華南理工大學
SOUTH CHINA UNIVERSITY OF TECHNOLOGY

大质量转移反应中团簇发射机制研究

汇报人：王子涵　　指导老师：冯兆庆

目录

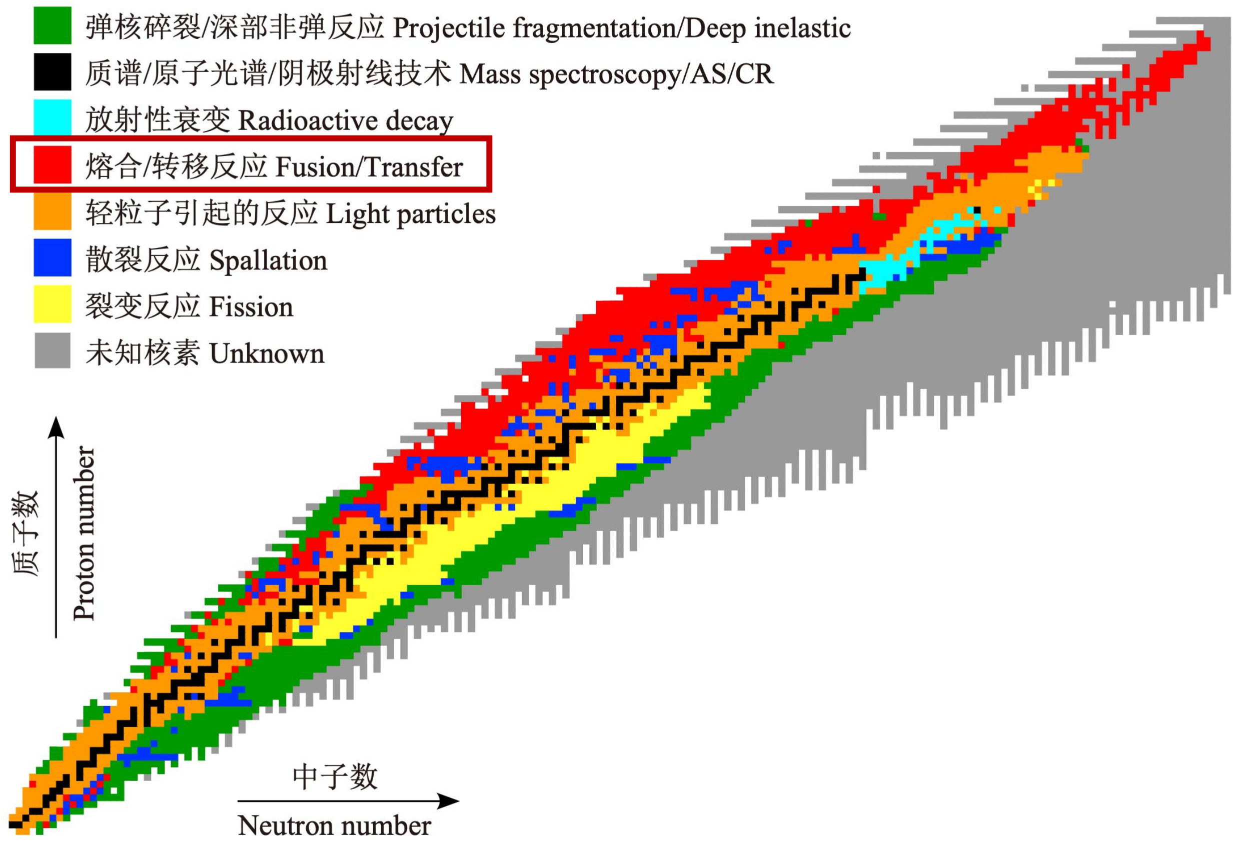
1.研究背景——多核子转移反应

In the multi-nucleon transfer (MNT) reactions:

(1) Generate broad isotope distribution depending on transfer channels.

(2) Angular and excitation energy of compound nucleus distribute widely.

(3) Producing neutron-rich heavy and superheavy nuclei.



ELSEVIER

Nuclear Physics A

Volume 176, Issue 2, 29 November 1971, Pages 284-288

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, J. Wilczyński

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	^{238}U+^{198}Pt→^{241}U	Phys. Rev. Lett. 130, 132502 (2023)

1.研究背景——前平衡结团发射

前平衡结团发射机制的理论研究

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

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

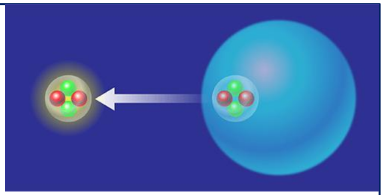
Zhao-Qing Feng*
School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510640, China

(Received 2 January 2023; revised 21 March 2023; accepted 15 May 2023; published 22 May 2023)

- **The Dinuclear System (DNS) Model**
  - **Phys. Rev. C 107, 054613 (2023)**

- **The Exciton Model**
  - **Rev. Nucl. Sci. 25, 123 (1975)**
  - **Phys. Rev. C 16, 1404 (1977)**
  - **Int. J. Mod. Phys. E 19, 1134 (2010)**

研究前平衡结团
发射机制的重要意义



- **the correlation of spatial configuration of nucleons**
- **the cluster structure of the stable or unstable nuclide**
- **the cluster formation mechanism in nuclear reactions**
- **the kinetic mechanism of MNT reactions**
- **… …**

N·H
ELSEVIER

Physics Reports 374 (2003) 1–89

PHYSICS REPORTS

www.elsevier.com/locate/physrep

Cluster emission, transfer and capture in nuclear reactions

P.E. Hodgson[a], E. Běták[b,1]

[a]The Denys Wilkinson Building, Department of Physics, University of Oxford, Oxford OX1 3RH, UK
[b]Institute of Physics, Slovak Academy of Sciences, 84228 Bratislava, Slovakia

Received 3 June 2002
editor: G.E. Brown

前平衡结团发射截面的实验测量

- RIKEN：$^{14}N+^{159}Tb$，^{169}Tm，^{181}Ta，^{197}Au，^{209}Bi
- IMP：$^{12}C+^{209}Bi$

2.B: 2.N

Nuclear Physics **A349** (1980) 285–300;

PRODUCT CROSS SECTIONS FOR THE REACTION OF ^{12}C WITH ^{209}Bi*

JIN GEN-MING
Institute of Modern Physics, Academia Sinica, Lanzhou, The People's Republic of China †
and
The Niels Bohr Institute, Copenhagen Ø, Denmark

XIE YUAN-XIANG, ZHU YONG-TAI, SHEN WEN-GING, SUN XI-JUN, GUO JUN-SHENG, LIU GUO-XING, YU JU-SHENG and SUN CHI-CHANG
Institute of Modern Physics, Academia Sinica, Lanzhou, The People's Republic of China

and

J. D. GARRETT
The Niels Bohr Institute, Copenhagen Ø, Denmark

Received 18 June 1980

E NUCLEAR REACTIONS $^{209}Bi(^{12}C, ^{12}C)$, $(^{12}C, X)$, $(^{12}C, F)$, $E = 61–73$ MeV; measured $\sigma(\theta, \text{elastic})$, $\sigma(\theta, \text{evaporation residue})$, $\sigma(\text{fission})$, $\sigma(E_x, \theta)$; $^{209}Bi(^{12}C, Li)$, $(^{12}C, Be)$, $(^{12}C, B)$, $E = 73$ MeV; measured $\sigma(E_{Li}, \theta)$, $\sigma(Be, \theta)$, $\sigma(B, \theta)$. ^{221}Ac deduced fission barriers.

- *Nucl. Phys. A349 (1980) 285-300*

2.B: 2.N

Nuclear Physics **A334** (1980) 127–143;

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

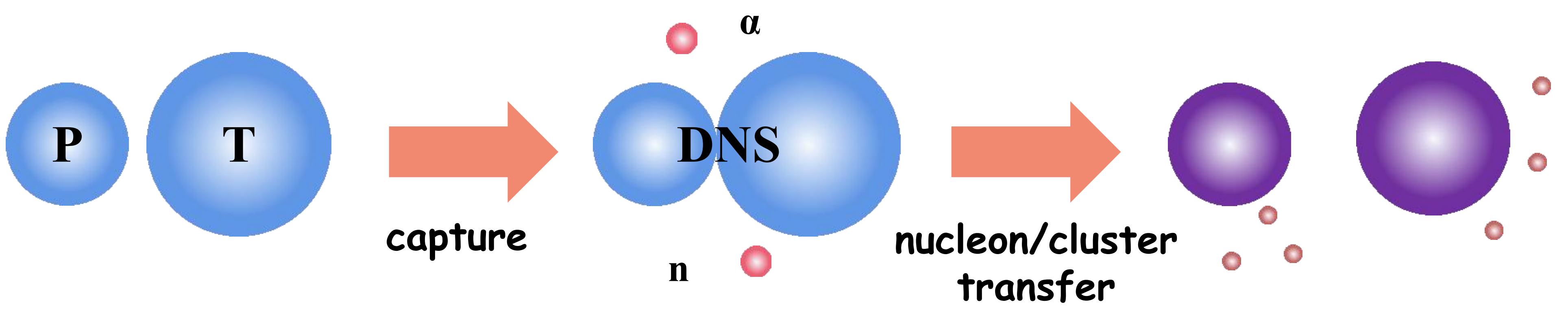
Received 19 September 1979

Abstract: The α-particle emission following ^{14}N-induced reactions on various heavy targets at 85–115 MeV has been studied. Cross sections of heavy residual nuclei produced after α-emission were measured in the case of the ^{209}Bi target and were found to be close to the angle-integrated cross sections of α-particles, indicating that the α-emission mainly takes place in a binary process. The measured angular distributions of α-particles are pronouncedly forward-peaked, while the energy spectra are always characterized by the Maxwellian distribution even at forward angles and reproduced excellently by the statistical evaporation formula when nuclear temperature is treated as a free parameter. The resultant value of the temperature is high (4–6 MeV) at forward angles and decreases monotonically with increasing emission angles.

The energy and angular distributions of protons, deuterons and tritons were also measured in the $^{181}Ta+^{14}N$ reaction at 115 MeV. The results are similar to those of α-particles. In particular, nuclear temperatures turned out nearly equal to each other, being consistent with the hot-spot interpretation for the relevant preequilibrium light-particle emission.

E NUCLEAR REACTIONS ^{159}Tu, ^{169}Tm, ^{181}Ta, ^{197}Au, $^{209}Bi(^{14}N, X)$, $E = 85–115$ MeV; measured $\sigma(E, \theta)$ for p, d, t, α and σ for reaction residues; Si detectors.

- *Nucl. Phys. A334 (1980) 127-143*



➢ 冯兆庆. 近垒重离子熔合反应和超重核合成机制研究[D]. 甘肃: 中国科学院近代物理研究所,2007

➢ 前平衡结团发射截面：

$$\sigma_\nu(E_k,\theta,t)=\sum_{J=0}^{J_{\max}}\sum_{Z_1=Z_\nu}^{Z_{\max}}\sum_{N_1=N_\nu}^{N_{\max}}\sigma_{cap}(E_{c.m.},J)\times\int f(B)\times P(Z_1,N_1,E_1(E_{c.m.},J),t,B)\times\boxed{P_\nu(Z_\nu,N_\nu,E_k)}dB$$

$$\nu=n,p,d,t,{}^3He,\alpha,{}^{6,7}Li,{}^{8,9}Be$$

结团发射概率： $P_\nu(Z_\nu,N_\nu,E_k)=\Delta t\dfrac{\Gamma_\nu}{\hbar}$， $\Delta t=0.5\times10^{-22}s$

2.模型介绍——双核系统模型

➢ capture：

➢ **俘获截面：** $$\sigma_{cap} = \frac{\pi\hbar^2(2J+1)T(E_{c.m.},J)}{2\mu E_{c.m.}} \qquad \mu = m_n \frac{A_P A_T}{A_P + A_T}$$

➢ **穿透概率：** $$T(E_{c.m.},J) = \int f(B)\, T(E_{c.m.},J,B)\,dB$$

1. for the light and medium systems：the Hill-Wheeler formula ➢ *Phys. Rev., 1953, 89: 1102-1145*

2. for the heavy systems：the classical trajectory approach

$$T(E_{c.m.},J,B) = 0,\ \ E_{c.m.} < B + \frac{J(J+1)\hbar^2}{2\mu R_C^2},\quad T(E_{c.m.},J,B) = 1,\ \ E_{c.m.} > B + \frac{J(J+1)\hbar^2}{2\mu R_C^2}$$

➢ **位垒分布函数：**

$$\Delta = (B_C - B_S)/2$$

高斯型 $$f(B) = \frac{1}{N}\exp\left(-\left(\frac{B-B_m}{\Delta}\right)^2\right)$$

$$B_m = (B_C + B_S)/2$$

$$\int f(B)\, dB = 1$$

➢ *Phys. Rev., 2001, C64: 034606*
➢ *Phys. Rev., 2001, C65: 014607*

- **transfer：**

  - **主方程：**

只考虑核子n，p转移：

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

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

核子n，p转移+结团d，t，3He，4He转移：

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

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

- *Nucl. Phys. A 771, 50 (2006)*
- *Nucl. Phys. A 816, 33 (2009)*
- *Phys. Rev. C 76, 044606 (2007)*
- *Phys. Rev. C 108, L051601 (2023)*

2.模型介绍——双核系统模型

- **transfer:**

- **前平衡粒子的动能分布:**

the Monte Carlo method, $\varepsilon_\nu = \left(0,\ E^* - B_\nu - Vc - E_{rot}\right)$

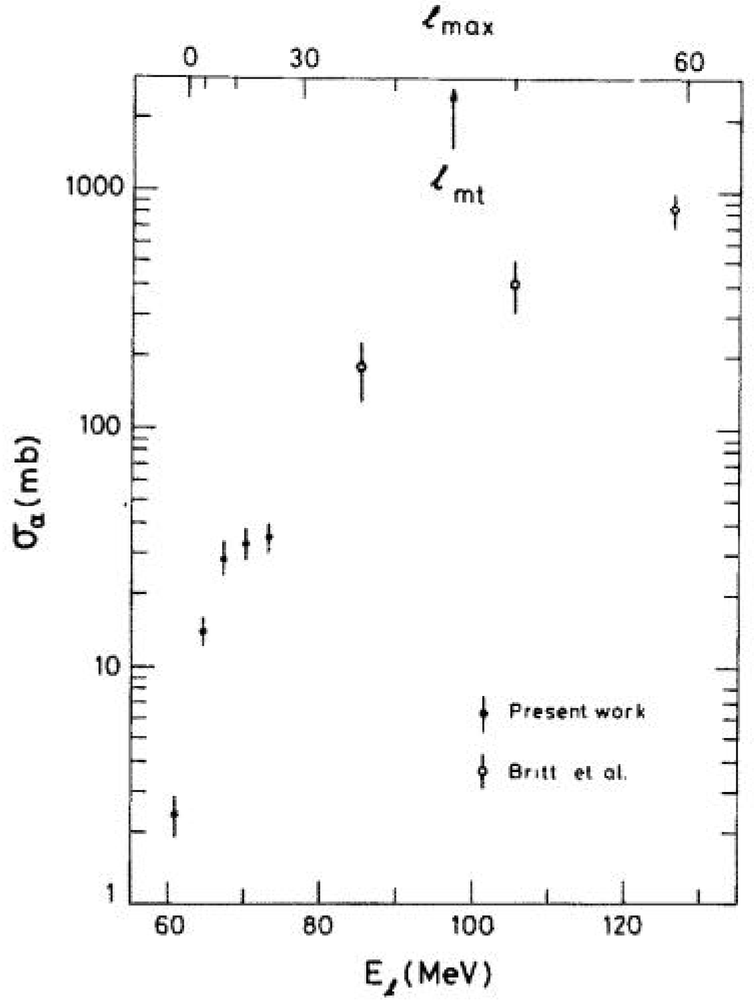
1.中子:Watt Spectrum

$$\frac{dN_n}{d\epsilon_n} = C_n \frac{\epsilon_n^{1/2}}{T_w^{3/2}} \exp\left(-\frac{\epsilon_n}{T_w}\right) \qquad T_\omega = 1.7 \pm 0.1 MeV$$

- *Phys. Rev. C 45, 719 (1992)*

2.带电粒子:Boltzmann Distribution

$$\frac{dN_\nu}{d\epsilon_\nu} = 8\pi E_k \left(\frac{m}{2\pi T_\nu}\right)^{1/2} \exp\left(-\frac{\epsilon_\nu}{T_\nu}\right) \qquad T_\nu = \sqrt{\frac{E^*}{a}},\quad a = A/12$$



IMP: $^{12}C+^{209}Bi$

2.模型介绍——双核系统模型

- **transfer:**
- **前平衡粒子的角分布:**

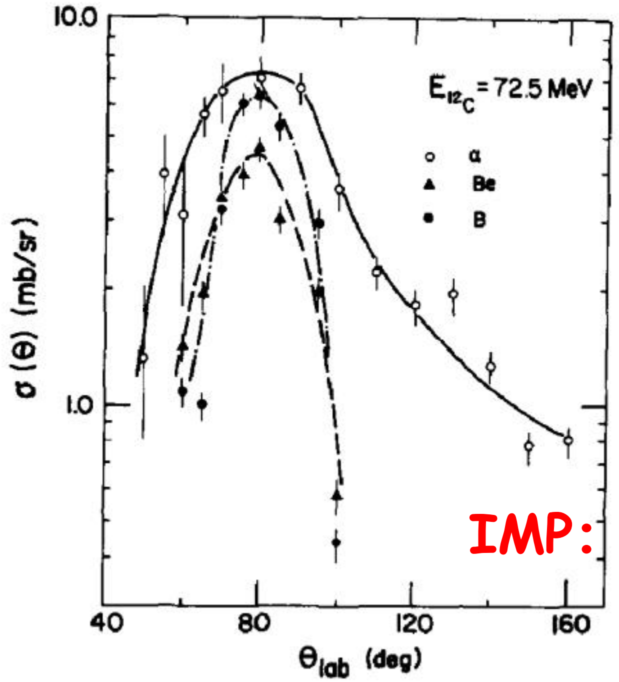
the deflection function method

$$\Theta(J_i) = \Theta_C(J_i) + \Theta_N(J_i).$$

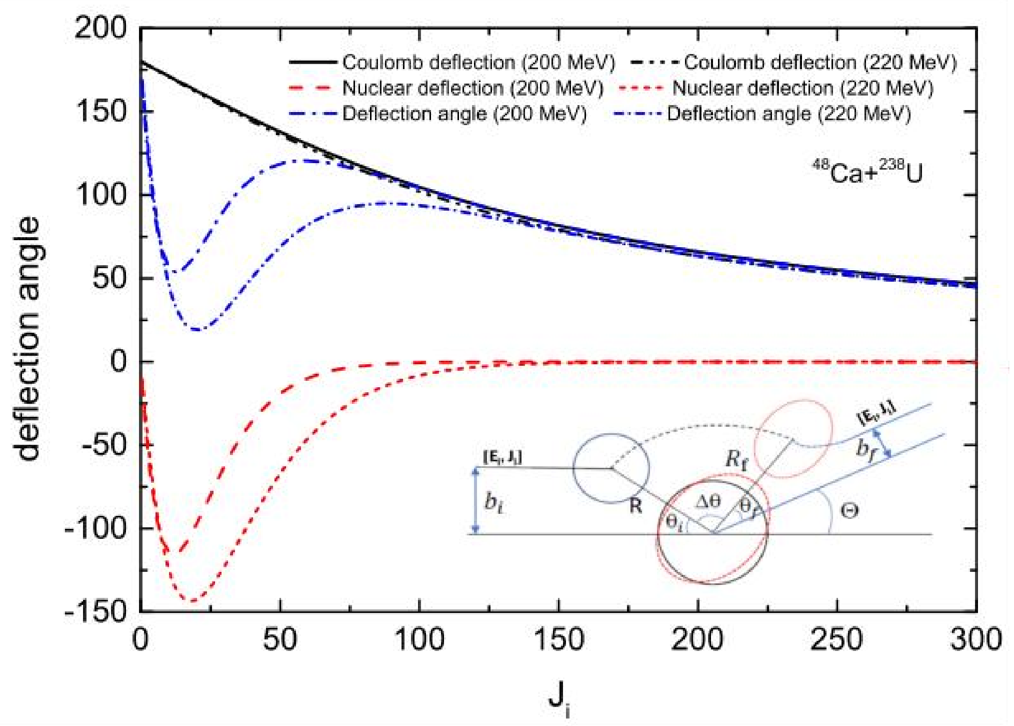
1.库仑偏转 $$\Theta(J_i)_C = 2\arctan\frac{Z_p Z_t e^2}{2E_{\mathrm{c.m.}}b}$$

2.核偏转 $$\Theta(J_i)_N = -\beta\Theta_C^{\mathrm{gr}}(J_i)\frac{J_i}{J_{\mathrm{gr}}}\left(\frac{\delta}{\beta}\right)^{J_i/J_{\mathrm{gr}}}$$

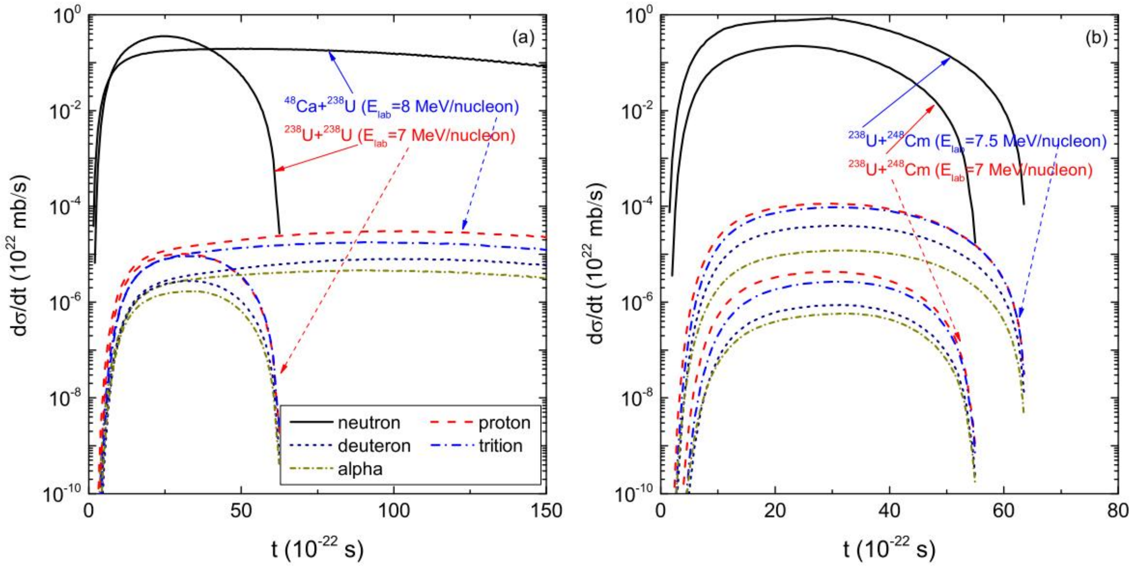
- *Z. Phys. A 284, 209 (1978)*
- *Eur. Phys. J. A 58, 162 (2022)*

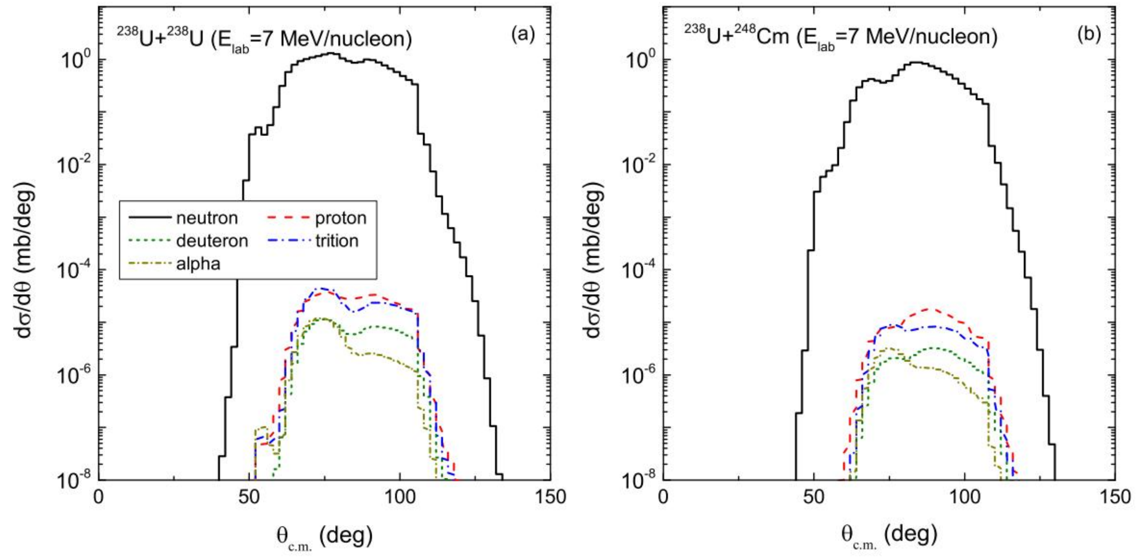


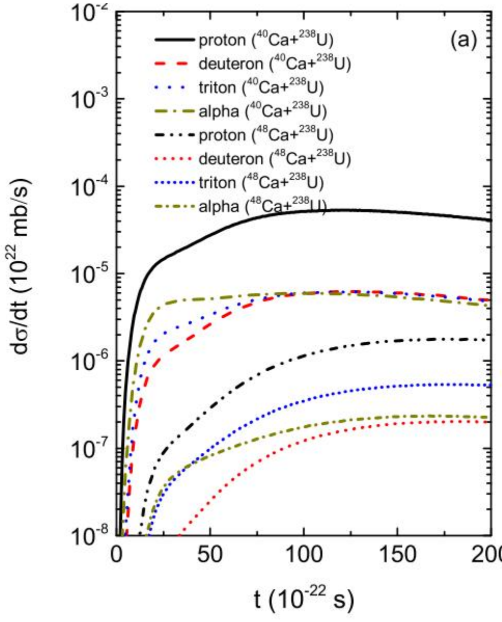
IMP: $^{12}C+^{209}Bi$



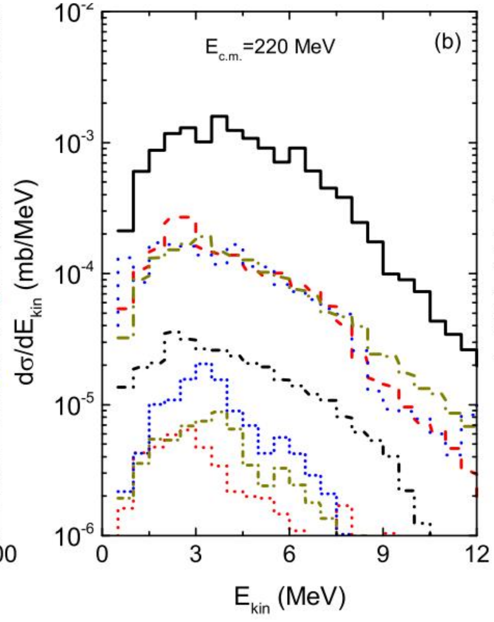
3.结果讨论——$^{48,40}Ca$,$^{238}U+^{238}U$,^{248}Cm



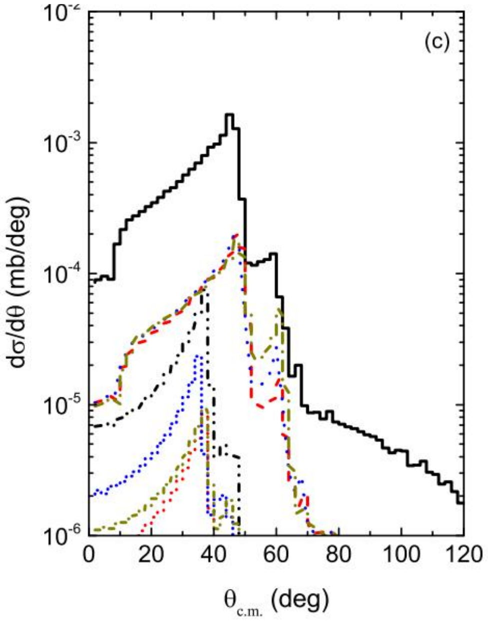




前平衡粒子产生率

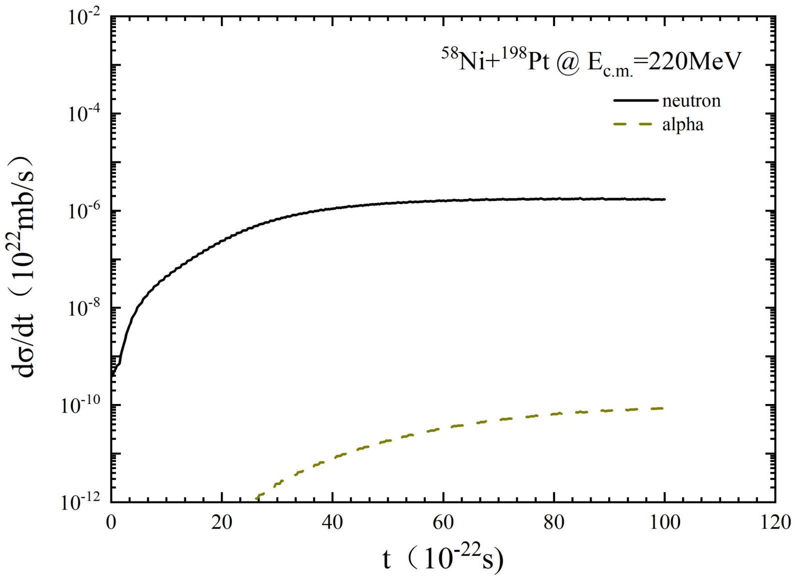


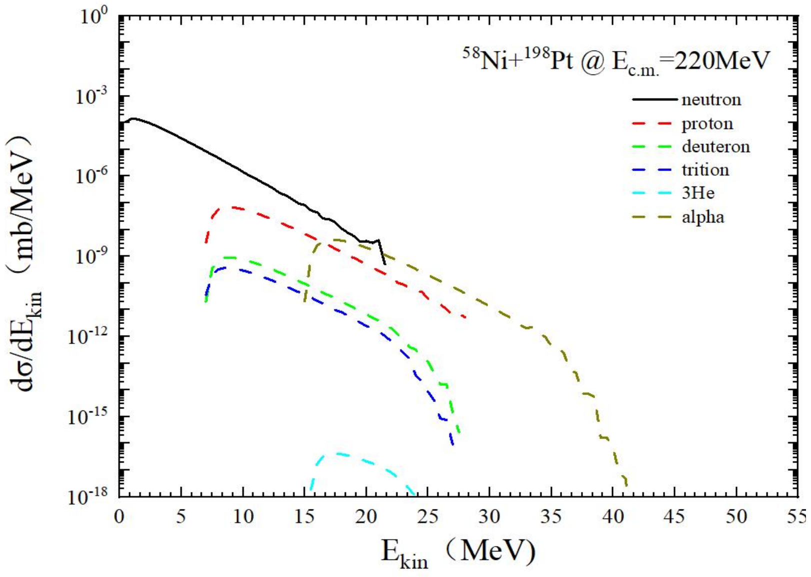
前平衡粒子动能谱

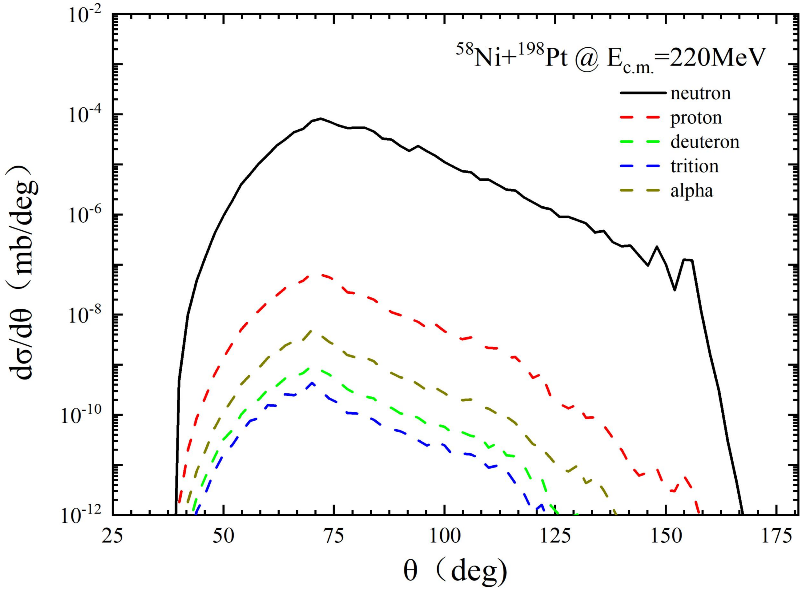


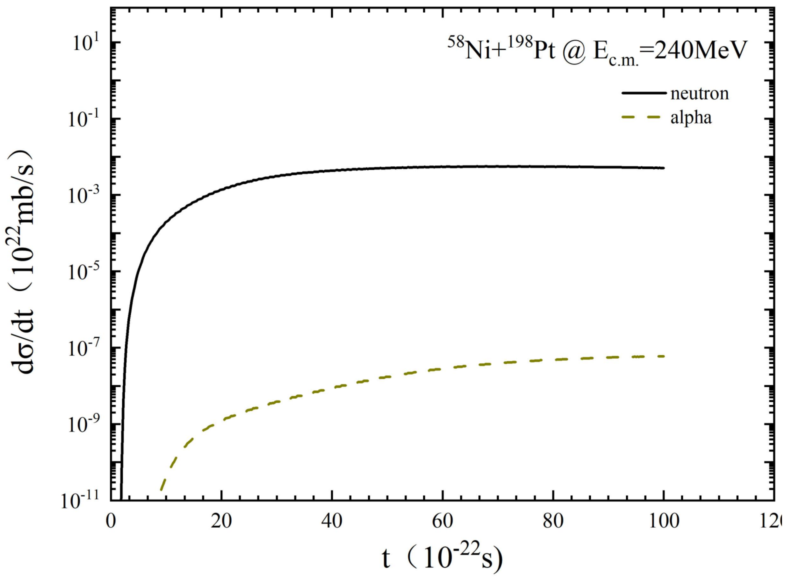
前平衡粒子角分布

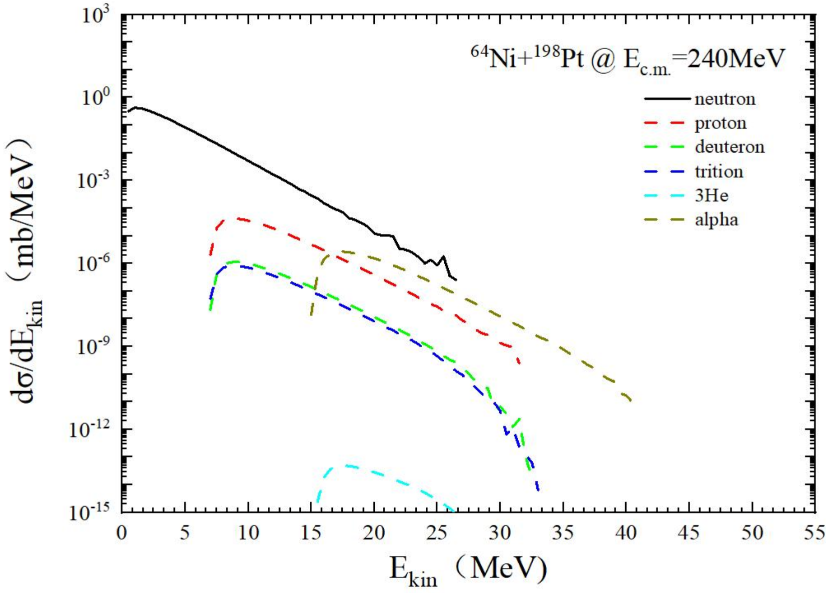
3.结果讨论——$^{58,64,72}Ni+^{198}Pt$

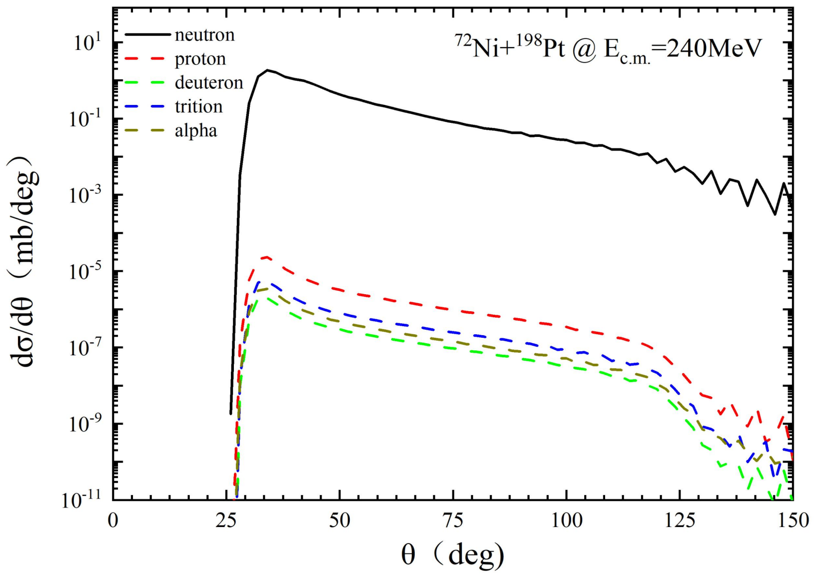








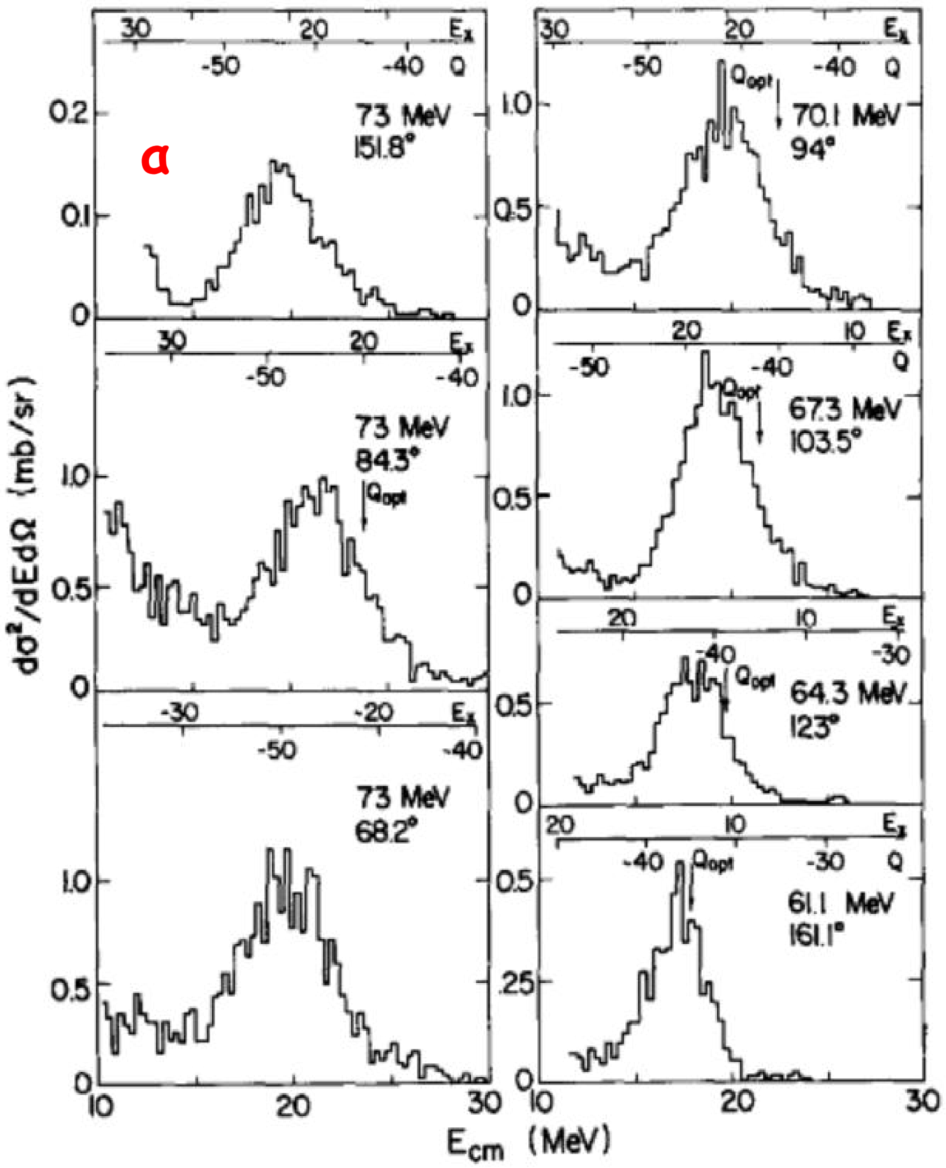


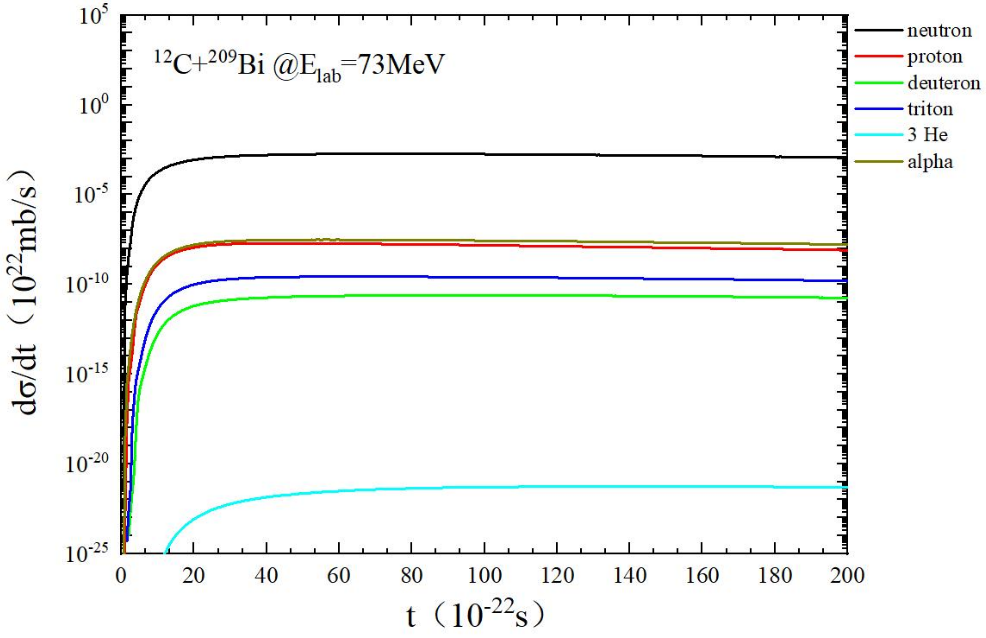


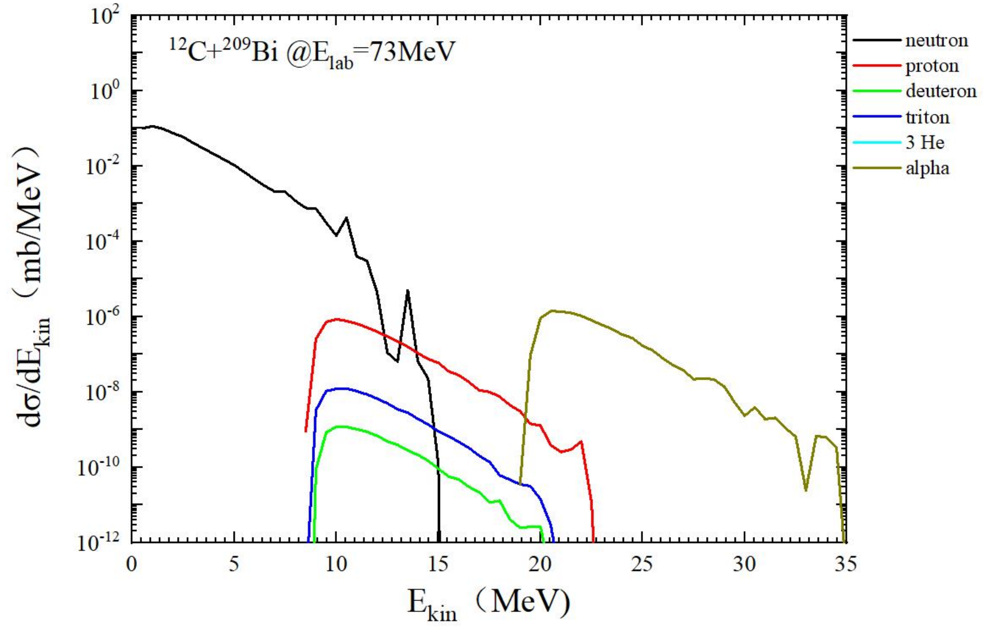
前平衡粒子的时间演化过程　　**前平衡粒子动能谱**　　**前平衡粒子角分布**

3.结果讨论——$^{12}C+^{209}Bi$

IMP：$^{12}C+^{209}Bi$

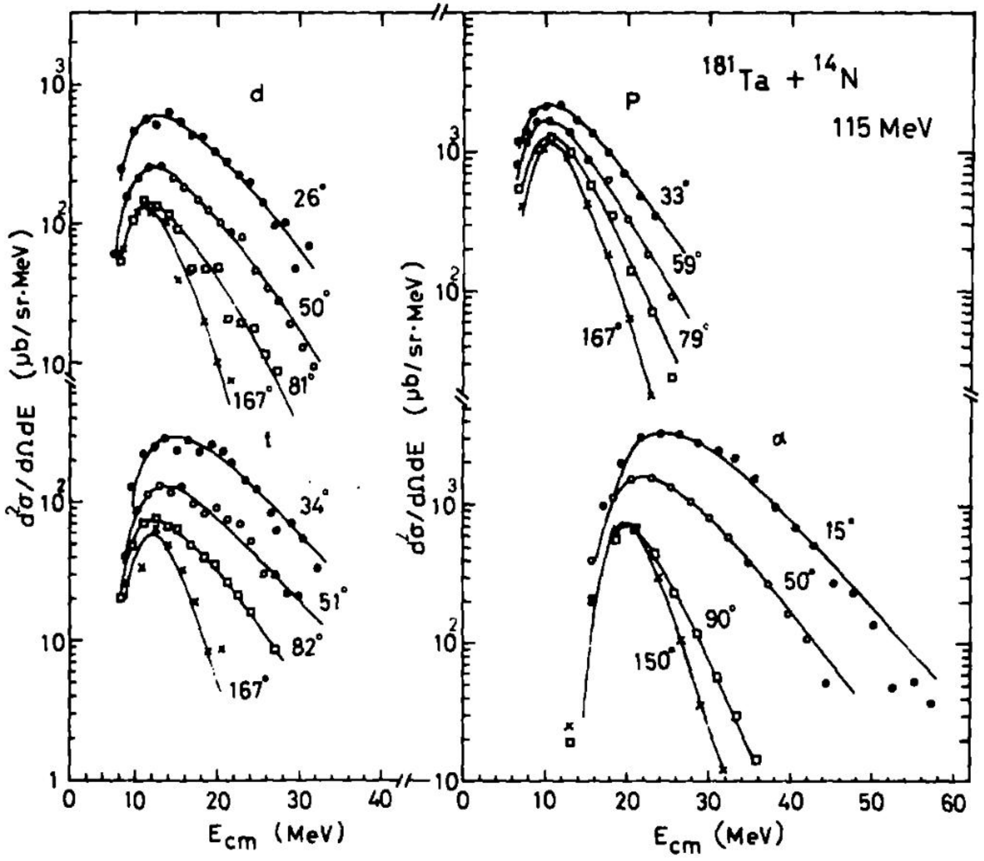


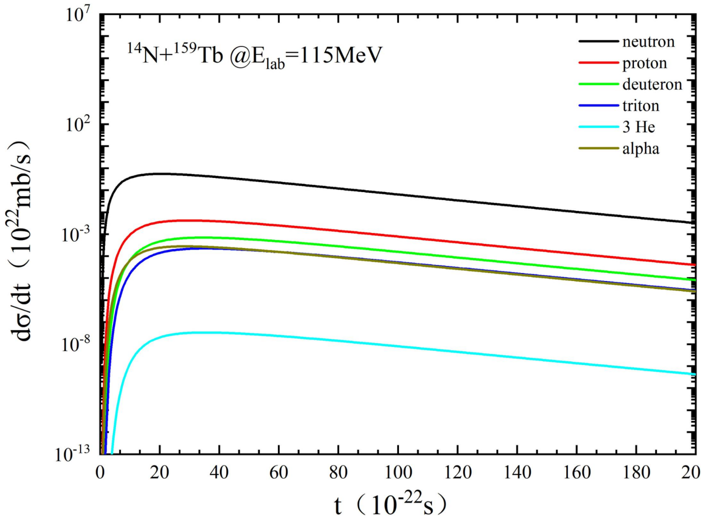


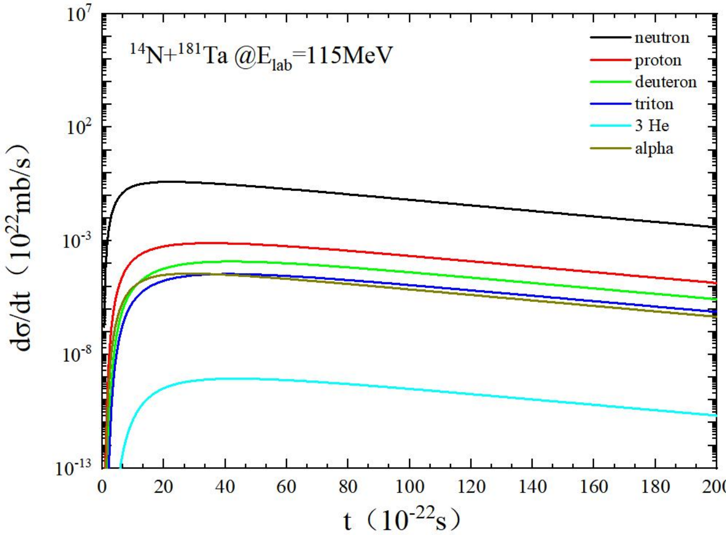


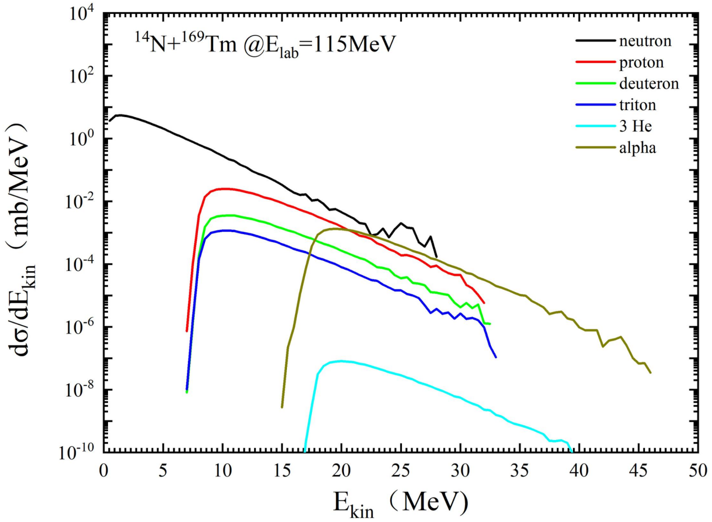
3.结果讨论——$^{14}N+^{159}Tb, ^{169}Tm, ^{181}Ta$

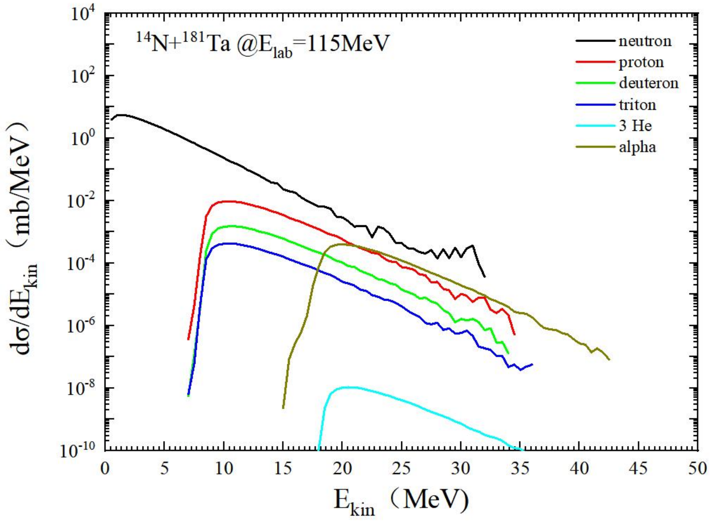
RIKEN：$^{14}N+^{181}Ta$





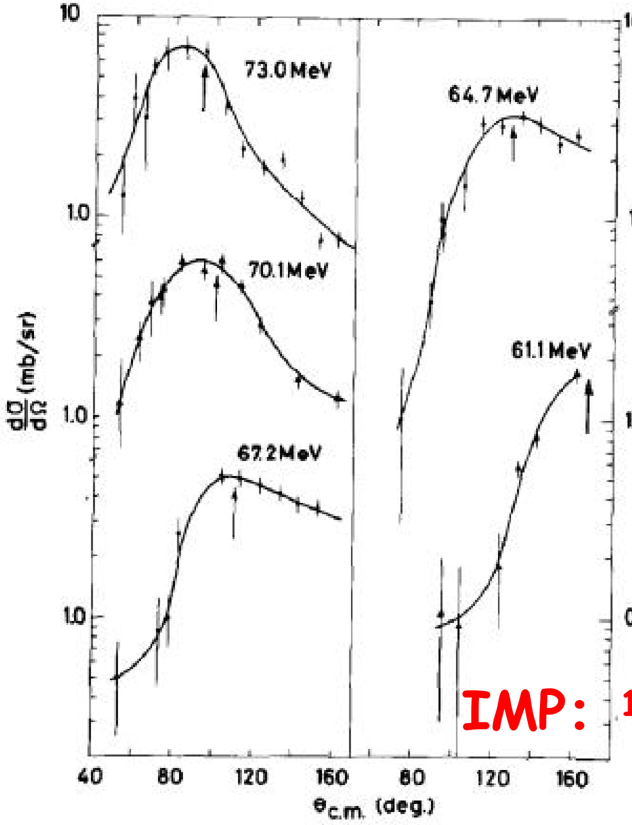




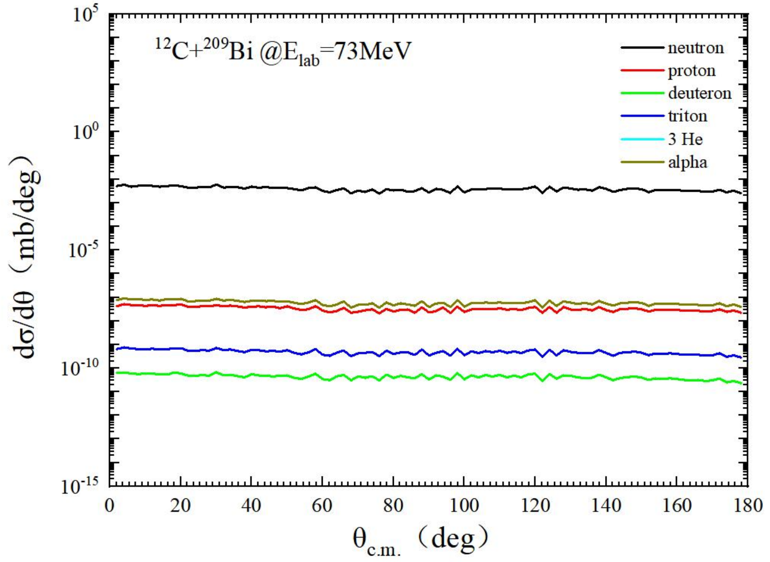


4.总结展望

- 前平衡结团被认为是在核子转移过程中由初始DNS碎片衰变而发射出来的，它的发射一直持续到复合核的形成。
- 前平衡结团可以实现与转移片段相似的反应动力学，如角动量分布，它的发射蕴含着核反应中核子关联的重要信息。
- 前平衡结团的生成速率与反应体系和束流能量有关，其发射截面与分离能和库仑势垒密切相关。中子被发射的概率最大，α和p，d，t的发射速率在大小上是相当的，3He最小。
- 不足：模型中没有考虑反应系统的结构信息，较轻反应系统的角分布不能很好地描述实验结果。
- 展望：Consider the influence of cluster structure of projectile nuclides, such as ^{12}C, ^{16}O, on the cluster emission, spectroscopic factor.



IMP: $^{12}C+^{209}Bi$



敬请各位专家、老师批评指正！

THANK YOU