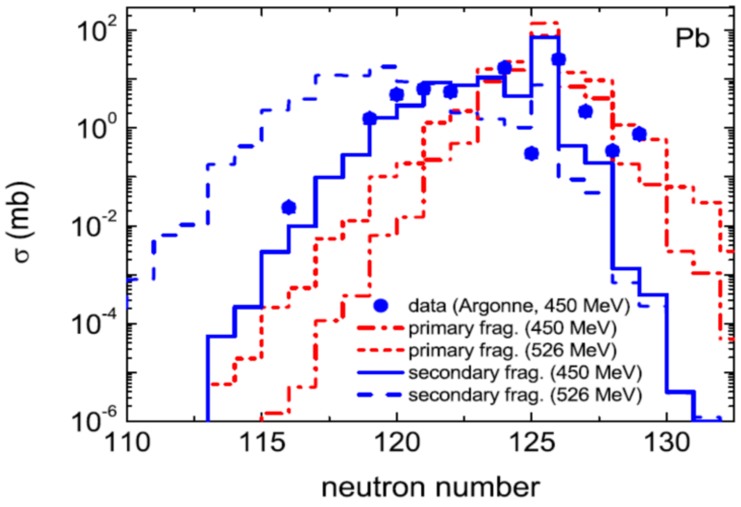
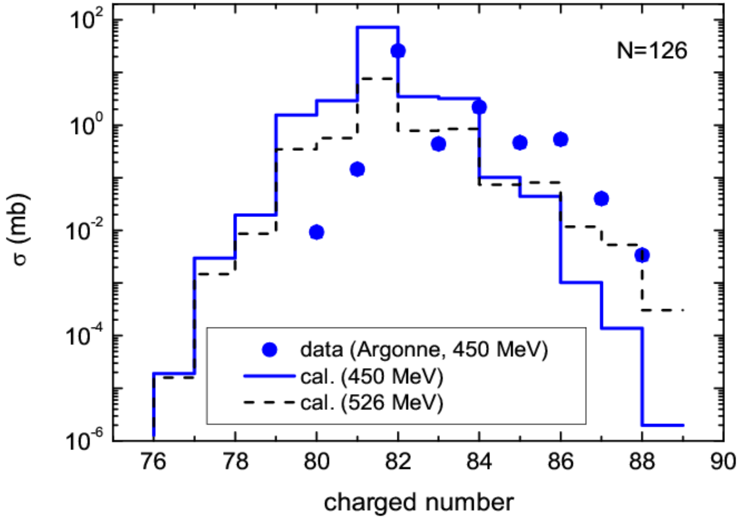
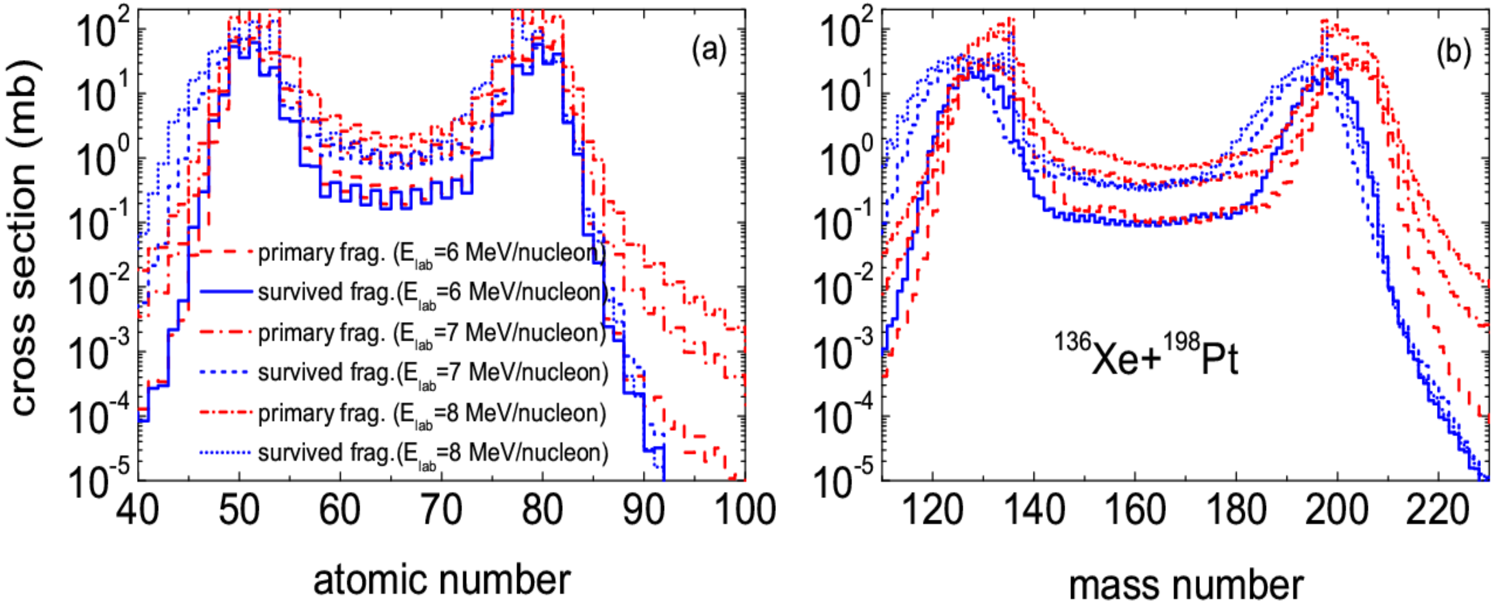
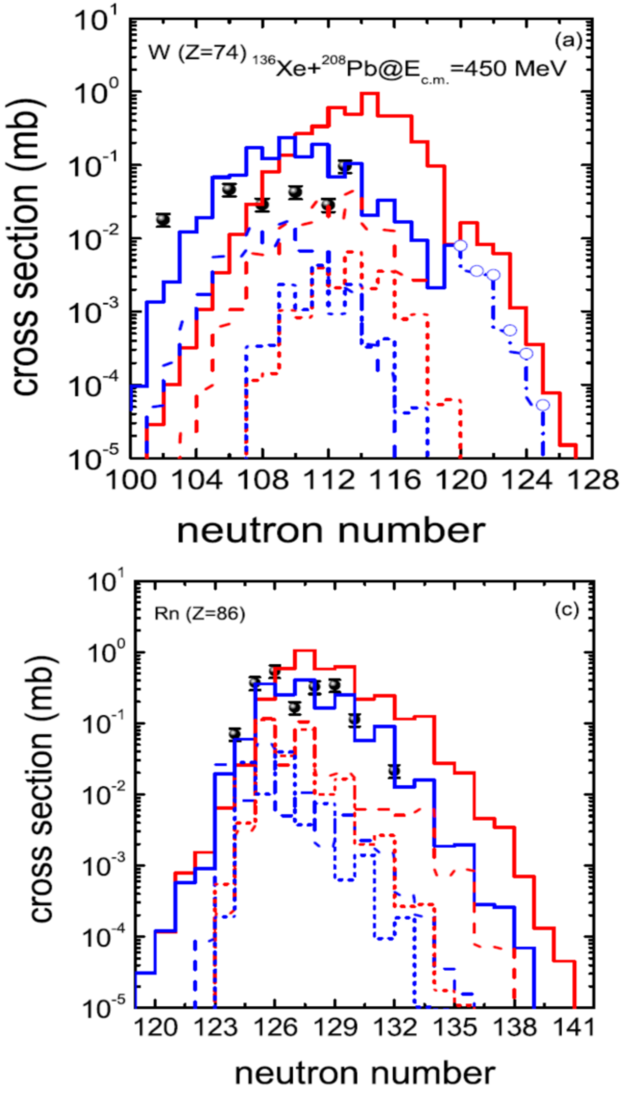






3. Cluster transfer and cluster emission in massive transfer reactions

Cluster transfer effect on the MNT fragment production



PHYSICAL REVIEW C **108**, L051601 (2023)

Letter

Effect of cluster transfer on the production of neutron-rich nuclides near $N = 126$ in multinucleon-transfer reactions

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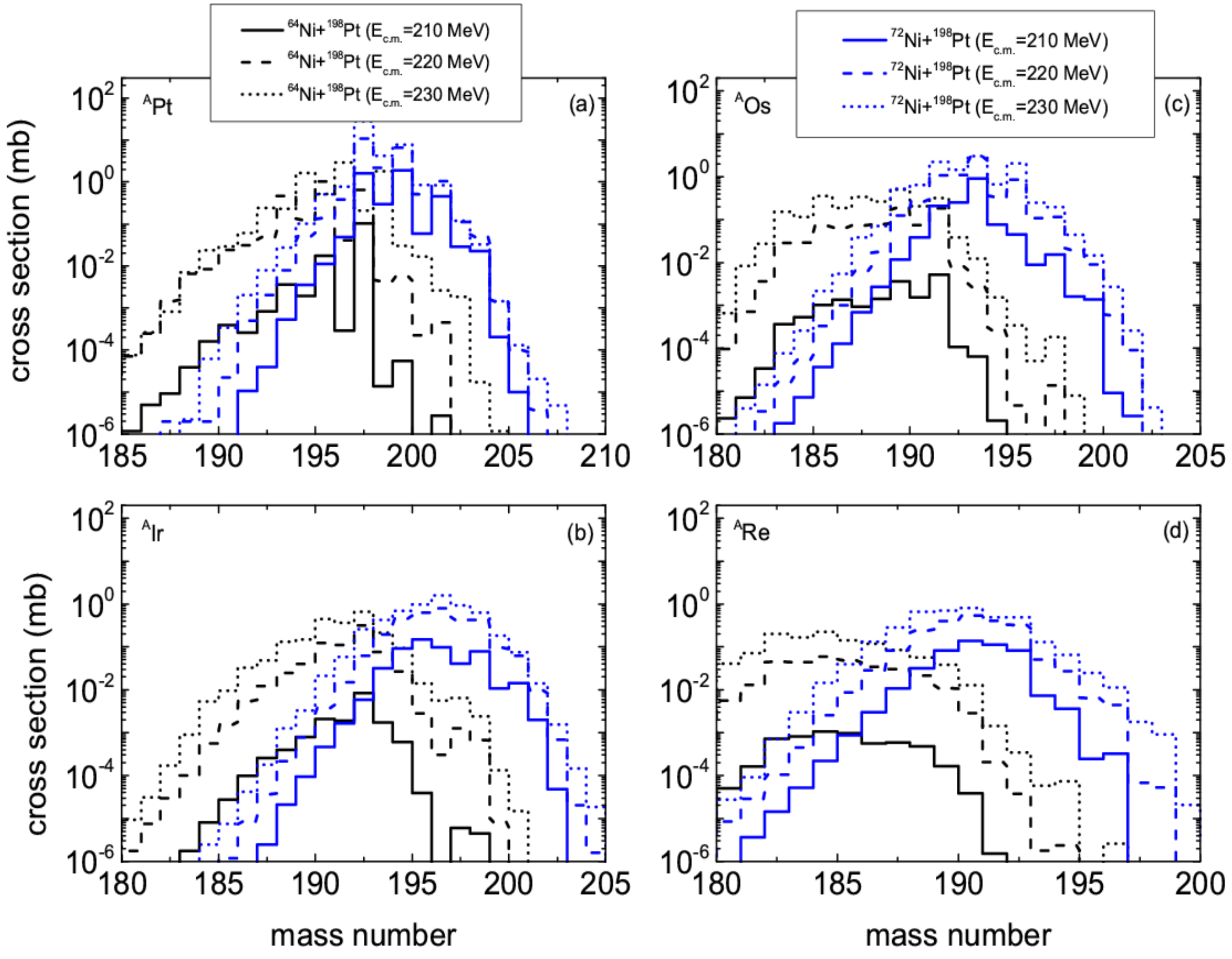
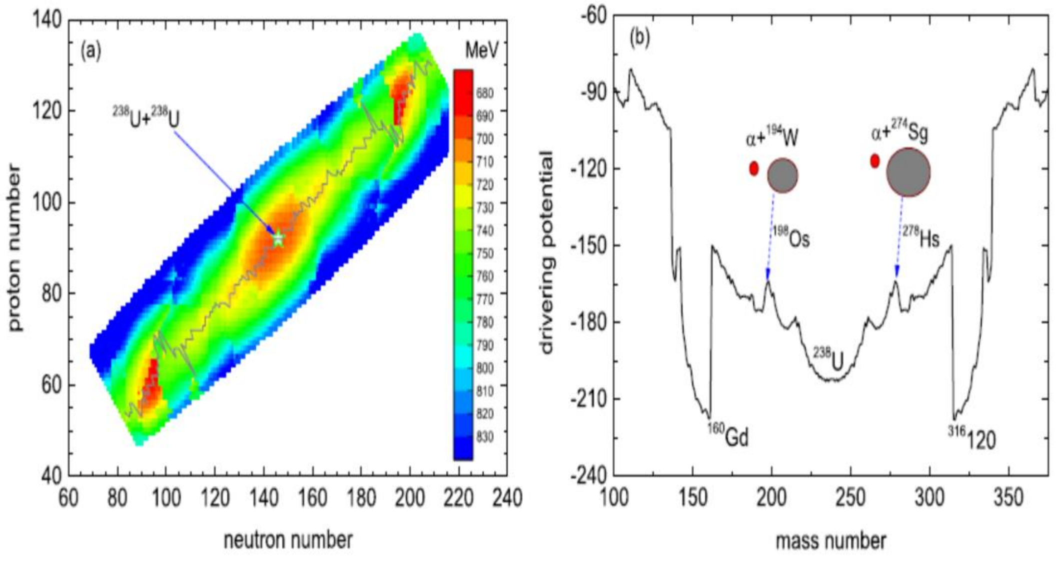
Phys. Rev. C 108, L051601 (2023), arXiv:2308.03127



大质量转移反应中前平衡结团发射研究

PHYSICAL REVIEW C **107**, 054613 (2023)



Preequilibrium cluster emission in massive transfer reactions near the Coulomb barrier energy

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基于双核模型研究大质量转移反应中结团发射机制

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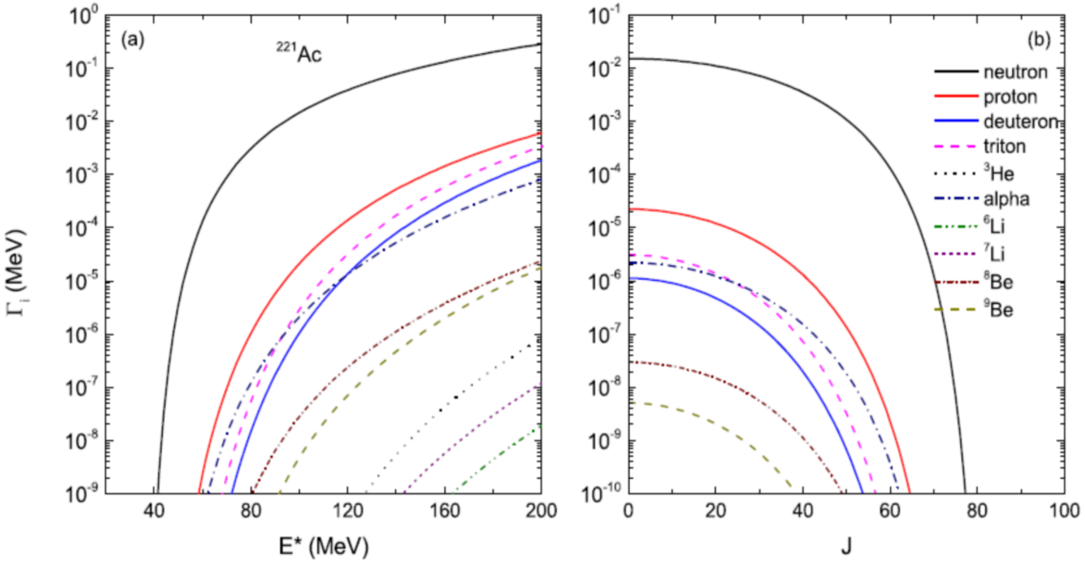
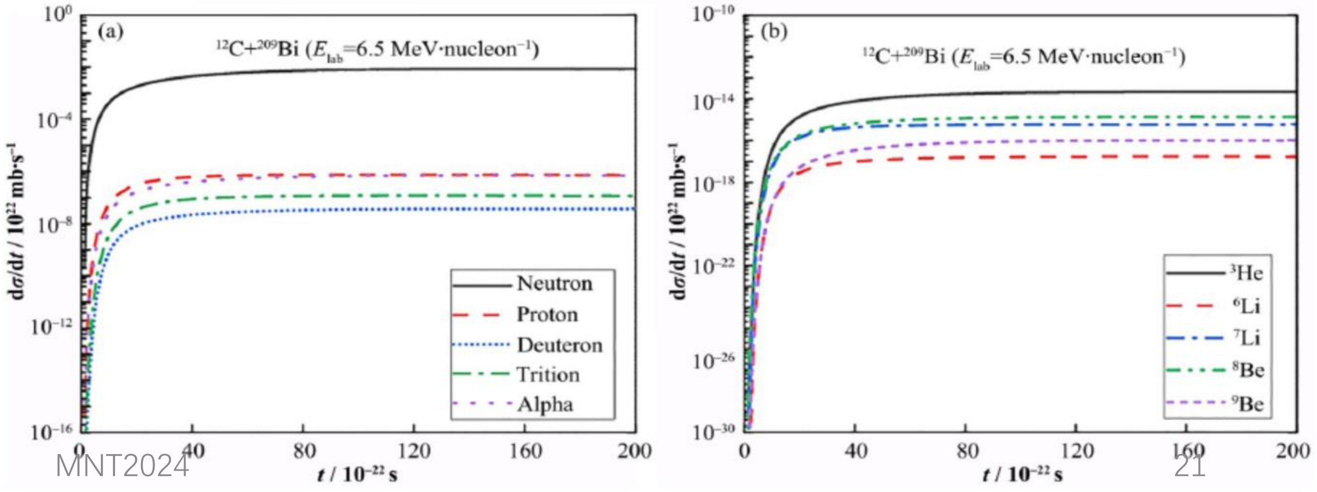
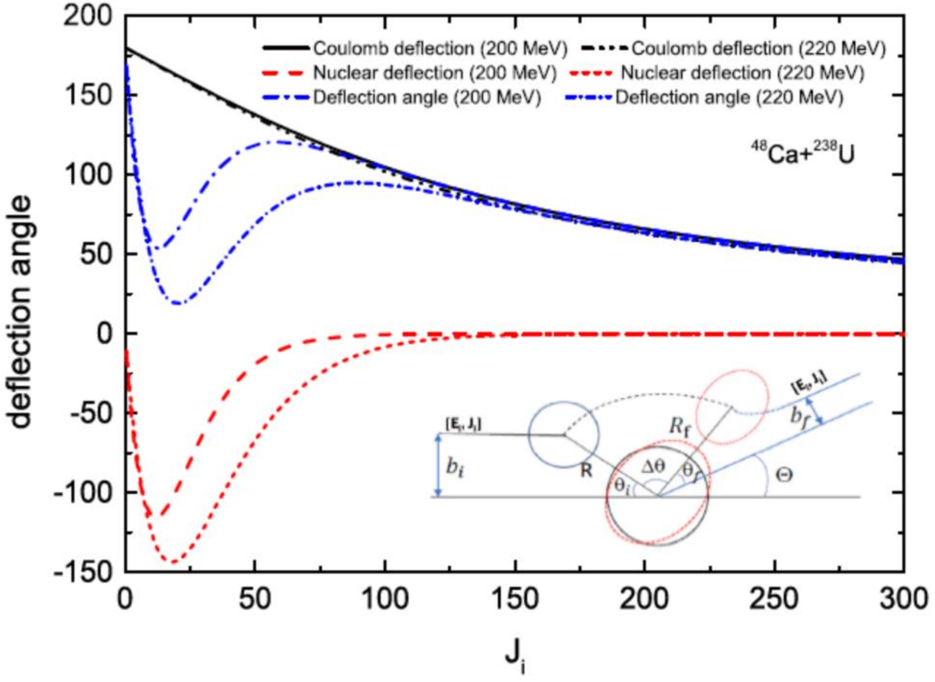
（华南理工大学 物理与光电学院 广州 510641）







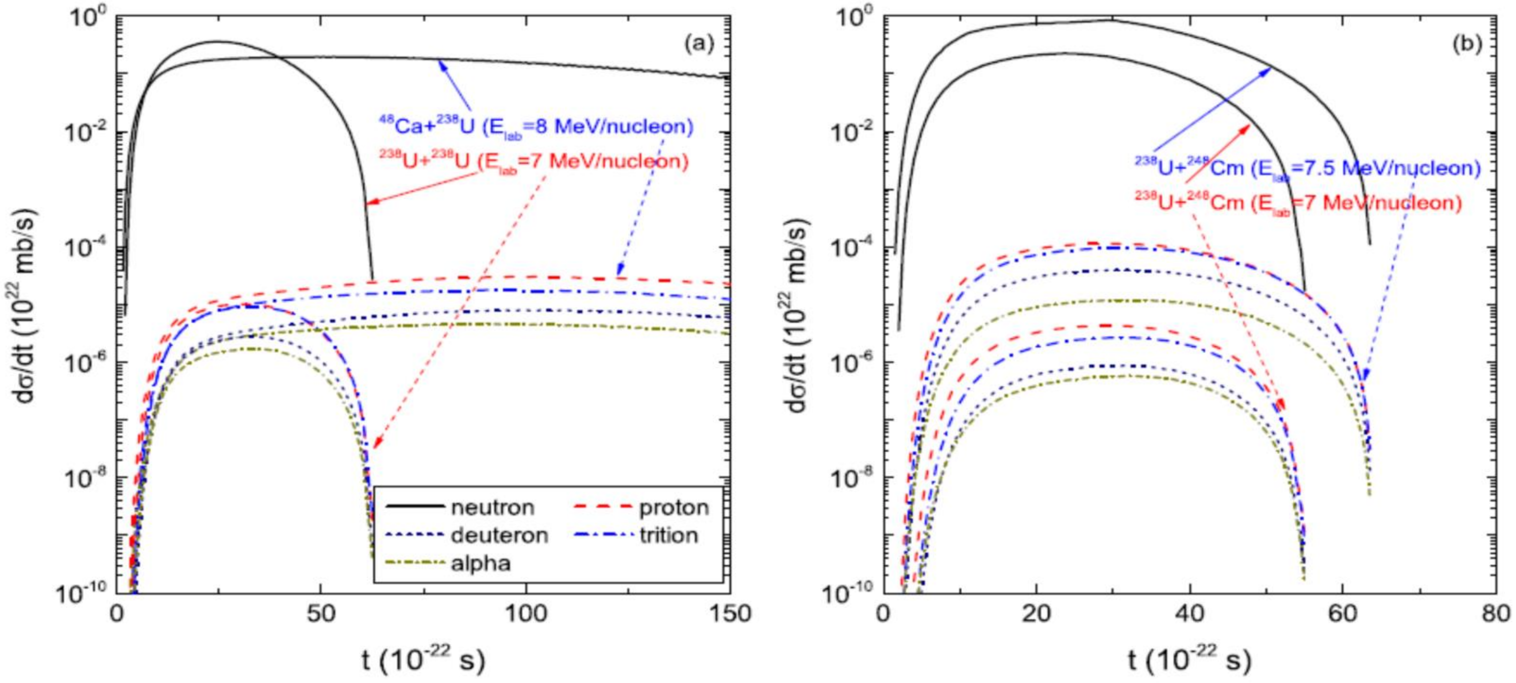
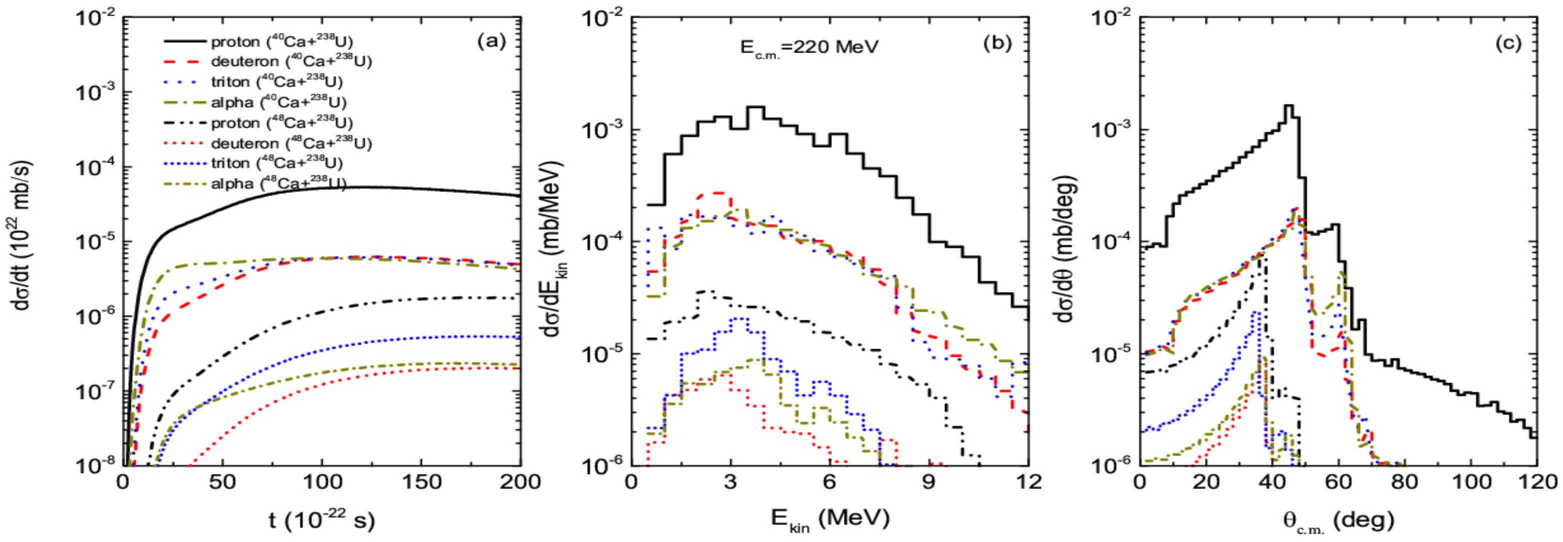


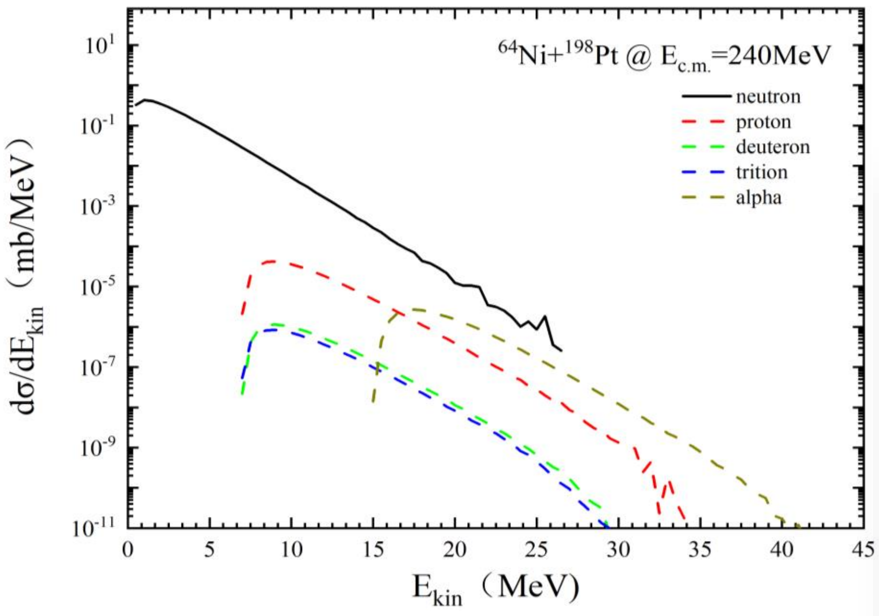
TABLE I. Production cross sections of neutron, proton, deuteron, triton, ^{3}He, α, ^{7}Li, and ^{8}Be in the preequilibrium process of massive transfer reactions.

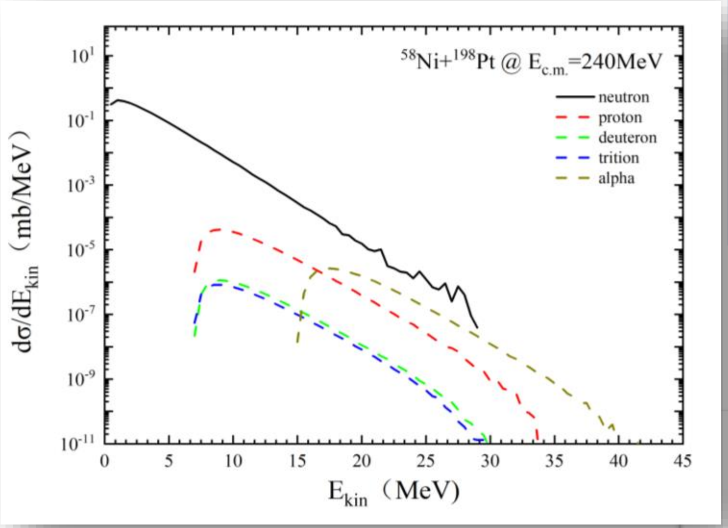
System	$E_{c.m.}$ (MeV)	σ_n (mb)	σ_p (mb)	σ_d (mb)	σ_t (mb)	$\sigma_{^3He}$ (mb)	σ_α (mb)	$\sigma_{^7Li}$ (mb)	$\sigma_{^8Be}$ (mb)
^{12}C+^{209}Bi	69	2.63	0.26×10^{-3}	0.12×10^{-4}	0.41×10^{-4}	0.62×10^{-11}	0.22×10^{-3}	0.19×10^{-12}	0.42×10^{-12}
^{40}Ca+^{238}U	220	24.65	0.15×10^{-1}	0.17×10^{-2}	0.18×10^{-2}	0.62×10^{-8}	0.20×10^{-2}	0.16×10^{-10}	0.53×10^{-11}
^{48}Ca+^{238}U	180	0.11×10^{-1}	0.84×10^{-12}	0.21×10^{-14}	0.24×10^{-13}	$<10^{-16}$	0.77×10^{-13}	$<10^{-16}$	$<10^{-16}$
^{48}Ca+^{238}U	200	1.63	0.42×10^{-5}	0.18×10^{-6}	0.66×10^{-6}	$<10^{-16}$	0.54×10^{-6}	$<10^{-16}$	$<10^{-16}$
^{48}Ca+^{238}U	220	23.16	0.40×10^{-3}	0.44×10^{-4}	0.12×10^{-3}	0.23×10^{-11}	0.60×10^{-4}	0.74×10^{-14}	0.53×10^{-15}
^{48}Ca+^{238}U	240	96.11	0.61×10^{-2}	0.11×10^{-2}	0.28×10^{-2}	0.61×10^{-9}	0.94×10^{-3}	0.48×10^{-11}	0.34×10^{-12}
^{238}U+^{238}U	833	20.59	0.61×10^{-3}	0.17×10^{-3}	0.55×10^{-3}	0.49×10^{-10}	0.11×10^{-3}	0.15×10^{-11}	0.11×10^{-12}
^{238}U+^{248}Cm	850	11.53	0.23×10^{-3}	0.46×10^{-4}	0.14×10^{-3}	0.63×10^{-11}	0.31×10^{-4}	0.20×10^{-12}	0.16×10^{-13}
^{238}U+^{248}Cm	911	56.27	0.71×10^{-2}	0.24×10^{-2}	0.60×10^{-2}	0.41×10^{-8}	0.77×10^{-3}	0.10×10^{-9}	0.56×10^{-11}

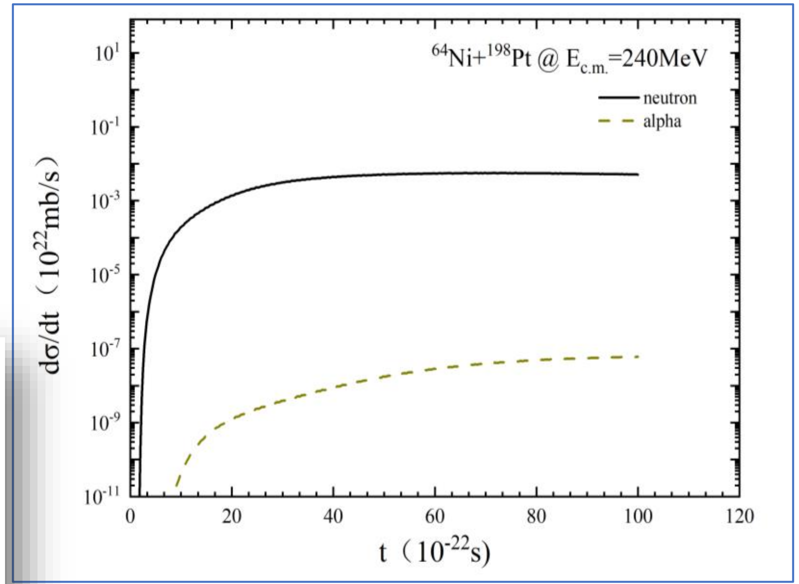


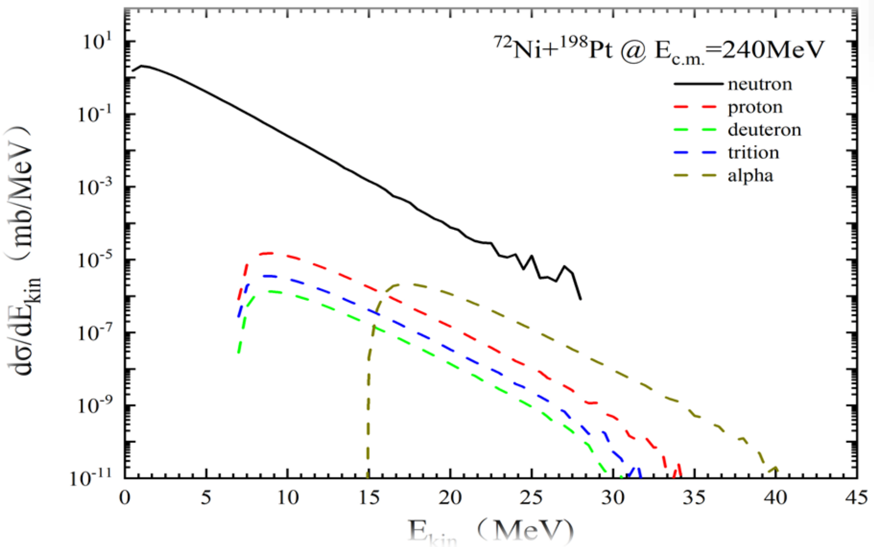
Preequilibrium cluster emission

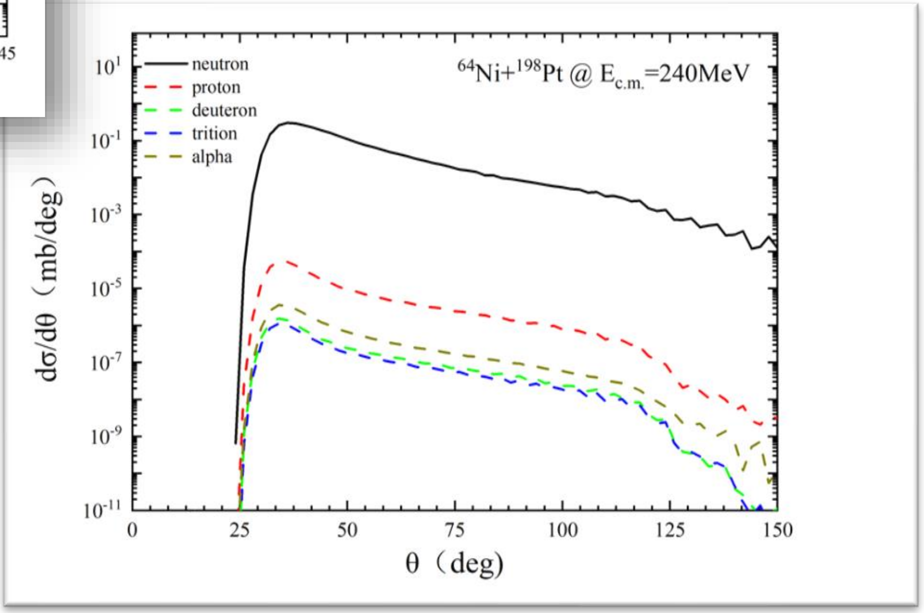
$^{58,64,72}Ni+^{198}Pt$ @ $E_{c.m.}$=240MeV











IV. Summary and perspective

- The maximal cross sections with **10 fb** for the reaction of $^{54}Cr(^{243}Am,3n)^{294}119$ corresponding to $E_{c.m.}$=239.43 MeV and **4 fb** for $^{54}Cr(^{248}Cm,3n)^{299}120$ at 33 MeV, $E_{c.m.}$=240.77 MeV, E_{lab}=5.43 MeV/nucleon.
- Shell effect plays an important role on the MNT fragments formation. New neutron-rich isotopes around N=162 is the stepstone to reach the 'island of stability'. The cluster transfer in the MNT reactions broadens the isotopic distribution and slightly enhances the fusion probability.
- Preequilibrium clusters enable the similar reaction dynamics with the MNT reactions

Perspective: Influence of cluster structure of projectile nuclides, such as ^{12}C, ^{16}O, on the cluster emission, spectroscopic factor.

Thank you for your attention!