超重核領域のインビームγ線分光

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東工大　重松、河野、小川; 防衛医大　牧嶋; 駒沢大　金子　; 茨城大　當銘

超重核領域における核構造実験の状況

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

Z~102　In-beam γ, isomer-γ, α−γ ;

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

Z~94　In-beam γ ;　unsafe Coulomb

JAEAでの実験

Z~102　α−γ ;　fusion: ^{18}O+^{248}Cm, using He-jet

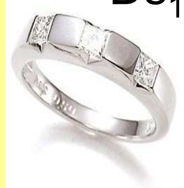
☞ *Z~94 neutron-rich In-beam γ*

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

展望

超重核領域の核構造研究

$^{294}Ds_{184}$



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) ?*

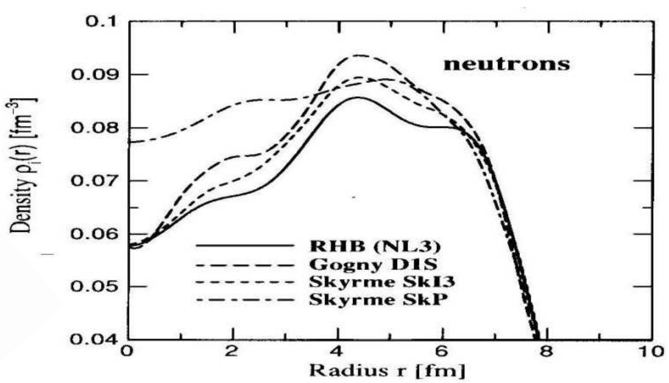
特異な構造　⇒　*新しい原子核描像の構築*

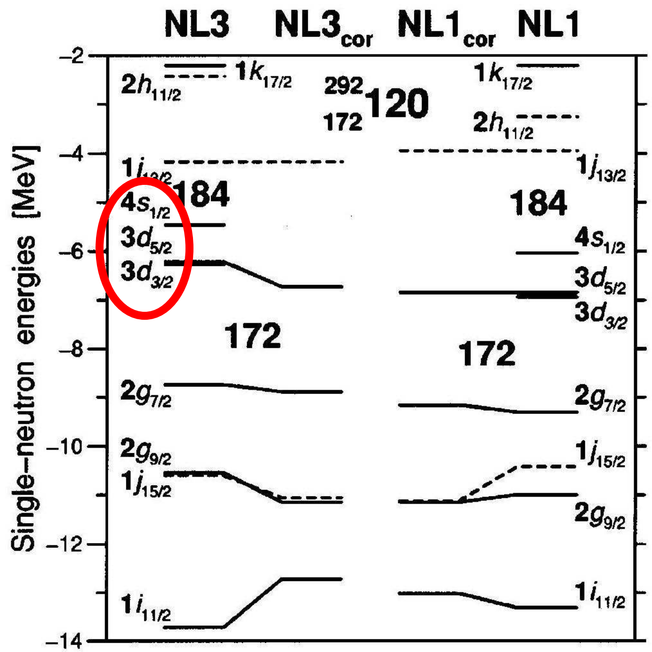
e.g., Balloon 原子核　120=126-(p軌道) , 172=184-(s,d軌道）

核分裂　　*微視的な取り扱い？*

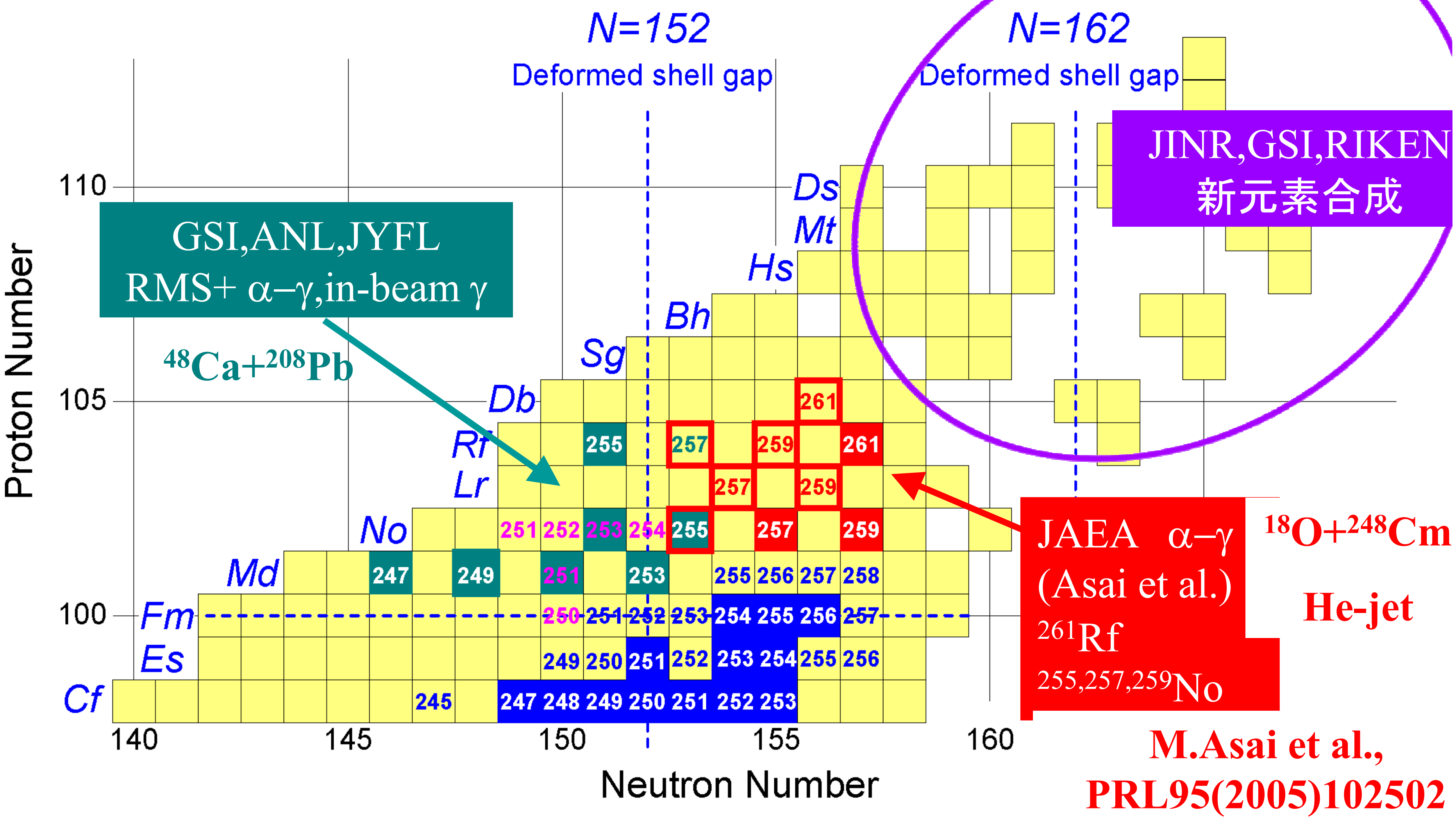
Balloon Nucleus ***120_{172}***

Central Depression of Nucleon Density



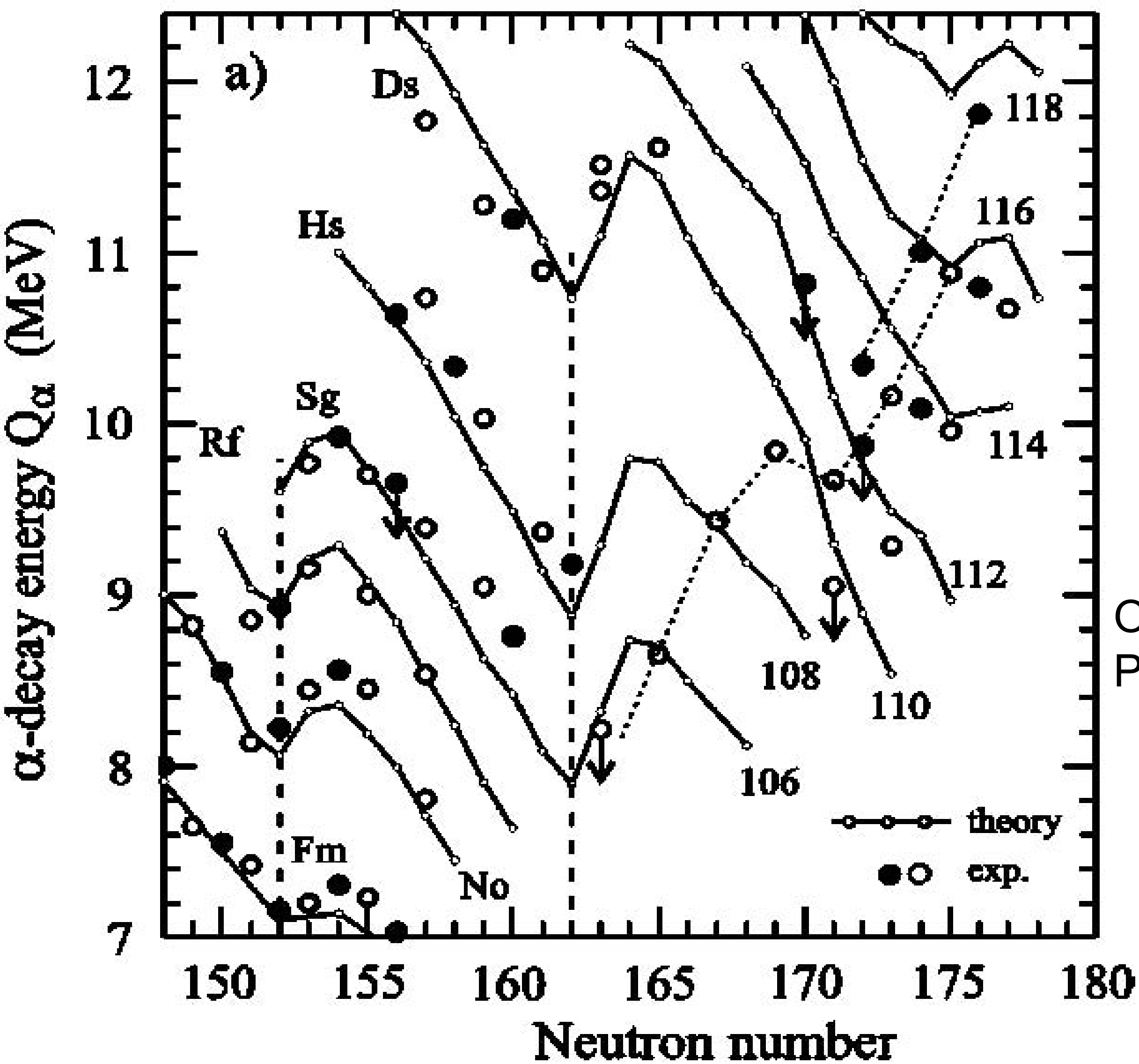


超重核領域の核構造実験の現状



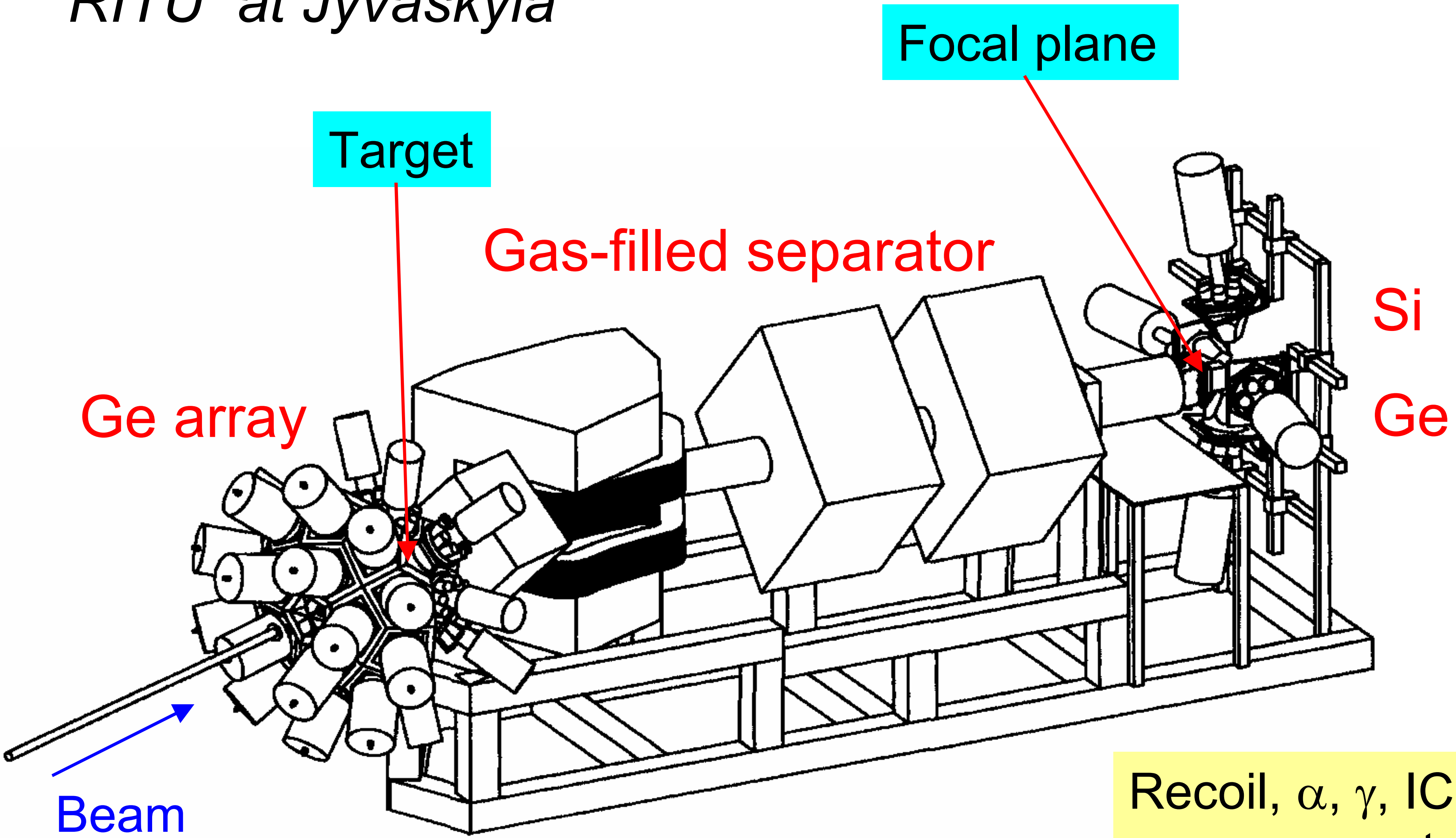
No experimental data for spin-parity and Nilsson-orbital assignments for Z >101 and N >153 nuclei

超重核領域の核構造実験の現状
Qα　JINR(Dubna)



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

RITU at Jyvaskyla

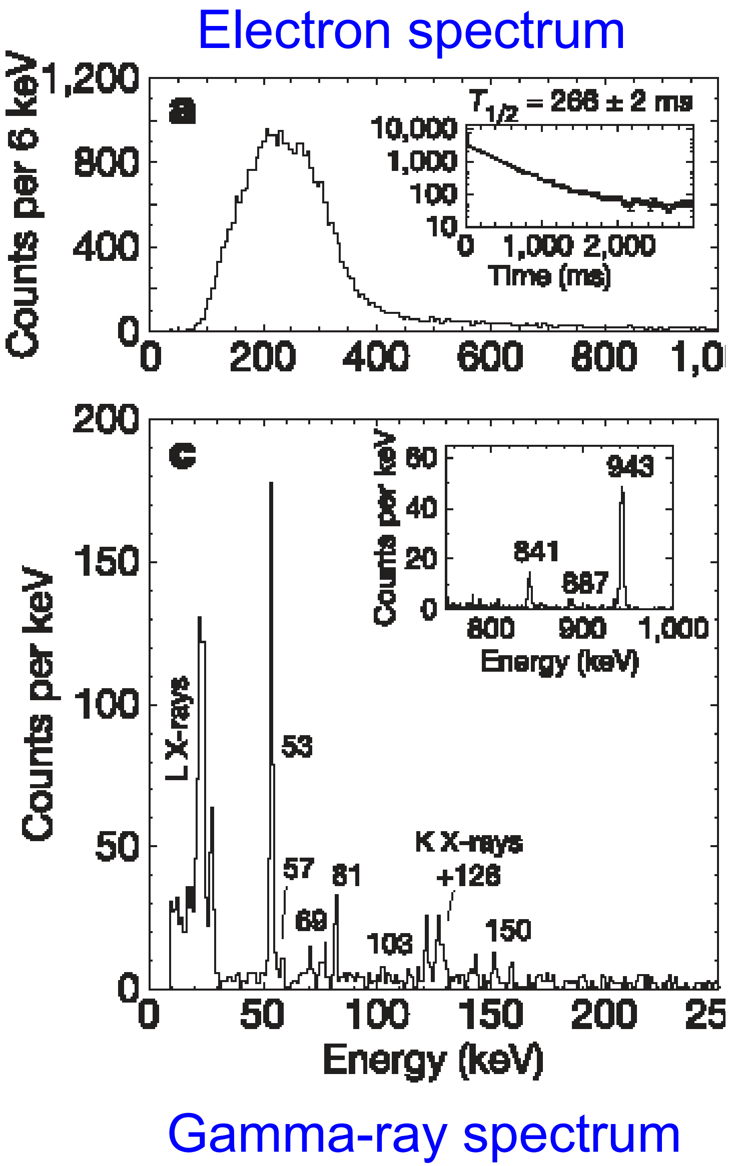


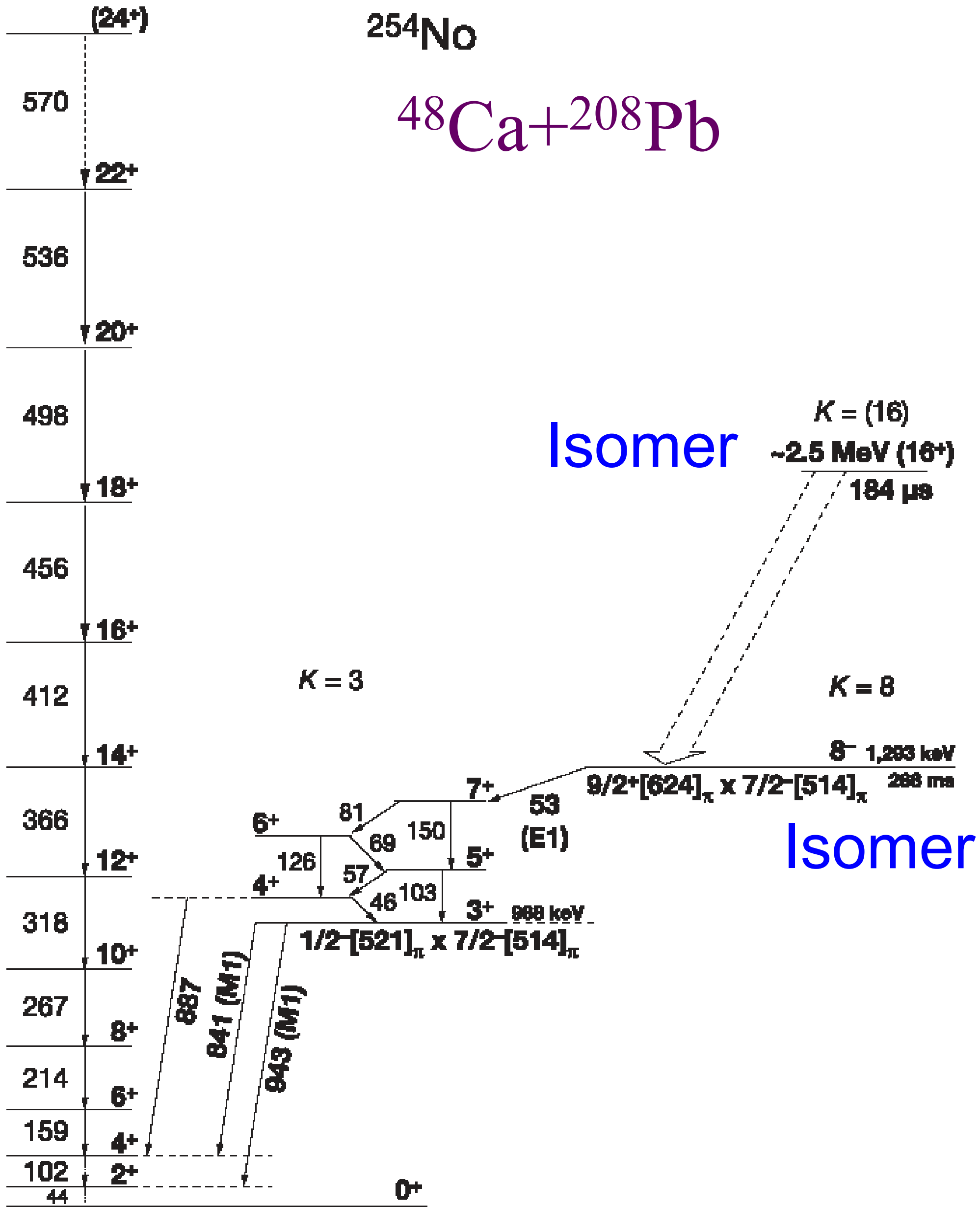
Recoil, α, γ, ICE measurements

In-beam γ-ray spectroscopy with recoil decay tagging

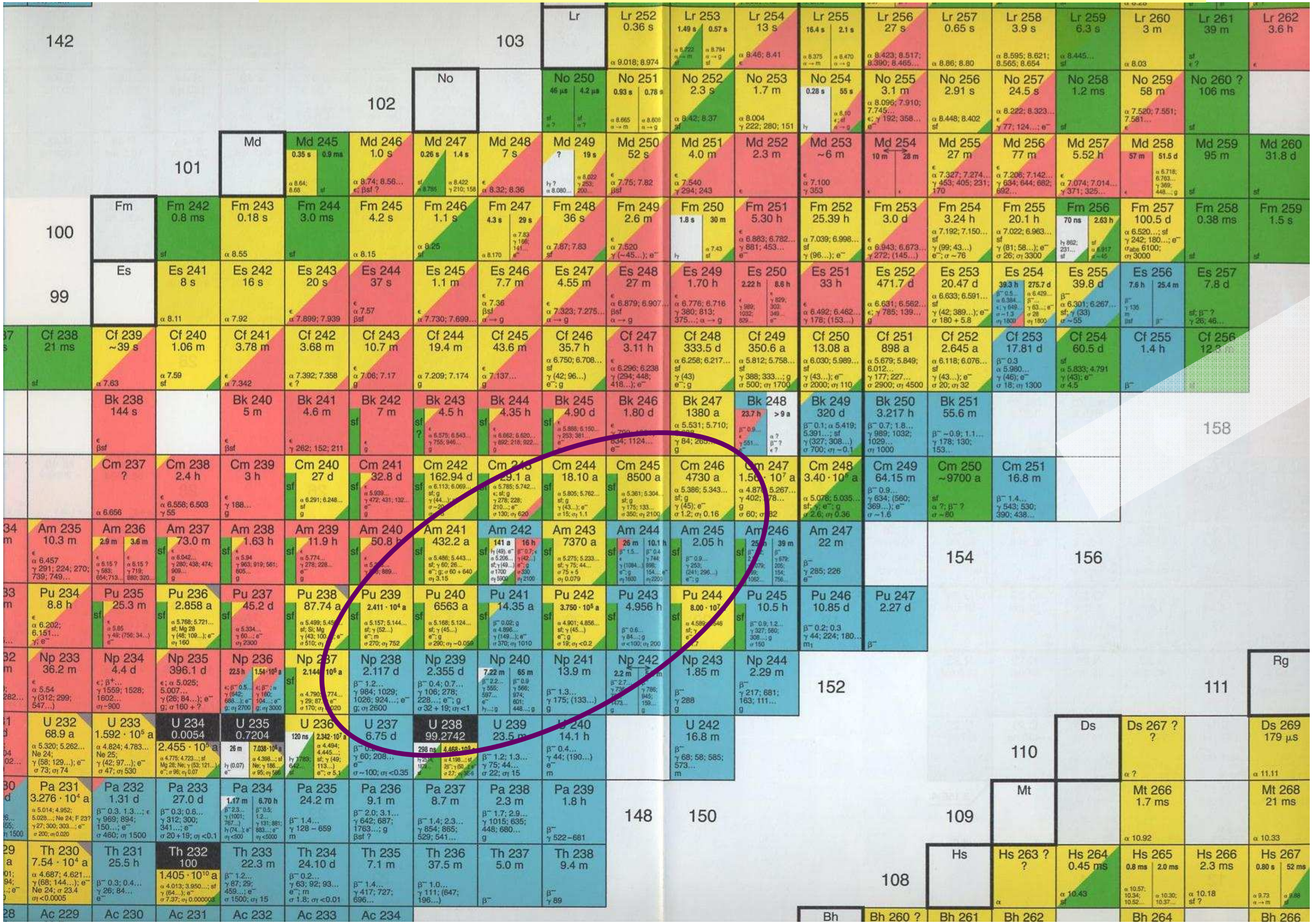
Julin *et al.*, NP A685 (2001) 221c.

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

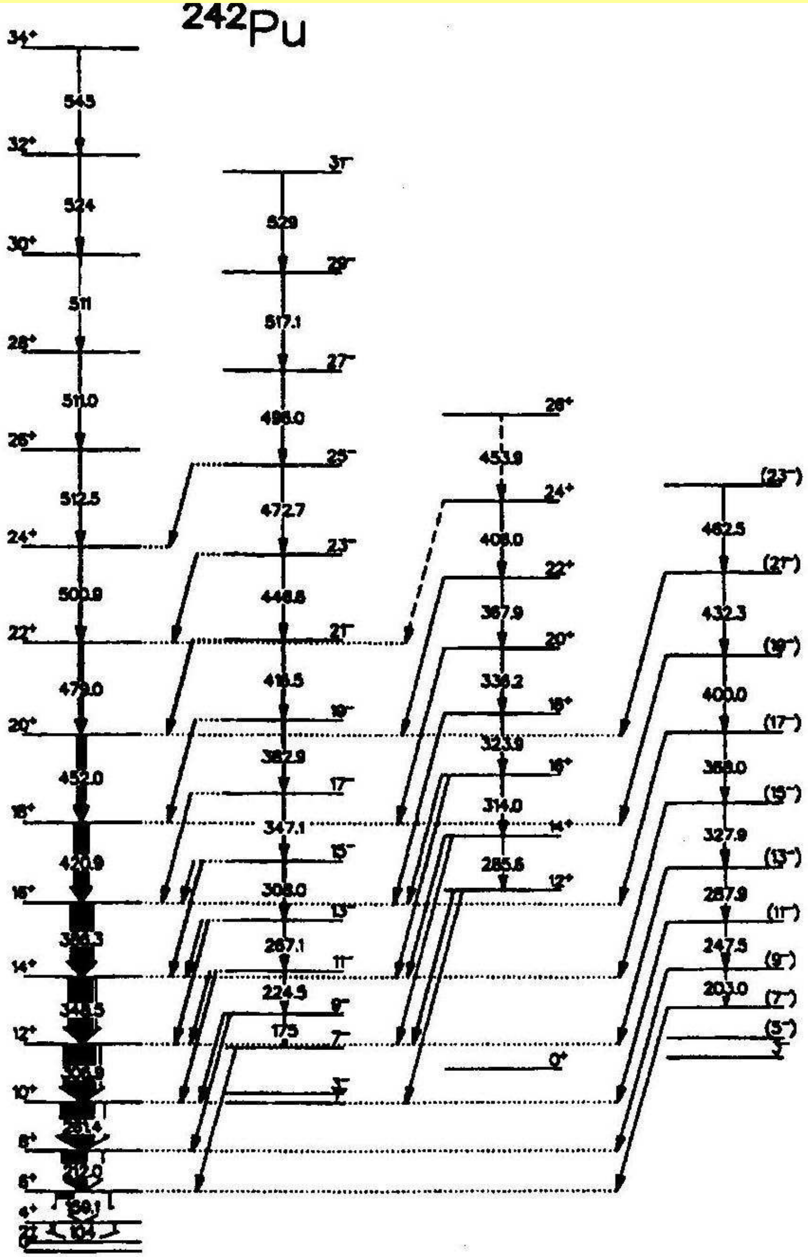




超重核領域の核構造実験の現状
Unsafe Coulomb ANL(Gammasphere)



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 & Supercoducting Booster &TRIAC (Tokai Radioactive Ion Accelerator Complex)

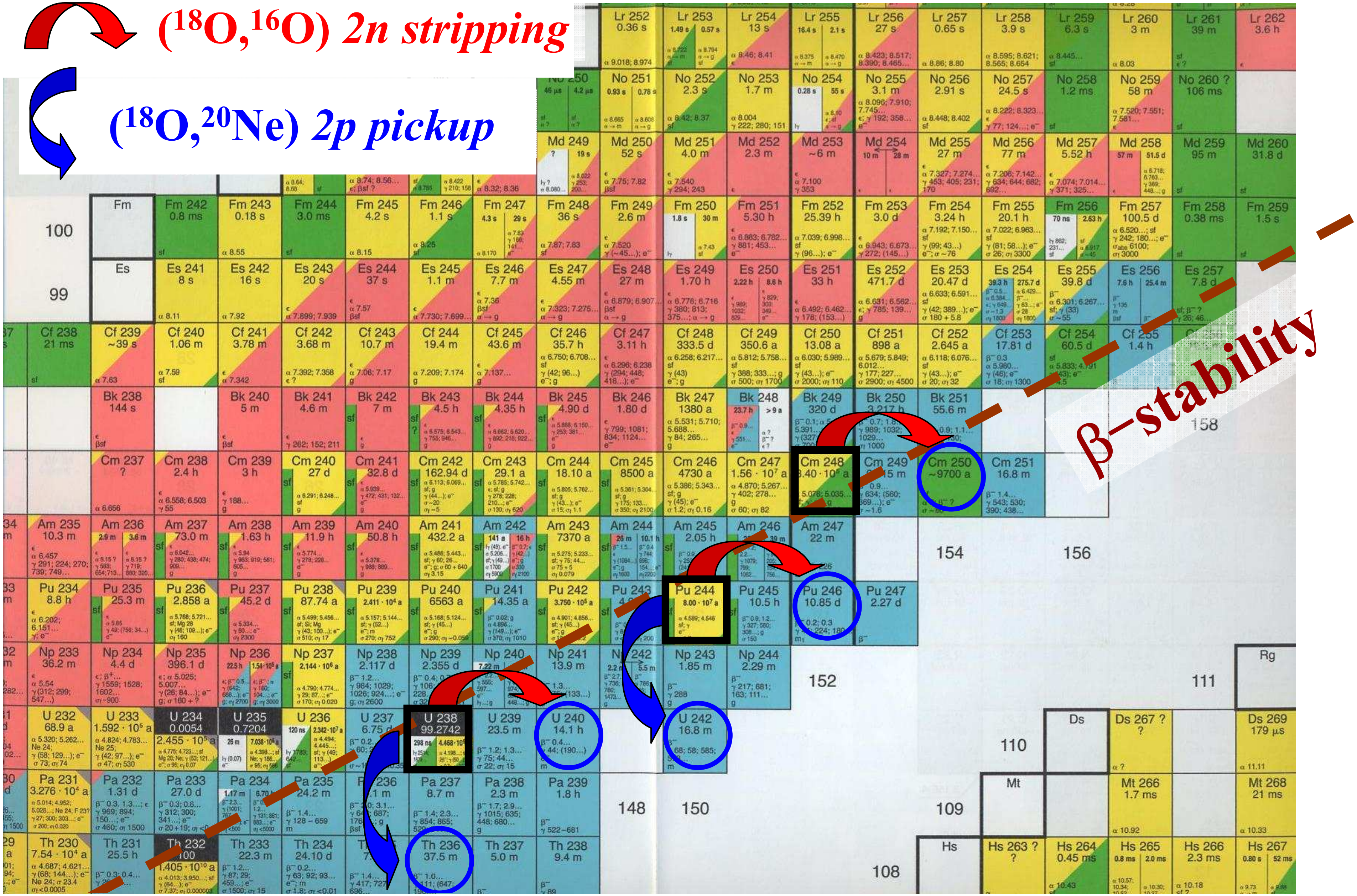
- V_T=18MV ; new acceleration tubes; ECR ion source on the terminal
- Superconducting linac booster; 40 quarter-wave resonators: V ~ 30MV

  ^{18}O (15MeV/u), ^{76}Ge(10MeV/u), ^{127}I(6MeV/u), …
- TRIAC: joint project between JAEA & KEK

  Tandem(RI ; p+UC, ^{7}Li+C,…) → ISOL → Charge breeder → SCRFQ+IH-LINAC

  ^{8}Li (1.1MeV/u, 10^5/s),….

Neutron-rich Transuranium Nuclei

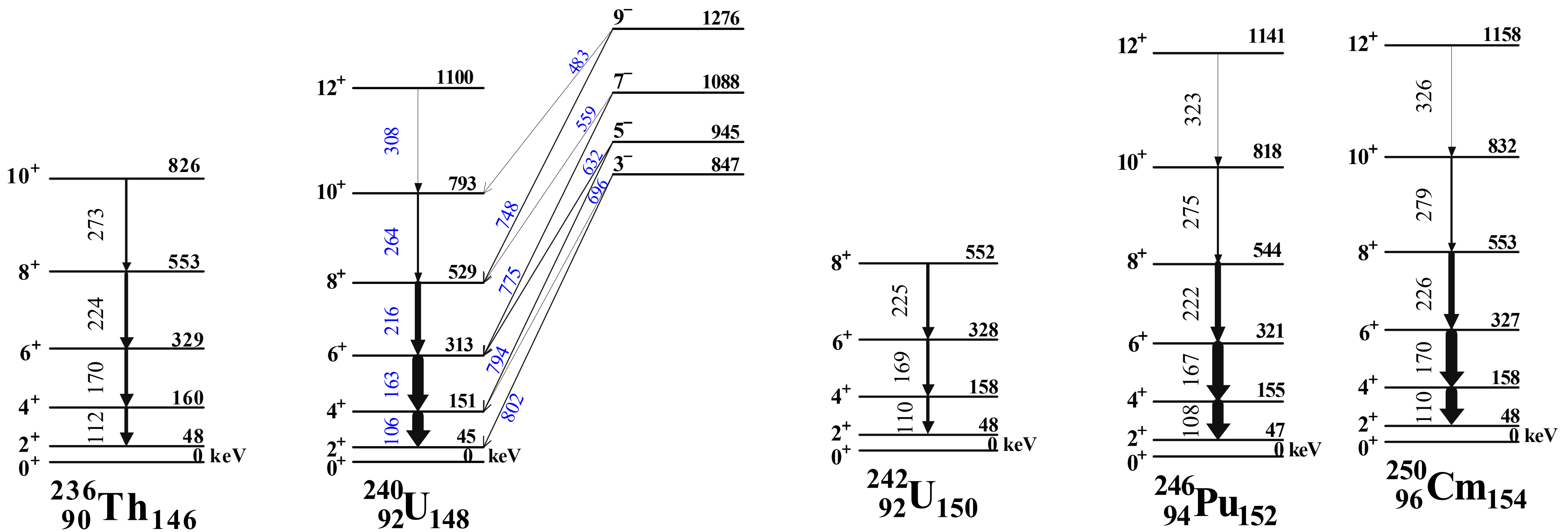


超重核のインビームγ線分光

1) 重イオン核子移行反応:　(^{18}O,^{16}O), (^{18}O,^{20}Ne), (^{16}O,^{15}O)….
2) アクチノイド標的:　^{238}U(Z=92), ^{244}Pu(Z=94), ^{248}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}Th, $^{240,242}U$, ^{246}Pu, ^{250}Cm で初めてのγ線測定



Experimental Setup
- $^{18}O + ^{248}Cm$ experiment -

Beam : ^{18}O(162MeV, V_T=18MV), i=0.3pnA, [adjust with ϕ2.5mm aperture]

Target: ^{248}Cm (0.8mg/cm^2) on Al(0.9mg/cm^2) ; ϕ3mm, 60μg, 45kBq

Detectors: 4 Si ΔE(75μm)-E placed at 40(+/- 11) degree [Si ELID wafer]

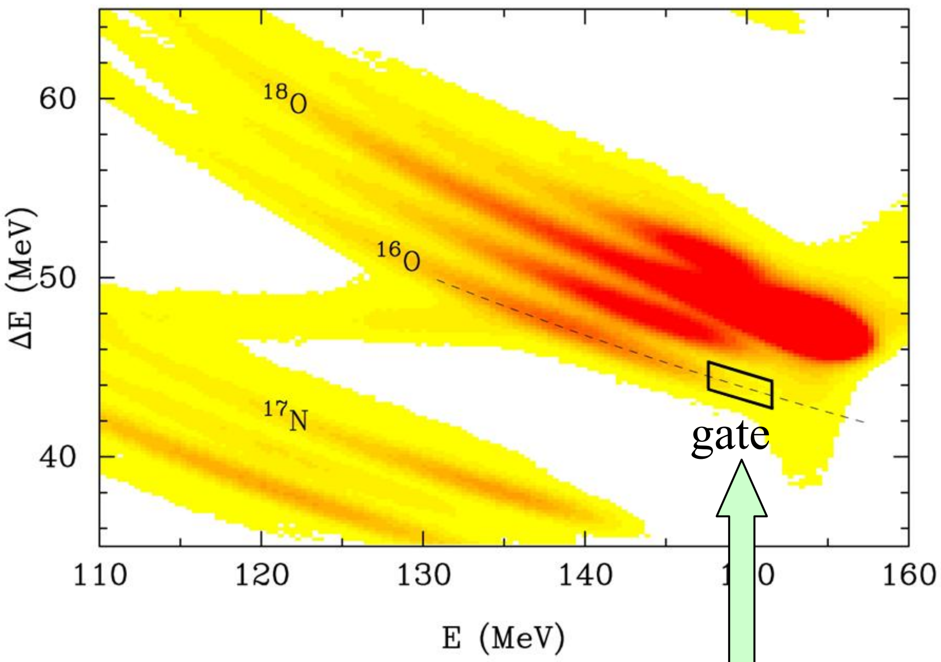
6 Ge detectors; εff = 12% @ 0.2 MeV, 3%@1.3MeV

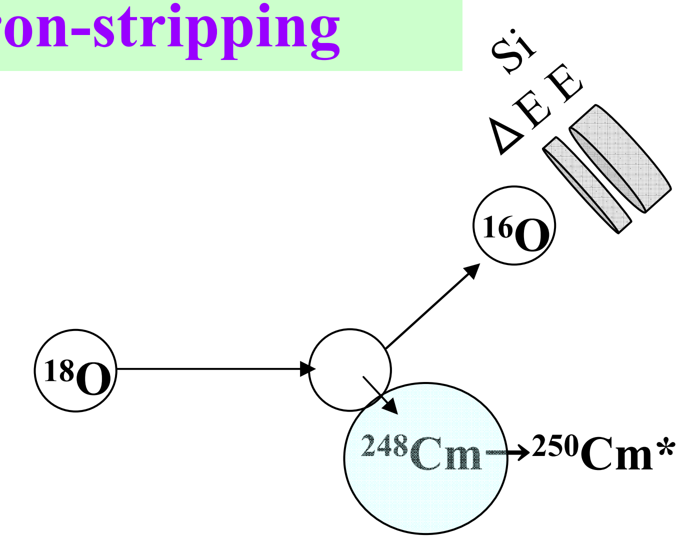
Si ΔE-E Detectors

E-ΔE Plot & γ-ray Spectra of $^{250}Cm_{154}$

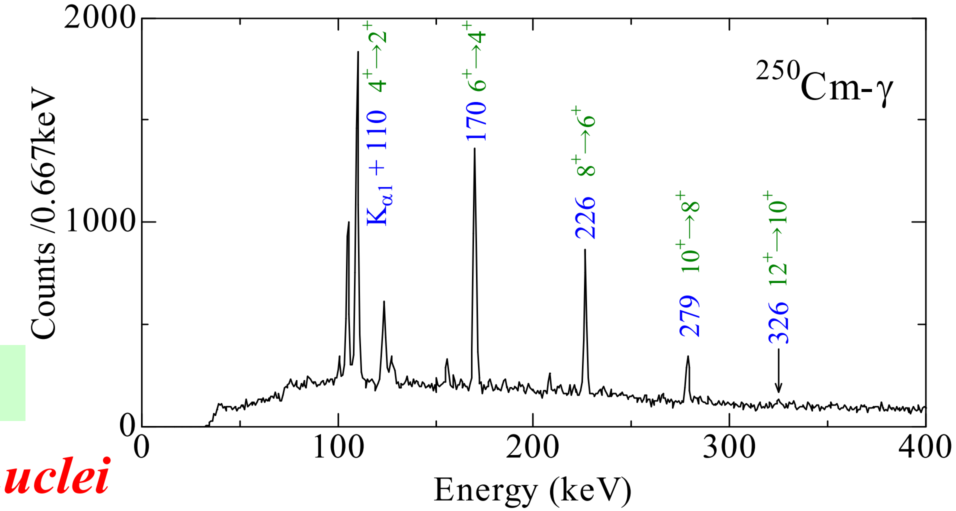
$^{248}Cm(^{18}O,^{16}O)^{250}Cm$; 2neutron-stripping

Si E-ΔE PLOT





E_x of $^{250}Cm < S_n$



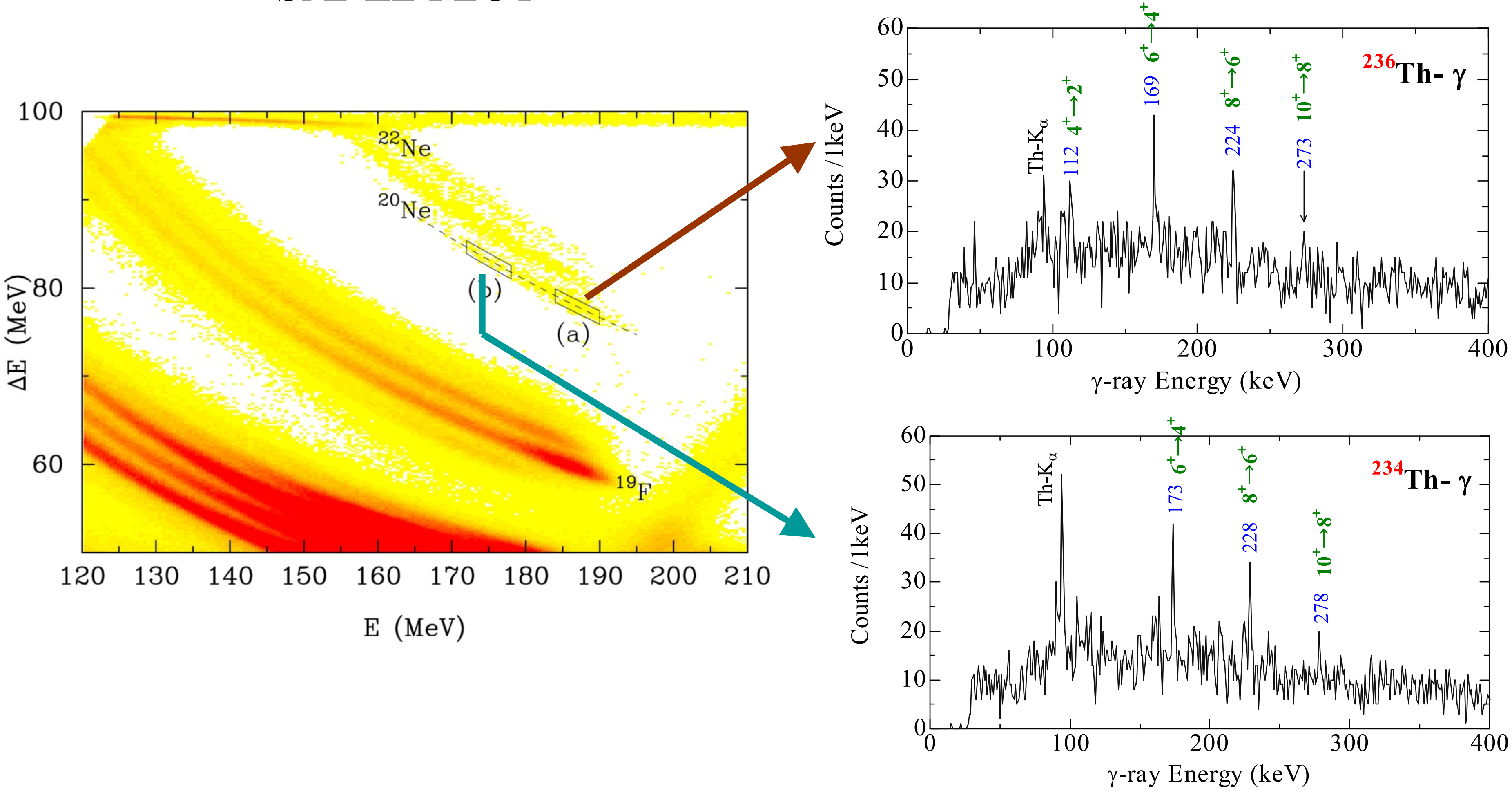
Complete selection of γ-rays in residual nuclei
by measuring outgoing particles
- Z, M, and kinetic energies -

E-ΔE Plot & γ-ray Spectra of $^{236}Th_{146}$

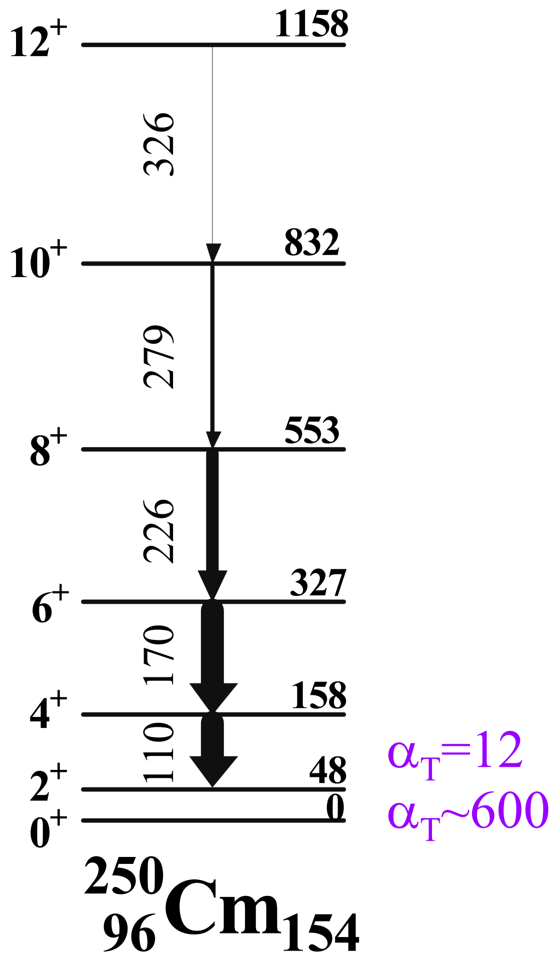
$^{238}U(^{18}O,^{20}Ne)^{236}Th$; 2proton-pickup

$\sigma \sim \mu b$

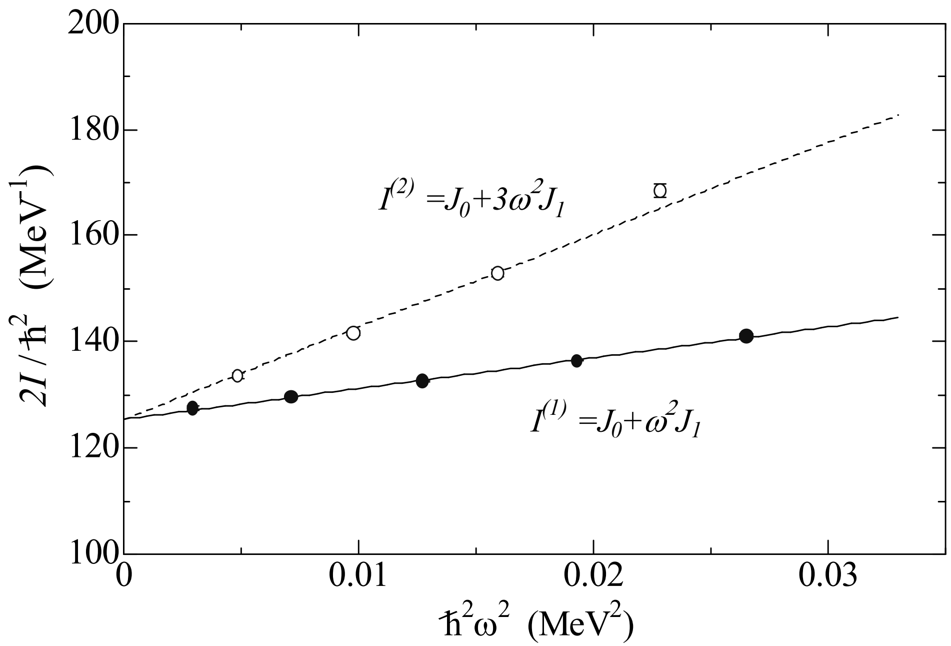
Si E-ΔE PLOT



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



Moments of inertia

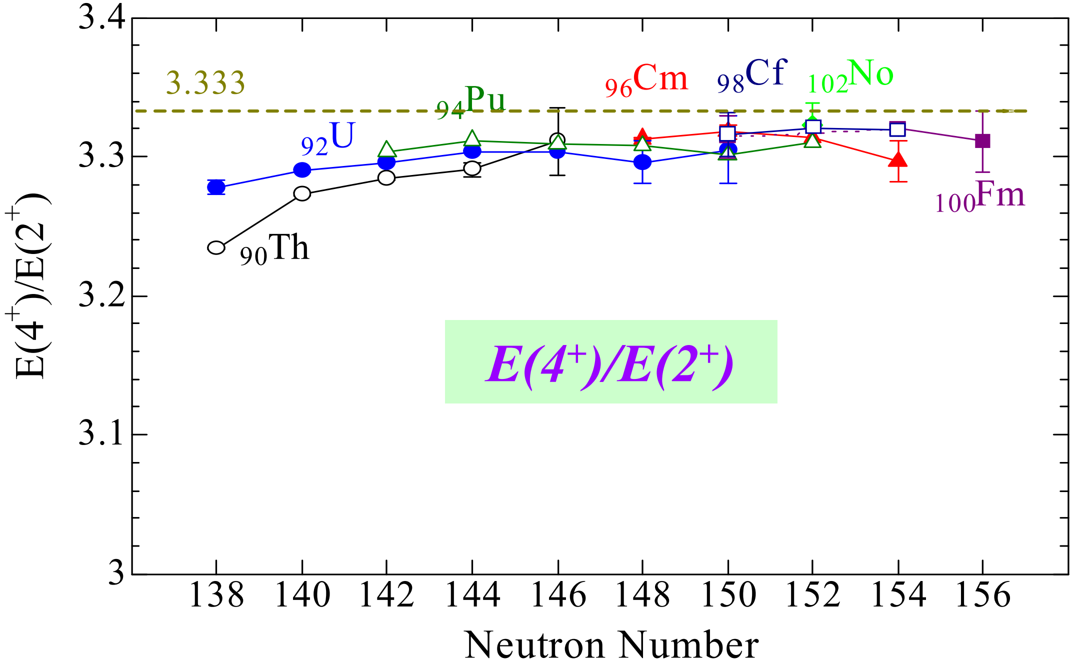


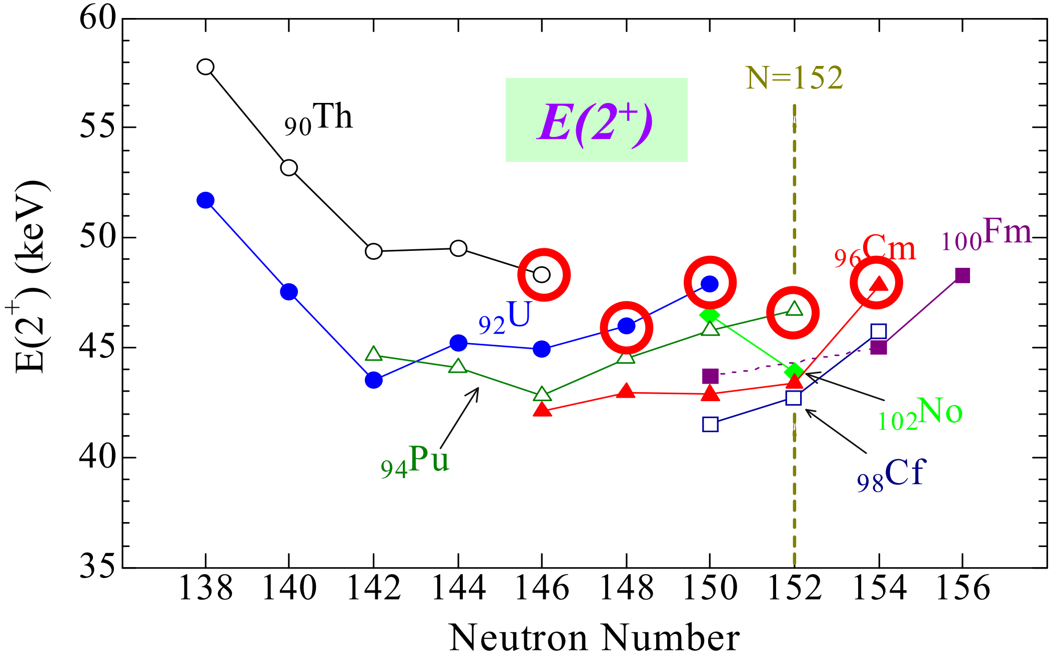
$I^{(1)} = (2I-1)\hbar^2/E\gamma$

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

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

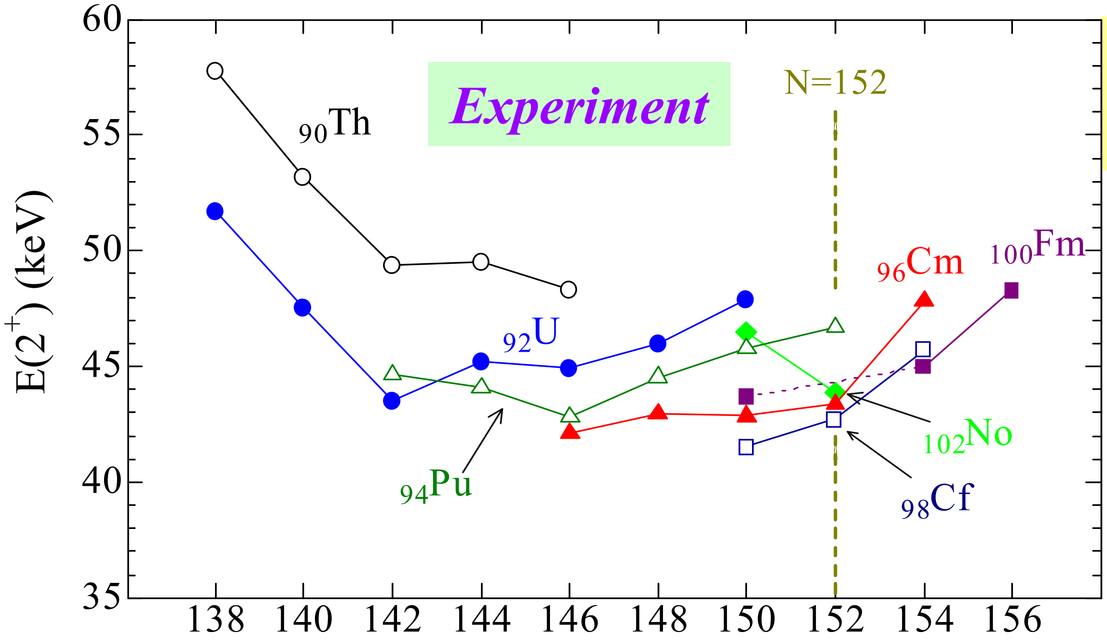
Systematics of
E(4⁺)/E(2⁺) & E(2⁺)
in the actinide region

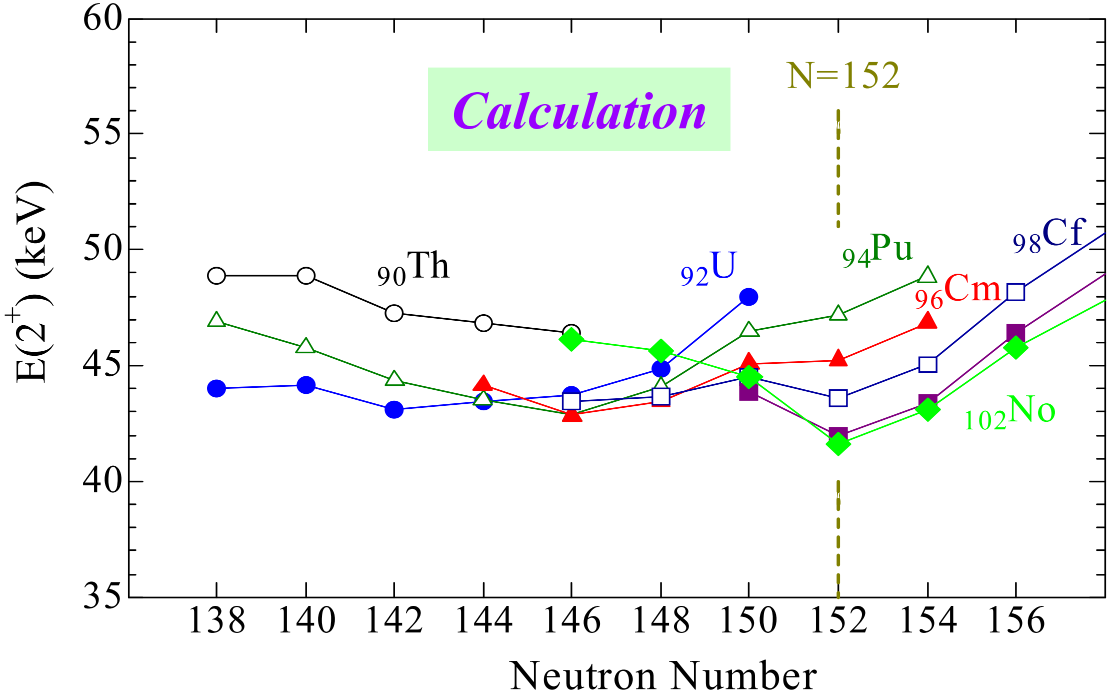




Five new data
from our experiments

Moments of Inertia and N=152 Deformed Subshell Closure





if deformed shell gap exists,

pairing energy gap (Δ)↓

moment of inertia ↑ (E_{2+}↓)

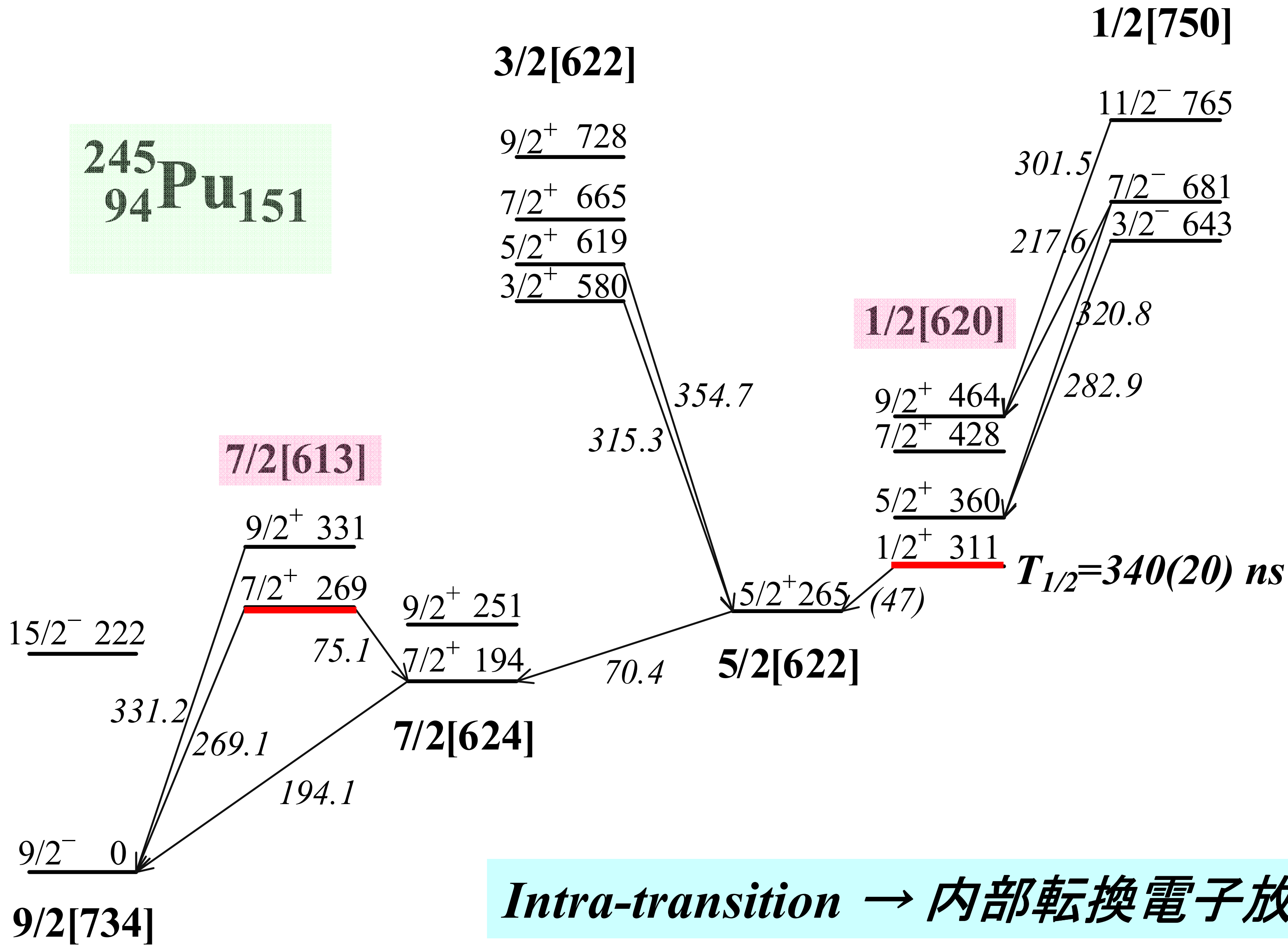
cranking model

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

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

Sobiczewski et al., PRC 63(2001)034306

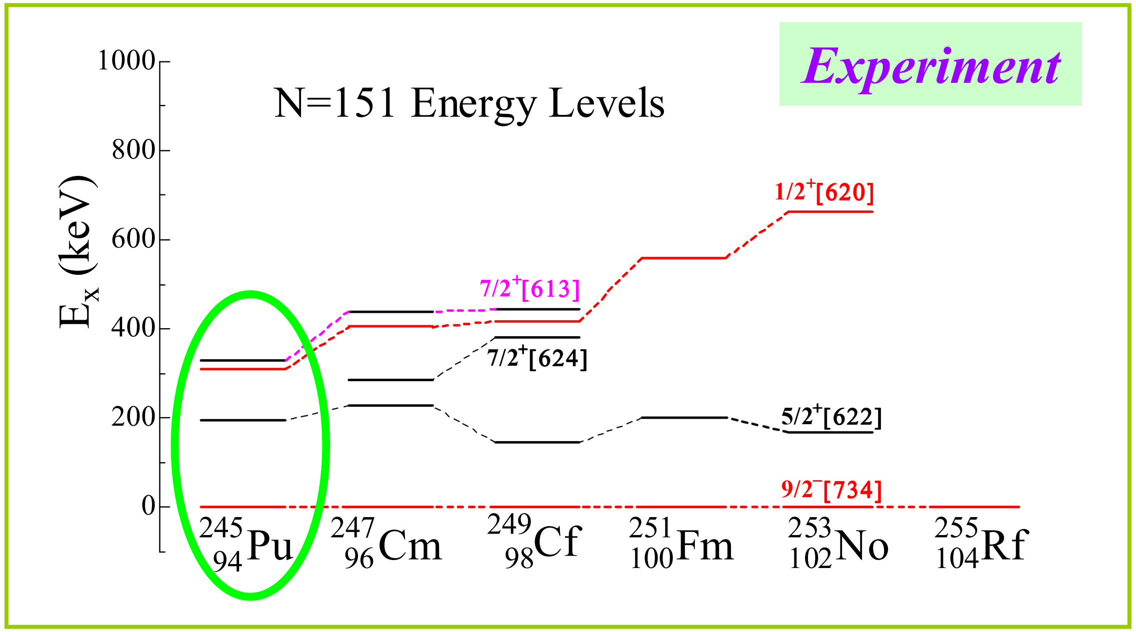
奇核におけるエネルギー準位

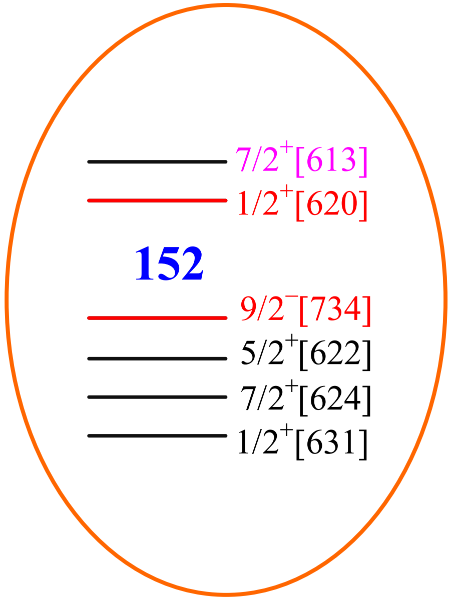


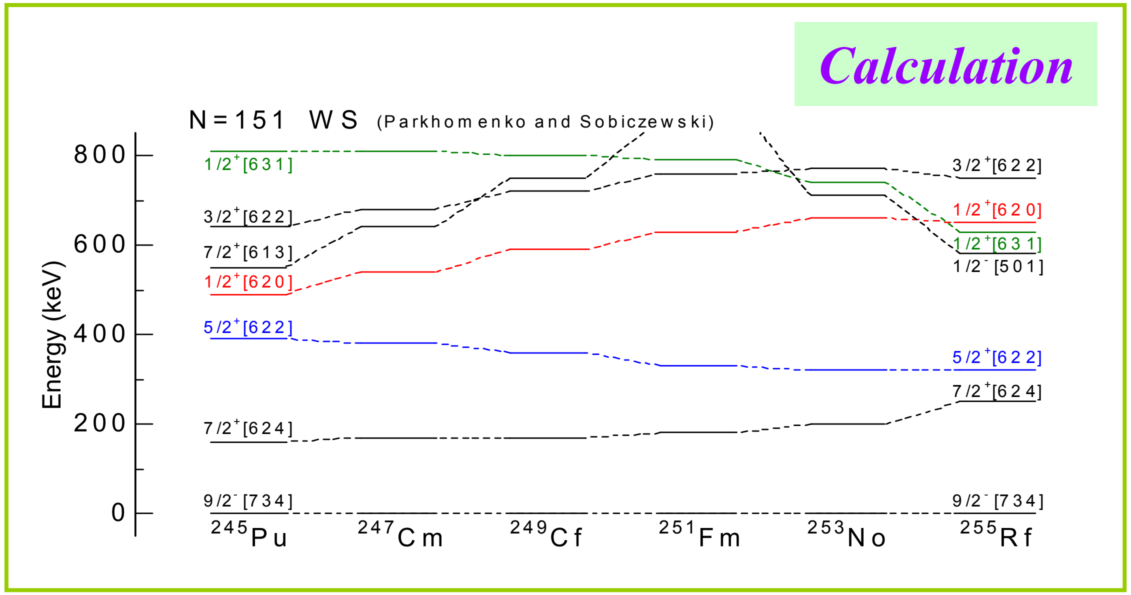
Intra-transition → 内部転換電子放出

(d,p)の実験データ('70 ANL)を参照してレベルスキーム構築

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 ≥ 96 は閉殻、Z=94 で消滅*
- **N=164球形閉殻の可能性を示唆**
  - *N～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~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}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 ーインビーム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

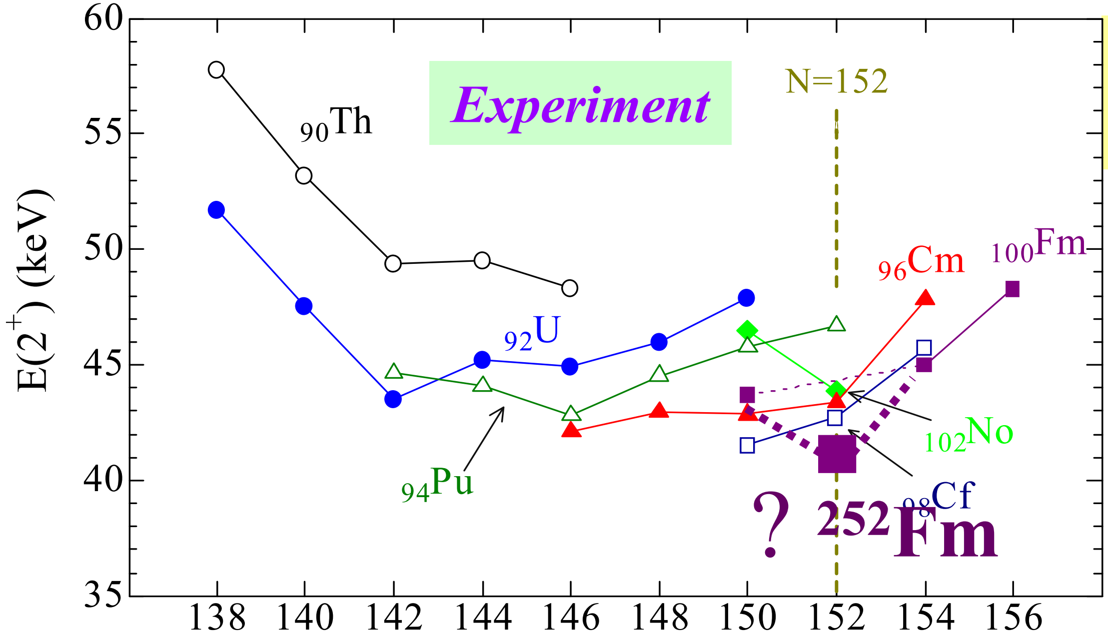
^{249,250,251}Cf target (0.4mg/cm^2) on Al(0.8mg/cm^2)

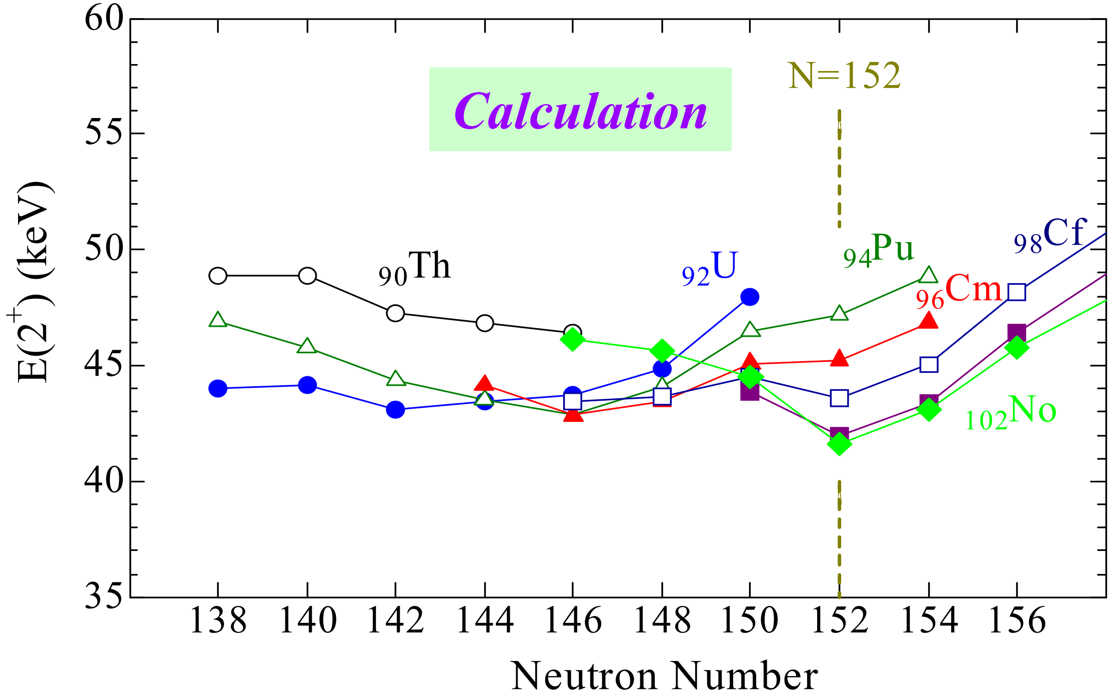
^{249}Cf:60%, ^{250}Cf:14%, ^{251}Cf:26%

ϕ0.8mm, 2μg, 1.5MBq → Si 14kcps, Ge 10kcps

- *$^{252}Fm_{152}$の励起準位 → E(2$^+$)と変形閉殻との相関*
- *^{248,250,252}Cfの高スピン状態*
- *^{251}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

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

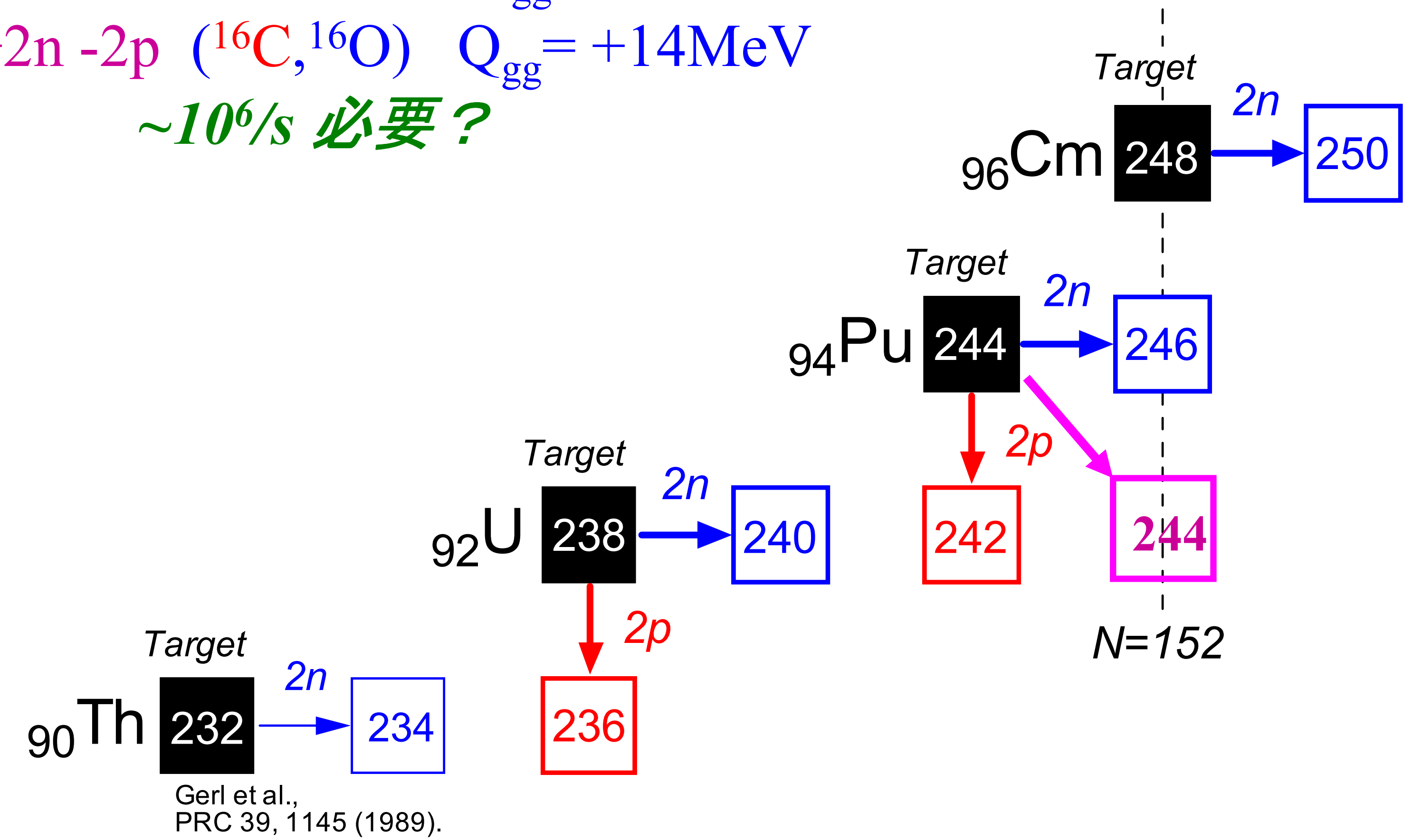
$$E_\alpha = \sqrt{(\varepsilon_\alpha - \lambda)^2 + \Delta^2}$$

Sobiczewski et al., PRC 63(2001)034306

不安定核ビームを用いた核子移行実験 *e.g.,* ^{16}C

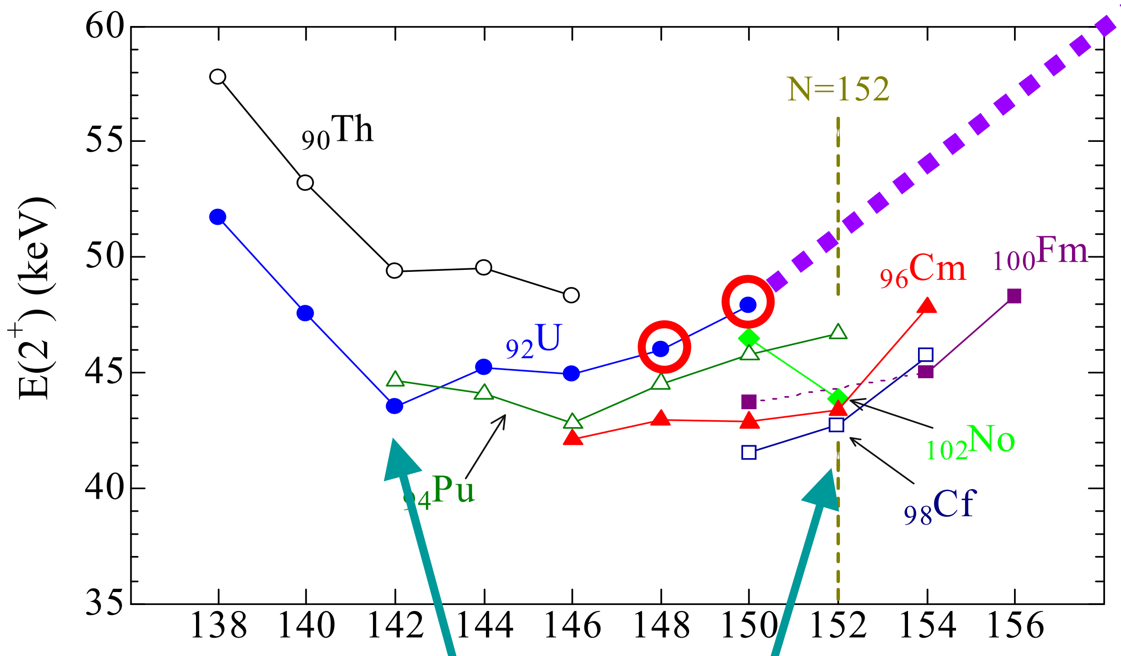
- +2n (^{18}O,^{16}O) $\sigma \sim 10^2 \mu b$ $i \sim 10^9/s$
- -2p (^{18}O,^{20}Ne) $\sigma \sim \mu b$
- +2n -2p (^{18}O,^{18}Ne) Q_{gg}= -11MeV
- +2n -2p (^{16}C,^{16}O) Q_{gg}= +14MeV

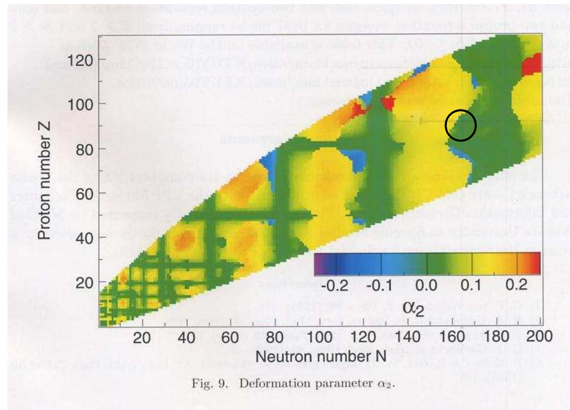
  ~10^6/s 必要？



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

$^{256}_{92}U_{164}$は丸い？





Deformed shell closure

高角運動量軌道のエネルギー準位の測定

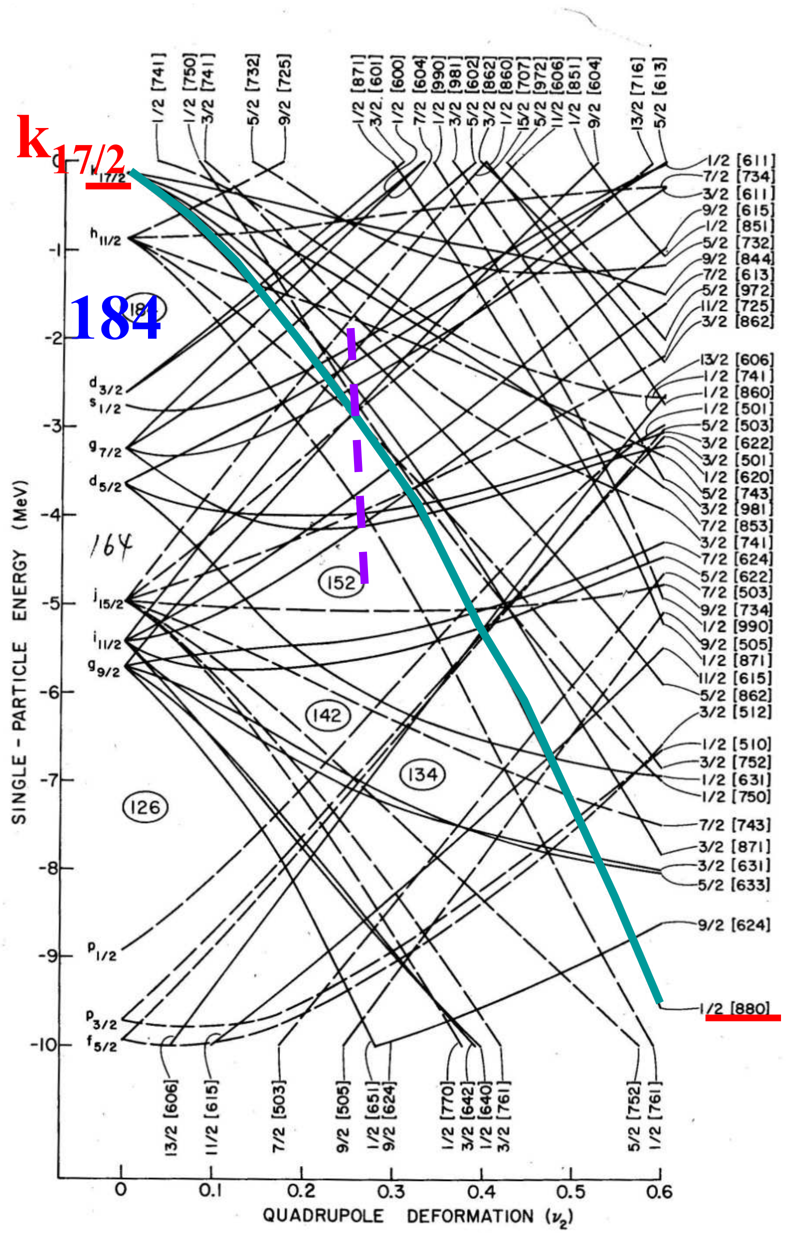
Identify energy levels of
½[880] $k_{17/2}$ in ^{249}Cm

×2/(

^{248}Cm(^{16}O,^{15}O)^{249}Cm
(^{13}C,^{12}C)^{249}Cm

(^{18}O,^{17}O)^{249}Cm

Cross Section (mb/sr)



$(\alpha,{}^3He)$ GrandRaiden ${}^{248}Cm$標的？

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

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

I. Ahmad[a], B.B. Back[a], R.R. Chasman[a], J.P. Greene[a], T. Ishii[a,1], L.R. Morss[a], G.P.A. Berg[b], A.D. Bacher[b], C.C. Foster[b], W.R. Lozowski[b], W. Schmitt[b,2], E.J. Stephenson[b], T. Yamanaka[b,3]

Nucl. Phys. A646(199