Super Heavy Element Studies at RAON

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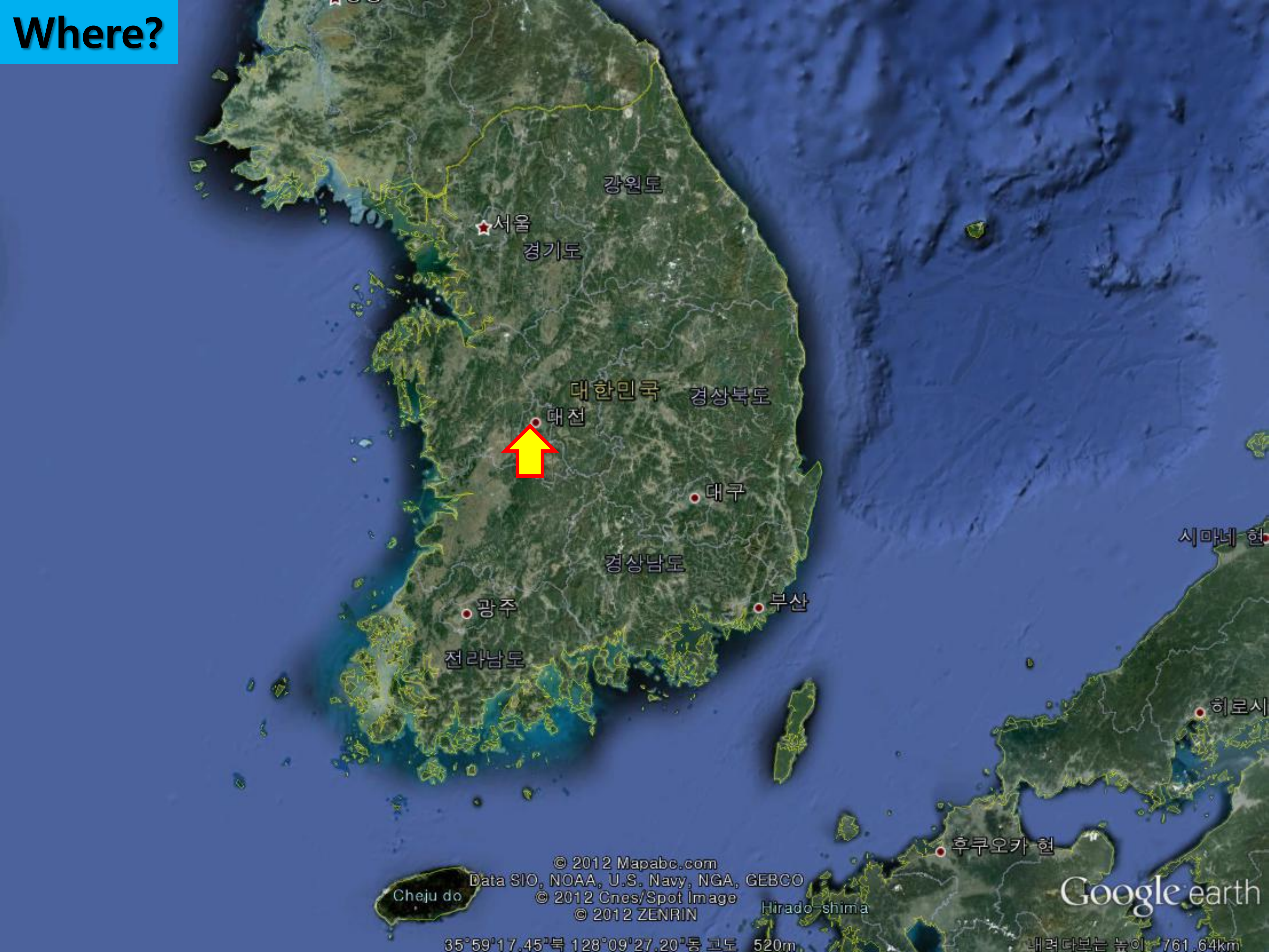
Happy Birthday, James!!!

라온 (RAON): RISP accelerator complex,
a pure Korean word, meaning “delightful” or “happy”

Based on Baseline Design Summary (August 2012) and RISP domestic science meeting (February 2013).

Where?


강원도
서울
경기도
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경상북도
대전
대구
경상남도
광주
부산
전라남도
시마네 현
후쿠오카 현
Cheju do
Hirado-shima
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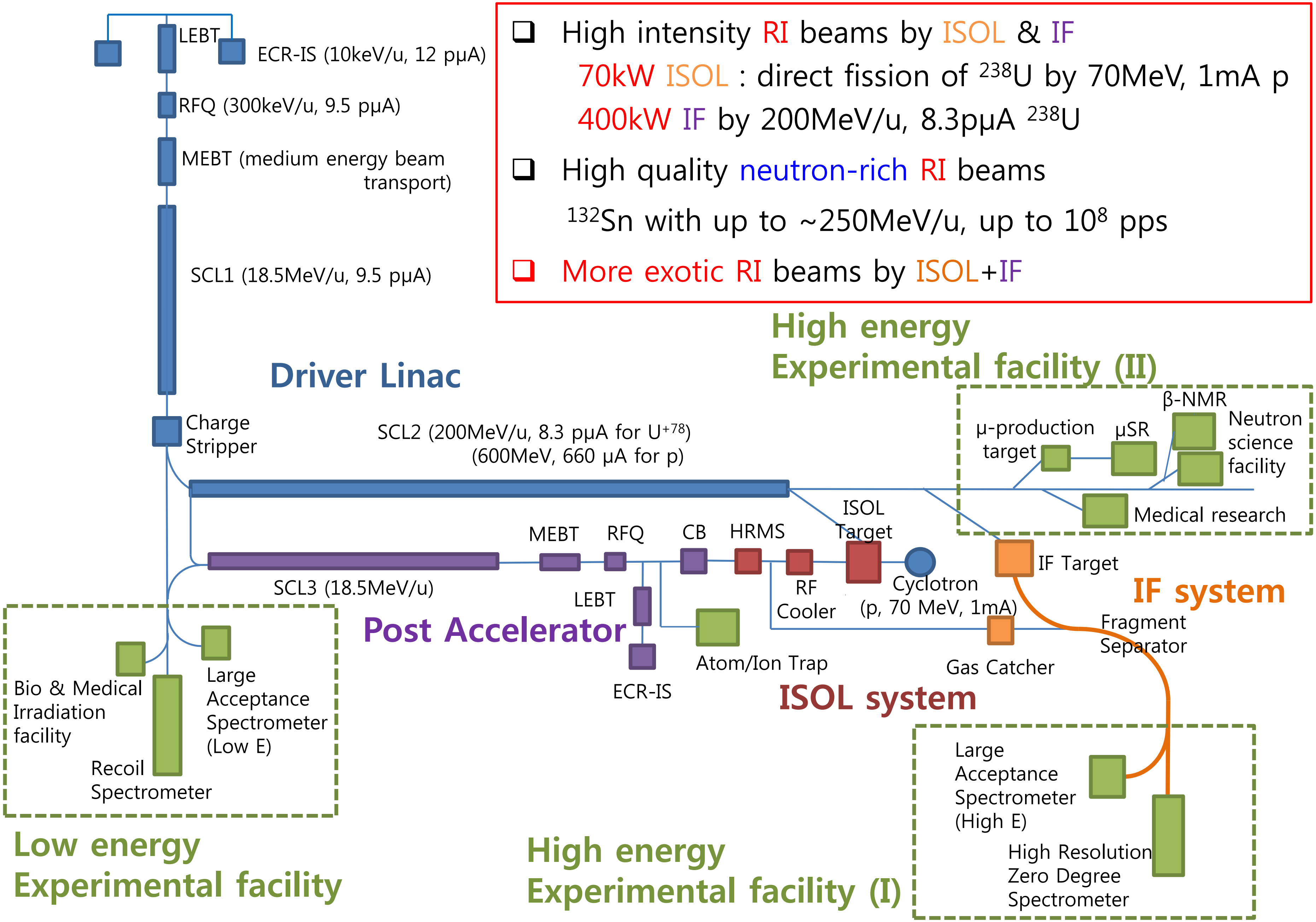
Google earth
35°59'17.45"북 128°09'27.20"동 고도 520m
내려다보는 높이 761.64km

RAON: RISP Accelerator Complex

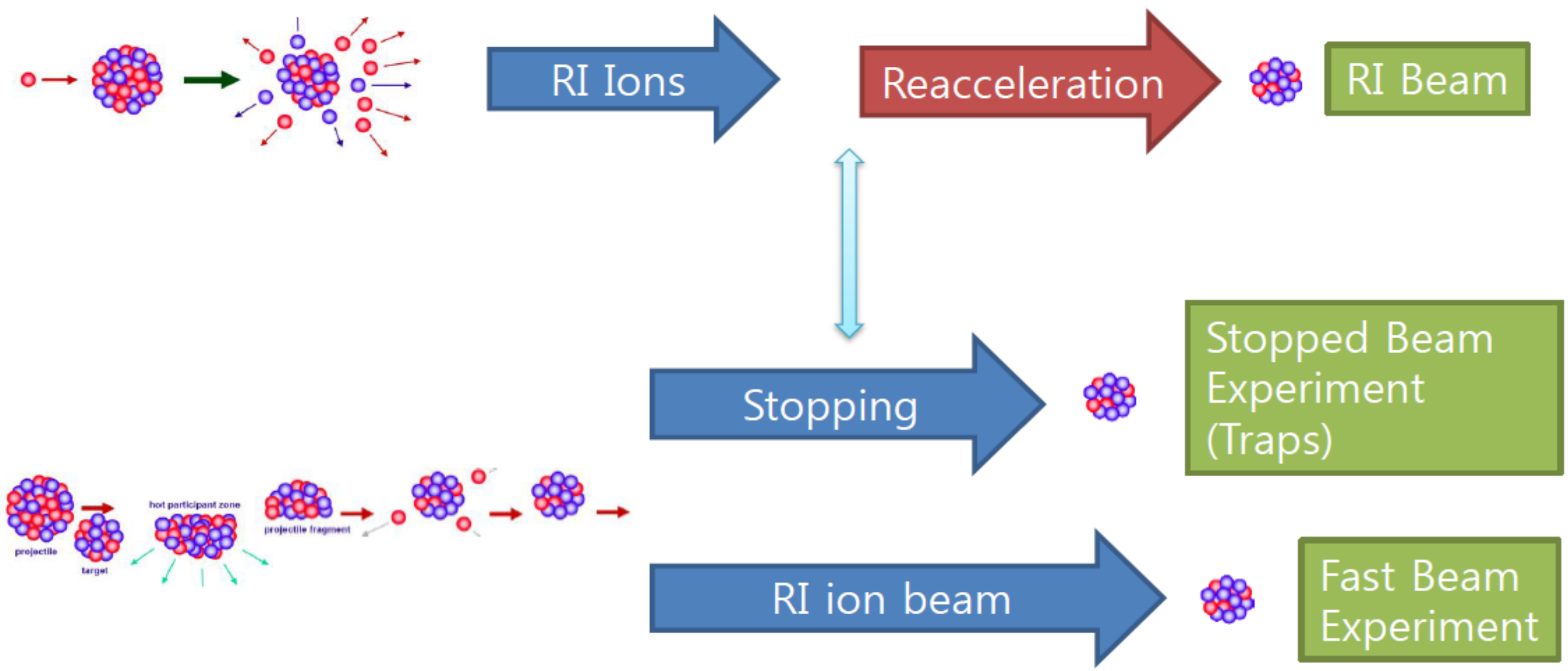
- ❑ High intensity RI beams by ISOL & IF
  - 70kW ISOL : direct fission of ^{238}U by 70MeV, 1mA p
  - 400kW IF by 200MeV/u, 8.3pμA ^{238}U
- ❑ High quality neutron-rich RI beams
  - ^{132}Sn with up to ~250MeV/u, up to 10^{8} pps
- ❑ More exotic RI beams by ISOL+IF



* ISOL-type facilities: radioactive ions are produced at rest in a thick target either by direct bombardment with particles from a driver accelerator or via fission induced both by fast and thermal secondary neutrons.

* In-flight (IF) facilities: a high energy ion beam is fragmented in a suitable thin target and the reaction products are and then transported to the secondary target.

ISOL(Isotope Separator On-Line)
p → thick target (eg. Uranium Carbide) → target spallation or fission (low energy)



IF(In-Flight Fragmentation)
Stable Heavy ion beam → thin target → projectile fragmentation (high energy)

Key Science Drivers of RISP

- **Highest priority research subjects**
  - Nuclear reaction experiments important to **nuclear-astrophysics** : e.g. $^{15}O(a,\gamma)^{19}Ne$, $^{45}V(p,\gamma)^{46}Cr$
  - Search for **super heavy elements**: $Z > 119$ ($Z \sim 120$)
  - Nuclear structure of **n-rich RI**: @ near N=126, @ 80<A<140
  - **Nuclear symmetry energy** at sub-saturation density
  - **Precision mass measurement** & Laser spectroscopy

- **Important scientific applications**
  - Material science : **β-NMR, μSR**
  - Medical and bio-science : **RI beam irradiation**
  - **Nuclear data** for Gen-IV NPP and nuclear waste transmutation

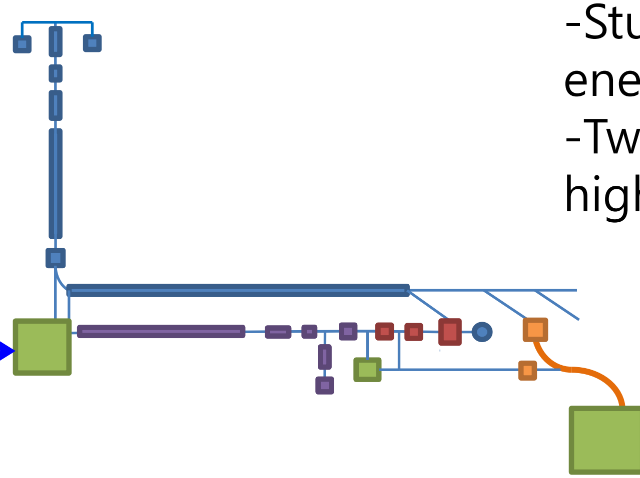
Rare Isotope Science Project

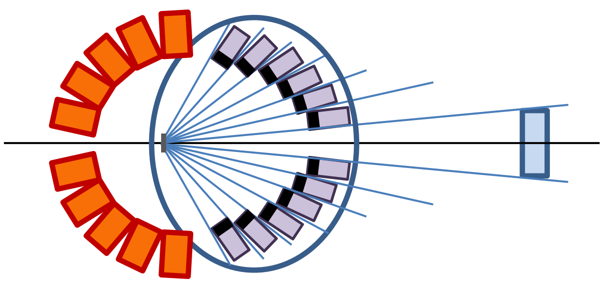
Experimental System

- **RISP experimental facility**
  - **Nuclear Science Facility**
    Reaction probability for nuclear astrophysics and nucleo-synthesis
    - **Recoil spectrometer**
    - **Large acceptance spectrometer**
    - **High resolution spectrometer & Zero-degree spectrometer**
  - **Application facility**
    Property of new materials, new method for cancer therapy, and nuclear data
    - **ß-Nuclear magnetic resonance(ß-NMR)& μ-spin rotation/relaxation (μ-SR)**
    - **Atom trap & Laser spectroscopy**
    - **Bio-medical facility**
    - **Neutron science facility**

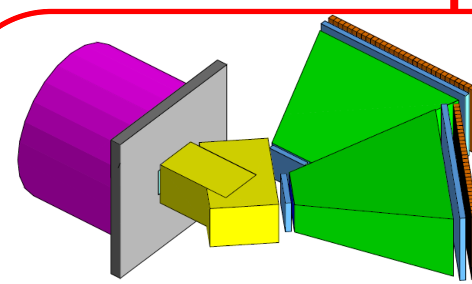
Large-Acceptance Multipurpose Spectrometer (LAMPS)

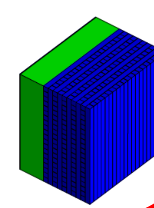
-Study of nuclear symmetry energy with RI and stable beam
-Two detector setup for low and high energy





LAMPS at low-energy exp. hall (LAMPS-L)





LAMPS at high-energy exp. hall (LAMPS-H)

- Nuclear symmetry energy

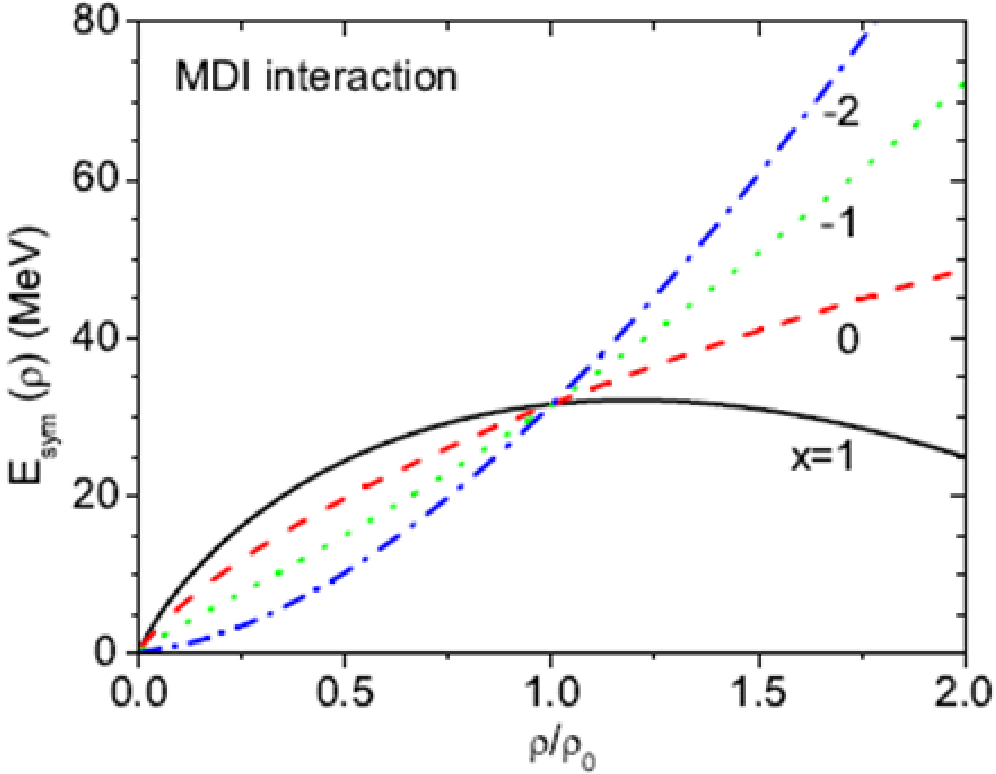
$$m = Zm_p + Nm_n - \frac{E_B}{c^2}$$

$$E_{\mathrm{B}} = a_{\mathrm{v}} A - a_a (N-Z)^2/A - a_c Z^2/A^{1/3} \\ - a_s A^{2/3} \pm a_\delta / A^{3/4}$$

$$E(\rho, \tilde{\alpha}) \simeq E(\rho, 0) + S_2(\rho)\tilde{\alpha}^2 \,,$$

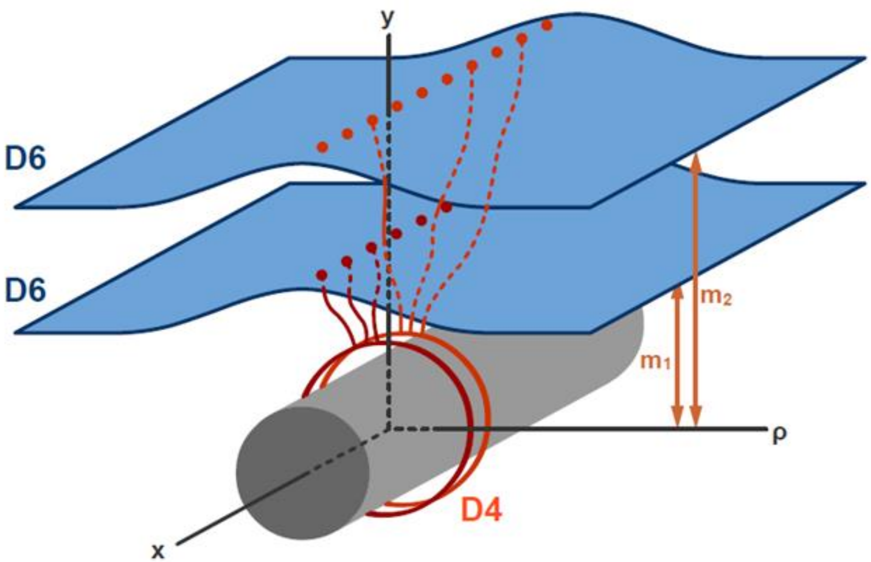
$$\tilde{\alpha} \equiv (N - Z)/A$$

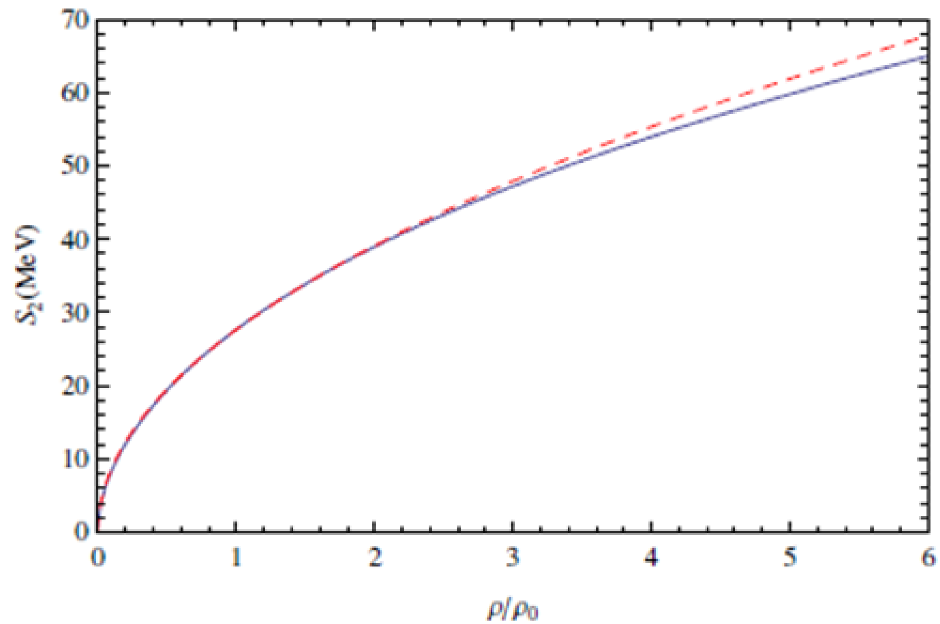
Z (N) is the number of protons (neutrons) in a nucleus.



Depending on the value of the parameter x, various high density behaviors are possible

L.W. Chen, C.M. Ko, and B.A. Li, Phys. Rev. Lett. 94, 032701 (2005)





Y. Kim, Y. Seo, I. J. Shin, and S.-J. Sin, JHEP 1106:011,2011

KOBRA (Korea Broad acceptance Recoil spectrometer and Apparatus)

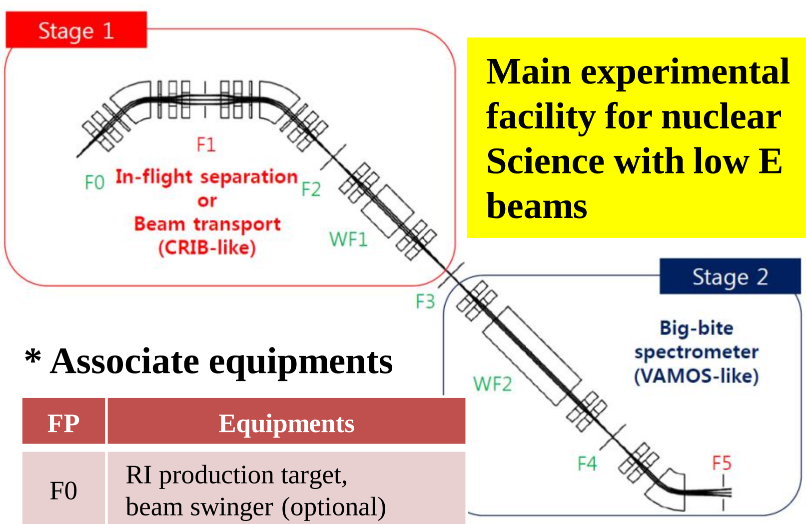
"The Low Energy Nuclear Physics Program is carrying out an outstanding program of high impact science with exciting directions for the future…"

Report of the NSAC subcommittee on Low Energy Nuclear Physics (2001)

KOBRA
High performance
spectrometer with detection system

@

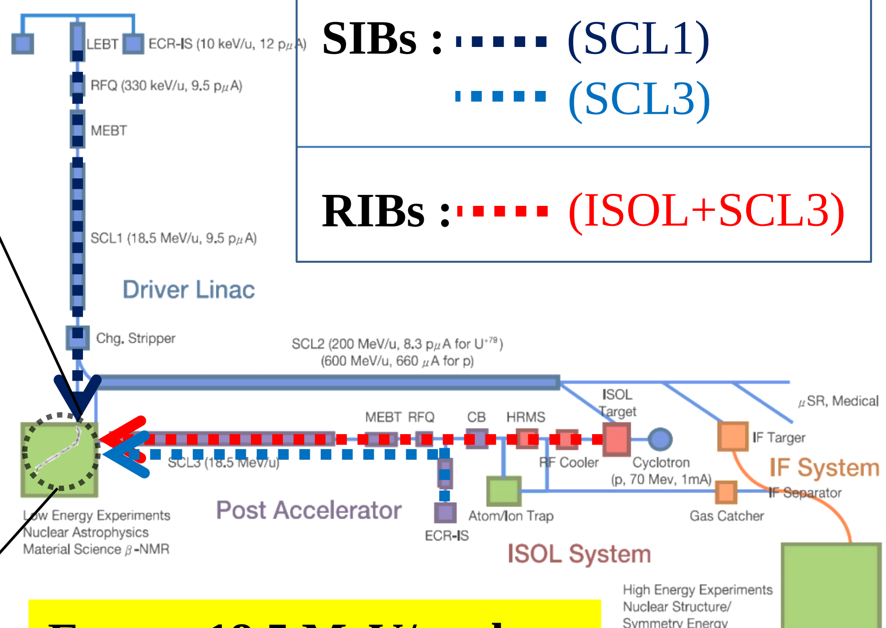
RAON
High quality & Low Energy
stable and radioactive ion beams



Main experimental facility for nuclear Science with low E beams

*** Associate equipments**

FP	Equipments
F0	RI production target, beam swinger (optional)
F3	gas-jet target, gamma-array, detection system, β-NMR
F5	Focal plane detection system



SIBs : ▪▪▪▪▪ (SCL1)
▪▪▪▪▪ (SCL3)

RIBs : ▪▪▪▪▪ (ISOL+SCL3)

E_{beam} < 18.5 MeV/nucleon

Science program

Nuclear structure

- Charge symmetry and charge independence in isobaric mirror nuclei at drip lines
- Two proton radioactivity – new radioactive decay phenomena
- Continuum states in unbound nuclei
- Spin physics – dipole/quadrupole moment, Island of inversion, Magic number

Nuclear astrophysics

- capture reactions – (p,gamma), (alpha,gamma), (n,gamma)
- resonant scattering – proton & alpha resonant elastic scattering
- transfer reactions – (d,p) / (alpha,p) reactions

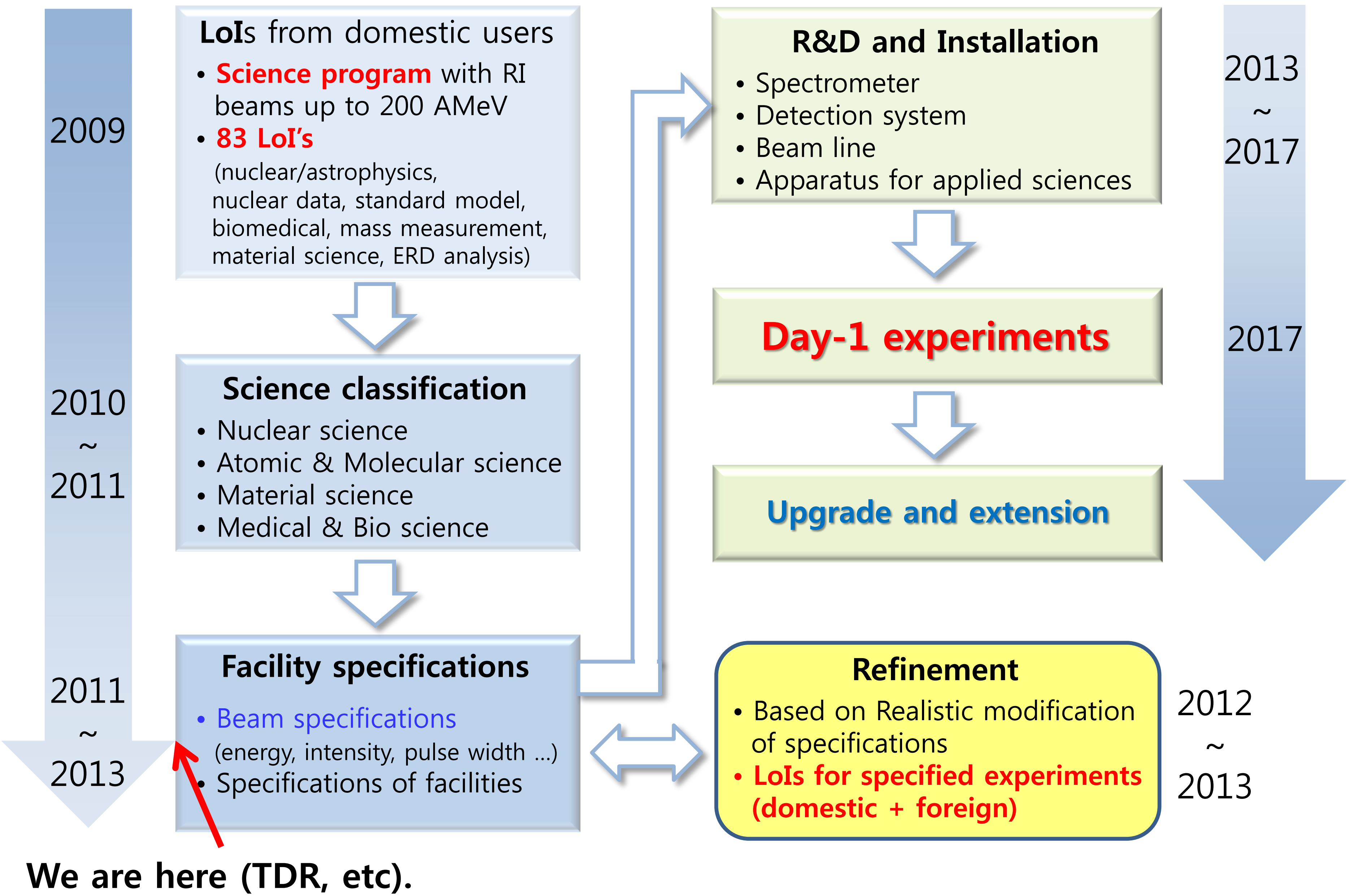
Rare event study

- super heavy elements search
- decay spectroscopy

Symmetry energy

- PDR (pigmy dipole resonance)
- GDR (giant dipole resonance)
- LAMP-L

Development Plan



Science program with beam schedule

(as of this February, subject to change)

Beam schedule	Science program	Exp. facility♯	Beam species on exp. target: Day1†	Beam species on exp. target: Extra 2 Years	Beam Intensity on exp. target (pps) (required/expected)
2017.June.1 ~ from SCL1 (<18.5 MeV/u)	Nuclear structure SHE search, rp-process, Spin physics	RS	^{58}Fe	^{64}Ni, ^{26m}Al (^{28}Si), ^{25}Al (^{28}Si), ^{44}Ti (^{42}Ca), ^{14,15}O (^{15}N)	^{15}N, ^{58}Fe ($<10^{9-10}$) ^{28}Si, ^{42}Ca, ^{64}Ni ($<10^{7}$) ^{25}Al, ^{26m}Al, ^{44}Ti, ^{14,15}O: (10^{5-6})
	Pigmy dipole resonance	LAS-L	^{58}Ni	^{40}Ca, ^{112}Sn	(10^{6-8} / $<10^{9-10}$)
	Biological effects	BM	^{12}C		($<10^{12}$ / $>10^{12}$)
2017.July.1 ~ from ISOL (~5 keV/u)	Fine structure, mass measurement	AT/LS	^{132}Sn	$^{130-135}$Sn	^{132}Sn ($<10^{5}$ / 10^{7})
2018.Jan.1 ~ ISOL-SCL3 (<18.5 MeV/u)	r-process	RS	^{132}Sn	$^{130-135}$Sn	^{132}Sn (10^{6} / 10^{7}), $^{130-135}$Sn (10^{3-6} / 10^{3-7})
	Pigmy dipole resonance	LAS-L	^{132}Sn	$^{60+n}$Ni, $^{130-135}$Sn	^{65,66}Ni (10^{6-8} / 10^{6-7})
SCL1-SCL2 (~ hundreds MeV/u)	New materials	μSR	Muon by (p, πx)→μ		p ~full intensity, μ (10^{8}/10^{9})
	Biological effects	BM	^{12}C		($<10^{12}$ / $>10^{12}$)
	Baseline experiments, Spin physics	LAS-H	^{40}Ca	^{58}Ni, ^{112}Sn, ^{132}Xe	(10^{6}~10^{8} / $<10^{9-11}$)
SCL1-SCL2(X) (~ tens MeV/u)	New material, Polarized beam	β-NMR	^{8}Li by (d,α)	^{11}Be	p, d ~full intensity, n ($<10^{12}$ / 10^{12}) ^{8}Li (10^{8} / 10^{9}), ^{11}Be(10^{7} / 10^{8})
	Neutron cross section	NSF	n by (p,n) (d,n)		
2018.Mar.1 ~ SCL1-SCL2-IF (~ hundreds MeV/u)	Nuclear structure	ZDS & HRS	^{128}Sn	^{132}Sn, ^{18}O	^{128}Sn (10^{6-8} / 10^{7}), ^{132}Sn (10^{6-8} / 10^{6})‡
	Symmetry energy	LAS-H	^{128}Sn	^{132}Sn, $^{44+n}$Ca, $^{60+n}$Ni, ^{144}Xe	
2018.Sep.1 ~ ISOL-SCL3-SCL2-IF(X) (~ hundreds MeV/u)	Nuclear structure	ZDS & HRS	^{132}Sn		^{132}Sn (10^{6-8} / 10^{7}), ^{144}Xe (10^{6-8} / 10^{6})
	Symmetry energy	LAS-H	^{132}Sn	^{144}Xe	

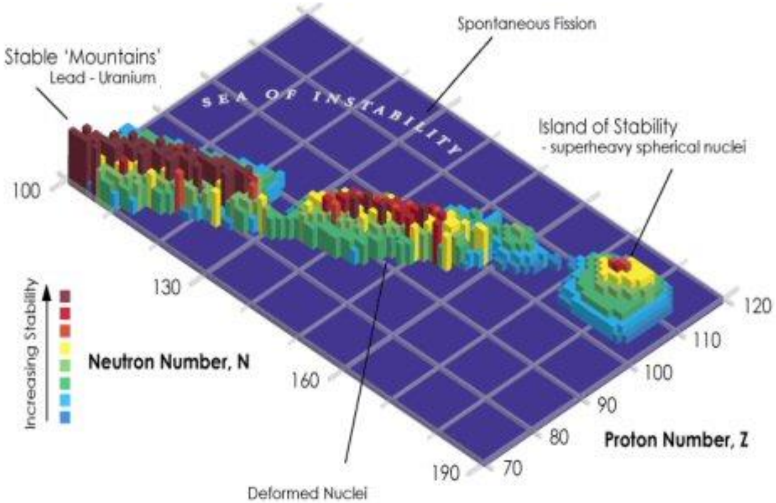
♯ **RS**: Recoil Spectrometer, **LAS**: Large Acceptance Spectrometer, **BM**: Bio & Medical, **AT/LS**: Atom Trap & Laser Spectrometer, **NSF**: Neutron Science Facility, **ZDS**: Zero Degree Spectrometer, **HRS**: High Resolution Spectrometer, † Beam purity >50 % from ISOL, Beam species : SI(black), RI(Blue), ‡ Beam available on Sep. 2018

Theory at RISP

- Nuclear reactions
- Nuclear structures
- Chiral EFT
- …

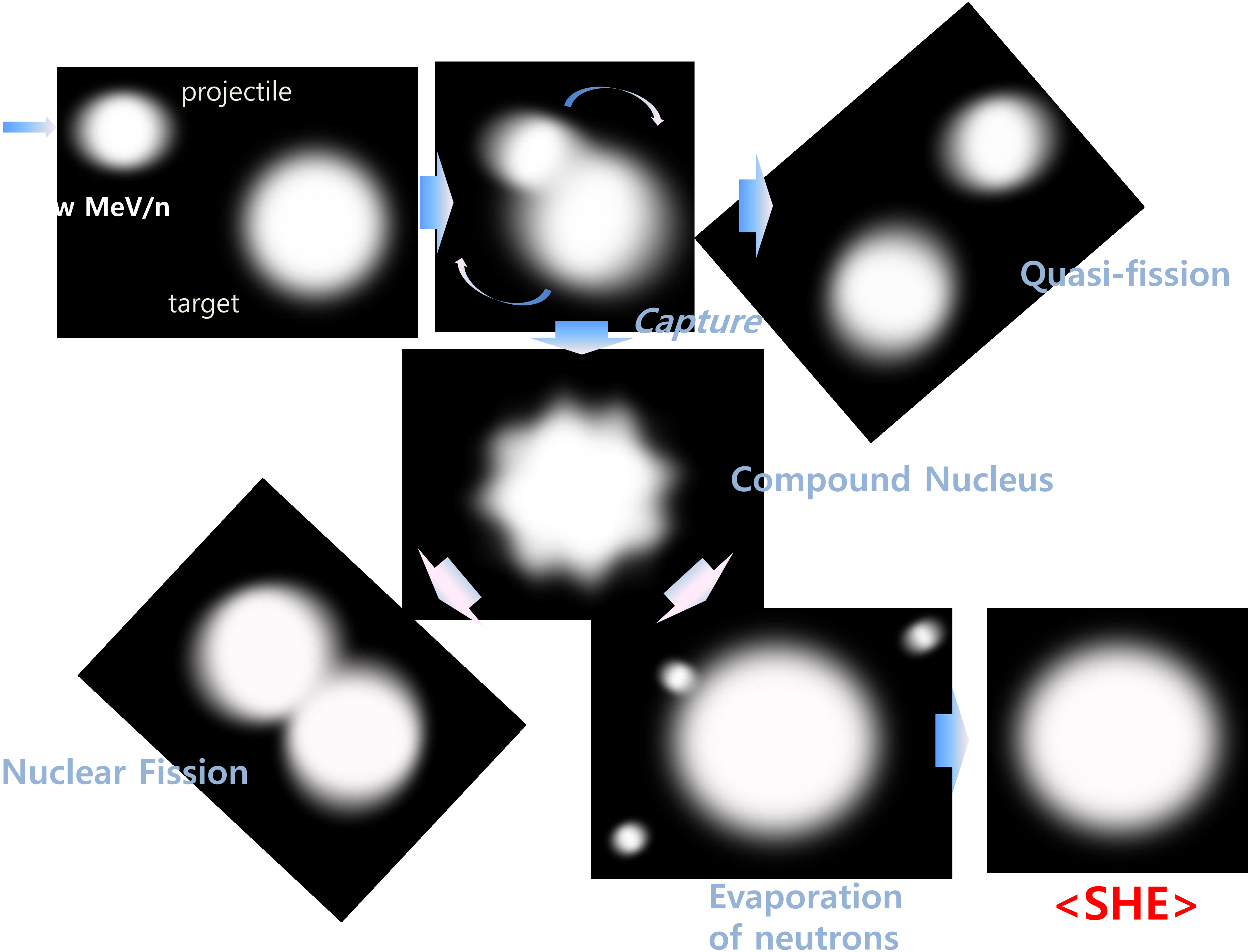
- Nuclear transport
- (Nuclear) astrophysics
- Particle (hadron) physics
- …

Super Heavy Element at RAON?



Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

- ✓ New heavy elements discovered and got their names (May, 2012)
  - Z=114 Flerovium (JINR, Dubna)
  - Z=116 Livermorium (JINR, Dubna)
- ✓ An island of stability at large atomic number has been expected. There can be exist spherical(deformed) shape super heavy elements.
- ✓ Already, super heavy elements up to Z=118 are experimentally observed.
- ✓ To reach Z>118, we need to study properties related to the synthesis of super heavy elements carefully.


projectile
w MeV/n
target
Capture
Quasi-fission
Compound Nucleus
Nuclear Fission
Evaporation
of neutrons
<SHE>

SHE in DNS concept

(V.V Volkov, G.G. Adamian, N.V. Antonenko, A.K. Nasirov, et al)

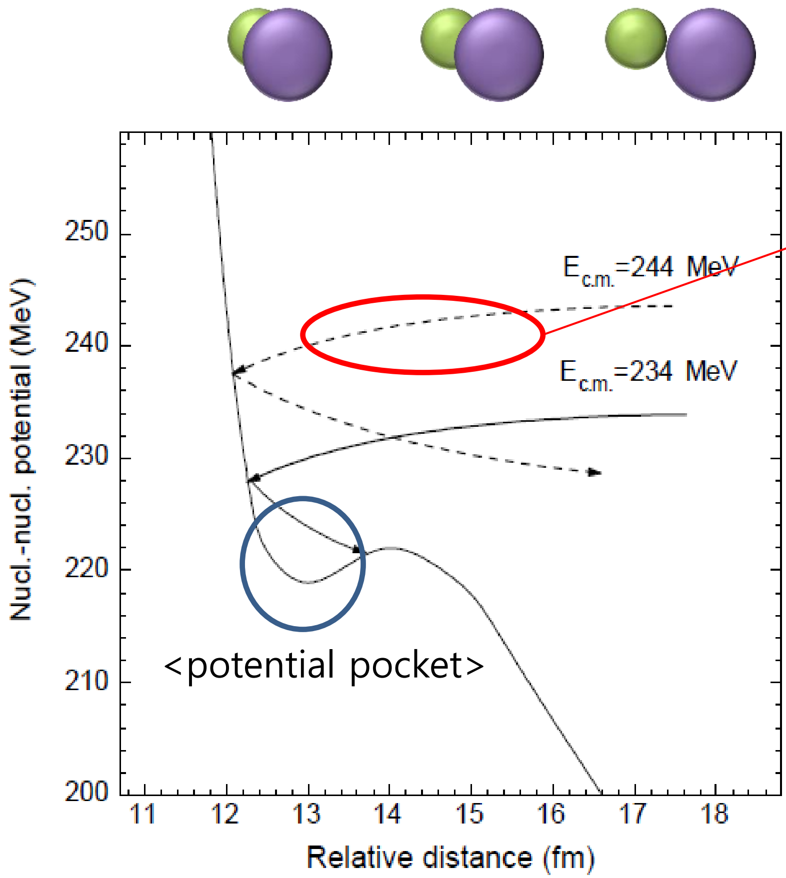
Compound nucleus (fusion): through transfers of nucleons from the light nucleus to the heavy one.

The dynamics of the DNS (di-nuclear system) is considered as a combined diffusion in the degrees of freedom of the mass symmetry η and of the relative distance describing the formation of the compound nucleus and the quasi-fission process (decay of the DNS), respectively

$$\eta = (A1 - A2)/(A1 + A2)$$

(A1 and A2 are the mass numbers of the DNS nuclei)

Capture Process and Potential Pocket



Energy dissipation by friction

In a deep-inelastic process, part of the kinetic energy excites di-nuclear system.

Capture Process

Hydrodynamical Hamiltonian for di-nuclear system

$$\begin{aligned} H &= \frac{m}{2}\int J(\mathbf{R},\mathbf{r})\frac{1}{\rho(\mathbf{R},\mathbf{r})}J(\mathbf{R},\mathbf{r})d^3\mathbf{r} \\ &+ \frac{h^2}{8m}\int\frac{(\nabla\rho(\mathbf{R},\mathbf{r}))^2}{\rho(\mathbf{R},\mathbf{r})}d^3\mathbf{r} + \frac{1}{2}\int\rho(\mathbf{R},\mathbf{r})v_{eff}(\mathbf{R},\mathbf{r},\mathbf{r}')\rho(\mathbf{R},\mathbf{r}')d^3\mathbf{r}' \end{aligned}$$

$$\hat{H} = \hat{H}_{rel}(\mathbf{R};\mathbf{P}) + \hat{H}_{in}(\xi) + \delta\hat{V}(\mathbf{R},\xi),$$

$$\hat{H}_{rel}(\mathbf{R};\mathbf{P}) = \frac{\hat{\mathbf{P}}^2}{2\mu} + \hat{\mathcal{V}}(\hat{\mathbf{R}}),$$ Relative motion

$$\begin{aligned} \hat{H}_{in} &= \frac{m}{2}\int\hat{j}_P(\mathbf{R}-\mathbf{r})\frac{1}{\rho(\mathbf{R},\mathbf{r})}\hat{j}_P(\mathbf{R}-\mathbf{r})d^3\mathbf{r} + \int\hat{\rho}_P(\mathbf{R}-\mathbf{r})\hat{v}_{eff}(\mathbf{R},\mathbf{r},\mathbf{r}')\hat{\rho}_P(\mathbf{R}-\mathbf{r}')d^3\mathbf{r}' \\ &+ \frac{m}{2}\int\hat{j}_T(\mathbf{r})\frac{1}{\rho(\mathbf{R},\mathbf{r})}\hat{j}_T(\mathbf{r})d^3\mathbf{r} + \int\hat{\rho}_T(\mathbf{R},\mathbf{r})\hat{v}_{eff}(\mathbf{R},\mathbf{r},\mathbf{r}')\hat{\rho}_T(\mathbf{R},\mathbf{r}')d^3\mathbf{r}'. \qquad (1.5) \end{aligned}$$ Intrinsic motion

$$\hat{H}_{in}(\xi) = \sum_{i=1}^{A_P}\left(\frac{-h^2}{2m}\Delta_i + \hat{V}_P(\mathbf{r}_i - \mathbf{R}(t))\right) + \sum_{i=1}^{A_T}\left(\frac{-h^2}{2m}\Delta_i + \hat{V}_T(\mathbf{r}_i)\right) + h_{residual},$$

Woods-Saxon pot. : $V_P(\mathbf{r}-\mathbf{R}) = -V_{(0)}^{N_P,Z_P}\left\{1+\exp\left[\frac{|\mathbf{r}-\mathbf{R}(t)|-R_P}{a}\right]\right\}^{-1}$

Capture Process

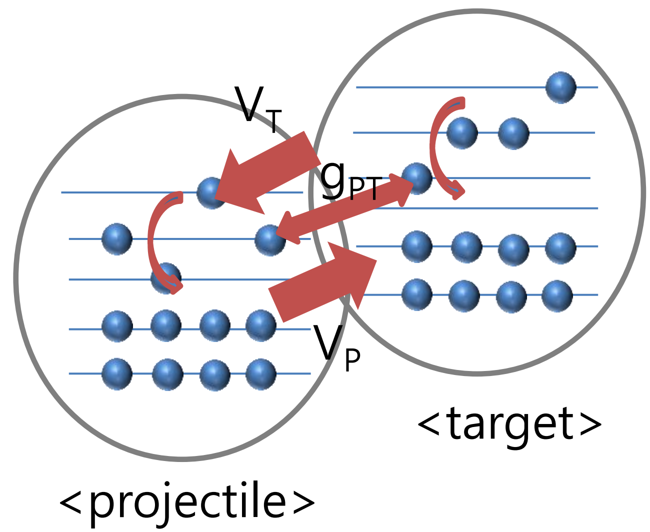
<Coupling term between relative and intrinsic motion>

$$\delta\hat{V}(\mathbf{R}(t);\xi) = \sum_{i\neq i'} V_{ii'}(\mathbf{R}(t))\mathrm{a}_i^{+}\mathrm{a}_{i'}$$

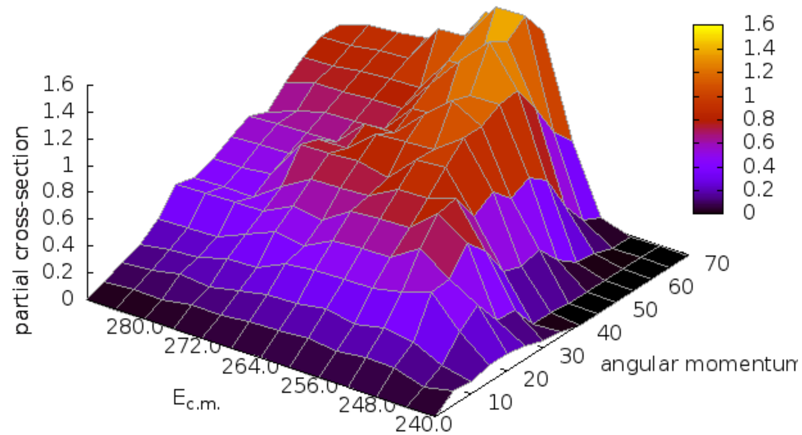
$$= \sum_{P\neq P'} \Lambda^{(T)}_{PP'}(\mathbf{R}(t))\mathrm{a}_P^{+}\mathrm{a}_{P'} + \sum_{T\neq T'} \Lambda^{(P)}_{TT'}(\mathbf{R}(t))\mathrm{a}_T^{+}\mathrm{a}_{T'} + \sum_{T,P} \mathrm{g}_{PT}(\mathbf{R}(t))(\mathrm{a}_P^{+}\mathrm{a}_T + h.c.),$$

$$\begin{cases} \Lambda^{(T)}_{PP'}(\mathbf{R}(t)) = < P|V_T(\mathbf{r})|P' >, \\ \Lambda^{(P)}_{TT'}(\mathbf{R}(t)) = < T|V_P(\mathbf{r}-\mathbf{R}(t))|T' >, \\ g_{PT}(\mathbf{R}(t)) = \frac{1}{2} < P|V_P(\mathbf{r}-\mathbf{R}(t)) + V_T(\mathbf{r})|T > \end{cases}$$

The energy of system is converted to excited energy of each nucleon and exchange energy of multi-nucleon. We call this "friction".



Capture Process

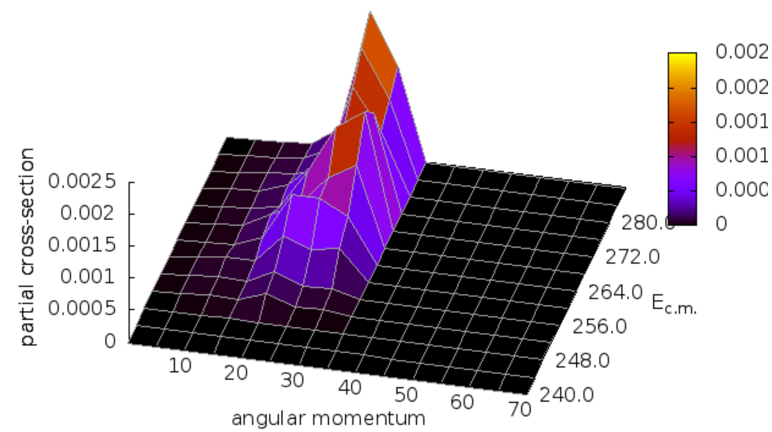


<Energy and angular momentum dependence of capture cross-section>

At high angular momentum, partial capture cross-sections have large values.

<Energy and angular momentum dependence of fusion cross-section>

Partial fusion cross-sections have large values at small angular momentum.



Driving Potential

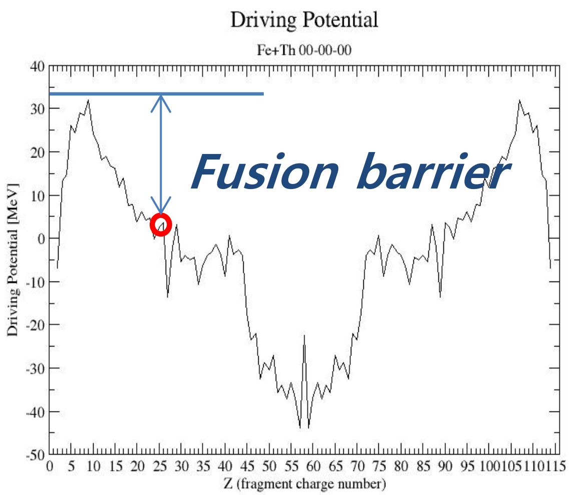
$$U_{dr}(A,Z;R,l) = B_1 + B_2 + V(Z,l;R) - (B_{CN} + V_{CN}(l))$$

B_1,B_2 and B_{CN} : The binding energies of the nuclei

R : Relative distance

l : Angular momentum of the compound nucleus

$V_{CN}(l)$: The rotational energy of the compound nucleus



Driving Potential

$$U_{dr}(A, Z; R, l) = B_1 + B_2 + V(Z, l; R) - (B_{CN} + V_{CN}(l))$$

<Nucleus-Nucleus potential>

$$V_0(\mathbf{R}) = V_C(\mathbf{R}) + V_{nucl}(\mathbf{R}) + V_{rot}(\mathbf{R}),$$

$$V_C(R) = \frac{Z_1 Z_2}{R} e^2 + \frac{Z_1 Z_2}{R^3} e^2 \left\{ \left(\frac{9}{20\pi} \right)^{1/2} \sum_{i=1}^{2} R_{0i}^2 \beta_2^{(i)} \mathcal{P}_2(\cos \alpha_i') + \frac{3}{7\pi} \sum_{i=1}^{2} R_{0i}^2 \left[\beta_2^{(i)} \mathcal{P}_2(\cos \alpha_i') \right]^2 \right\}$$

$$V_{nucl}(R) = \int \rho_1^{(0)}(\mathbf{r} - \mathbf{R}_1) f_{eff}[\rho(r)] \rho_2^{(0)}(\mathbf{r} - \mathbf{R}_2) d^3\mathbf{r}$$

Migdal NN force

$$\rho_i^{(0)}(\mathbf{r}, \mathbf{R}_i(t), \alpha_i, \beta_2^{(i)}) = \left\{ 1 + \exp\left[\frac{|\mathbf{r} - \mathbf{R}_i(t)| - R_{0i}(1 + \beta_2^{(i)} Y_{20}(\alpha_i))}{a} \right] \right\}^{-1}$$

$$V_{rot}(R) = \hbar^2 \frac{l(l+1)}{2\mu R^2}$$

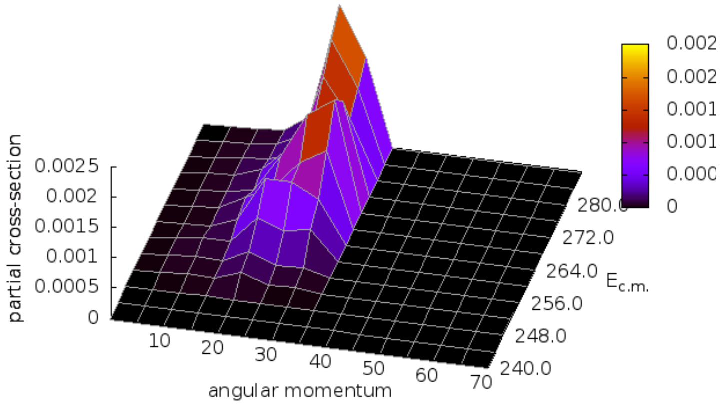
Fusion Process

Cross-section for evaporation residues

$$\sigma_{er}(E) = \sum_{\ell=0}^{\ell_{cap}} (2\ell+1)\sigma_\ell^{cap}(E) P_{CN}(E,\ell) W_{sur}(E,\ell)$$

Fusion cross-section

$$\sigma_\ell^{fus} = \sigma_\ell^{cap}(E) P_{CN}(E,\ell)$$



Probability for formation of compound nucleus

$$P_{CN} = \frac{\rho(E^*_{DNS} - B^*_{fus})}{\rho(E^*_{DNS} - B^*_{fus}) + \rho(E^*_{DNS} - B_{qf})}$$

Level density

$$\rho(E^*_{DNS} - B^*_K) = \frac{g(\varepsilon_F) K_{rot}}{2\sqrt{g_1(\varepsilon_F) g_2(\varepsilon_F)}} \frac{\exp\left[2\pi\sqrt{g(\varepsilon_F)(E^*_{DNS} - B^*_K)/6}\right]}{\left[\frac{3}{2} g(\varepsilon_F)(E^*_{DNS} - B^*_K)\right]^{\frac{1}{4}} (E^*_{DNS} - B^*_K)\sqrt{48}}.$$

Fission Barrier

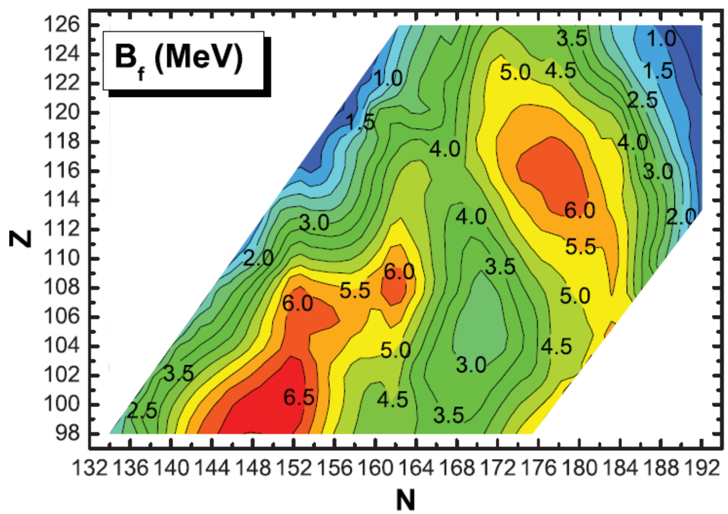
<Temperature and angular momentum dependence of fission barrier>

$$B_f(L,T) = B_f^m(L) - h(T)q(L)\delta W$$

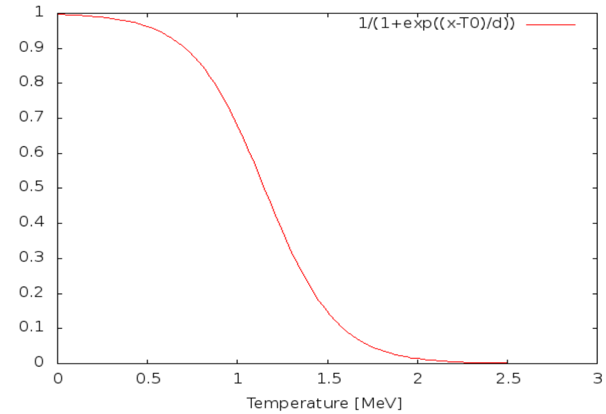
$$h(T) = \{1 + \exp[(T - T_0)/d\,]\}^{-1}$$

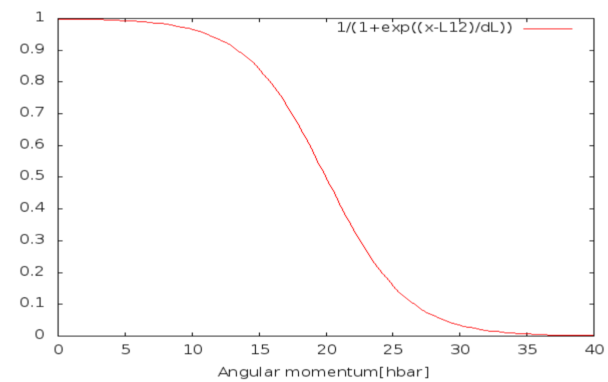
$$q(L) = \{1 + \exp[(L - L_{1/2})/\Delta L]\}^{-1}$$

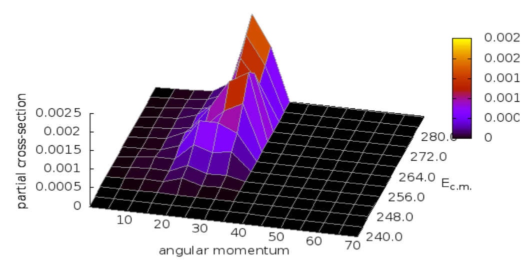
$$d = 0.2\ \mathrm{MeV},\quad T_0 = 1.15\ \mathrm{MeV},\quad \Delta L = 3\hbar,\quad L_{1/2} = 20\hbar$$



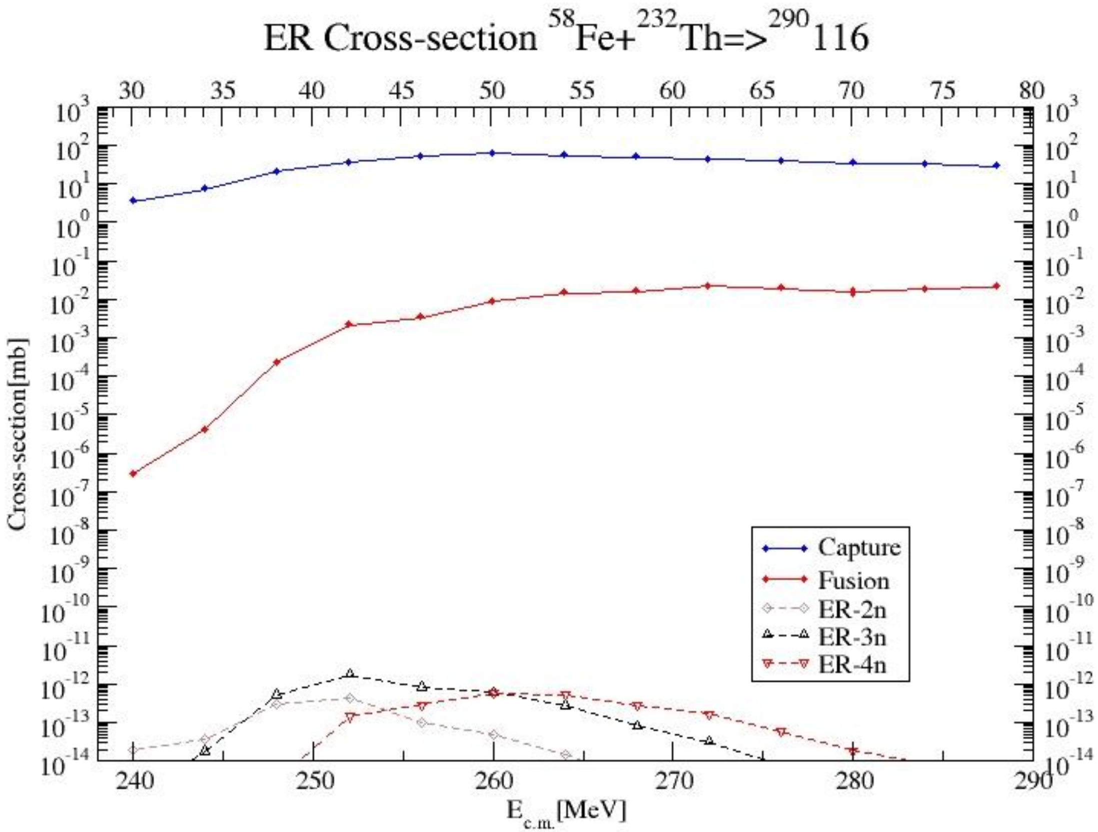
Kowal, et al. PRC82 (2010) 014303







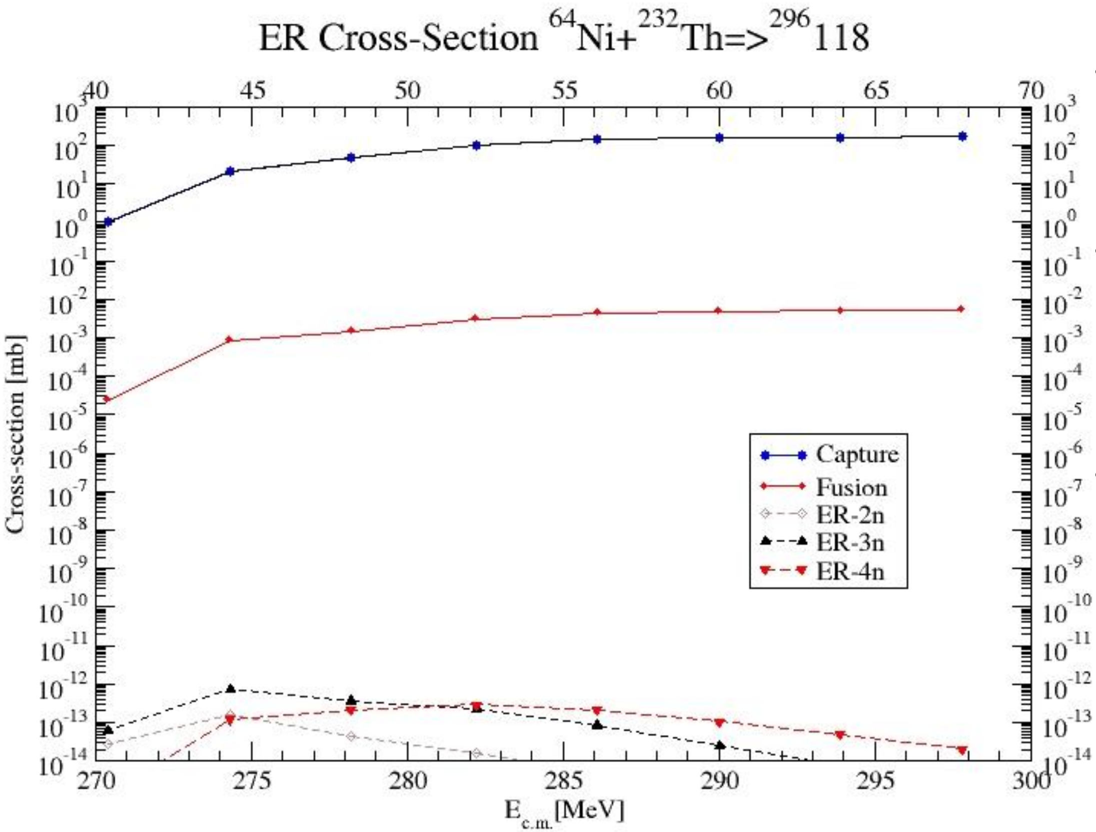
Result for Fe+Th



- The super heavy element (Z=116) could be formed with excitation energy over 30 MeV.
- Near E_ex=40MeV, the three-neutron evaporation residue(ER-3n) cross-section has the maximum value.
- The ER cross-section is expected to be~10 fb.

Kyungil Kim (RISP/IBS), A. K. Nasirov (BLTP, Dubna), YK

Result for Ni+Th



- The super heavy element (Z=118) could be formed with excitation energy over 40 MeV.
- Near E_{ex}=45MeV, the three-neutron evaporation residue(ER-3n) cross-section has the maximum value.
- The ER cross-section is expected to be~1 fb.

SHE summary

- In heavy-ion collisions at low energies, capture processes can be understood by frictional energy losses in DNS.

- With driving potentials, we obtain fusion barriers. Then, fusion cross-section is obtained by a product between a capture cross-section and a probability of making compound nucleus.

- After the fusion of SHE, a few neutrons are evaporated from SHE during de-excitation stage. Very few SHEs can survive against fission.

- We obtain the cross-sections:

  - Fe+Th (Fusion) : ~10^{-2} mb
  - Fe+Th (ER-3n) : ~10 fb

  - Ni+Th (Fusion) : ~10^{-3} mb
  - Ni+Th (ER-3n) : ~1 fb

감사합니다!