

超重核領域のインビーム γ 線分光

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原子力機構 牧井、浅井、塚田、豊嶋、松田、静間、市川

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超重核領域における核構造実験の状況

$Z > 110$ *New element (isotope) search* $\rightarrow T_{1/2}, Q\alpha$

$Z \sim 102$ *In-beam γ , isomer- γ , α - γ ;*

fusion: $^{48}\text{Ca} + ^{208}\text{Pb}$, using RMS

$Z \sim 94$ *In-beam γ ; unsafe Coulomb*

JAEAでの実験

$Z \sim 102$ α - γ ; *fusion: $^{18}\text{O} + ^{248}\text{Cm}$, using He-jet*

👉 $Z \sim 94$ *neutron-rich In-beam γ*

transfer: ($^{18}\text{O}, ^{16}\text{O}$), using Si ΔE -E

展望

超重核領域の核構造研究

殻構造

— 重い原子核はどこまで存在するか？ 長寿命の超重核は存在するか？

球形閉殻 Magic Numbers: $Z=114, 120, 126?$ $N=164, 172, 184?$

変形閉殻 $N=152, 162$ (Z dependence) ?

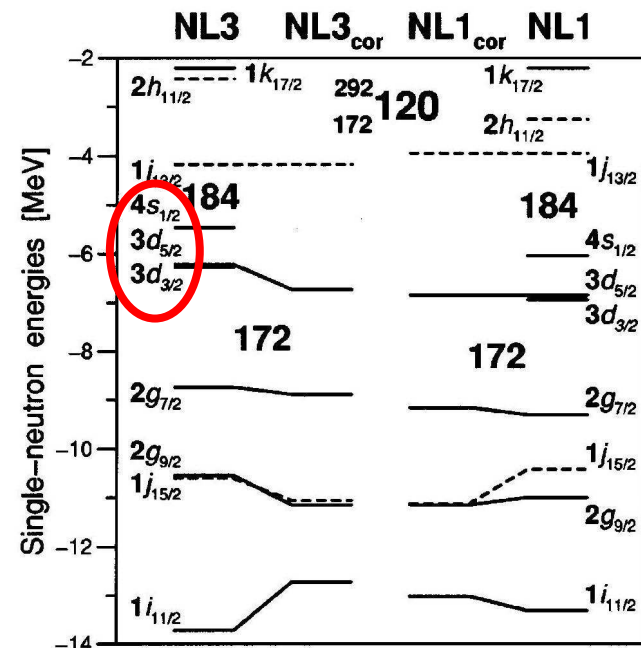
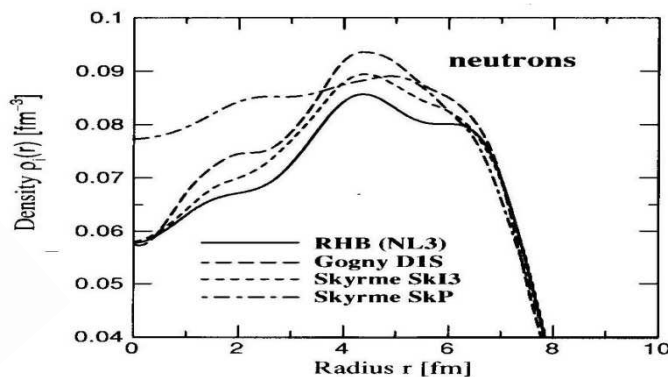


特異な構造 ⇒ 新しい原子核画像の構築

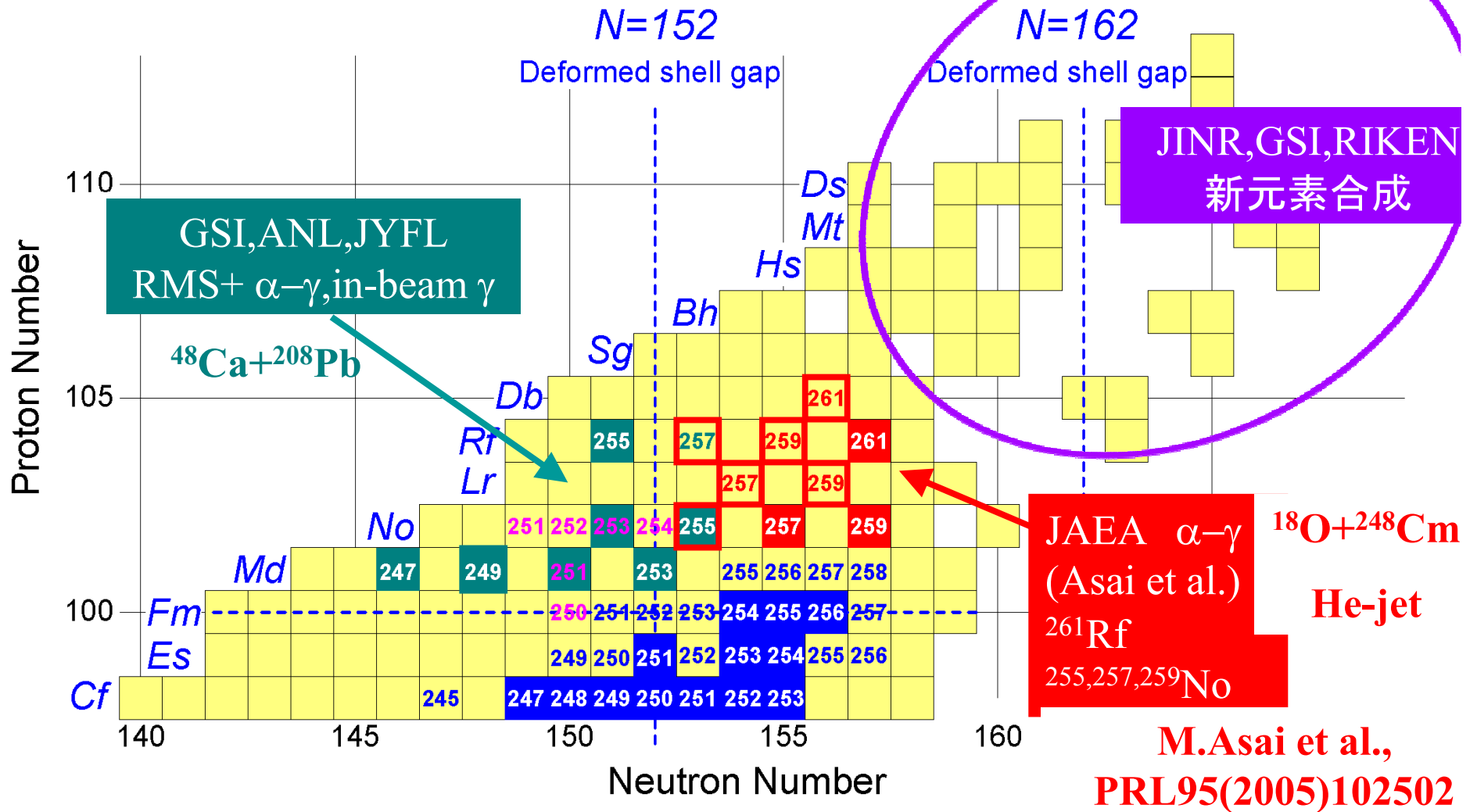
e.g., Balloon 原子核 $120=126-(p$ 軌道), $172=184-(s,d$ 軌道)

核分裂 微視的な取り扱い？

Balloon Nucleus 120_{172} Central Depression of Nucleon Density

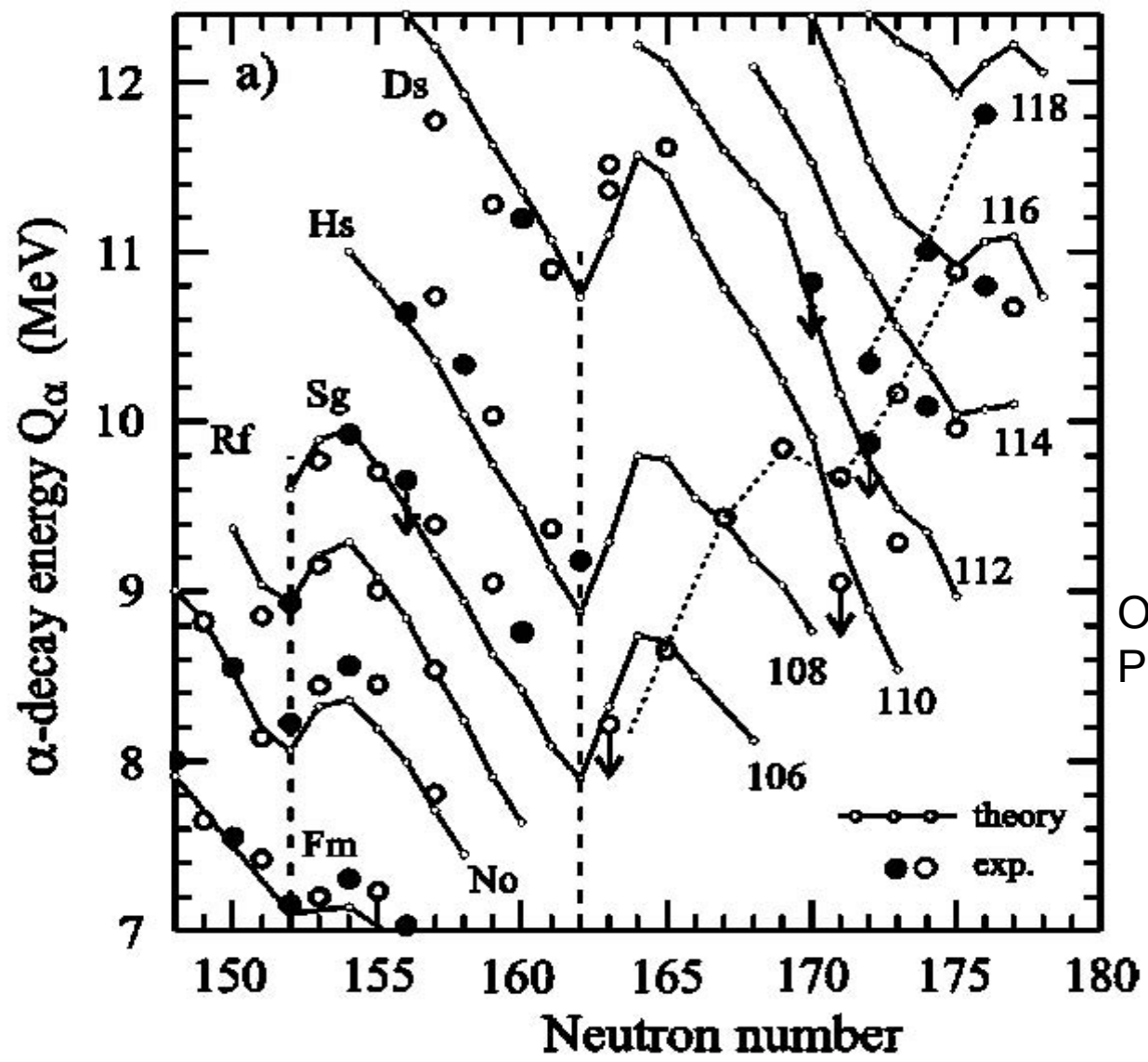


超重核領域の核構造実験の現状



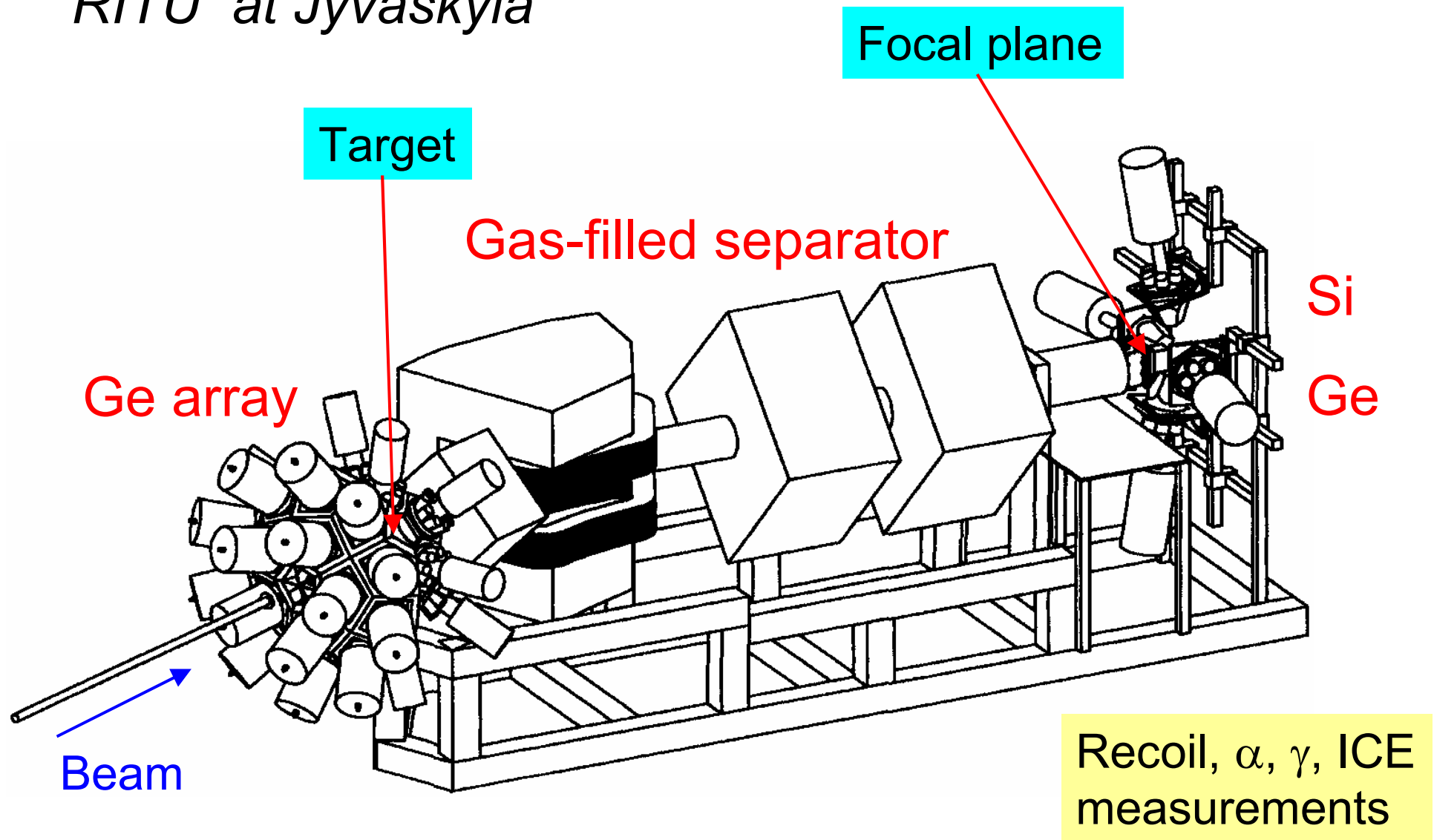
超重核領域の核構造実験の現状

Q α JINR(Dubna)



Oganessian *et al.*,
 PRC70(2004)064609

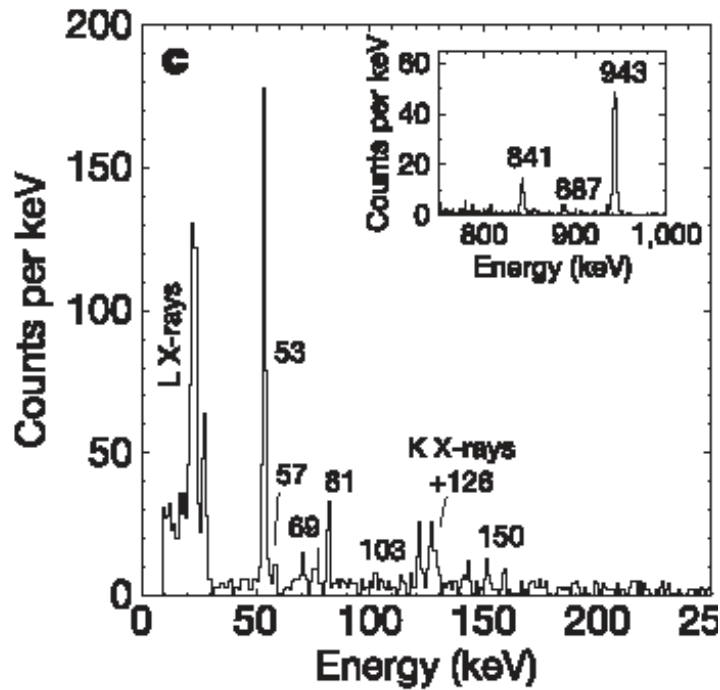
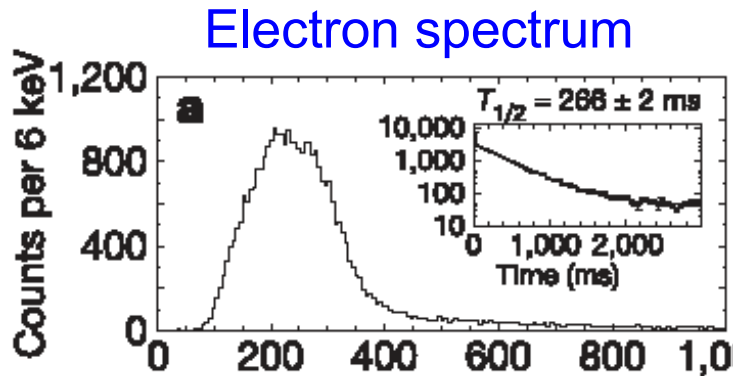
RITU at Jyvaskyla



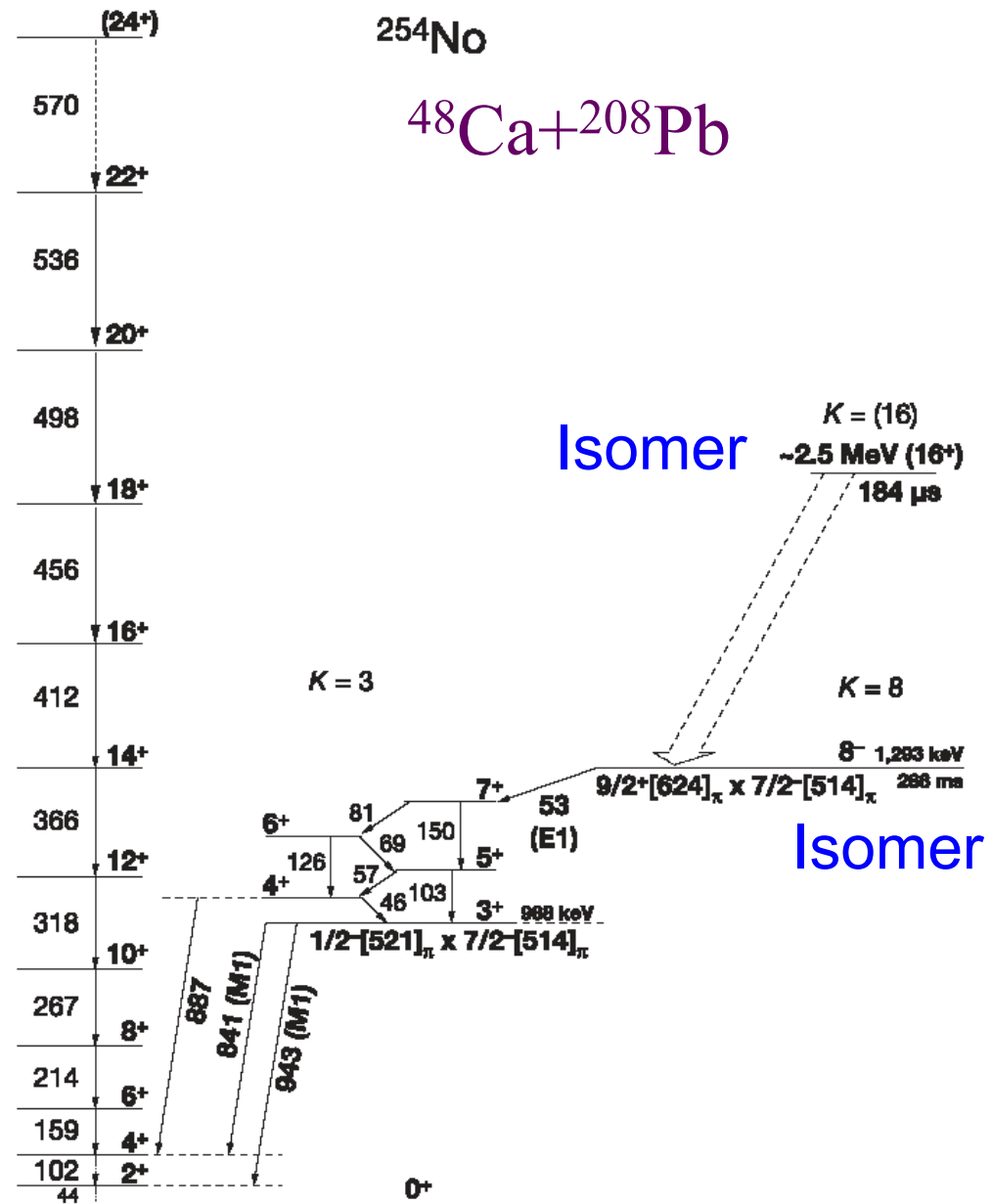
In-beam γ -ray spectroscopy
with recoil decay tagging

Julin *et al.*, NP A685 (2001) 221c.

Herzberg *et al.*, Nature 442 (2006) 896.



Gamma-ray spectrum

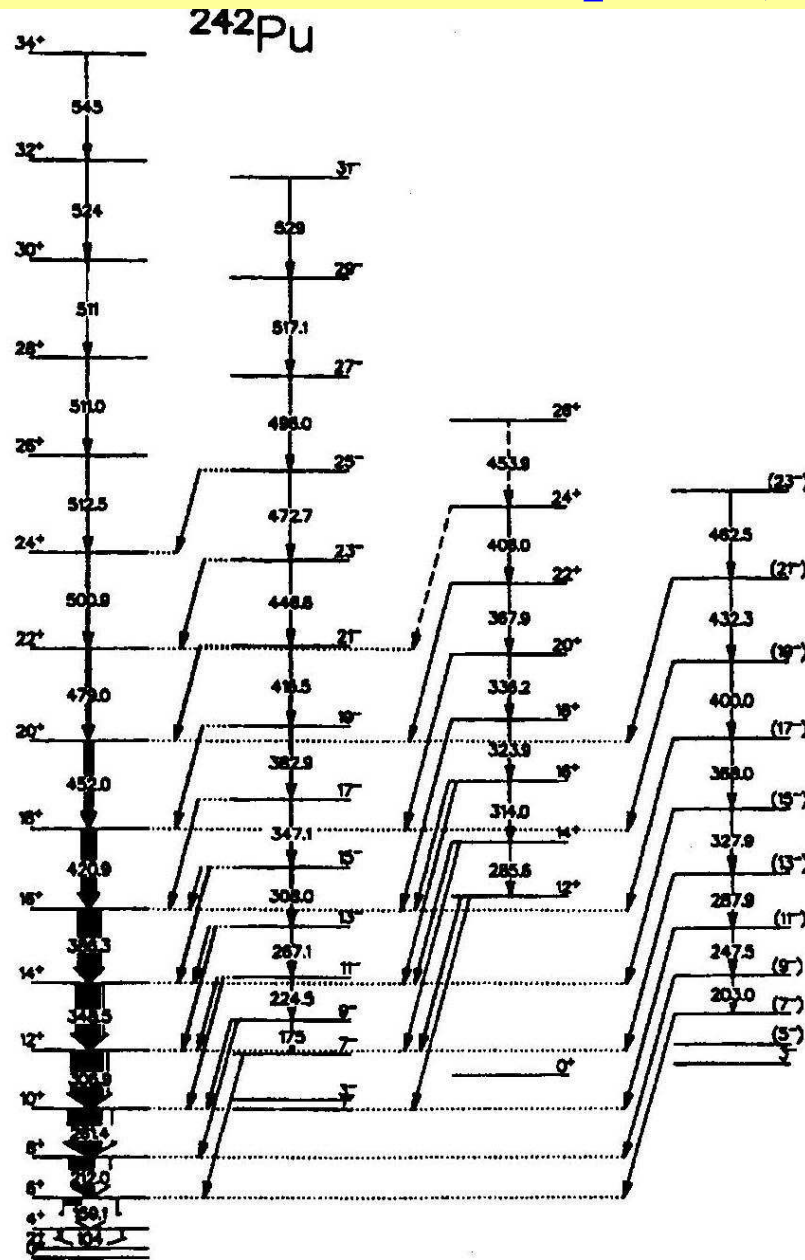


超重核領域の核構造実験の現状

Unsafe Coulomb ANL(Gammasphere)

142	103										Lr	Lr 252 0.36 s	Lr 253 1.49 s 0.57 s	Lr 254 13 s	Lr 255 16.4 s 2.1 s	Lr 256 27 s	Lr 257 0.65 s	Lr 258 3.9 s	Lr 259 6.3 s	Lr 260 3 m	Lr 261 39 m	Lr 262 3.6 h									
102											No	No 250 46 μs 4.2 μs	No 251 0.93 s 0.76 s	No 252 2.3 s	No 253 1.7 m	No 254 0.28 s 55 s	No 255 3.1 m	No 256 2.91 s	No 257 24.5 s	No 258 1.2 ms	No 259 58 m	No 260 ? 106 ms									
101												Md	Md 245 0.35 s 0.9 m	Md 246 1.0 s	Md 247 0.26 s 1.4 s	Md 248 7 s	Md 249 ? 19 s	Md 250 52 s	Md 251 4.0 m	Md 252 2.3 m	Md 253 ~6 m	Md 254 10 m 28 m	Md 255 27 m	Md 256 77 m	Md 257 5.52 h	Md 258 57 m 51.6 d	Md 259 95 m	Md 260 31.8 d			
100													Fm	Fm 242 0.8 ms	Fm 243 0.18 s	Fm 244 3.0 ms	Fm 245 4.2 s	Fm 246 1.1 s	Fm 247 4.3 s 29 s	Fm 248 36 s	Fm 249 2.6 m	Fm 250 1.8 s 30 m	Fm 251 5.30 h	Fm 252 25.39 s	Fm 253 3.0 d	Fm 254 3.24 h	Fm 255 20.1 h	Fm 256 70 ns 2.63 h	Fm 257 100.5 d	Fm 258 0.38 ms	Fm 259 1.5 s
99													Es	Es 241 8 s	Es 242 16 s	Es 243 20 s	Es 244 4.2 s	Es 245 1.1 m	Es 246 7.7 m	Es 247 4.55 h	Es 248 27 m	Es 249 1.70 h	Es 250 2.22 h 88 h	Es 251 35 h	Es 252 47.7 d	Es 253 20.47 d	Es 254 39.3 h 276.7 d	Es 255 39.8 d	Es 256 7.6 h 25.4 m	Es 257 7.8 d	
17 s	Cf 238 21 ms	Cf 239 ~39 s	Cf 240 1.06 m	Cf 241 3.78 m	Cf 242 3.68 m	Cf 243 10.7 m	Cf 244 19.4 m	Cf 245 43.6 m	Cf 246 35.7 h	Cf 247 3.11 h	Cf 248 333.5 d	Cf 249 350.6 a	Cf 250 13.08 a	Cf 251 898 a	Cf 252 2.645 a	Cf 253 17.81 d	Cf 254 60.5 d	Cf 255 1.4 h	Cf 256 12 s												
158														Bk	Bk 238 144 s	Bk 240 5 m	Bk 241 4.6 m	Bk 242 7 m	Bk 243 4.5 h	Bk 244 4.35 h	Bk 245 4.90 d	Bk 246 1.80 d	Bk 247 1380 a	Bk 248 237 h > 9 a	Bk 249 320 d	Bk 250 3.217 h	Bk 251 55.6 m				
154															156					158											
154																Cm	Cm 237 ?	Cm 238 2.4 h	Cm 239 3 h	Cm 240 27 d	Cm 241 32.1 d	Cm 242 162.94 d	Cm 243 29.1 a	Cm 244 18.10 a	Cm 245 8500 a	Cm 246 4730 a	Cm 247 1.56 × 10 ⁷ a	Cm 248 3.40 × 10 ⁸ a	Cm 249 64.15 m	Cm 250 ~9700 a	Cm 251 16.8 m
34 m	Am 235 10.3 m	Am 236 2.9 m 3.6 m	Am 237 73.0 m	Am 238 1.63 h	Am 239 11.9 h	Am 240 50.8 h	Am 241 432.2 a	Am 242 141 a 16 h	Am 243 7370 a	Am 244 36 m 101 h	Am 245 2.05 h	Am 246 25 a 39 m	Am 247 22 m	154			156														
33 m	Pu 234 8.8 h	Pu 235 25.3 m	Pu 236 2.858 a	Pu 237 45.2 d	Pu 238 87.74 a	Pu 239 2.411 × 10 ⁴ a	Pu 240 6563 a	Pu 241 14.35 a	Pu 242 4.956 h	Pu 243 3.760 × 10 ⁴ a	Pu 244 8.00 × 10 ⁴ a	Pu 245 10.5 h	Pu 246 10.85 d	Pu 247 2.27 d	156																
32 m	Np 233 36.2 m	Np 234 4.4 d	Np 235 2.144 × 10 ⁴ a	Np 236 2.23 h	Np 237 2.117 d	Np 238 2.117 d	Np 239 7.22 m 66 m	Np 240 2.355 d	Np 241 13.9 m	Np 242 2.2 m 1.85 m	Np 243 1.85 m	Np 244 2.29 m	152			111															
31 d	U 232 68.9 a	U 233 1.592 × 10 ⁶ a	U 234 0.0054 a	U 235 0.7204 a	U 236 120 ms 2.342 × 10 ⁴ a	U 237 6.75 d	U 238 99.2742 a	U 239 23.5 m	U 240 14.1 h	U 241 1.85 m	U 242 16.8 m	110			Ds																
30 d	Pa 231 3.276 × 10 ⁴ a	Pa 232 1.31 d	Pa 233 27.0 d	Pa 234 1.47 m 6.70 h	Pa 235 24.2 m	Pa 236 9.1 m	Pa 237 8.7 m	Pa 238 2.3 m	Pa 239 1.8 h	148			150			109															
29 a	Th 230 7.54 × 10 ⁴ a	Th 231 25.5 h	Th 232 100	Th 233 22.3 m	Th 234 24.10 d	Th 235 7.1 m	Th 236 37.5 m	Th 237 5.0 m	Th 238 9.4 m	108			Hs			108															
28	Ac 229	Ac 230	Ac 231	Ac 232	Ac 233	Ac 234	148			150			109			108															
108											Bh	Bh 260 ?	Bh 261	Bh 262	109			110			111										
109											Hs	Hs 263 ?	Hs 264 0.45 ms	Hs 265 0.8 ms 2.0 ms	Hs 266 2.3 ms	Hs 267 0.80 s 52 ms	108			109			110								
110											Mt	Mt 266 1.7 ms	Mt 268 21 ms	109			110			111											
111											Ds	Ds 267 ?	Ds 269 179 μs	110			111														

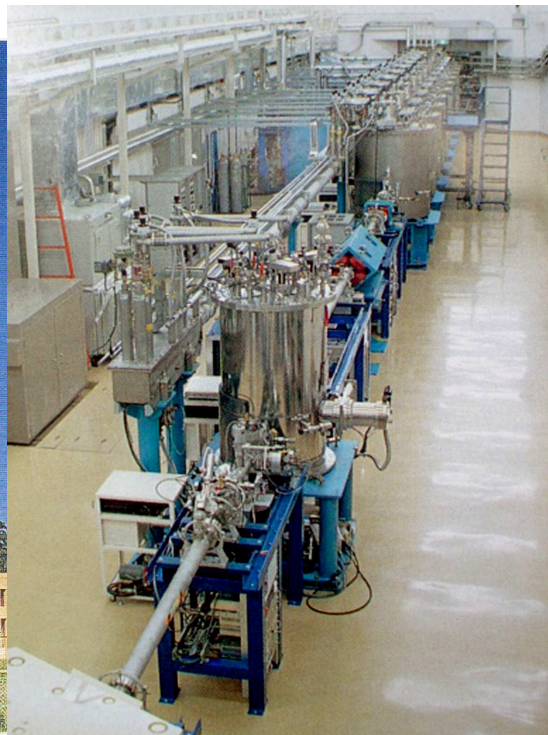
超重核領域の核構造実験の現状 Coulomb (Gammasphere)



JAEAでのインビーム γ 実験

JAEA-Tokai Tandem & Superconducting Booster & TRIAC (Tokai Radioactive Ion Accelerator Complex)

- $V_T=18\text{MV}$; new acceleration tubes; ECR ion source on the terminal
- Superconducting linac booster; 40 quarter-wave resonators: $V \sim 30\text{MV}$
 ^{18}O (15MeV/u), ^{76}Ge (10MeV/u), ^{127}I (6MeV/u), ...
- TRIAC: joint project between JAEA & KEK
Tandem(RI ; p+UC, $^7\text{Li}+\text{C}, \dots$) \rightarrow ISOL \rightarrow Charge breeder \rightarrow SCRFQ+IH-LINAC
 ^8Li (1.1MeV/u, $10^5/\text{s}$),....

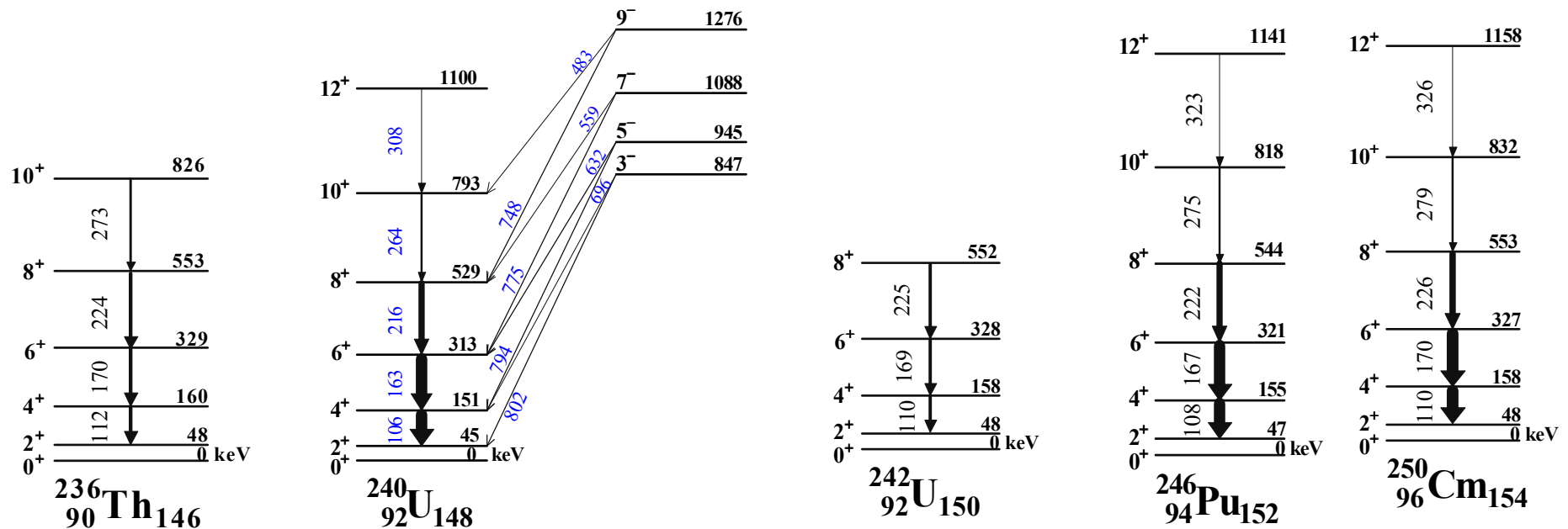


超重核のインビーム γ 線分光

- 1) 重イオン核子移行反応: $(^{18}\text{O}, ^{16}\text{O}), (^{18}\text{O}, ^{20}\text{Ne}), (^{16}\text{O}, ^{15}\text{O})\dots$
- 2) アクチノイド標的: $^{238}\text{U}(Z=92), ^{244}\text{Pu}(Z=94), ^{248}\text{Cm}(Z=96)$
- 3) 核反応チャンネルを識別: Si ΔE -E

残留核の γ 線を A, Z で完全に分離

中性子過剰核 $^{236}\text{Th}, ^{240,242}\text{U}, ^{246}\text{Pu}, ^{250}\text{Cm}$ で初めての γ 線測定



Experimental Setup

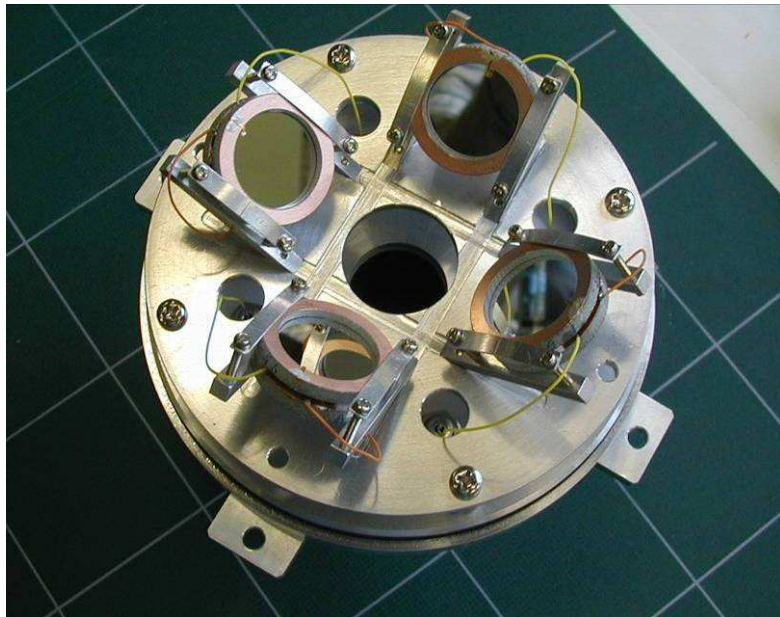
- $^{18}\text{O} + ^{248}\text{Cm}$ experiment -

Beam : ^{18}O (162MeV, $V_T=18\text{MV}$), $i=0.3\text{pnA}$, [adjust with $\phi 2.5\text{mm}$ aperture]

Target: ^{248}Cm ($0.8\text{mg}/\text{cm}^2$) on Al($0.9\text{mg}/\text{cm}^2$) ; $\phi 3\text{mm}$, $60\mu\text{g}$, **45kBq**

Detectors: 4 Si $\Delta E(75\mu\text{m})$ -E placed at $40(+/- 11)$ degree [Si ELID wafer]

6 Ge detectors; $\text{eff} = 12\% @ 0.2 \text{ MeV}$, $3\% @ 1.3\text{MeV}$



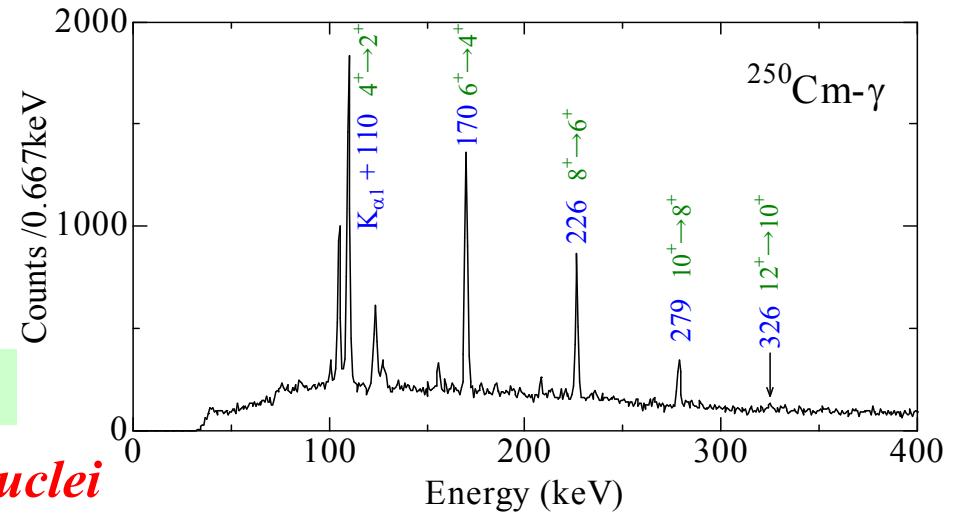
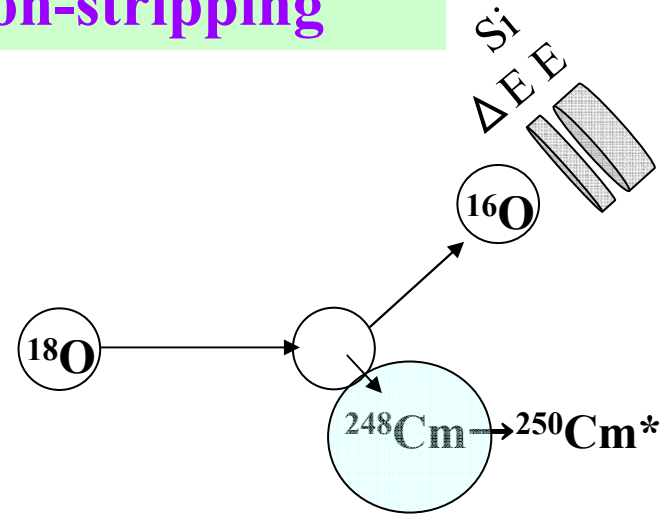
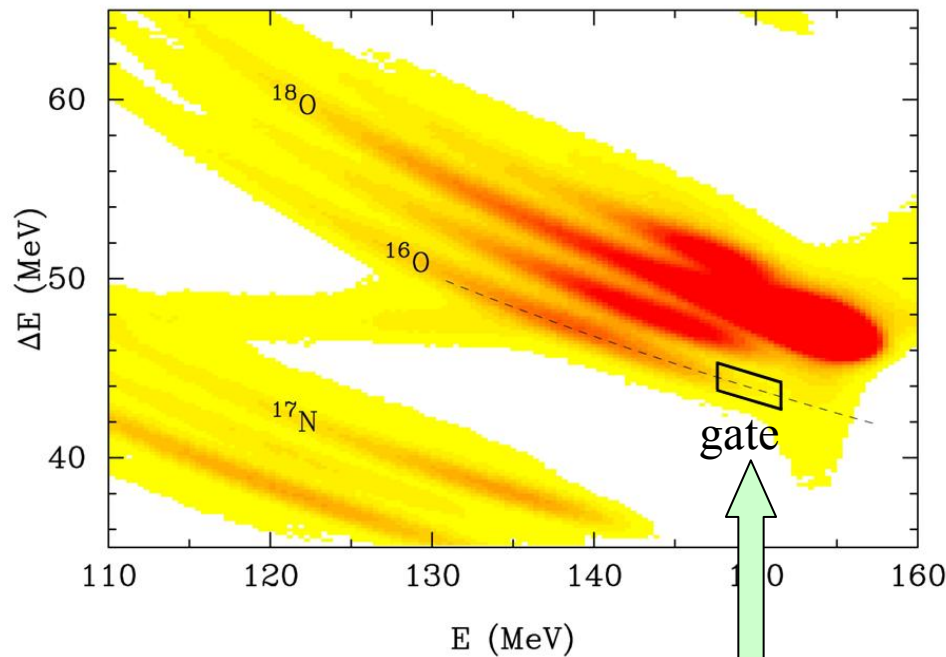
Si ΔE -E Detectors



E- ΔE Plot & γ -ray Spectra of $^{250}\text{Cm}_{154}$

$^{248}\text{Cm}(^{18}\text{O}, ^{16}\text{O})^{250}\text{Cm}$; 2neutron-stripping

Si E- ΔE PLOT



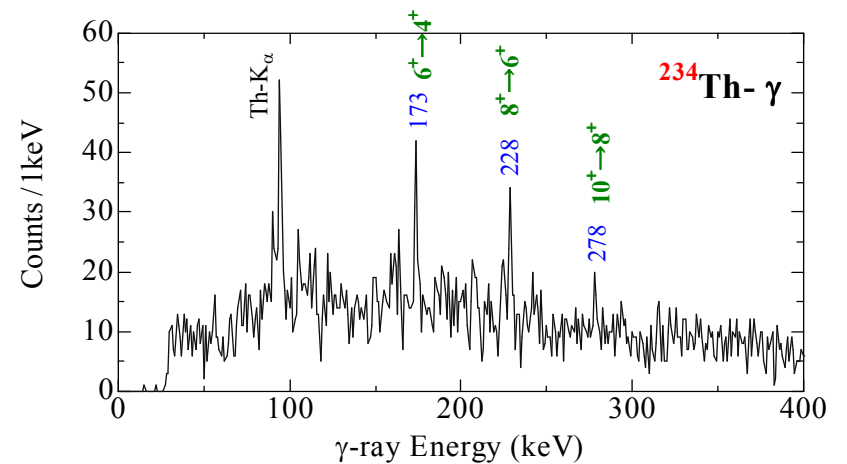
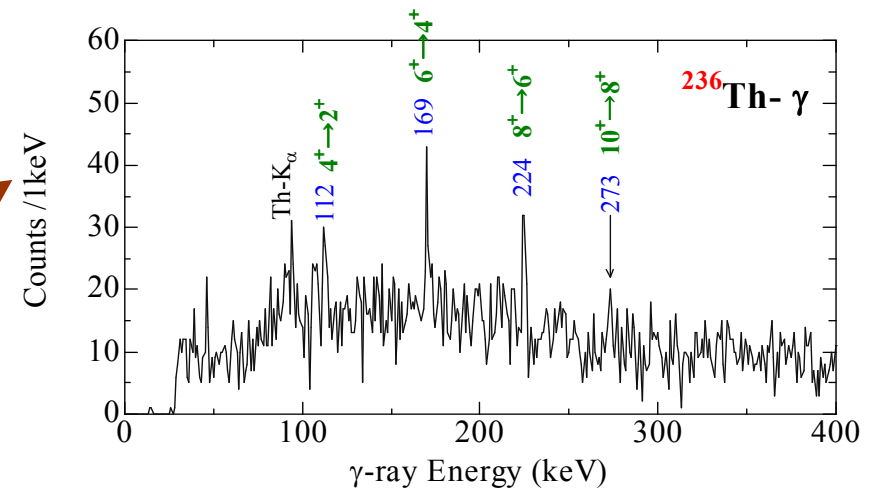
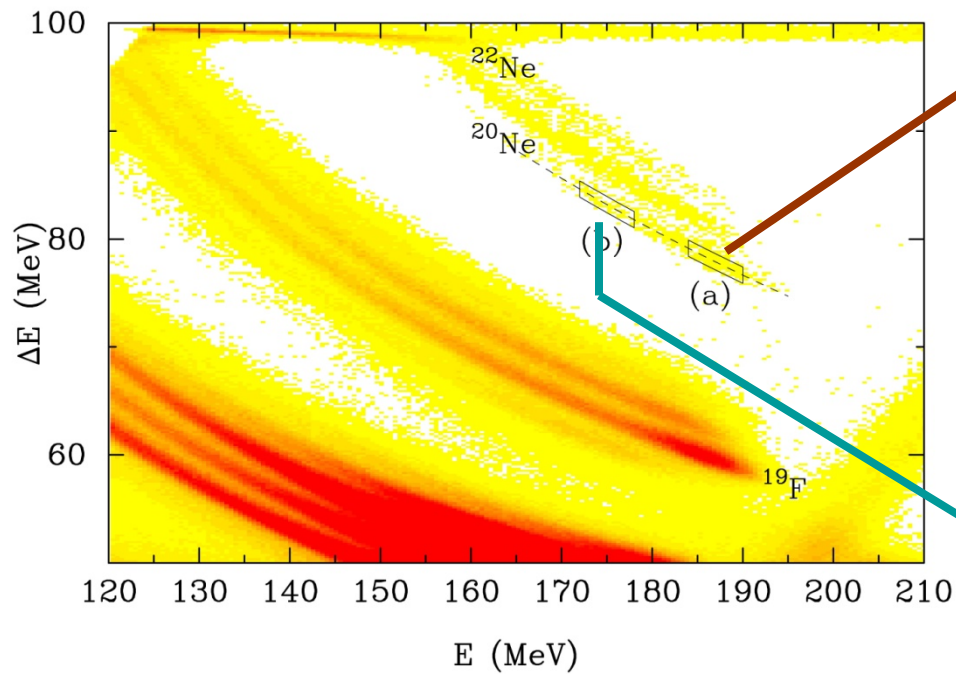
*Complete selection of γ -rays in residual nuclei
by measuring outgoing particles
- Z, M, and kinetic energies -*

E- Δ E Plot & γ -ray Spectra of $^{236}\text{Th}_{146}$

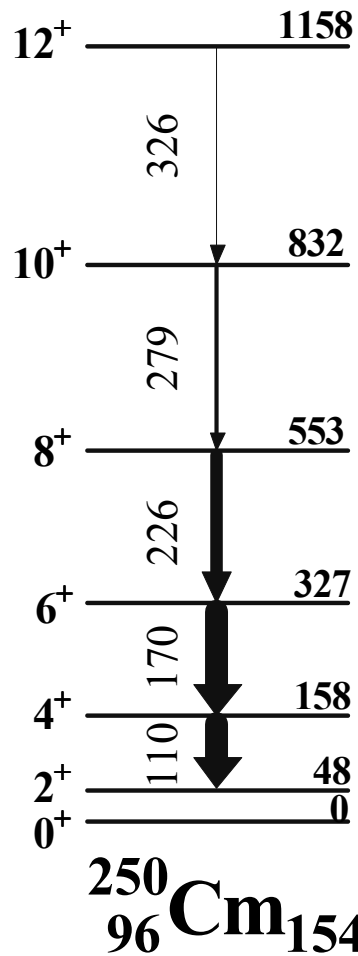
$^{238}\text{U}(^{18}\text{O},^{20}\text{Ne})^{236}\text{Th}$; 2proton-pickup

$\sigma \sim \mu\text{b}$

Si E- Δ E PLOT

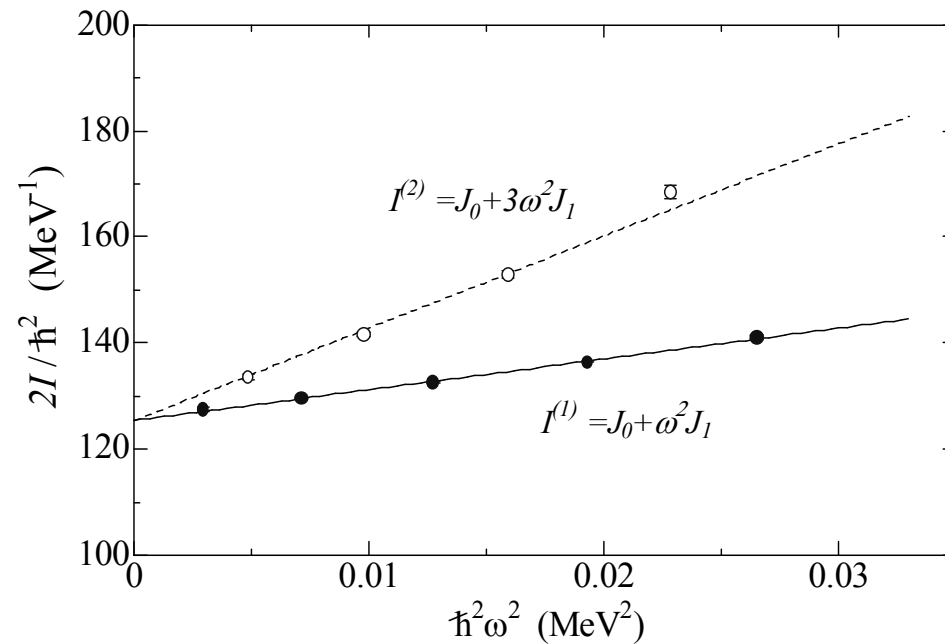


Moments of Inertia & Precise Estimation of the E(2⁺) Energy



$\alpha_T = 12$
 $\alpha_T \sim 600$

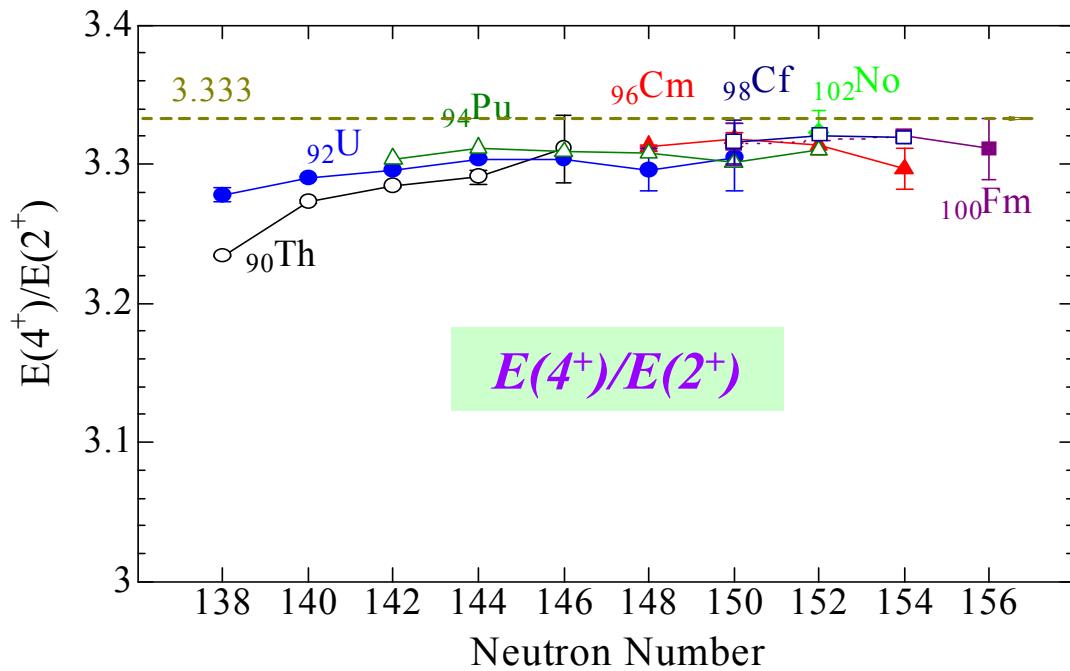
Moments of inertia



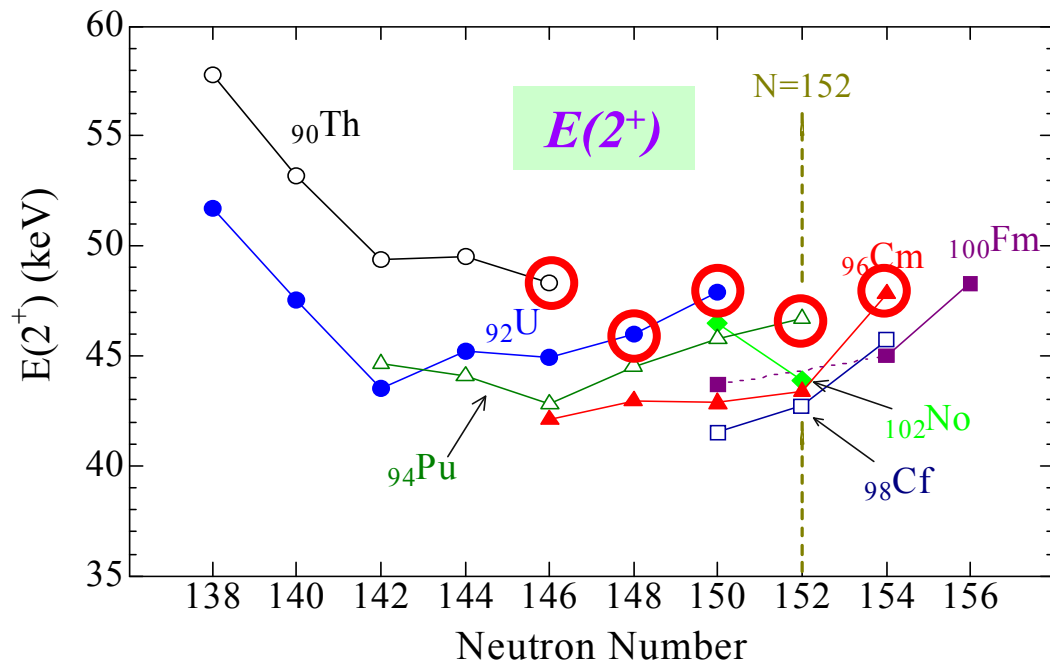
$$I^{(1)} = (2I-1)\hbar^2/E\gamma$$

$$I^{(2)} = 4\hbar^2/\Delta E\gamma$$

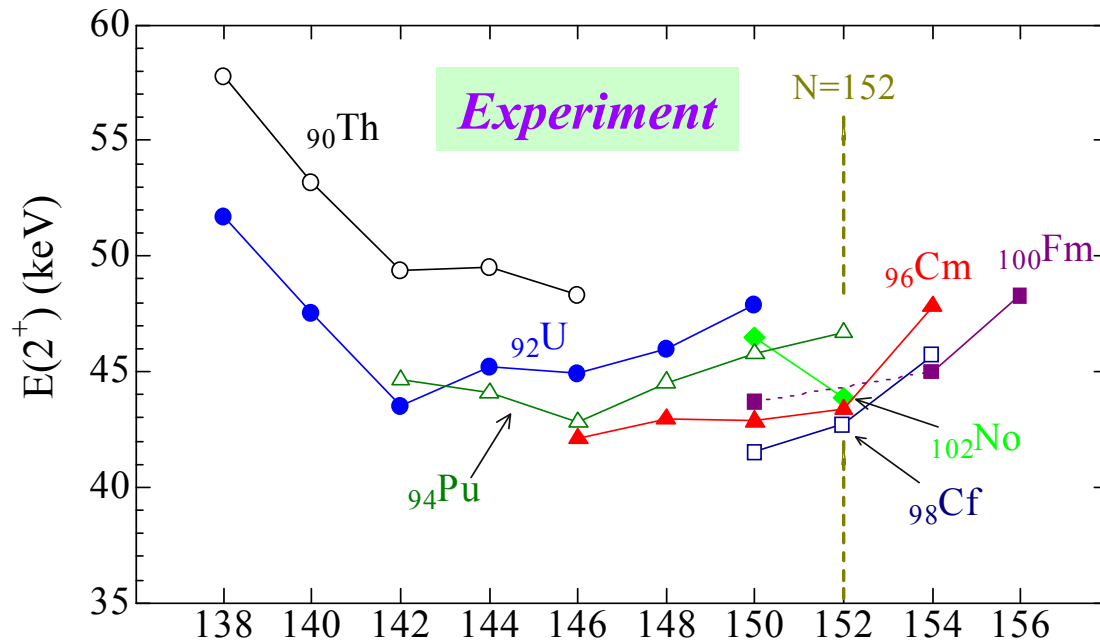
$$\hbar\omega = E\gamma / (\text{sqrt } I(I+1) - \text{sqrt } (I-2)(I-1))$$



**Systematics of
 $E(4^+)/E(2^+)$ & $E(2^+)$
 in the actinide region**



Moments of Inertia and N=152 Deformed Subshell Closure

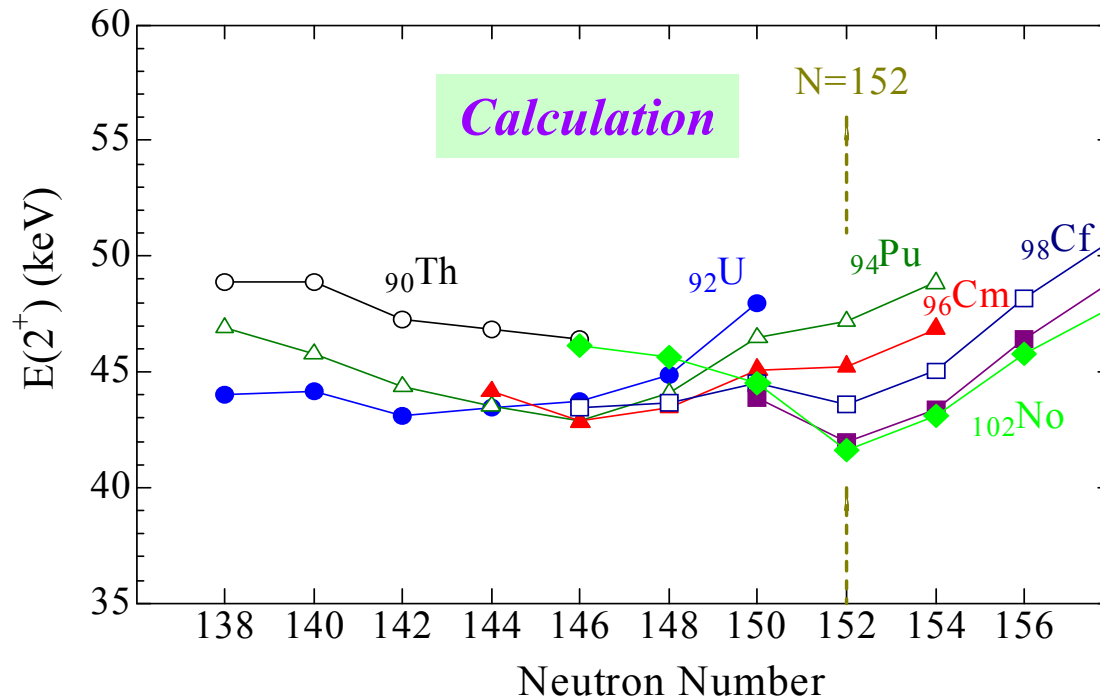


if deformed shell gap exists,
 pairing energy gap (Δ) \downarrow
 moment of inertia \uparrow (E_{2^+}) \downarrow

cranking model

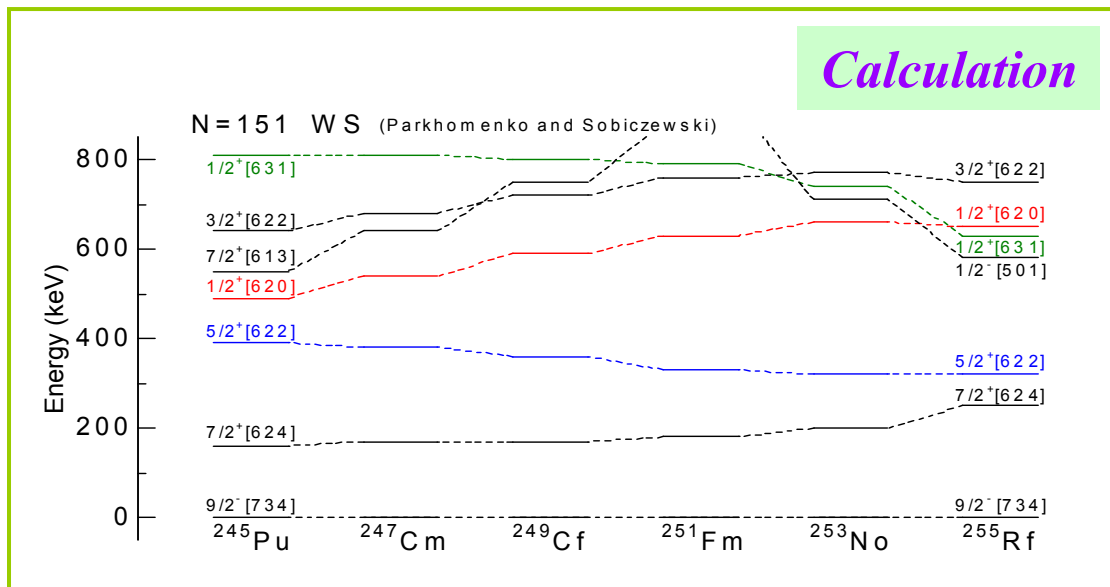
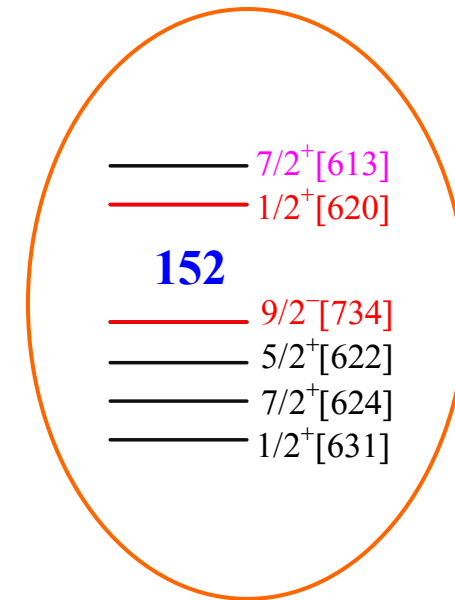
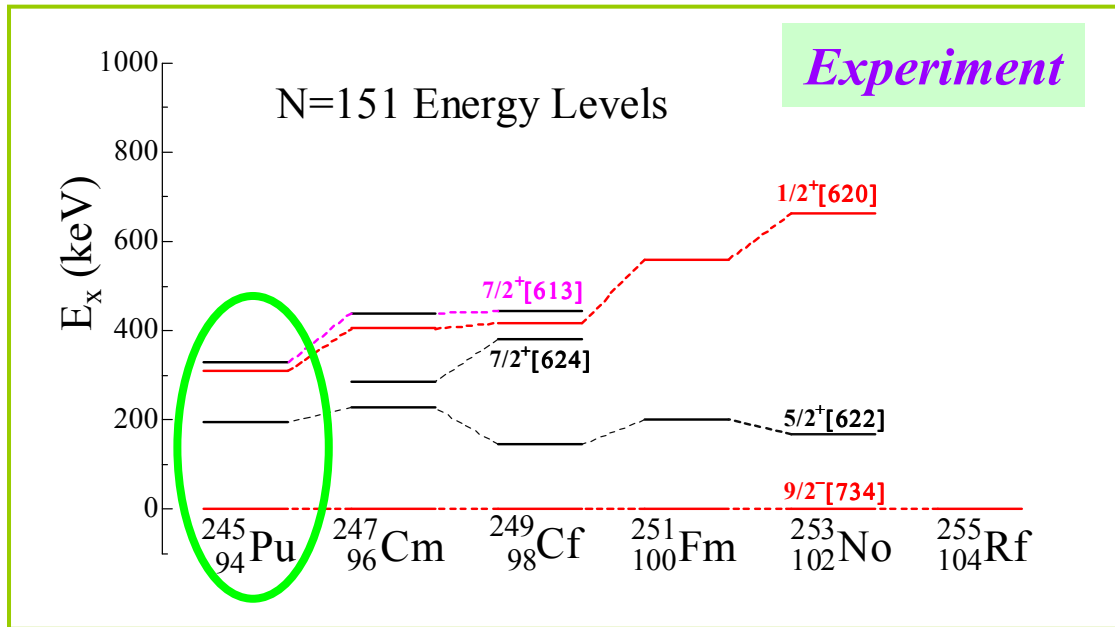
$$\mathcal{J}_{\text{超}} = \hbar^2 \sum_{\alpha\beta} \frac{|\langle \alpha | \hat{J}_x | \beta \rangle|^2}{E_\alpha + E_\beta} (u_\alpha v_\beta - v_\beta u_\alpha)^2$$

$$E_\alpha = \sqrt{(\varepsilon_\alpha - \lambda)^2 + \Delta^2}$$



*Sobiczewski et al.,
 PRC 63(2001)034306*

Energy Gap of the N=152 Deformed Subshell



*Parkhomenko et al.,
Act. Phys. Pol
B36 (2005)3115*

JAEAでのインビーム γ 実験のまとめ

- 中性子過剰の超ウラン元素で、初めての脱励起 γ 線測定
(^{18}O , ^{16}O) +2n; ^{240}U , ^{246}Pu and ^{250}Cm up to 12^+
(^{18}O , ^{20}Ne) -2p; ^{236}Th and ^{242}U up to 10^+ and 8^+
- N=152 変形閉殻の Z依存性を解明
 $Z \geq 96$ は閉殻、 $Z=94$ で消滅
- N=164球形閉殻の可能性を示唆
 $N \sim 146$ で E_{2^+} が極小
- 八重極相関に第2極大点が存在することを確立
 $N \sim 145$ で、 $K=0$ のバンドヘッドエネルギーが極小
- 奇核の励起構造の解析に着手
 ^{245}Pu 解析終了、 ^{249}Cm 解析中

^{240}U : T. Ishii et al., Phys. Rev. C 72 (2005) 021301(R)

^{250}Cm : T. Ishii et al., J. Phys. Soc. Jpn. 75 (2006) 043201

^{242}U , ^{236}Th : T. Ishii et al., submitted

$^{245,246}\text{Pu}$: H. Makii et al., submitted

今後の展開

Cf (Z=98)標的を用いたインビーム γ 線分光実験

Cf標的 – インビーム γ 線実験で初めて

高い比放射能

→ 最小の大きさの標的と最高のエミッタンスのビーム

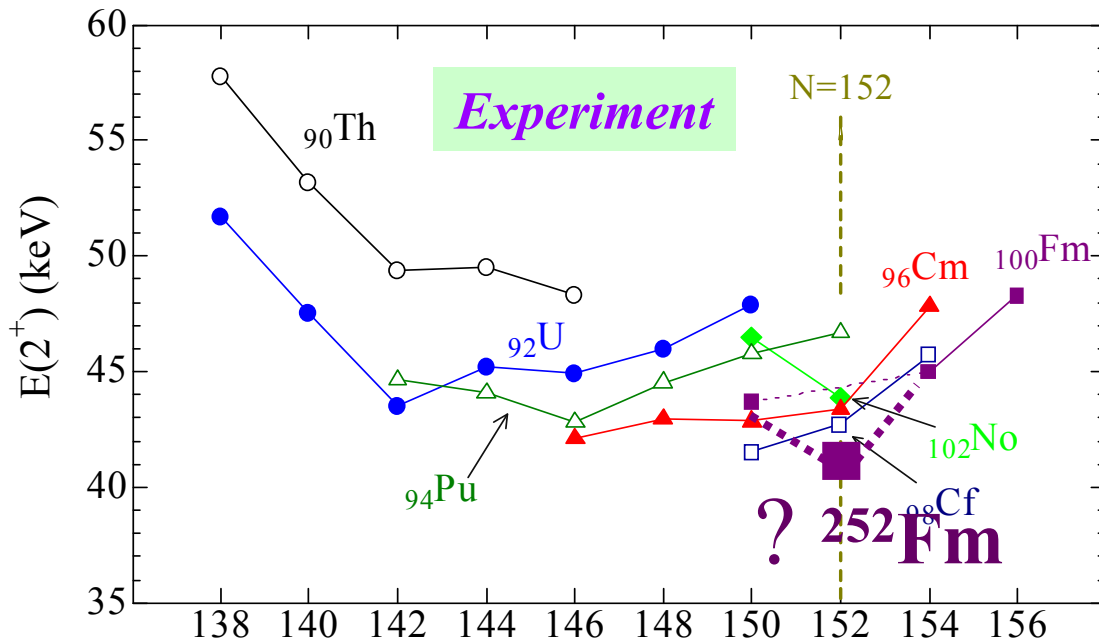
$^{249,250,251}\text{Cf}$ target (0.4mg/cm²) on Al(0.8mg/cm²)

^{249}Cf :60%, ^{250}Cf :14%, ^{251}Cf :26%

ϕ 0.8mm, 2 μ g, 1.5MBq → Si 14kcps, Ge 10kcps

- $^{252}\text{Fm}_{152}$ の励起準位 → $E(2^+)$ と変形閉殻との相関
- $^{248,250,252}\text{Cf}$ の高スピン状態
- $^{251}\text{Es}(Z=99)$ の単一粒子軌道(high-L) の確立

Moments of Inertia and N=152 Deformed Subshell Closure

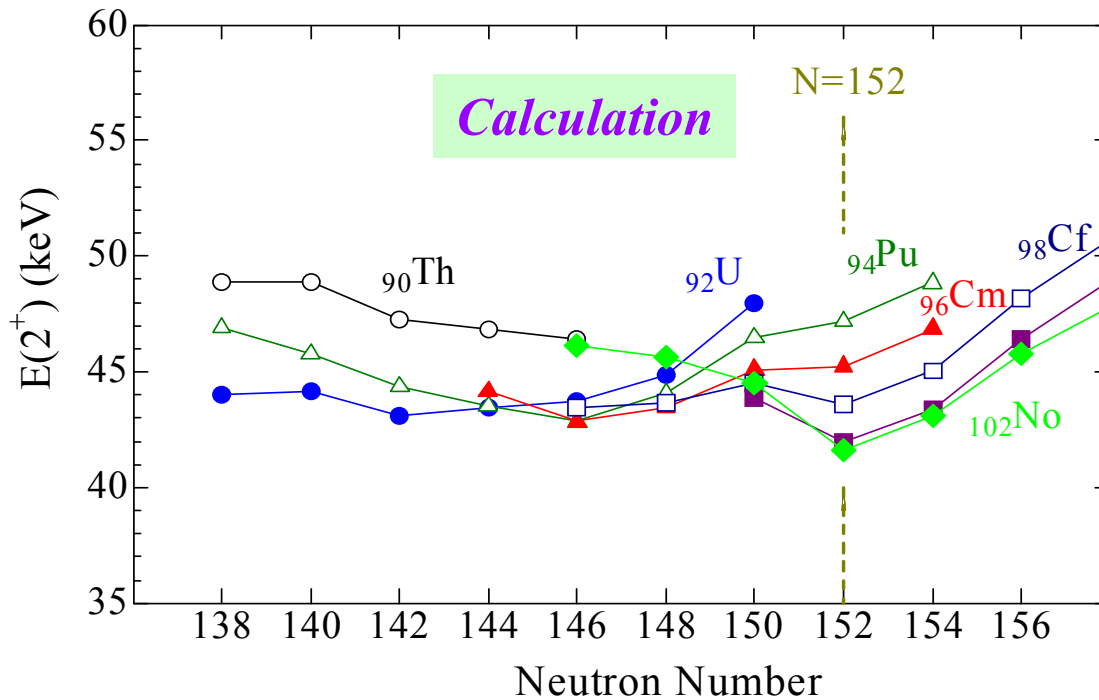


if deformed shell gap exists,
 pairing energy gap (Δ) ↓
 moment of inertia ↑ (E_{2^+}) ↓

cranking model

$$\mathcal{J}_{\text{超}} = \hbar^2 \sum_{\alpha\beta} \frac{|\langle \alpha | \hat{J}_x | \beta \rangle|^2}{E_\alpha + E_\beta} (u_\alpha v_\beta - v_\beta u_\alpha)^2$$

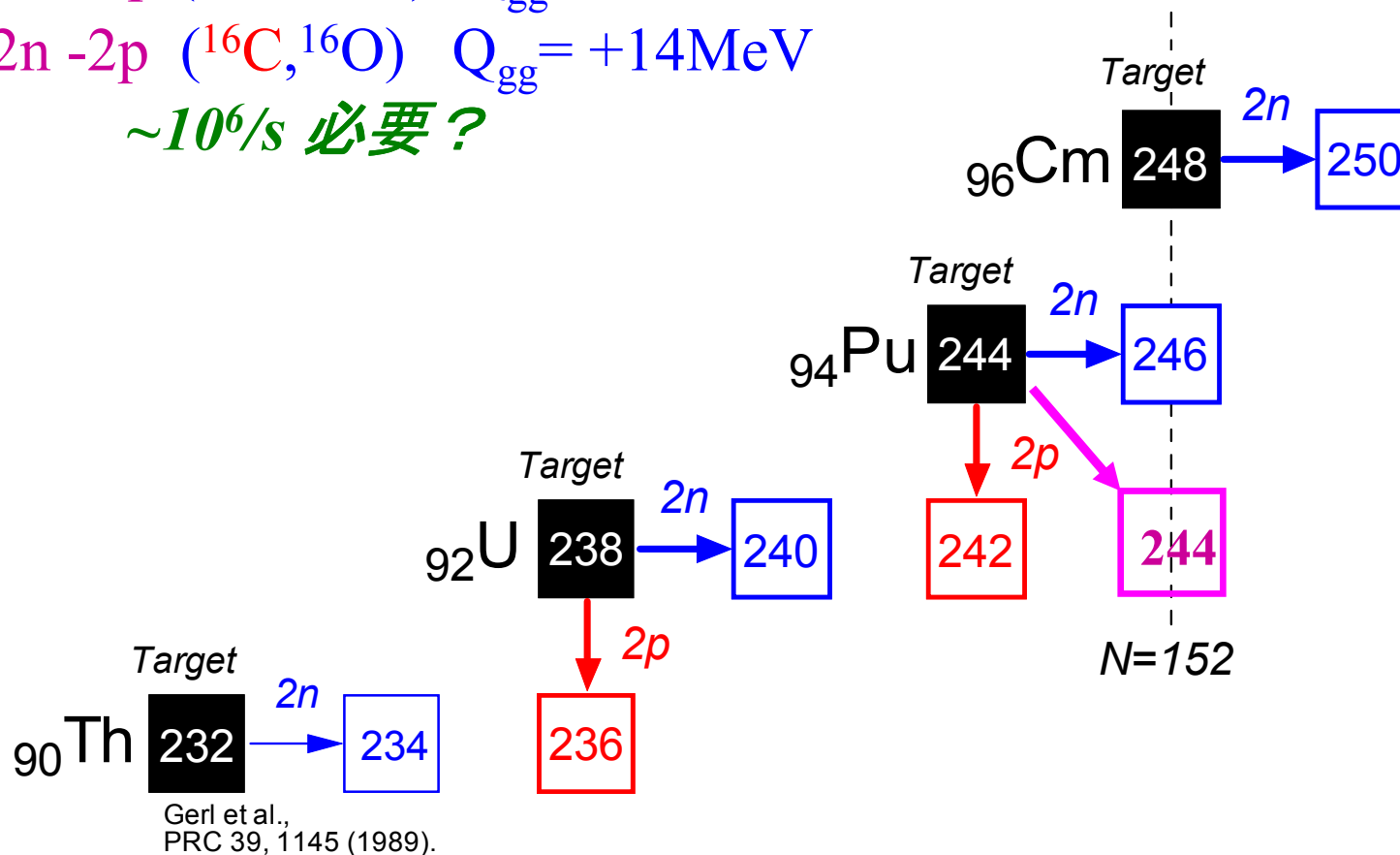
$$E_\alpha = \sqrt{(\epsilon_\alpha - \lambda)^2 + \Delta^2}$$



← *Sobiczewski et al.,
 PRC 63(2001)034306*

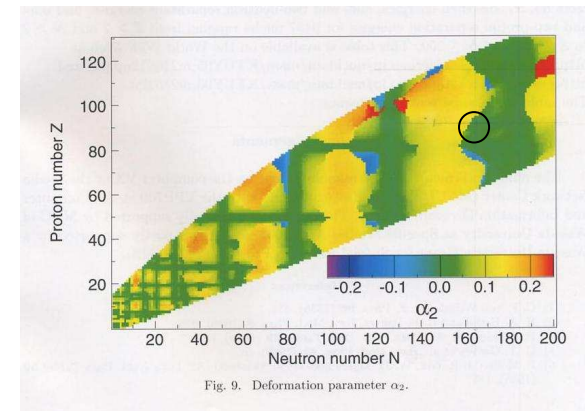
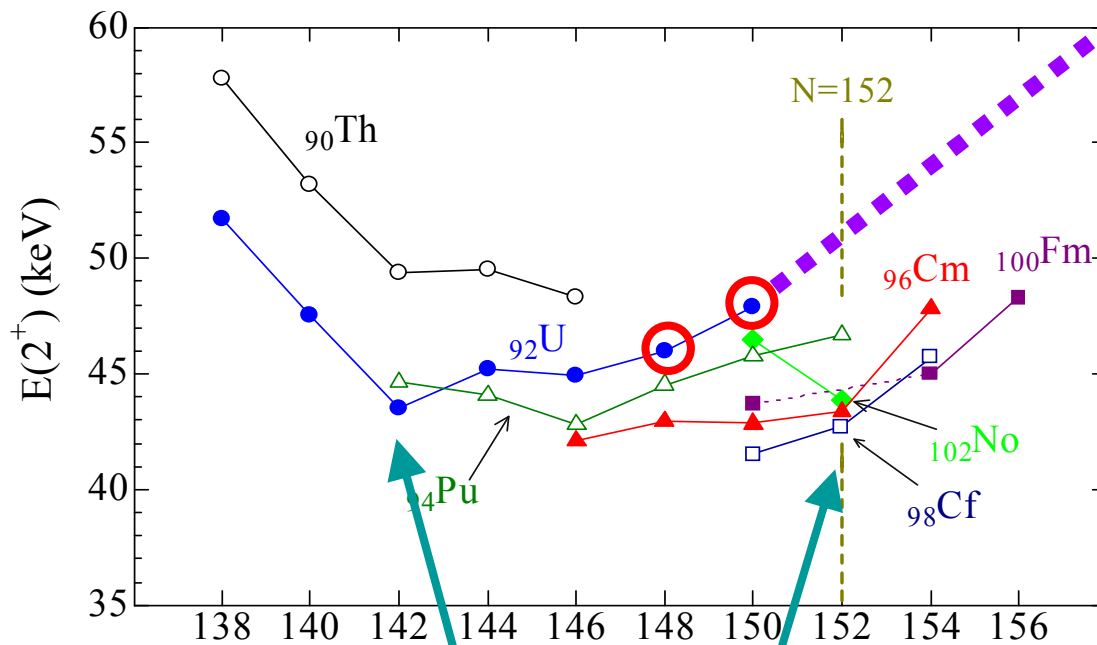
不安定核ビームを用いた核子移行実験 *e.g.*, ^{16}C

- $+2n$ ($^{18}\text{O}, ^{16}\text{O}$) $\sigma \sim 10^2 \mu\text{b}$ $i \sim 10^9/\text{s}$
- $-2p$ ($^{18}\text{O}, ^{20}\text{Ne}$) $\sigma \sim \mu\text{b}$
- $+2n -2p$ ($^{18}\text{O}, ^{18}\text{Ne}$) $Q_{\text{gg}} = -11\text{MeV}$
- $+2n -2p$ ($^{16}\text{C}, ^{16}\text{O}$) $Q_{\text{gg}} = +14\text{MeV}$
 $\sim 10^6/\text{s}$ 必要?



Possibility of spherical shell closure of N=164 for the U region

$^{256}_{92}\text{U}_{164}$ は丸い？



高角運動量軌道のエネルギー準位の測定

Identify energy levels of
 $\frac{1}{2}[880] k_{17/2}$ in ^{249}Cm

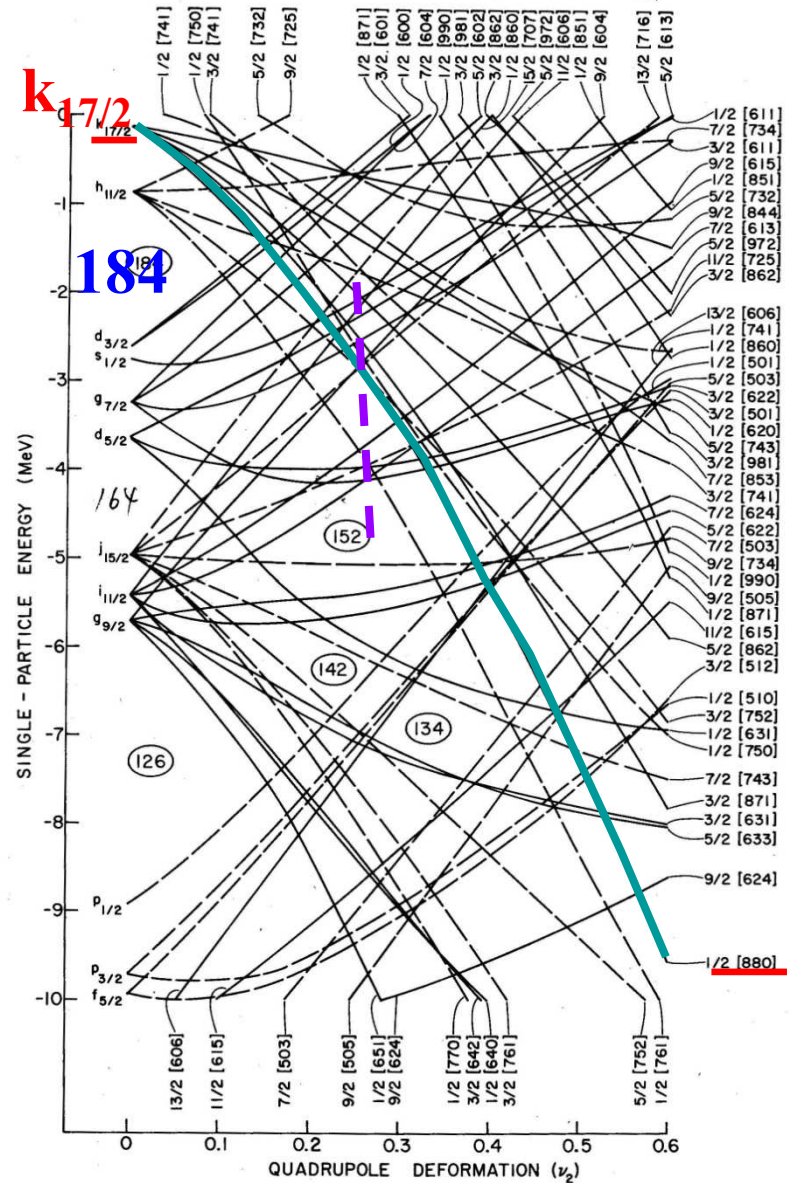
$^{248}\text{Cm}(^{16}\text{O}, ^{15}\text{O})^{249}\text{Cm}$

$(^{13}\text{C}, ^{12}\text{C})^{249}\text{Cm}$

$(^{18}\text{O}, ^{17}\text{O})^{249}\text{Cm}$

$\times 2/\lambda$

Cross Section (mb/sr)



$(\alpha, {}^3\text{He})$ Grand Raiden ${}^{248}\text{Cm}$ 標的？

${}^{248}\text{Cm}({}^4\text{He}, {}^3\text{He}){}^{249}\text{Cm}$ $E_\alpha = 99\text{MeV}$ @IUCF

Possible observation of the $1/2^+[880]$ orbital
in ${}_{96}^{249}\text{Cm}$

I. Ahmad^a, B.B. Back^a, R.R. Chasman^a, J.P. Greene^a, T. Ishii^{a,1},
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W.R. Lozowski^b, W. Schmitt^{b,2}, E.J. Stephenson^b, T. Yamanaka^{b,3}

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