



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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2018 Nov. Shanghai,

Introduction

deep-inelastic reaction

strong-dumped reaction different term same meaning

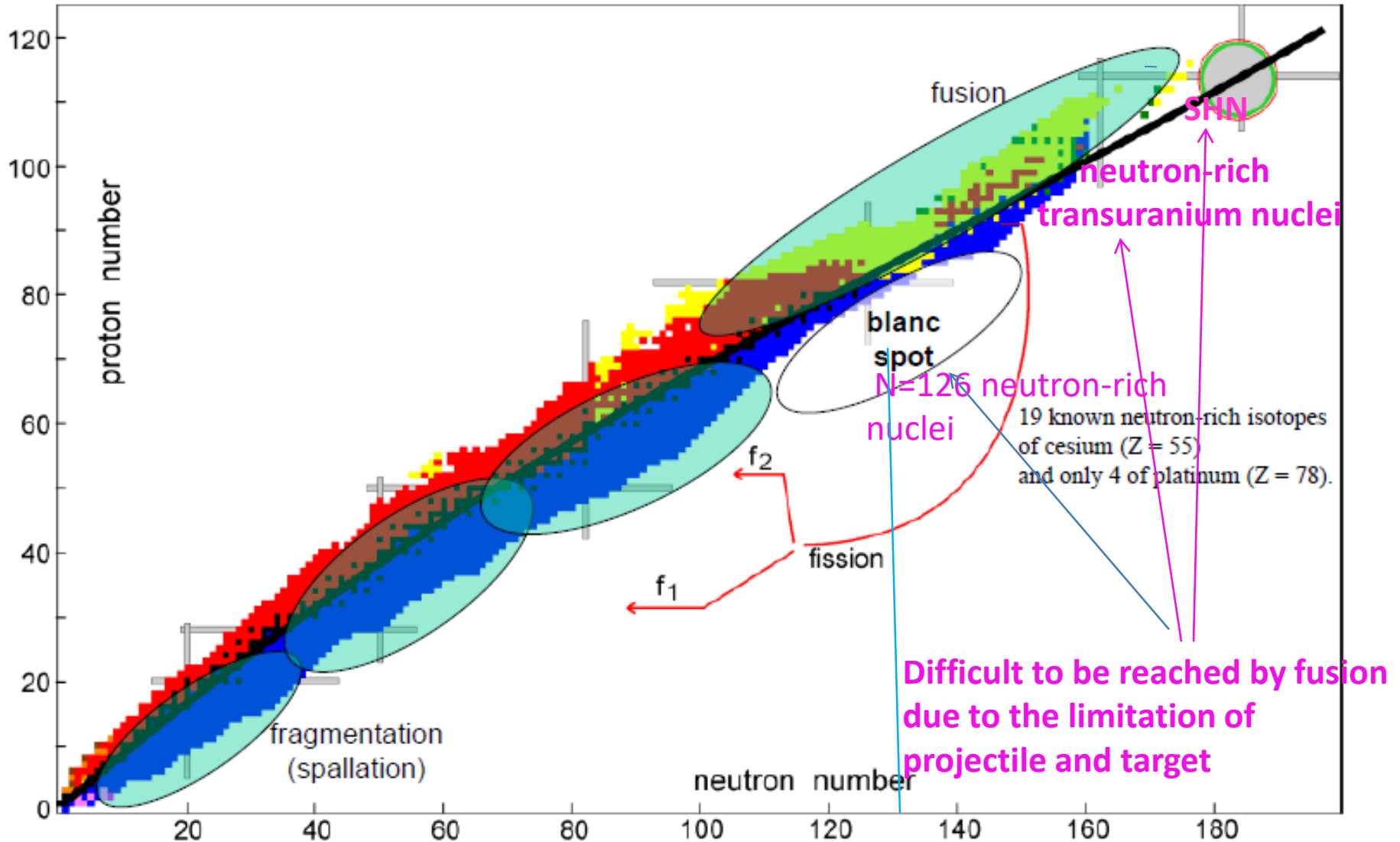
multinucleon transfer

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

“Blanc Spot” on the Nuclear Map



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



25 MeV/u,



$E_{\text{cm}} = 440 \text{ MeV}$



7 MeV/u

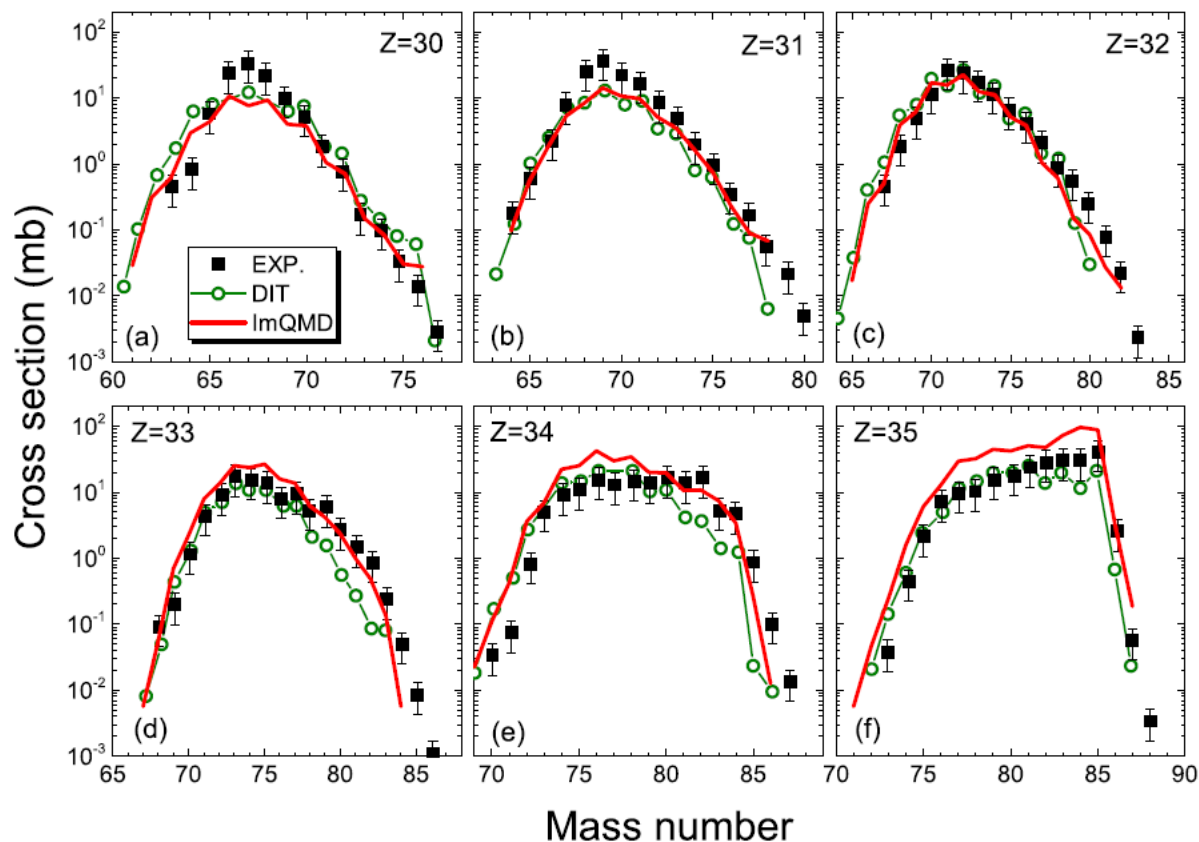
The reaction mechanism evolves with the size of reaction systems

- Intermediate size system**
 $^{86}\text{Kr} + ^{64}\text{Ni}$ at 25 MeV/n
Neutron-rich
understanding the competition between fusion, elastic-inelastic, deep-inelastic and multifragmentation processes
- rare-earth region**
 $^{154}\text{Sm} + ^{160}\text{Gd}$
at $E_{\text{cm}} = 440 \text{ MeV}$
Show the efficiency of MNT on the production of neutron-rich nuclei $Z = 58 - 76$, neutron-rich reaction system
- Actinide nuclei**
 $^{238}\text{U} + ^{238}\text{U}$
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 $^{86}\text{Kr}+^{64}\text{Ni}$ at 25MeV/n

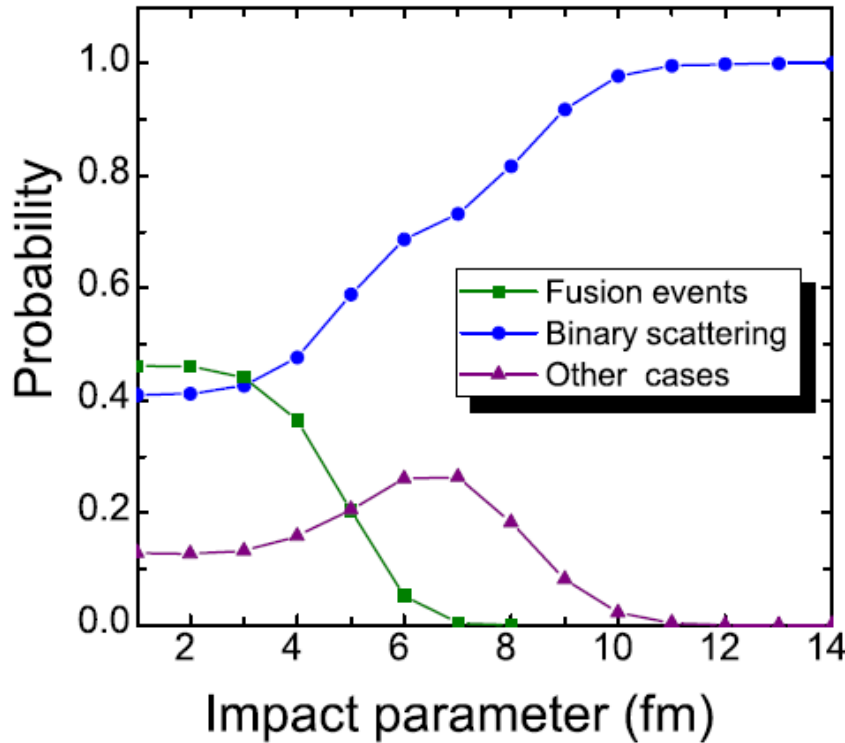
ImQMD +GEMINI calculation

Cross sections of proton removal and neutron pick up isotopes



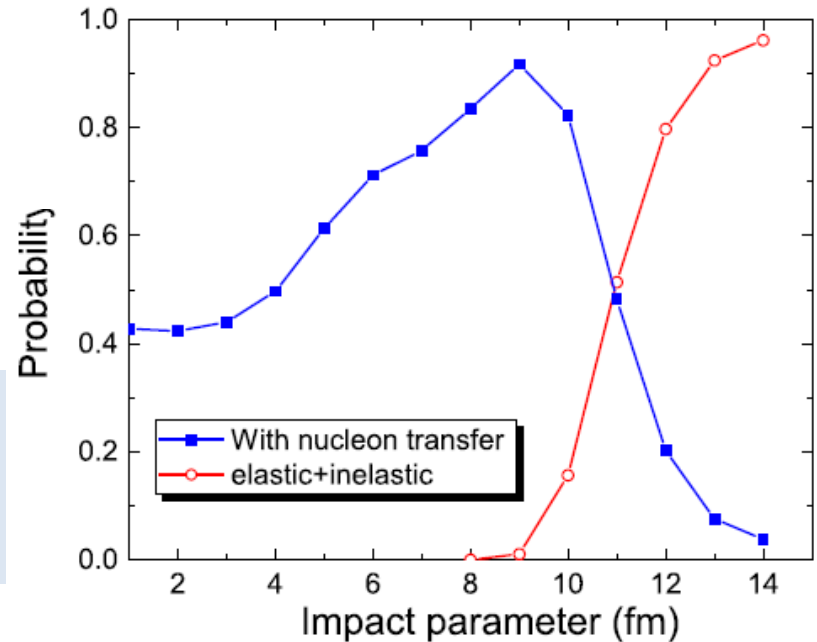
N. Wang , Phys.Rev.C 95,014607(2017)

Exp. Data and DIT/Germiini from G.A. Souliotis et.al Phys.Lett. B543,163



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 8-9fm)



$^{86}\text{Kr} + ^{64}\text{Ni}$ 25MeV/n

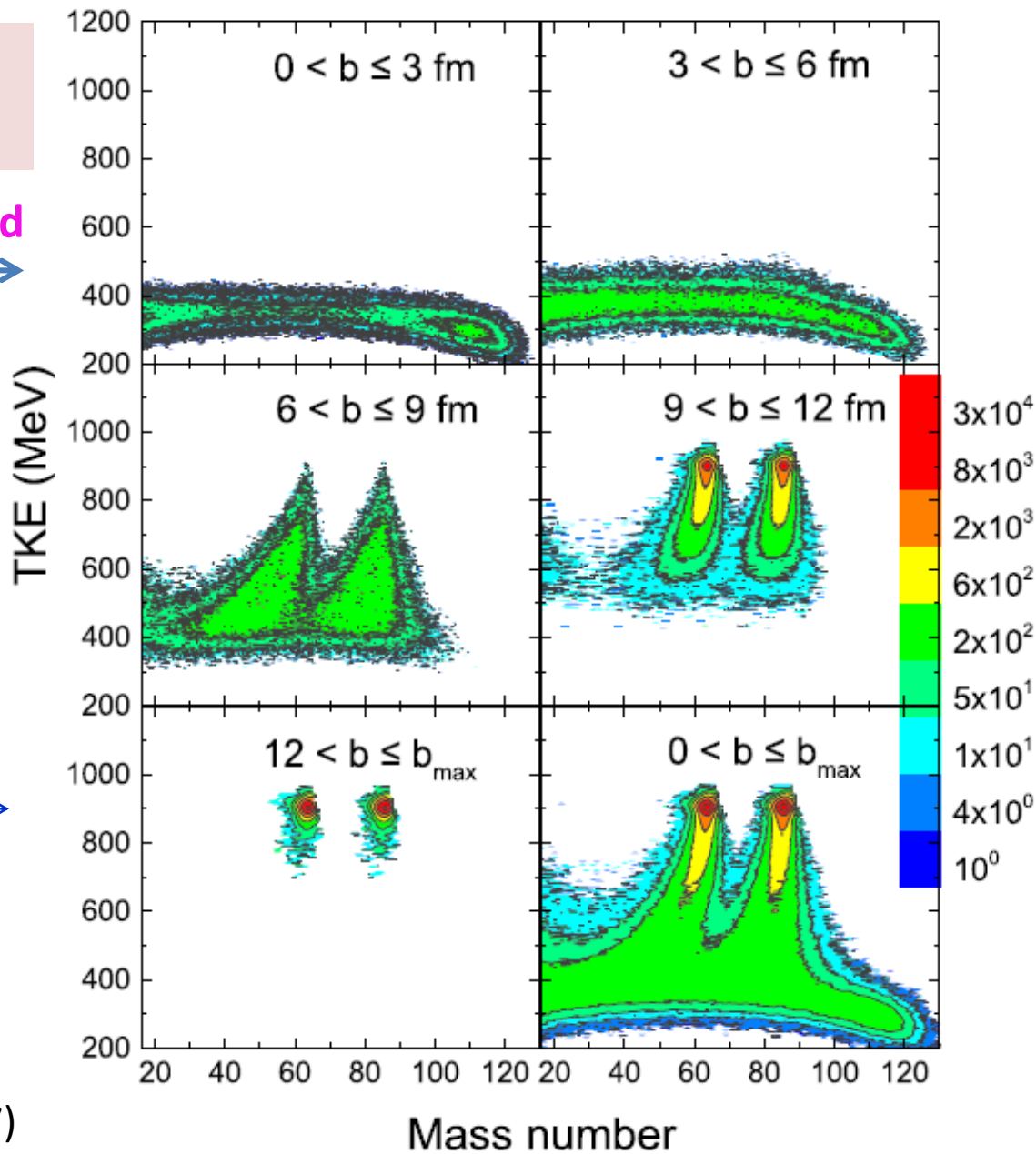
Reaction mechanism evolves with impact parameters

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

MNT dominate →

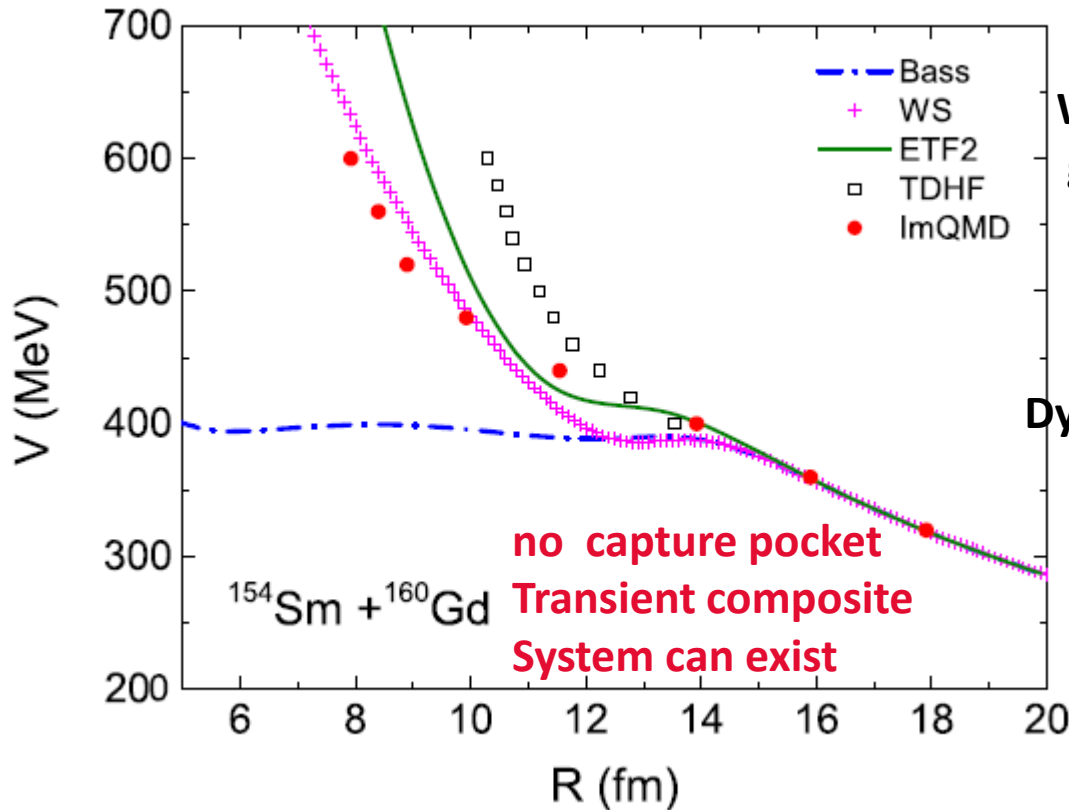
Peripheral collision: Large TKE → Elastic and inelastic scattering

Mass-TKE correlation



MNT in $^{154}\text{Sm}+^{160}\text{Gd}$ at $E_{\text{cm}}=440\text{MeV}$, 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.)

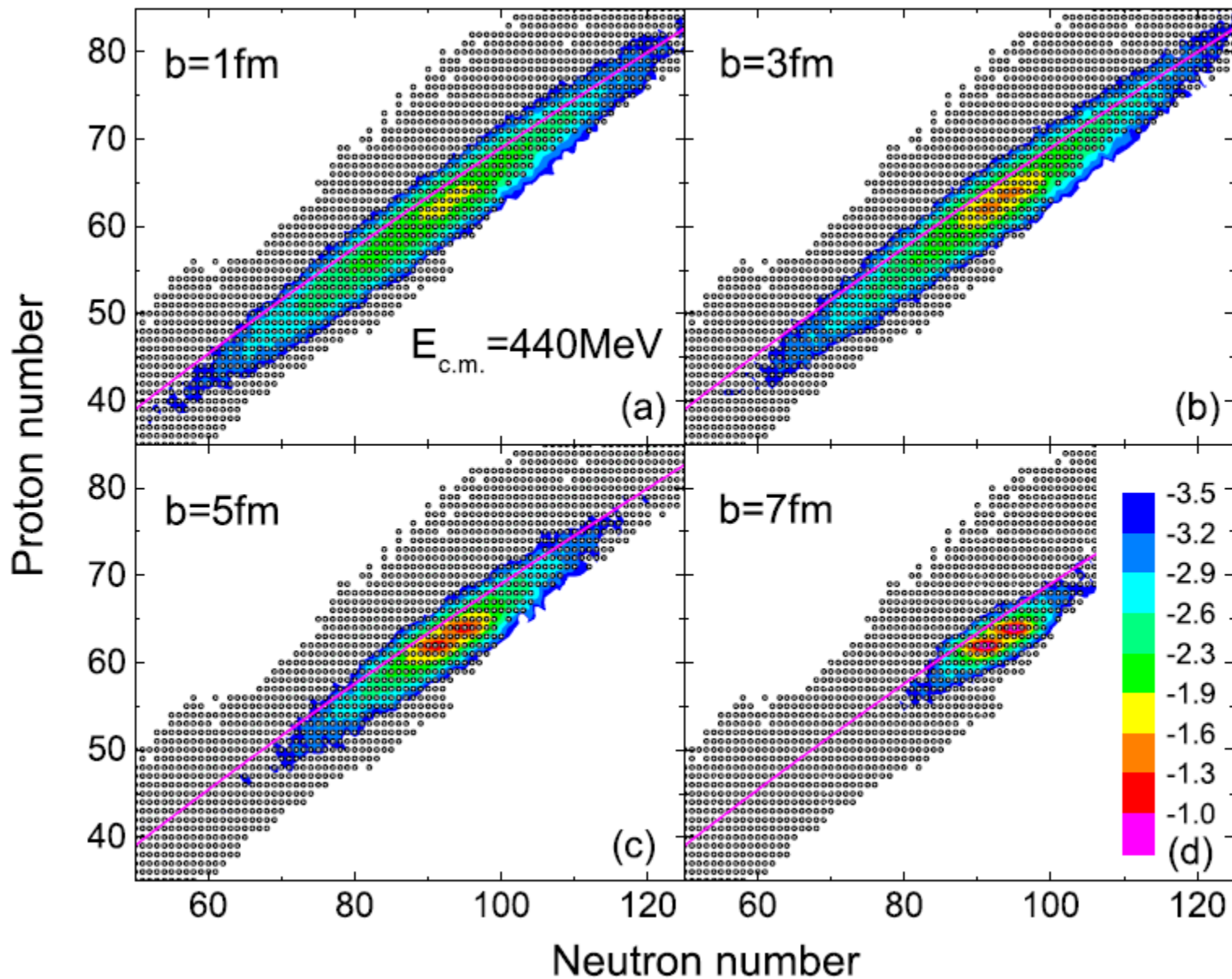
Dynamical pot. given by TDHF and ImQMD

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

Nucleus-nucleus potential

PLB 760,216-241 by Ning Wang,et.al.

Primary fragments(ImQMD t=2000fm/c)



cross sections of neutron-rich new isotopes (Z=58-76)

(ImQMD+GEMINI)

154Sm+160Gd at Ecm=440MeV

Table 1

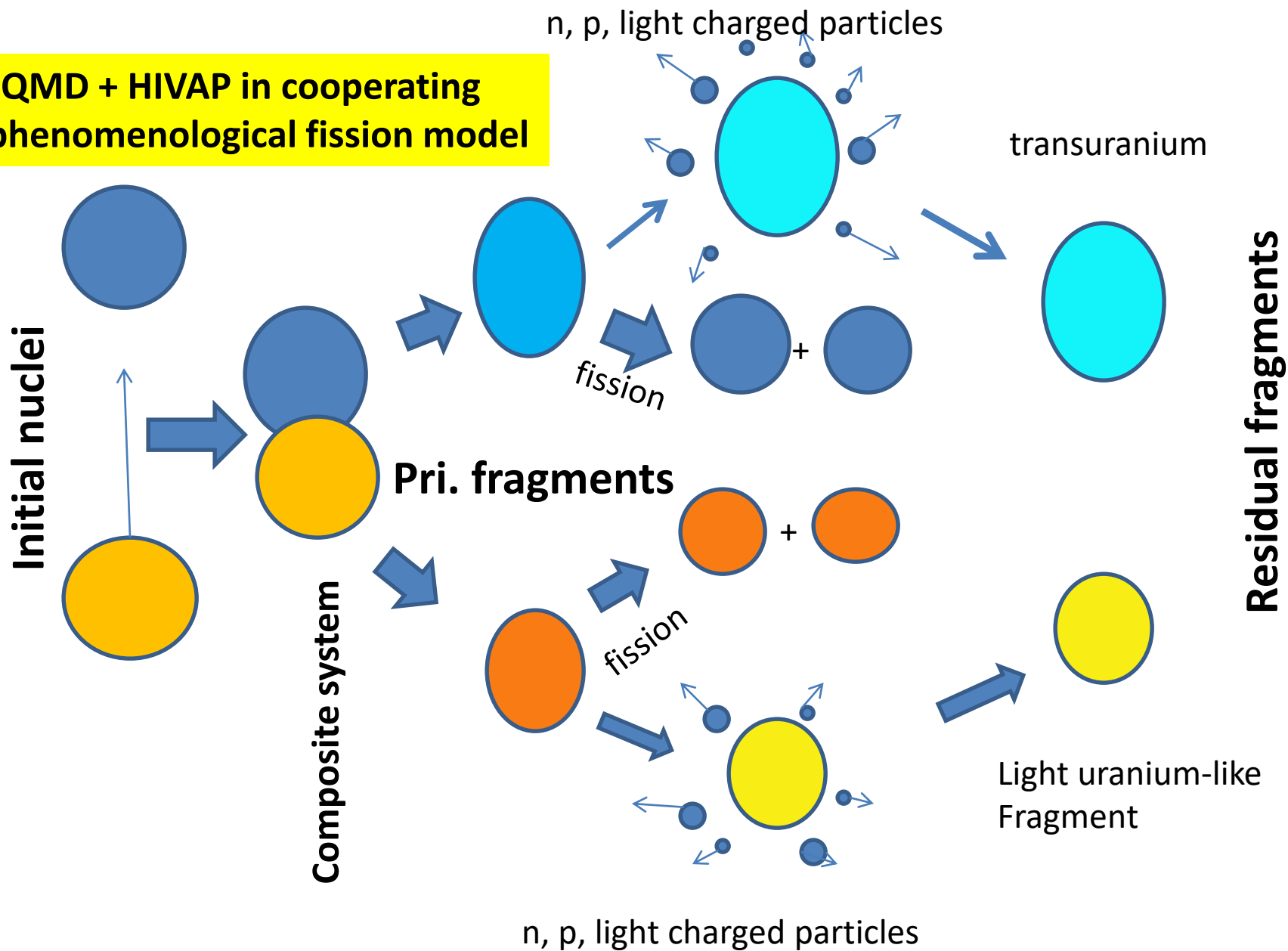
High efficiency!

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.

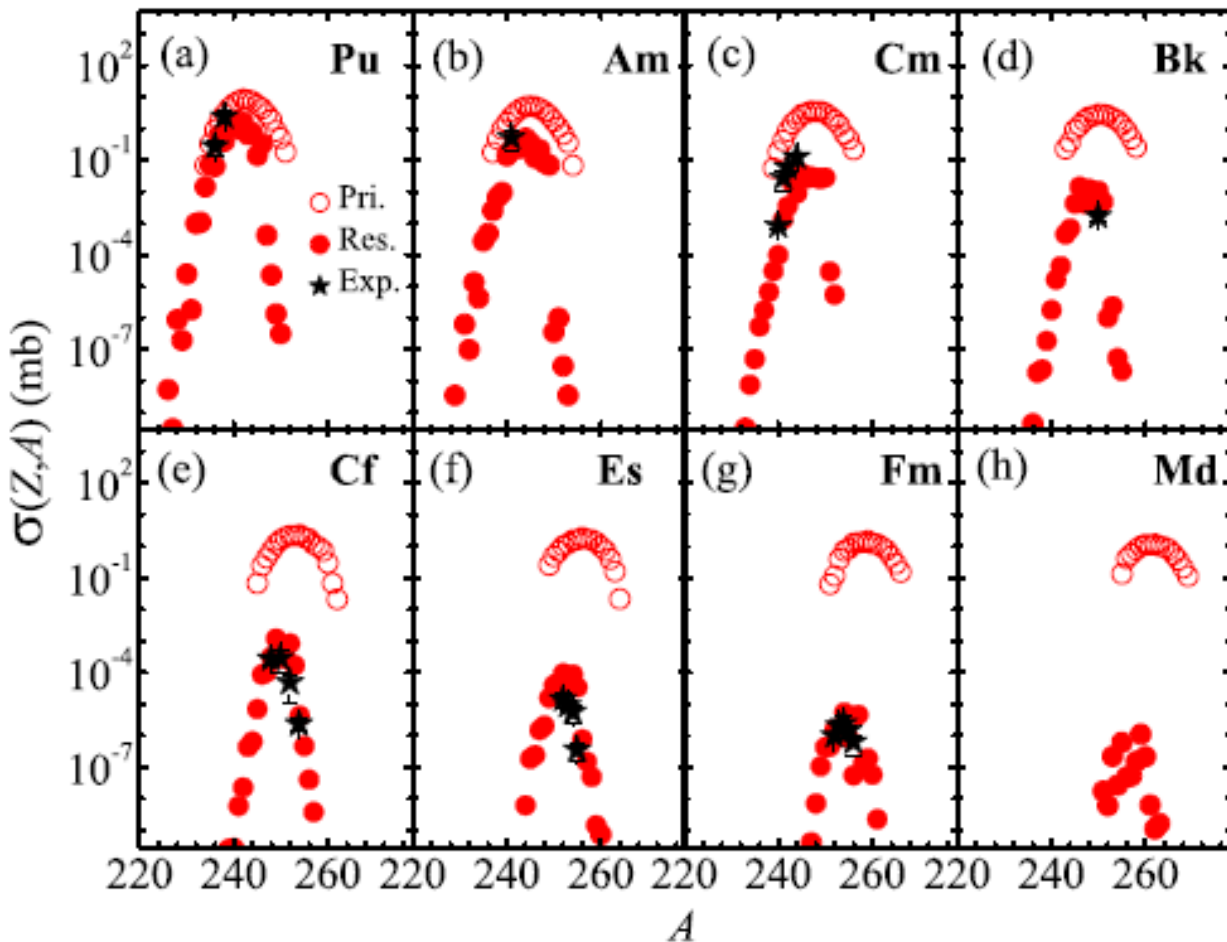
Z	N	$\sigma(\mu\text{b})$	Mass excess (MeV)	Z	N	$\sigma(\mu\text{b})$	Mass excess (MeV)		
58	94	-4p,2n	65	-59.33	68	105	975	-53.77	
62	100	0p,8n	31	-54.52	68	106	549	-52.31	
63	101	1p,9n	256	-52.74	68	107	96	-48.81	
63	102	1p,10n	54	-50.36	68	108	186	-46.89	
64	100		1543	-59.72	68	109	100	-42.98	
64	101		339	-56.29	68	110	44	-40.63	
64	102		194	-54.48	69	108	316	-47.63	
64	103		104	-50.62	69	109	92	-44.28	
65	100		3288	-60.40	69	110	35	-42.02	
65	102		806	-55.82	70	109	463	-46.71	
65	103		140	-52.53	70	110	186	-44.99	
65	104		161	-50.30	70	111	195	-41.38	
65	105		46	-46.41	70	112	46	-39.36	
66	104		469	-53.98	71	111	153	-41.77	
66	105		130	-50.18	71	113	59	-36.45	
66	106		117	-47.99	73	105	9p,9n	1639	-50.32
67	105		656	-51.40	73	116	9p,20n	138	-32.46
67	106		203	-49.33	75	119	11p,23n	54	-27.29
67	107		145	-45.76	76	121	12p,25n	180	-25.08

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

ImQMD + HIVAP in cooperating
a phenomenological fission model



Production of transuranium isotopes



Z=94-101

Features :

Magnitude of cross sections of primary fragments does not change much ,residual fragments decreases 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

Comparison with experimental data

$$\sigma(Z)$$

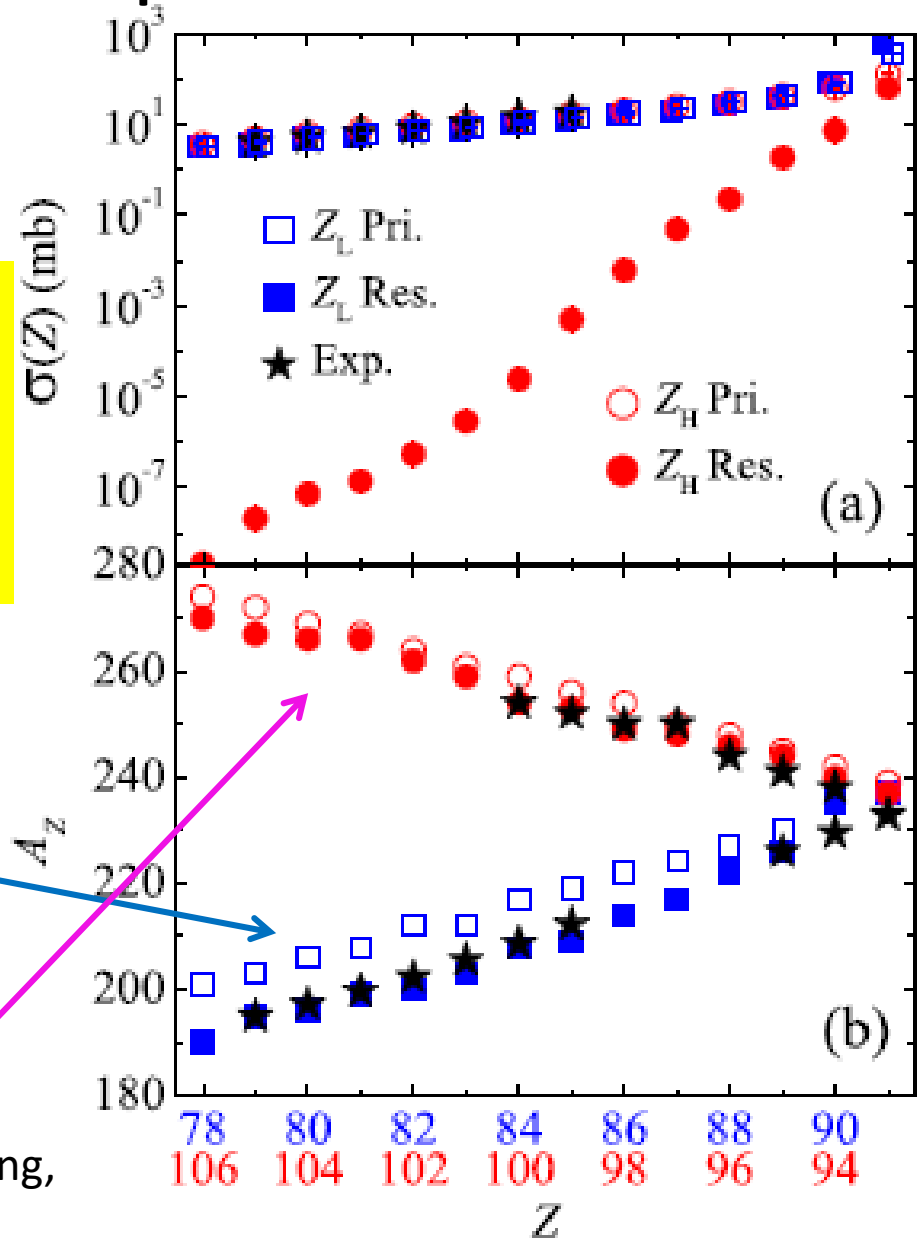
Production cross section of primary and residual fragments with charge Z

light uranium-like fragments
 $\sigma(Z)$ primary and residual similar
 transuranium fragments
 residual fragments decreases exponentially

$$A_Z$$

The mass number of the most probable primary and residual fragments

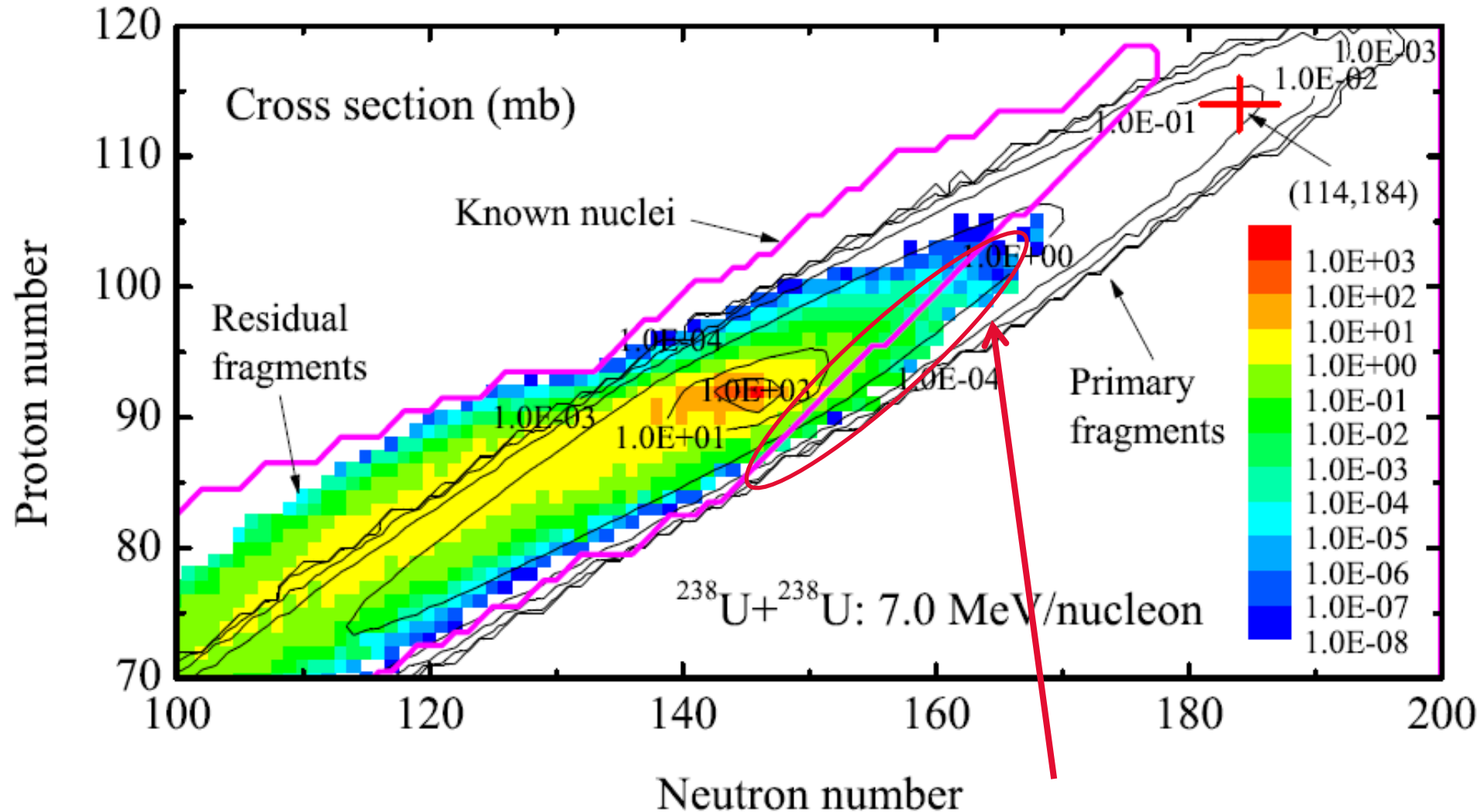
Light uranium fragments
 A_Z pri. fragments is larger than residual fragments
 Transuranium fragments A_Z pri. and resi. fragments are close



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)

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



K. Zhao, Z.Li, etc PRC94,024601 **New neutron-rich transuranium nuclei**
Better trend 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}Rn , ^{249}Cf , and neutron-rich isotopes $^{254-256}\text{Cf}$

Cross sections of pri.frag.



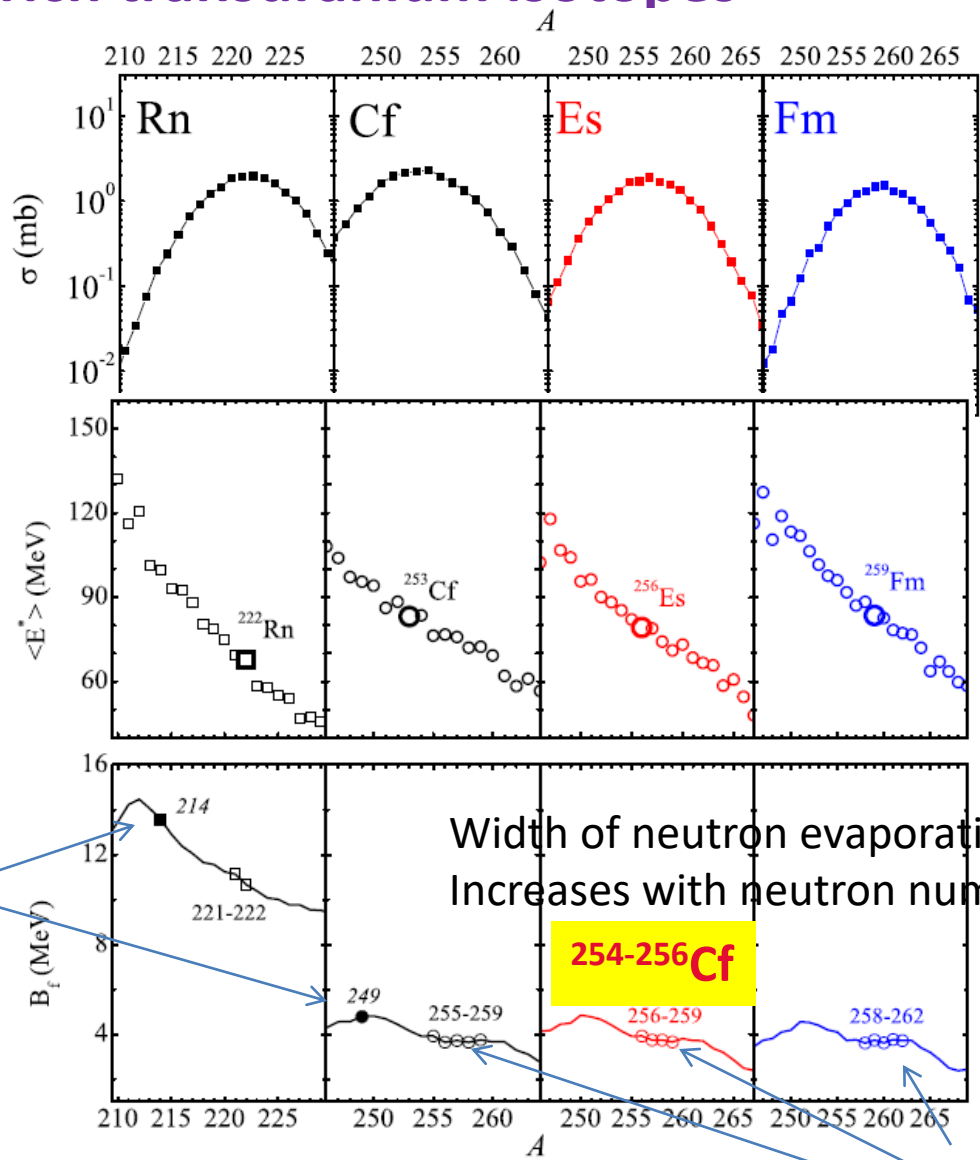
Excitation of pri.frag.



Isotope distribution of fission barrier



Competition between fission and evaporation neutrons



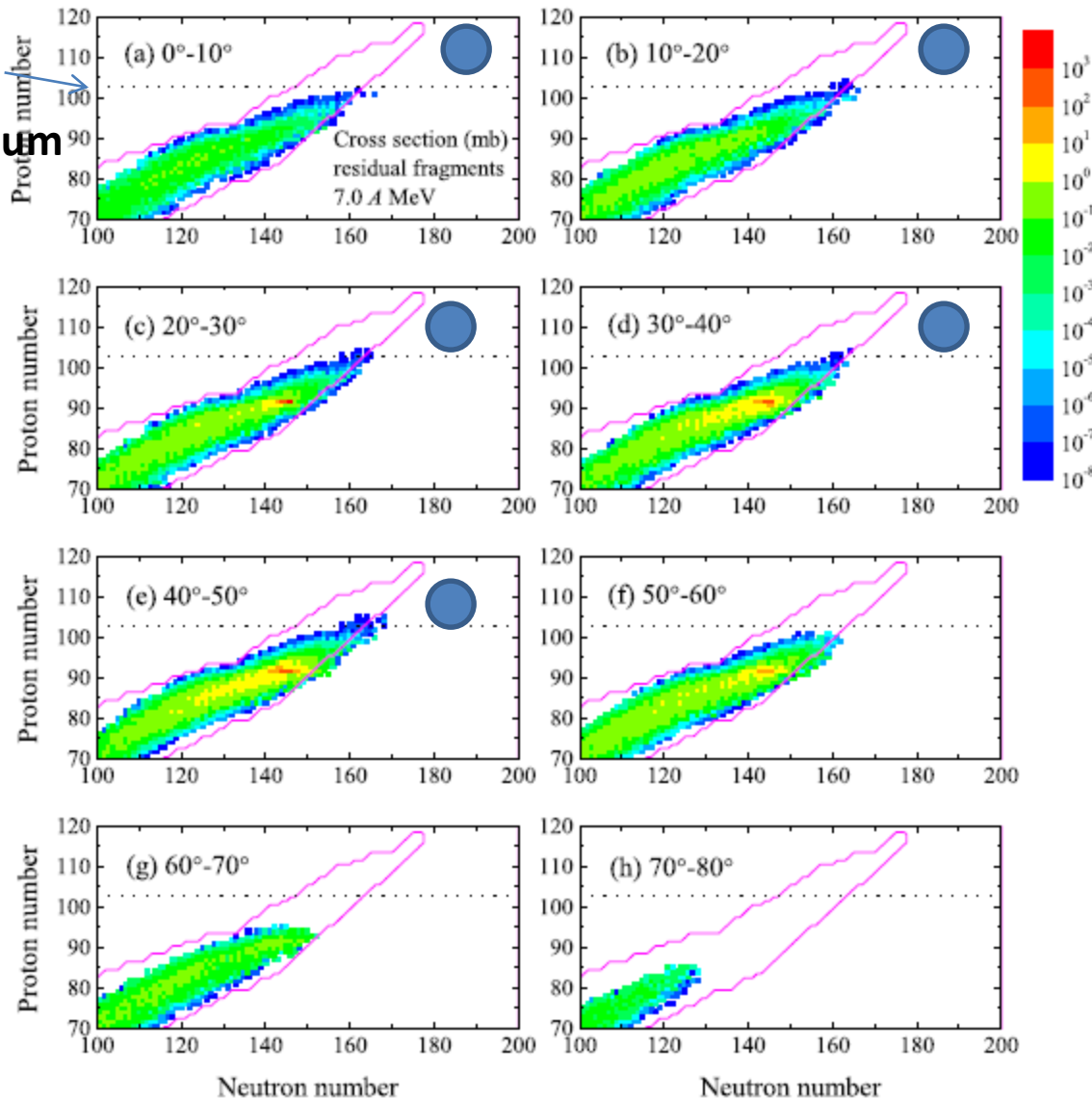
Width of neutron evaporation
 Increases with neutron number

254-256 Cf

Flat part

Outgoing angle distribution of residual fragments

Lr
Lawrencium



●
outgoing angles (lab)
of heavy transuranium
residual fragments

Useful for experimental
measurement

Summary and discussion

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

<http://www.ktf-split.hr/periodni/en/>

PERIOD	GROUP I IA	GROUP IUPAC	GROUP CAS	GROUP IUPAC	GROUP CAS	GROUP IUPAC	GROUP CAS	GROUP IUPAC	GROUP CAS	GROUP IUPAC	GROUP CAS	GROUP IUPAC	GROUP CAS	GROUP IUPAC	GROUP CAS	GROUP IUPAC	GROUP CAS	
1	1 1.0079 H HYDROGEN	2 4.0026 He HELIUM																
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM	5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON										
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM	13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON										
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIObIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM	114 (289) Uuq UNUNQUADIUM					

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LANTHANIDE														
57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.04 Yb YTTTERBIUM	71 174.97 Lu LUTETIUM
ACTINIDE														
89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
Relative atomic mass is shown with five significant figures. For elements with no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivard@netlinx.com)

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