Happy Birthday to Prof. Arima
I met Prof. Arima in 1980 at the international Conference on nuclear physics at Berkeley for the first time. When he knew I was from China he was so kindly to talk to me and encourage me. He talked about the pairing at the conference but I knew not much about the pairing at that time. Later, I listened to several times of his lectures and I learned more about the pairing. Now I understand more deeply of its importance in nuclear structure and also nuclear reaction.
Studies of multi-nucleon transfer reaction with Improved QMD model

1) Introduction
2) Systematic studies of multi-nucleon transfer reactions with Improved Quantum Molecular Dynamics model
3) Conclusion and discussion

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Collaborators: Kai Zhao, Ning Wang, Yinxun Zhang, Junlong Tian, Qingfeng Li, Xizhen Wu

2018 Nov. Shanghai,
Introduction

Deep-inelastic reaction
Strong-dumped reaction different term same meaning
Multinucleon transfer

Common understanding
Multinucleon transfer reactions are of great importance

1) Important tool for studies of nuclear structure and reaction, nucleon correlation and nuclear fission

2) Important tool for producing new neutron-rich nuclei

3) Prospective approach for synthesizing SHN
N=126 neutron-rich nuclei

Difficult to be reached by fusion due to the limitation of projectile and target
Systematic studies of multi-nucleon transfer reactions with ImQMD model

The quantum molecular dynamics model

A-body dynamics, microscopic approach

- many-body correlation and fluctuation are included
- Large number of degrees of freedom can be considered automatically

excitation, deformation of projectile and target, neck formation, nucleon transfer, different types of separation of composite system, nucleon emission

\[ ^{86}\text{Kr} + ^{64}\text{Ni} \quad ^{154}\text{Sm} + ^{160}\text{Gd} \quad ^{238}\text{U} + ^{238}\text{U} \]

\[ 25\text{MeV/u,} \quad \text{Ecm}=440\text{MeV} \quad 7\text{MeV/u} \]
The reaction mechanism evolves with the size of reaction systems.

**Intermediate size system**

\(^{86}\text{Kr}^{+}\text{Ni}^ {64}\) at 25MeV/n

Neutron-rich rare-earth region

\(^{154}\text{Sm}^{+}\text{Gd}^{160}\) at Ecm=440MeV

understanding the competition between fusion, elastic-inelastic, deep-inelastic and multifragmentation processes

Show the efficiency of MNT on the production of neutron-rich nuclei Z=58-76, neutron-rich reaction system

**Actinide nuclei**

\(^{238}\text{U}^{+}\text{U}^{238}\) at 7 MeV/n

Fusion is completely forbidden due to strong Coulomb repulsion

Study production of neutron-rich transuranium and light U-like isotopes by MNT
Studies of the reaction $^{86}$Kr+$^{64}$Ni at 25MeV/n

ImQMD +GEMINI calculation

Cross sections of proton removal and neutron pick up isotopes

Reaction mechanism evolves with impact parameters:
- Fusion: small impact parameter
- Binary process: elastic, inelastic, MNT
- Others: ternary breakup and multifragmentation, etc.

Binary scattering:
- Elastic+inelastic (peripheral)
- Deep inelastic (MNT) (peak at 8-9 fm)
$^{86}$Kr$+^{64}$Ni 25MeV/n

**Reaction mechanism evolves with impact parameters**

Central collision: a highly excited composite system, small TKE fusion, MNT, ternary breakup multifragmentation

Peripheral collision: Large TKE Elastic and inelastic scattering

MNT in $^{154}$Sm+$^{160}$Gd at Ecm=440MeV, production of unknown neutron-rich isotopes

no fusion, MNT dominant at small impact parameters

WS: woods-Saxon pot. parametrization given by With Broglia and Whither

ETF2 (given by Ning Wang, et al.)

Dynamical pot. given by TDHF and ImQMD

$$V(R) \sim E_{c.m.} - T(R).$$

Nucleus-nucleus potential

PLB 760,216-241 by Ning Wang, et al.
Primary fragments (ImQMD $t=2000\text{fm/c}$)

$E_{\text{c.m.}} = 440\text{MeV}$
cross sections of neutron-rich new isotopes (Z=58-76) (ImQMD+GEMINI)

Production cross sections of some neutron-rich nuclei with unmeasured masses. The predicted mass excesses of these nuclei from the WS4 model [67] are also listed.

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ImQMD + HIVAP in cooperating a phenomenological fission model

\[ ^{238}\text{U} + ^{238}\text{U} \text{ 7MeV/u} \]

- Initial nuclei
- Composite system
- Pri. fragments
- Residual fragments
- Transuranium
- Light uranium-like Fragment
- \( n, p, \text{light charged particles} \)
Production of transuranium isotopes

Features:
- Magnitude of cross sections of primary fragments does not change much, residual fragments decrease exponentially with Z.
- The most probable residual fragments shift to more less neutron isotopes compared with that of primary fragments as Z increases.

K. Zhao, Z. Li, N. Wang, Y. Zhang, Q. Li, Y. Wang, X. Wu, PRC 92, 024613 (2015)

Exp. data: Phys. Rev. C 88, 054615 (2013) and references there in
Production cross section of primary and residual fragments with charge Z

- Light uranium-like fragments
- Transuranium fragments

The mass number of the most probable primary and residual fragments decreases exponentially.

Light uranium fragments Az pri. fragments is larger than residual fragments
Transuranium fragments Az pri. and resi. Fragments are close

K. Zhao, Z. Li, N. Wang, Y. Zhang, Q. Li, Y. Wang, X. Wu, PRC 92, 024613 (2015)

Produced primary and residual fragments in $^{238}\text{U}^{+^{238}\text{U}}$ compared with known nuclei

Cross section (mb)

- Known nuclei
- Residual fragments
- Primary fragments

$^{238}\text{U}^{+^{238}\text{U}}$: 7.0 MeV/nucleon

New neutron-rich transuranium nuclei
Bettertrand towards SHN
Key factors influencing the formation of residual fragments useful for finding best reaction system for synthesizing heavy neutron-rich transuranium isotopes

Peak isotopes of res.frag. $^{214}\text{Rn}$, $^{249}\text{Cf}$, and neutron-rich isotopes $^{254-256}\text{Cf}$

Cross sections of pri.frag.

Excitation of pri.frag.

Isotope distribution of fission barrier

Width of neutron evaporation increases with neutron number

Competition between fission and evaporation neutrons
Outgoing angle distribution of residual fragments

Outgoing angles (lab) of heavy transuranium residual fragments

Useful for experimental measurement
MNT reactions in three reaction systems from intermediate size nuclei to actinide nuclei are studied. It shows the reaction mechanism evolves with reaction system size and reaction impact parameters. The MNT reactions of neutron-rich nuclei are very efficient for producing very neutron-rich nuclei. The key factors that influence the formation of neutron-rich transuranium nuclei are studied which will be useful for finding the best reaction systems for synthesizing extreme neutron-rich transuranium nuclei and possibly the SHN.
Thanks for attention

Congratulations to Prof. Arima 88’th birthday
Introduction I: What are rare isotopes?

PERIODIC TABLE OF THE ELEMENTS

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