形变核α衰变与原子核集体运动

- Introduction: α decay VS nuclear structure
- Nuclear collective motions
- MCCM for rotational and vibrational nuclei

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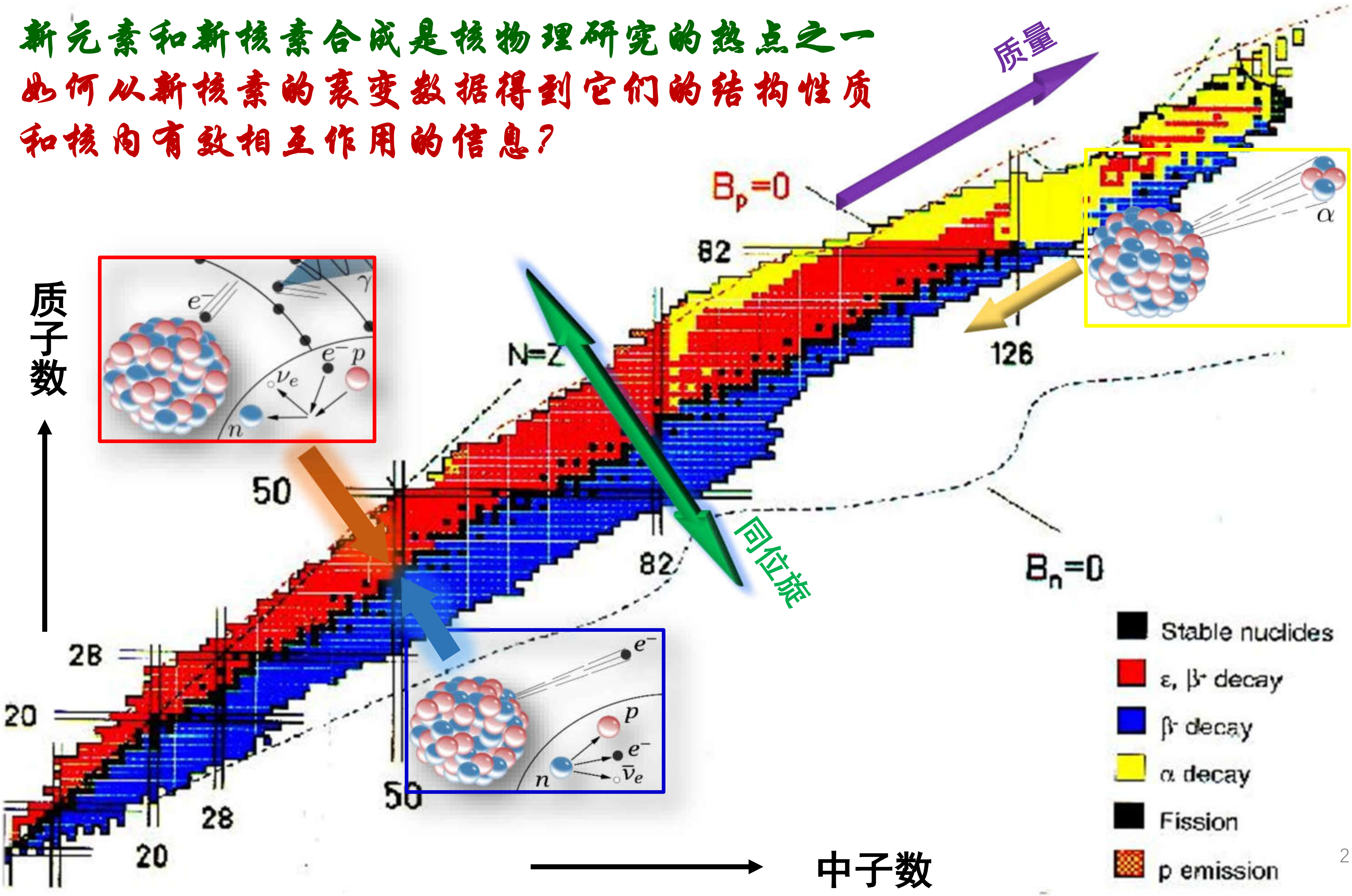
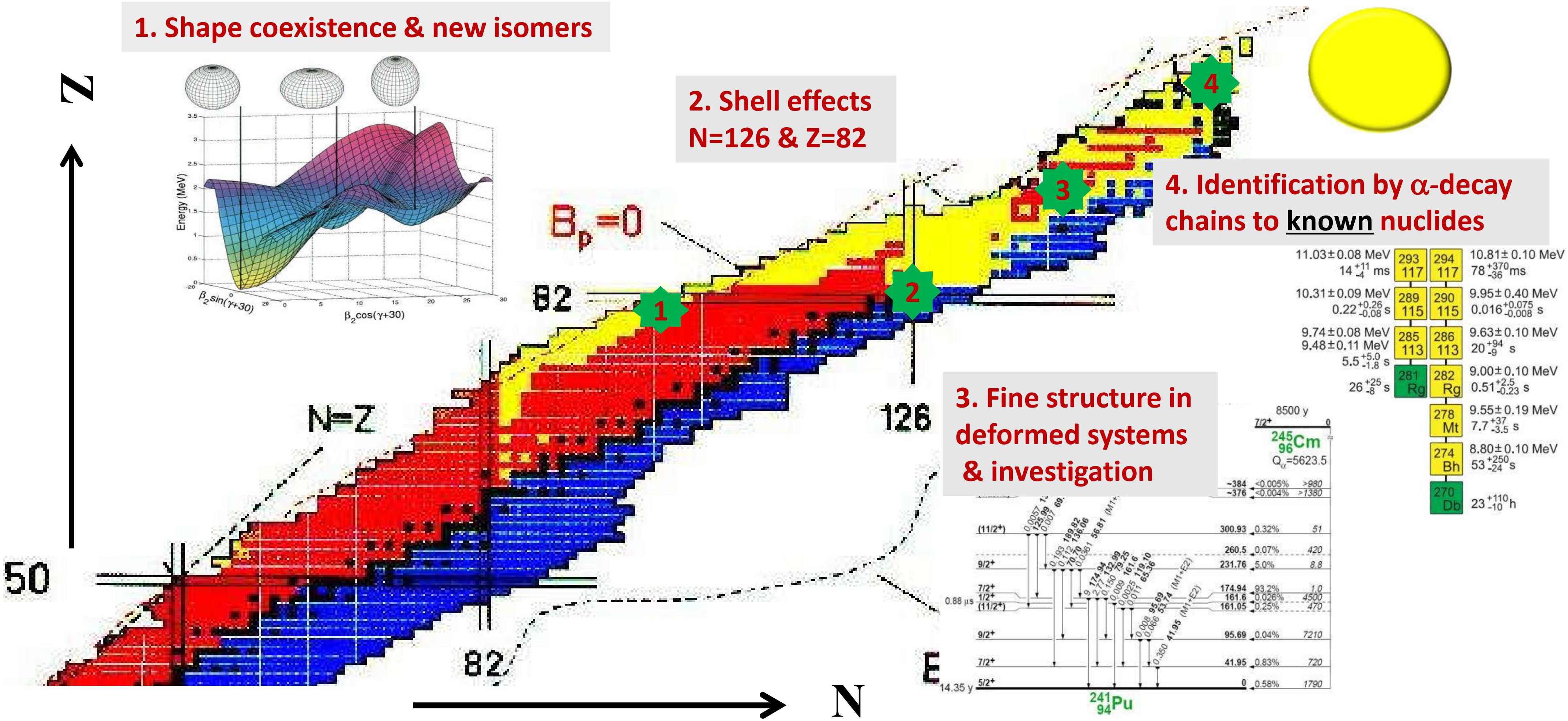
2022年7月2-6日 珠海

新元素和新核素合成是核物理研究的热点之一

如何从新核素的衰变数据得到它们的结构性质和核内有效相互作用的信息?



Wide and deep impact of α decay on nuclear physics



1. Nuclear charge radii

(1) Transition energies in muonic nuclei

(2) Elastic electron scattering experiments

providing information on charge radii *R*

(3) K_αx-ray isotope shifts (KIS)

(4) Optical isotope shifts (OIS)

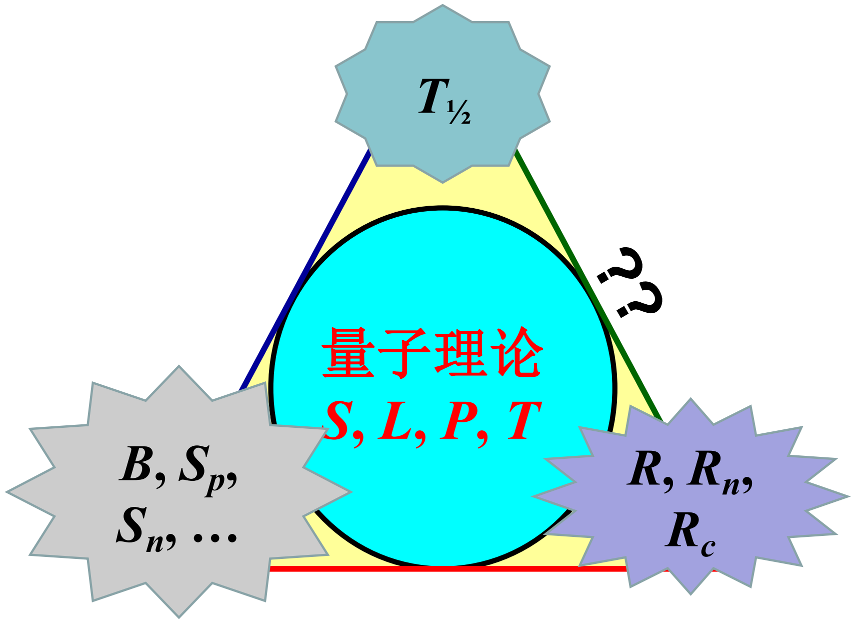
providing information on isotopic changes δR

(1-3) methods have been performed only on stable nuclei (several tens of milligrams of a target material are required)

(4) method can be performed for radioactive atoms with lifetimes down to 1 ms.

I. Angeli and K. P. Marinovab, At. Data Nucl. Data Tables 99, 69 (2013).

获得超重核和远离稳定线核结构性质的新途径



Ni, Ren, et al., PRC 87, 024310 (2013);
Qian, Ren, Ni, PRC 89, 024318 (2014)

超重核电荷半径第一个结果（基于alpha衰变实验数据）

2. Neutron skin thickness

(1) Hadron scattering experiments

pions, protons, and antiprotons

(2) Parity violation in electron scattering

(3) Pygmy dipole resonances and electric dipole polarizabilities

(4) Isospin diffusion in heavy-ion collisions

…

208Pb:

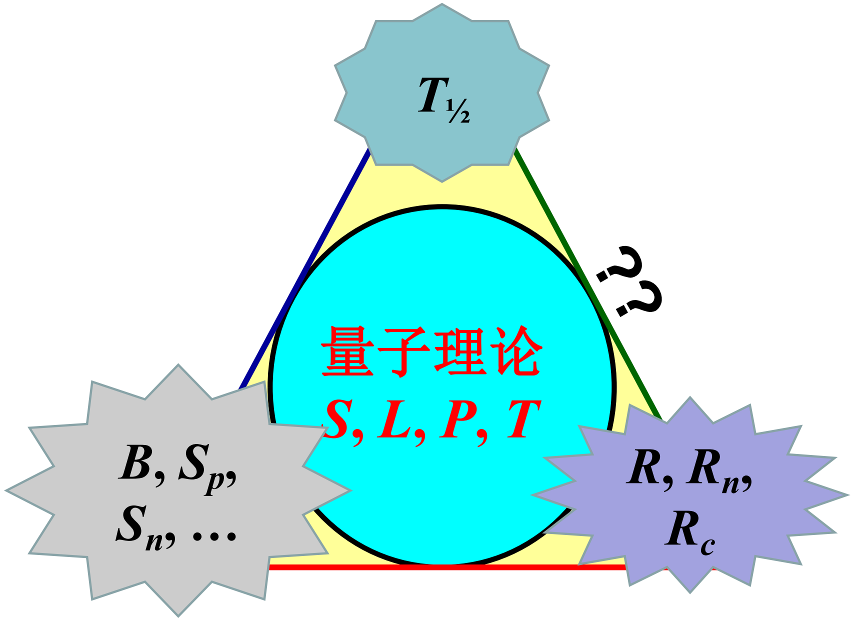
0.15 -- 0.22 fm (expt.)

uncertainties of more than 0.08 fm

C. M. Tarbert, et al., PRL (2014)

0.05 – 0.35 fm (calc.)

R. J. Furnstahl, NPA (2002)



$$\Delta r_{np} = R_n - R_p$$

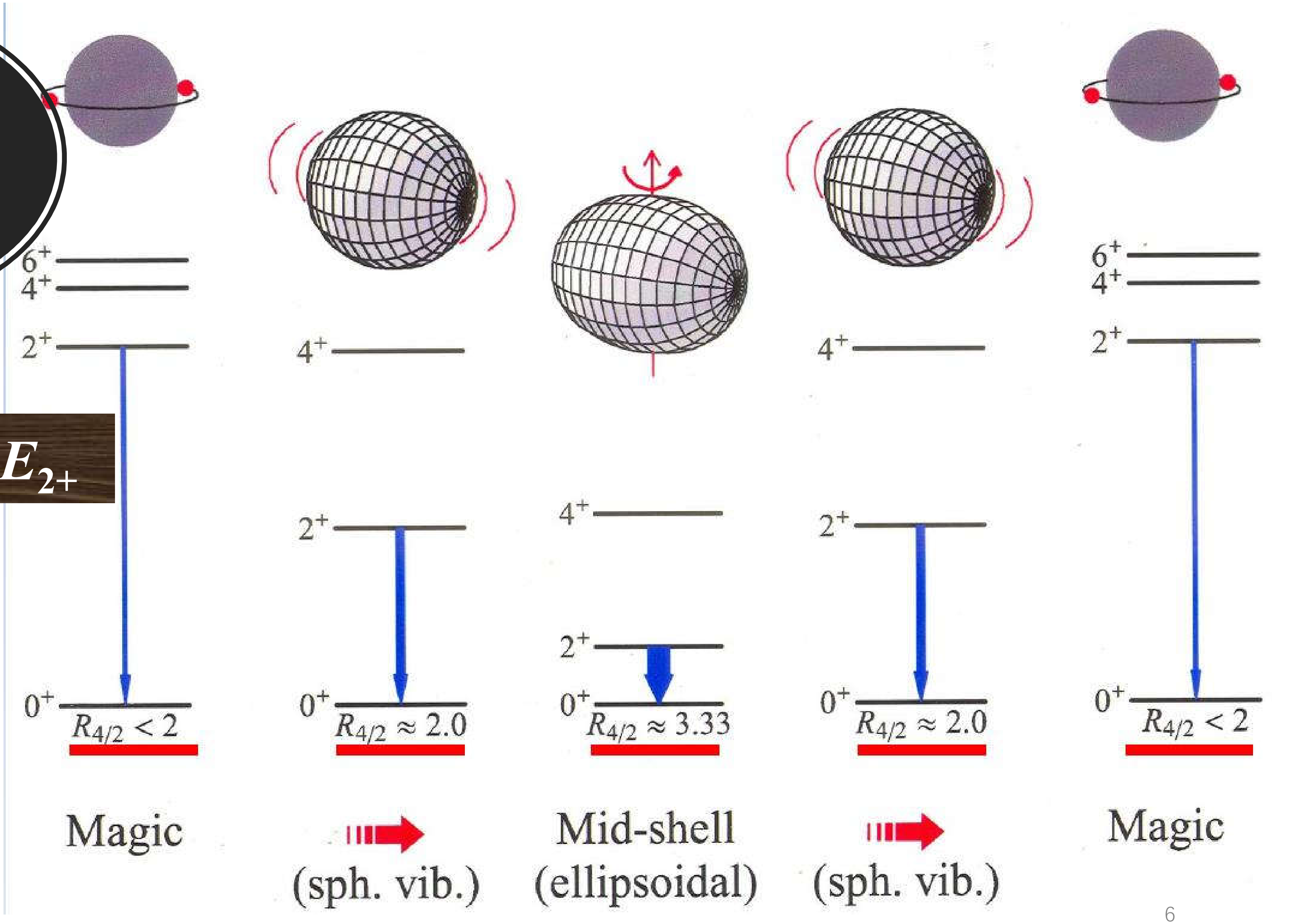
$$V(\vec{r}) = \iint d\vec{r}_1 d\vec{r}_2 \rho_1(\vec{r}_1) v(s) \rho_2(\vec{r}_2)$$

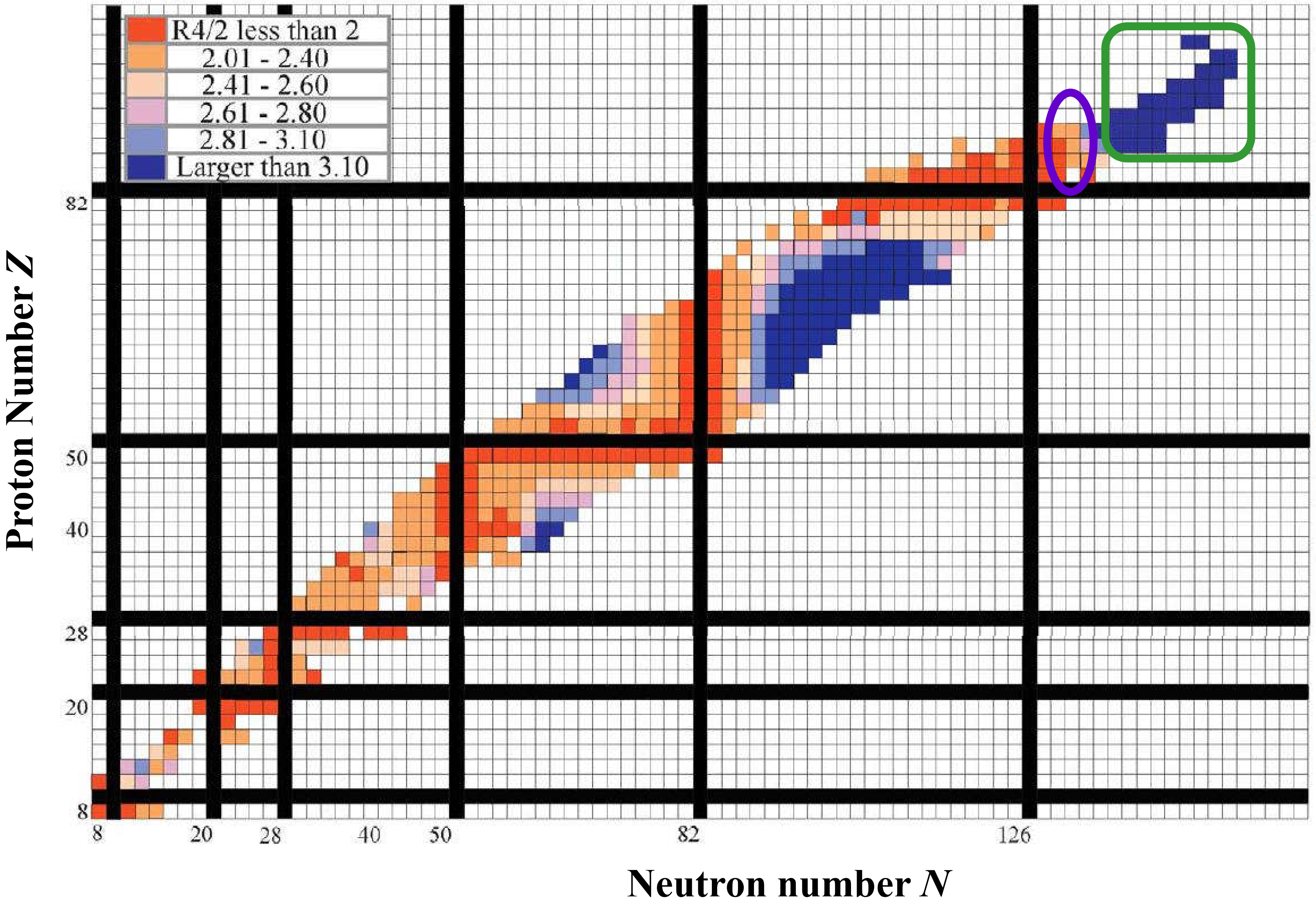
with $s = |\vec{r} + \vec{r}_2 - \vec{r}_1|$

Ni & Ren, PRC 92, 054322 (2015);
Ni & Ren, PRC 93, 054318 (2016)

Nuclear collective motion

$R_{4/2} = E_{4+}/E_{2+}$

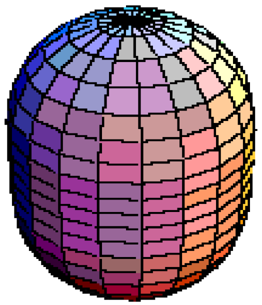


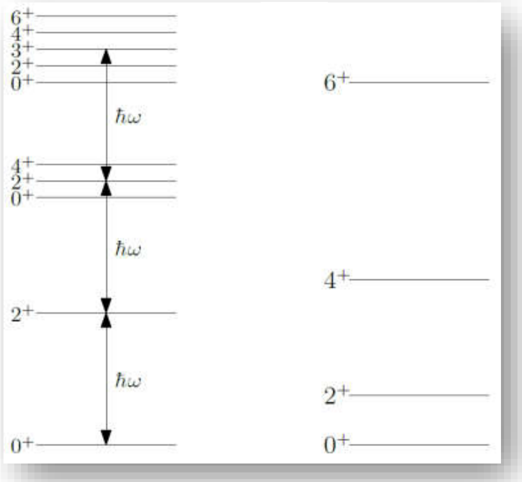


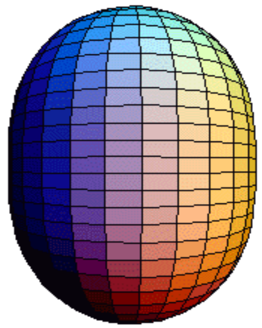
R4/2 less than 2
2.01 - 2.40
2.41 - 2.60
2.61 - 2.80
2.81 - 3.10
Larger than 3.10
Proton Number Z
82
50
40
28
20
8
8
20
28
40
50
82
126
Neutron number N

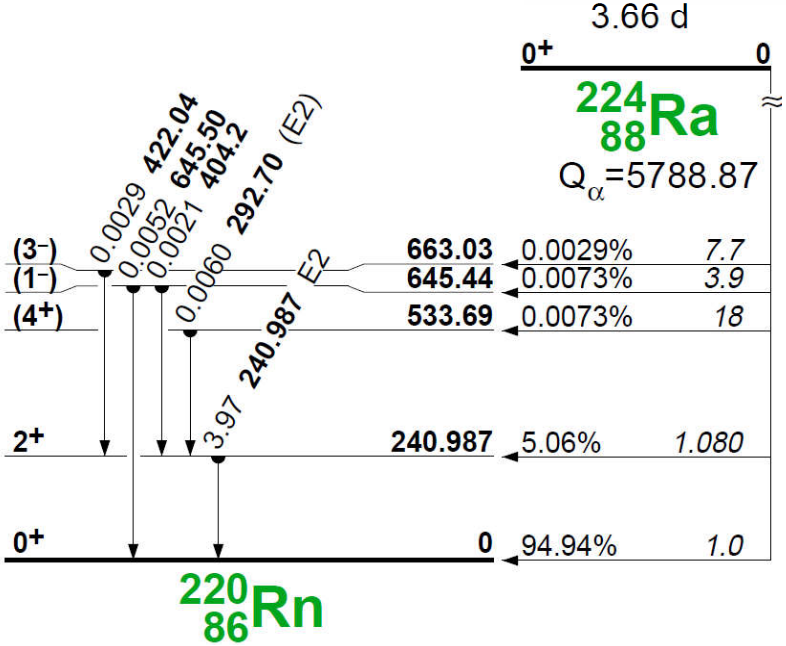
Vibrational

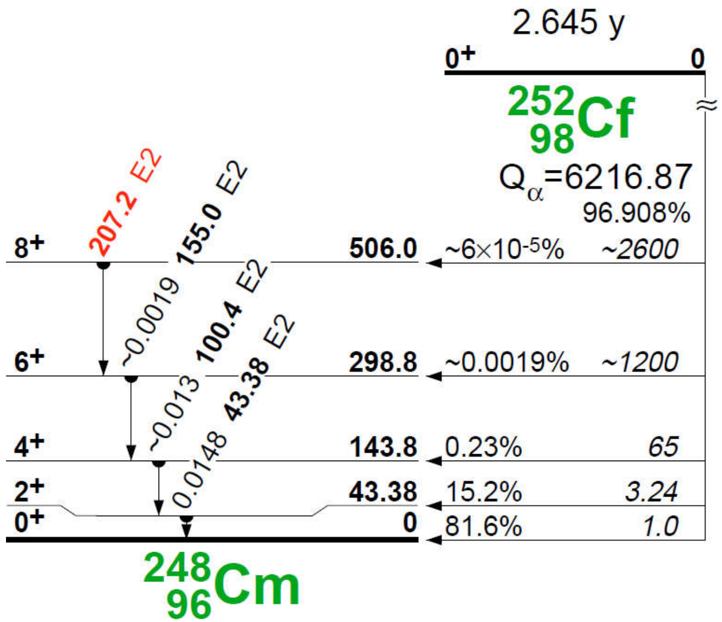
Rotational







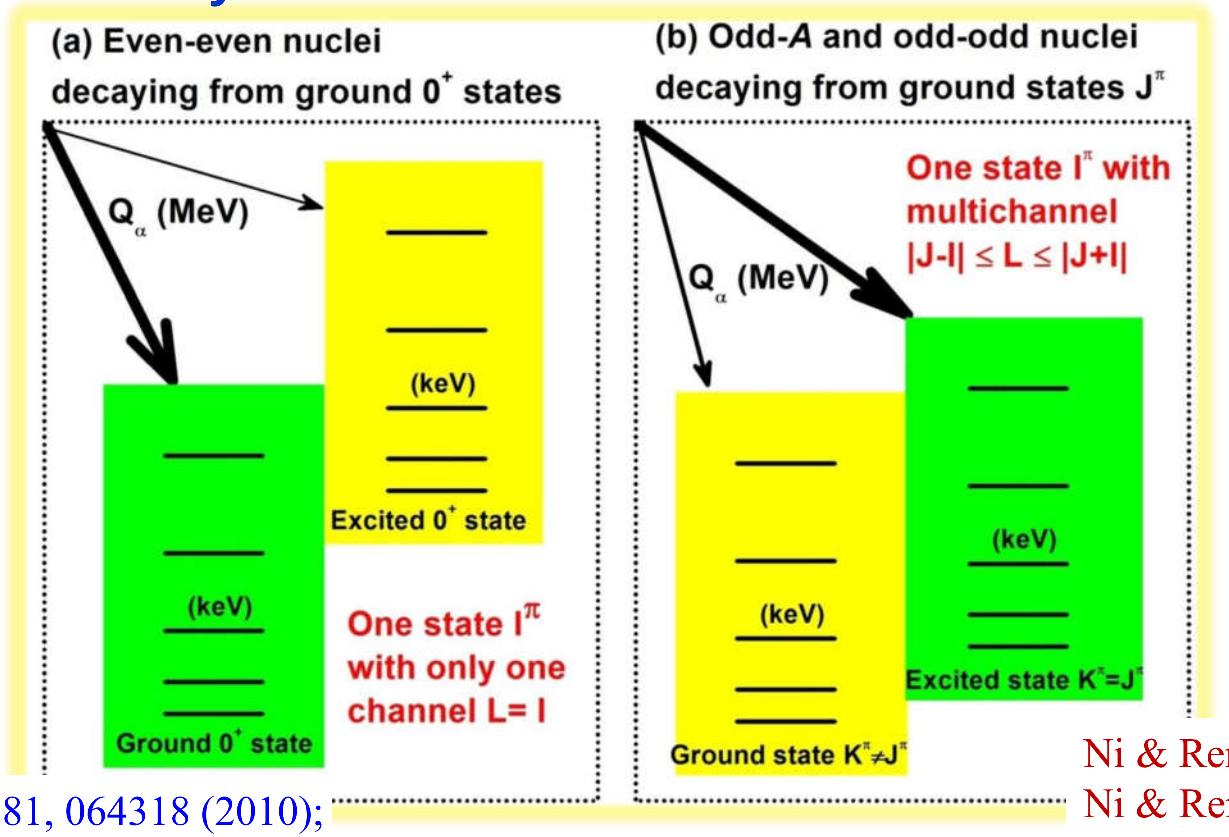




Multi-Channel Cluster Model (MCCM)

Research object： even-even → odd-mass → odd-odd nuclei

Number of decay channels considered： 4 → 5 → 25



Delion, Ren, Dumitrescu, Ni, JPG 2018 (Topical Review)

Ni & Ren, PRC 81, 064318 (2010);
Ni & Ren, PRC 83, 067302 (2011)

Ni & Ren, PRC 86, 054608 (2012);
Ni & Ren, PRC 87, 027602 (2013)

PHYSICAL REVIEW C **101**, 044308 (2020)

MCCM extended for vibrational nuclei

Effects of nuclear collective vibrations on the α-decay fine structure of vibrational nuclei with $A \approx 220$

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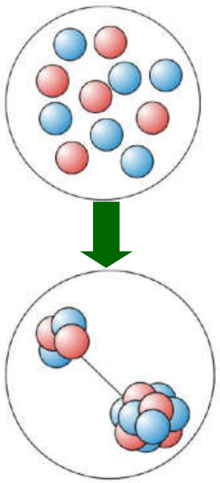
(Received 19 December 2019; revised manuscript received 27 February 2020; accepted 20 March 2020; published 15 April 2020)

The multichannel cluster model (MCCM) is generalized to investigate the effect of nuclear collective vibrations on the α-decay fine structure. Vibrational excitations up to two-phonon states are taken into account and coupled-channels calculations are performed for vibrational Rn, Ra, Th, and U isotopes. Without introducing any additional adjustable parameter, the calculated α-decay branching ratios to various vibrational states show good agreement with the experimental data. In particular, it is shown that the α-decay fine structure is strongly correlated with vibrational excitations, offering an alternative tool to explore the phonon states in daughter nuclei. Despite the $N = 126$ shell closure, the calculated α-decay half-lives are also found to be in good agreement with the experimental data. A unified description of the α-decay fine structure has been achieved by the MCCM for both rotational and vibrational nuclei.

MCCM for vibrational nuclei (I)



$$\boldsymbol{\Psi}_{JM} = \boldsymbol{\varphi}(\boldsymbol{\alpha})\boldsymbol{r}^{-1} \sum_{I\ell} \boldsymbol{u}^{J}_{n\ell I}(\boldsymbol{r})[\boldsymbol{Y}_{\ell}(\hat{\boldsymbol{r}}) \otimes \boldsymbol{\Omega}_{I}]_{JM}$$

$$-\frac{\hbar^2}{2\mu}\left[\frac{d^2}{dr^2} - \frac{\ell_I(\ell_I+1)}{r^2}\right]u_I(r) + \sum_J V_{I,J}(r)u_J(r) = (Q_0 - E_{J_d})u_I(r)$$

(1) Deformed Woods-Saxon shape potential

$$V(r,\hat{O}) = \frac{V_0}{1+\exp[(r-R_0-\hat{O})/a]}, \hat{O} = \frac{\beta_\lambda}{\sqrt{4\pi}} R_d\left(\boldsymbol{b}_\lambda^\dagger + \boldsymbol{b}_\lambda\right)$$

(2) Nuclear interaction matrix elements

$$V_{ij}(r) = \langle i|V(r,\hat{O})|j\rangle = \sum_\lambda \langle i|\lambda\rangle\langle\lambda|j\rangle V(r,\lambda), \quad \hat{O}|\lambda\rangle = \lambda|\lambda\rangle$$

K. Hagino, N. Rowley, A. T. Kruppa, CPC 123 (1999) 143

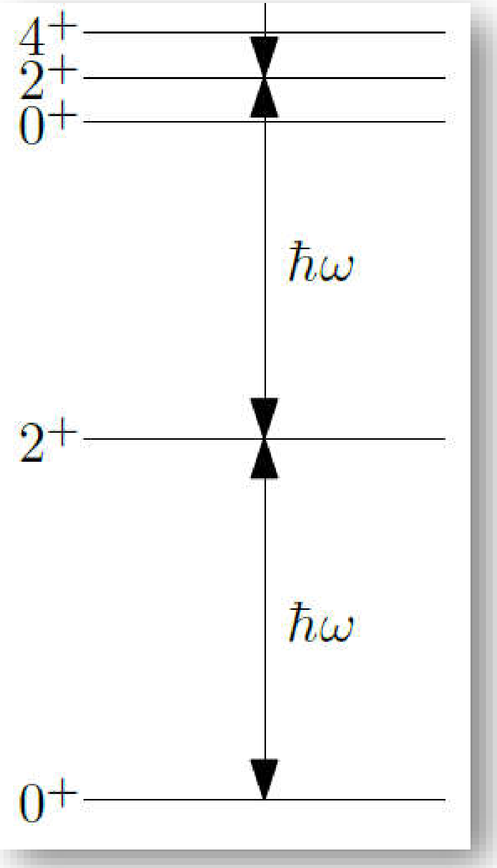
MCCM for vibrational nuclei (II)

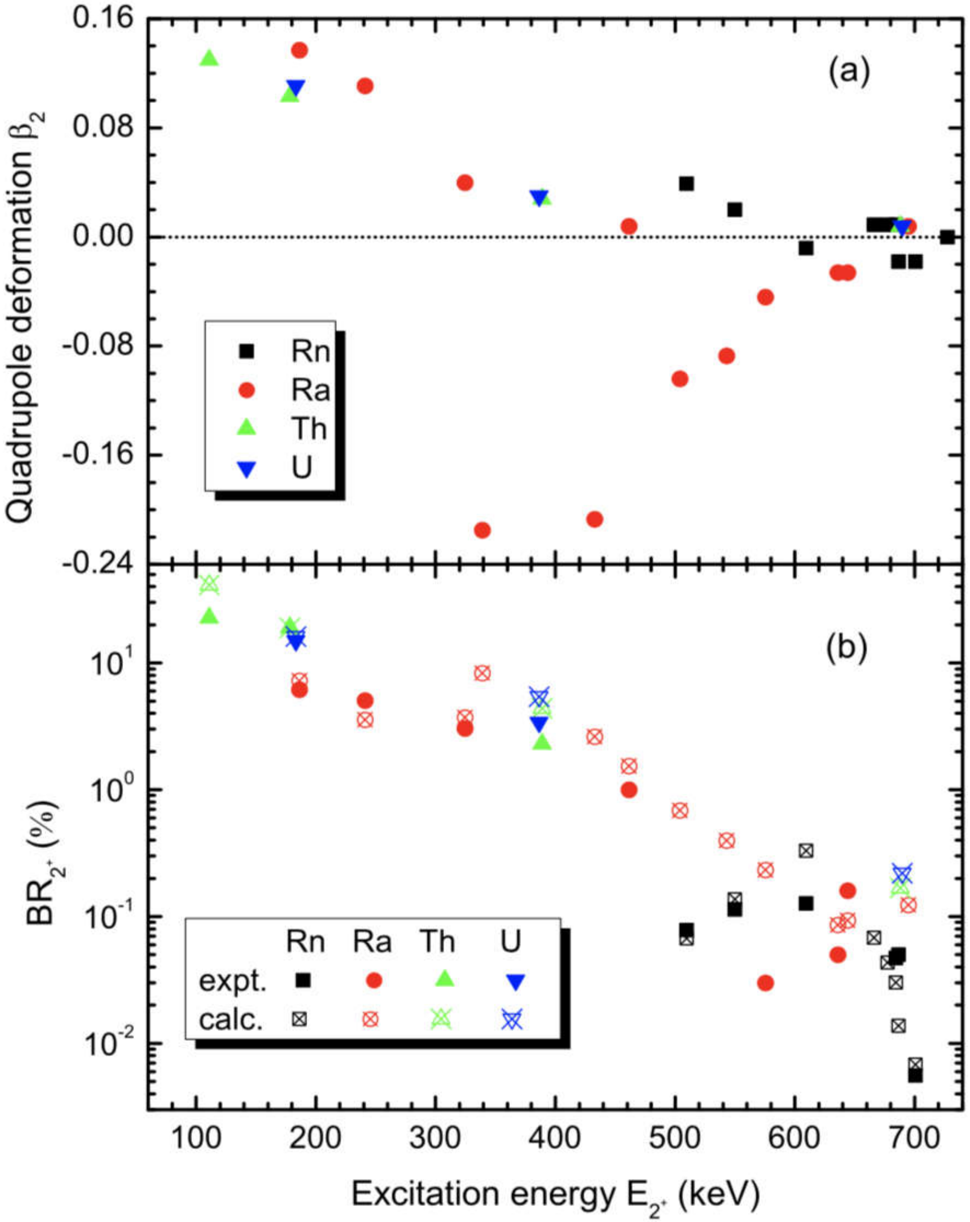
Excitation of vibrational nuclei can be regarded as phonons with angular momentum λ and parity $(-1)^\lambda$, like oscillations in solid bodies.

$$\boldsymbol{b}_\lambda^\dagger|n_\lambda\rangle = \sqrt{n_\lambda + 1}|n_\lambda + 1\rangle$$

$$\boldsymbol{b}_\lambda|n_\lambda\rangle = \sqrt{n_\lambda}|n_\lambda - 1\rangle$$

Fundamental quadrupole excitations $\lambda = 2$ are under investigation for even-even nuclei.
We focus on low-lying phonon excitation up to two-phonon states and the only two-phonon state included is the first excited 4^+ state.





Dependence of the α-decay fine structure on the vibration properties

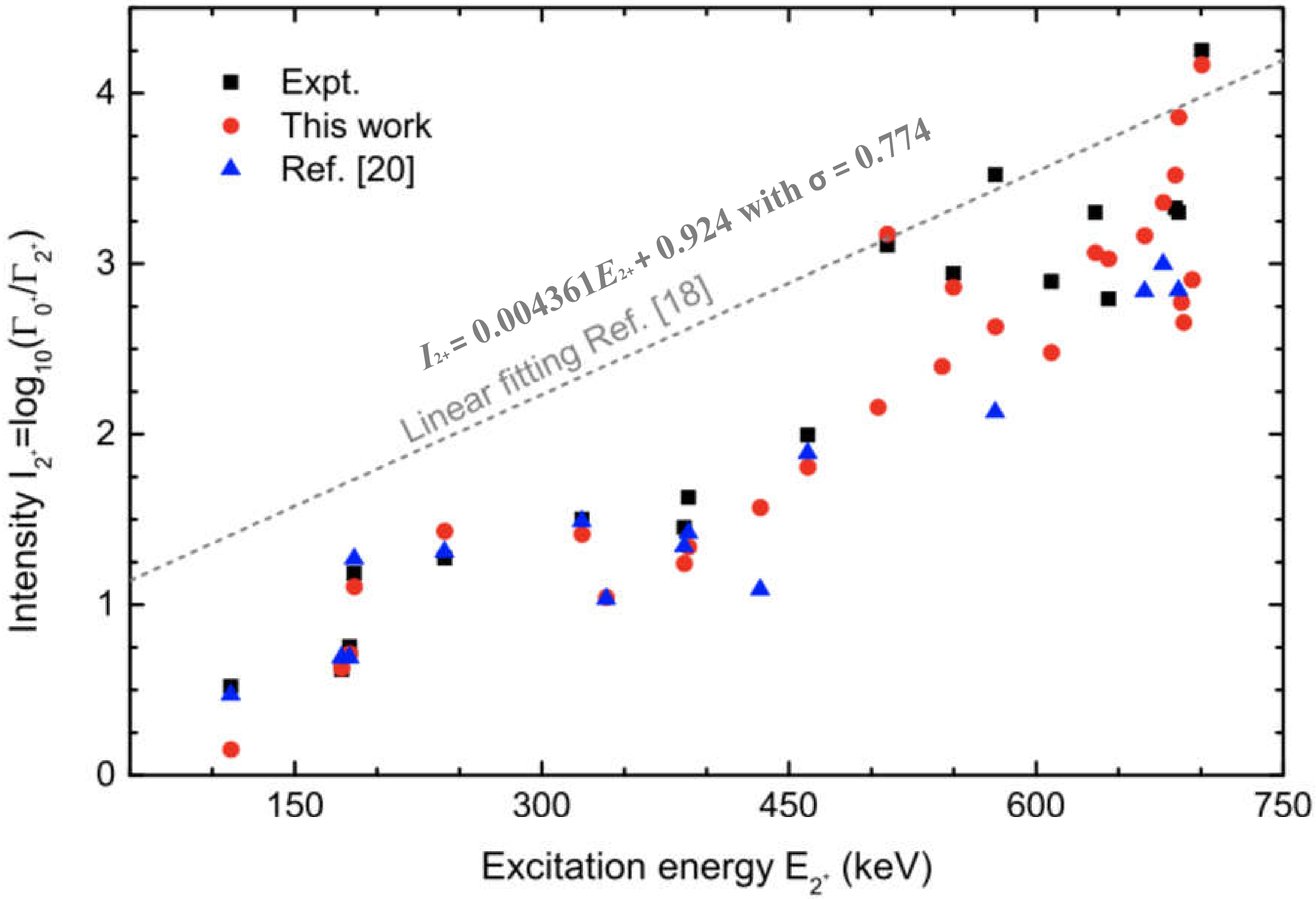
When the absolute value of β_2 is decreased to zero, the excitation energy E_{2+} tends to be increased from 100 keV to 740 keV.

On the whole, the BR_{2+} values tend to be decreased with increasing the excitation energy E_{2+}.

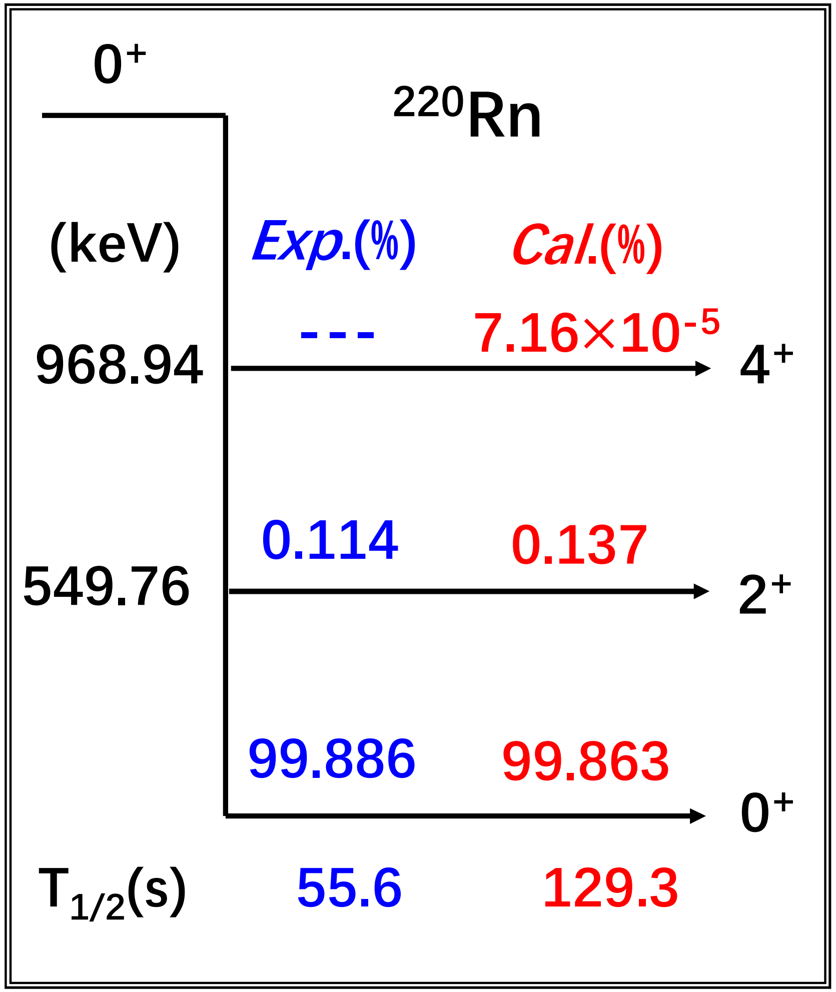
Abnormal behaviors:

$^{218-222}$Rn, $N \geq 132$, 500-600 keV;

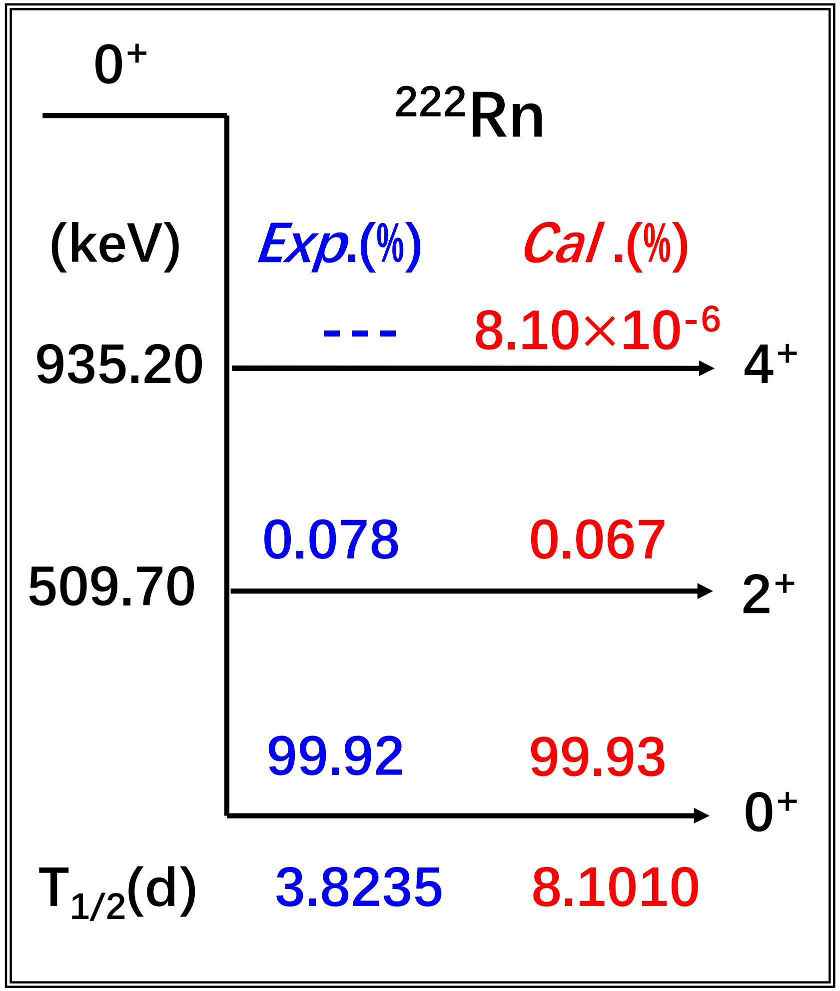
$^{210-214}$Ra, $N \leq 126$, 550-650 keV.



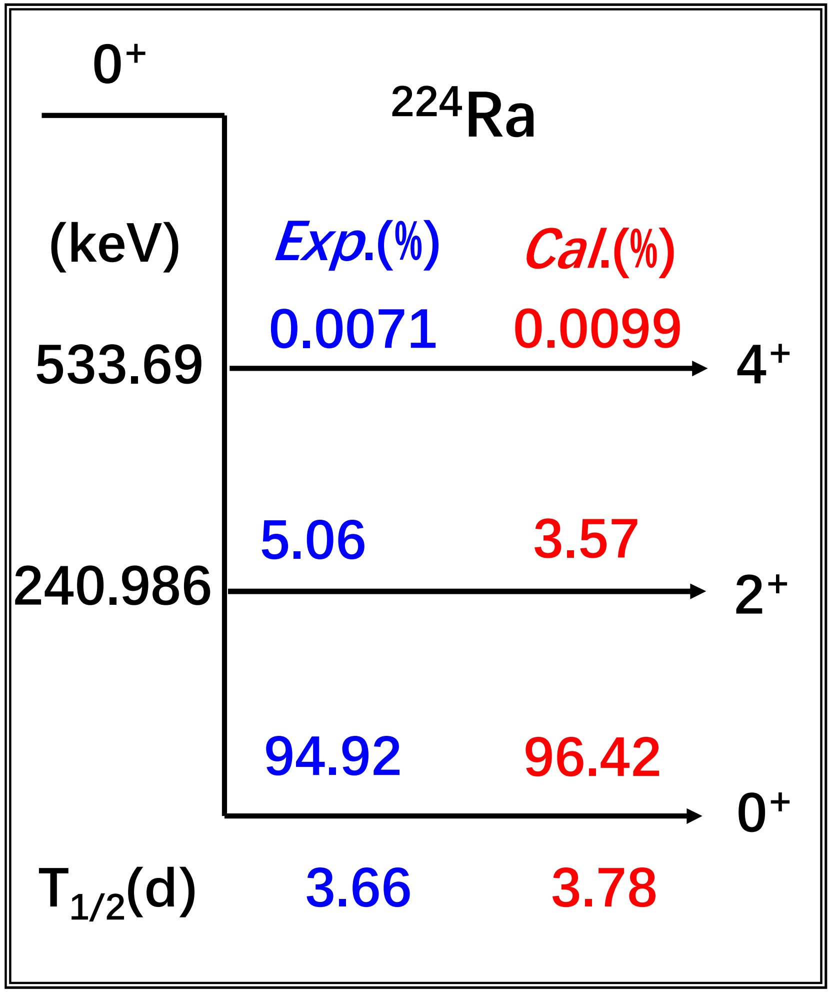
[18] S. Peltonen, D. S. Delion, and J. Suhonen, Phys. Rev. C **75**, 054301 (2007).
[20] D. S. Delion and A. Dumitrescu, At. Data Nucl. Data Tables **101**, 1 (2015).

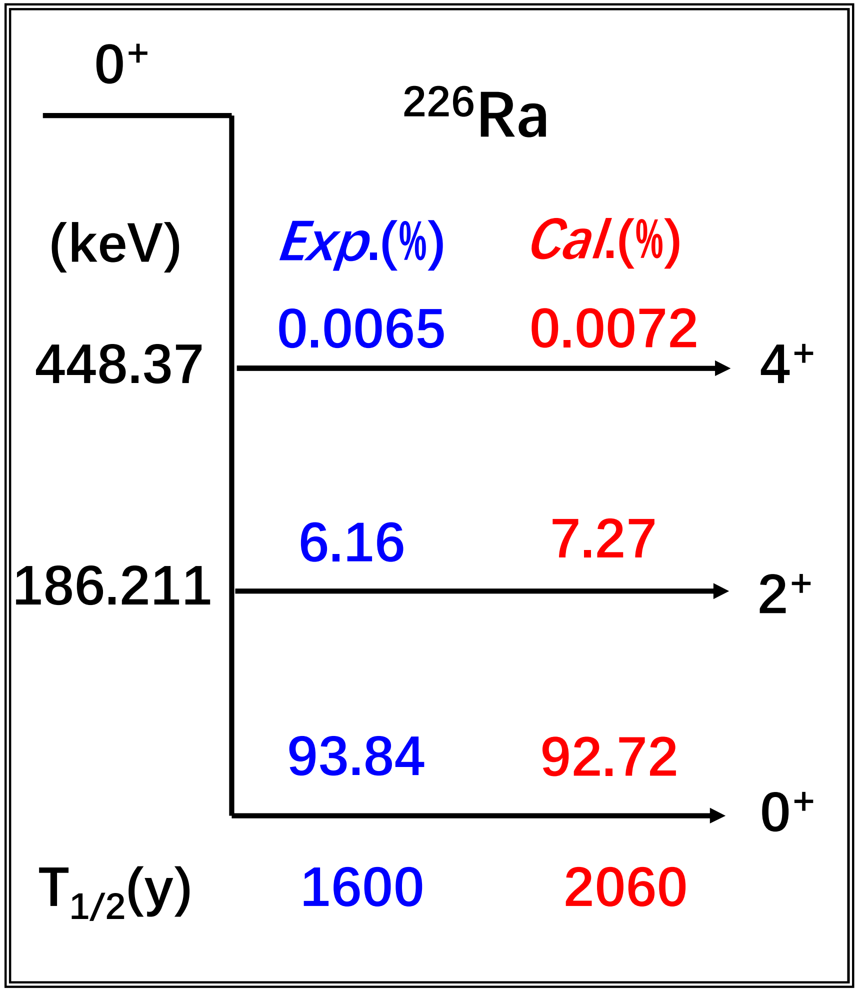

0+
^{220}Rn
(keV)
Exp.(%)
Cal.(%)
968.94

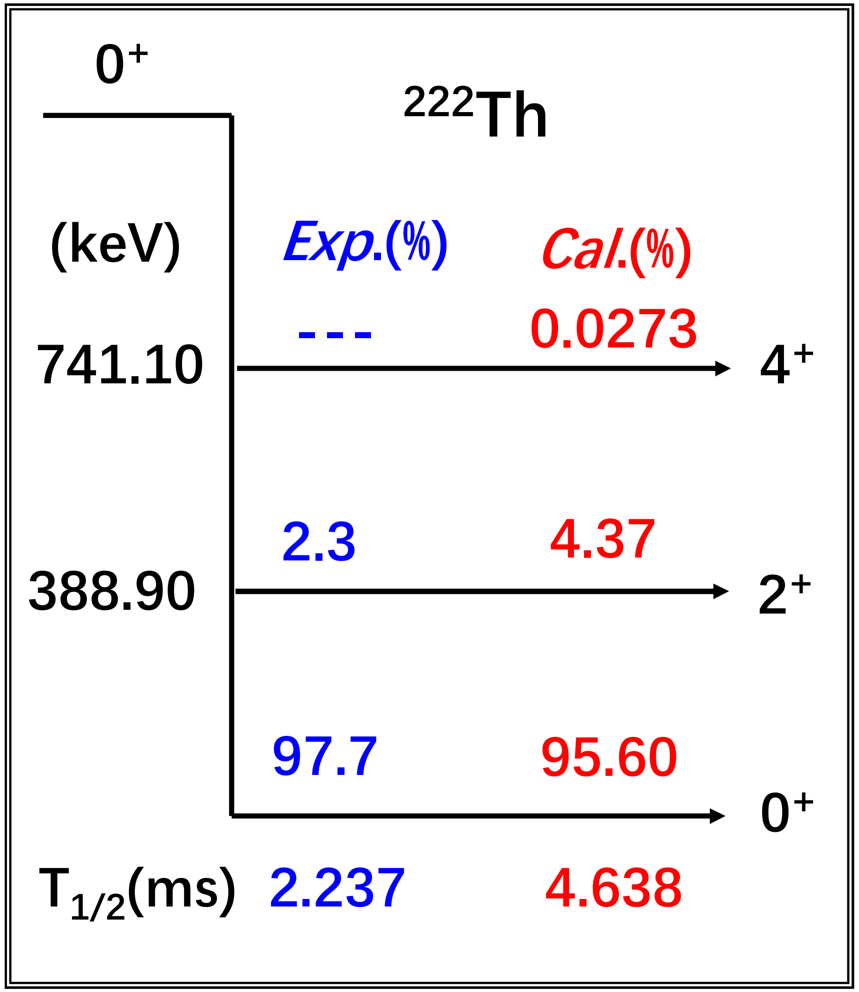
7.16×10^{-5}
4+
549.76
0.114
0.137
2+
99.886
99.863
0+
$T_{1/2}$(s)
55.6
129.3


0+
^{222}Rn
(keV)
Exp.(%)
Cal .(%)
935.20

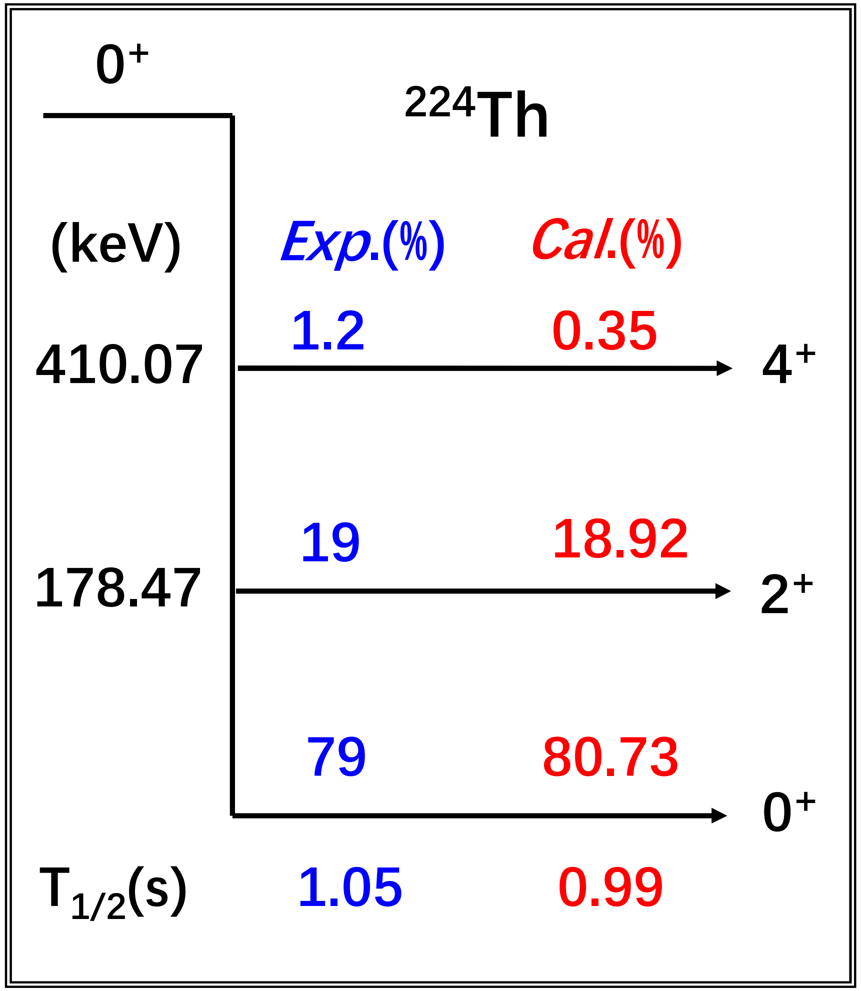
8.10×10^{-6}
4+
509.70
0.078
0.067
2+
99.92
99.93
0+
$T_{1/2}$(d)
3.8235
8.1010

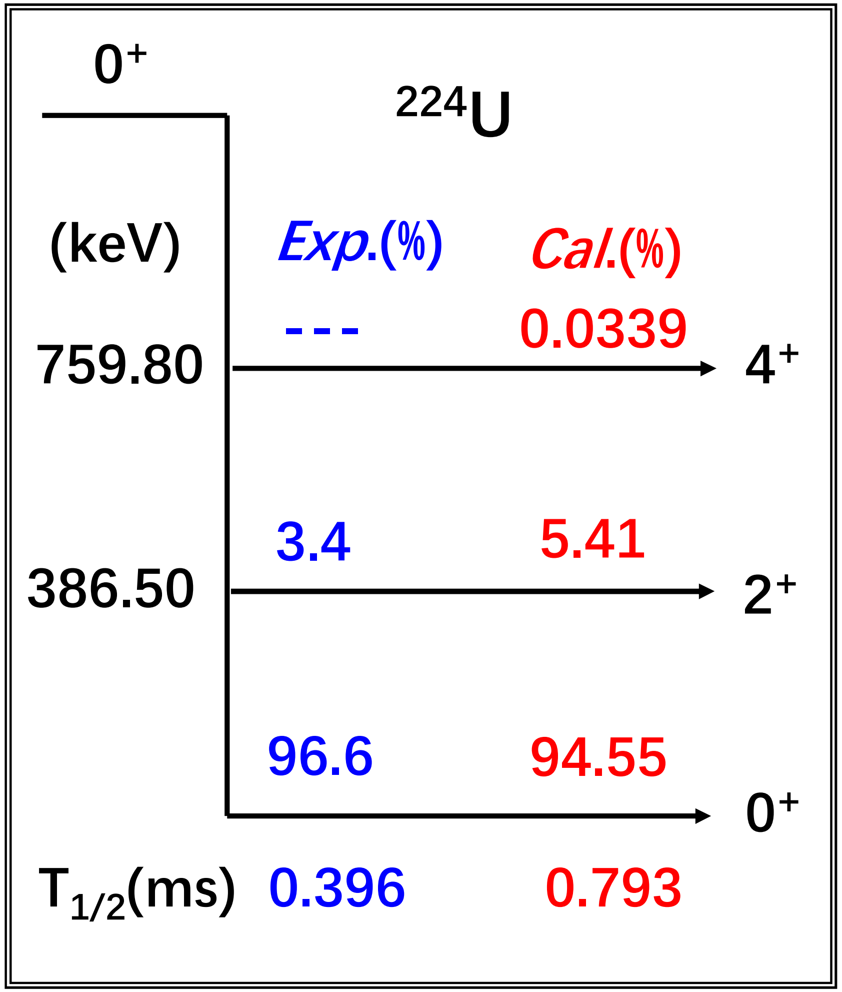

0+
224Ra
(keV)
Exp.(%)
Cal.(%)
533.69
0.0071
0.0099
4+
240.986
5.06
3.57
2+
94.92
96.42
0+
T1/2(d)
3.66
3.78


0+
226Ra
(keV)
Exp.(%)
Cal.(%)
448.37
0.0065
0.0072
4+
186.211
6.16
7.27
2+
93.84
92.72
0+
T1/2(y)
1600
2060


0+
222Th
(keV)
Exp.(%)
Cal.(%)
741.10

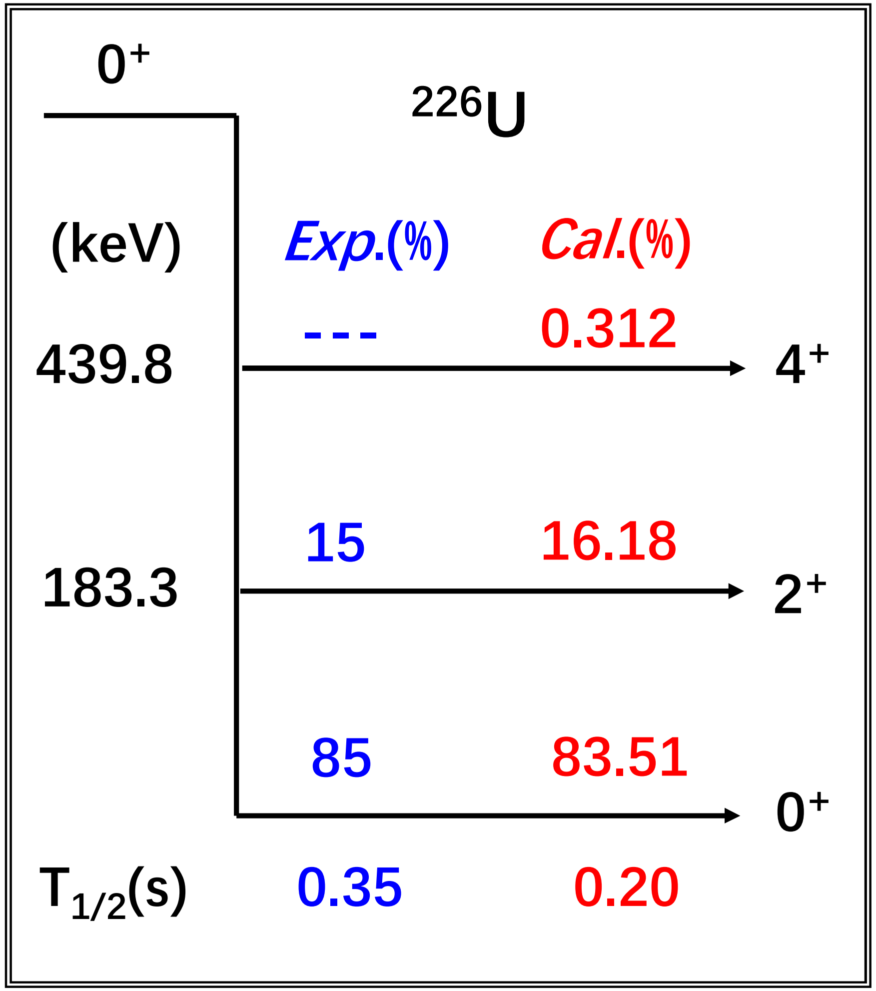
0.0273
4+
388.90
2.3
4.37
2+
97.7
95.60
0+
T1/2(ms)
2.237
4.638


0+
224Th
(keV)
Exp.(%)
Cal.(%)
410.07
1.2
0.35
4+
178.47
19
18.92
2+
79
80.73
0+
T1/2(s)
1.05
0.99



0+
224U
(keV)
Exp.(%)
Cal.(%)
759.80

0.0339
4+
386.50
3.4
5.41
2+
96.6
94.55
0+
T1/2(ms)
0.396
0.793



0+
226U
(keV)
Exp.(%)
Cal.(%)
439.8

0.312
4+
183.3
15
16.18
2+
85
83.51
0+
T1/2(s)
0.35
0.20

Summary

获得超重核和远离稳定线核结构性质的新途径

MCCM for the α-decay fine structure in rotational nuclei

Full and precise description for e-e, o-A, and o-o nuclei

获得超重新核素谱学性质

MCCM for the α-decay fine structure in vibrational nuclei:

The calculated results, show good agreement with the experimental data, in spite of the N=126 shell effects involved.

耦合道方法用于分析α转移反应实验数据

Shen, Guo…, PLB 2019

Physics Letters B 797 (2019) 134820

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

First experimental constraint of the spectroscopic amplitudes for the α-cluster in the ^{11}B ground state

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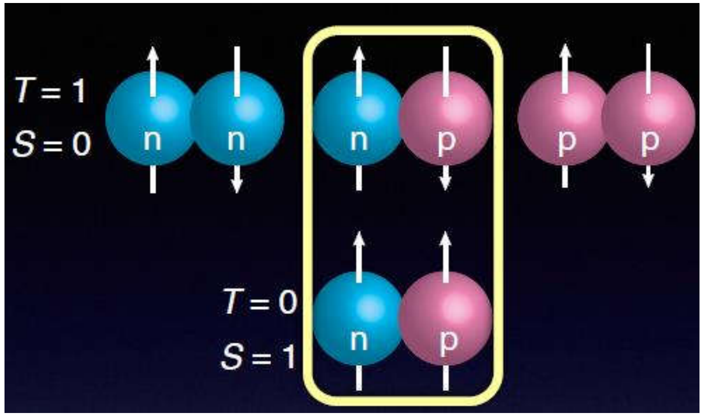
远离稳定线核β衰变性质的QRPA计算



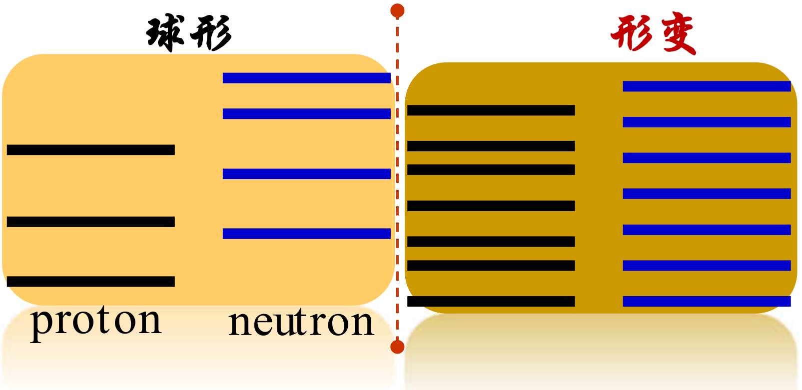
✓ 远离稳定线n-p对作用（重要）

1. 球形QRPA+真实核子-核子作用

Ni & Ren, J Phys G 41, 025107 (2014)

Ni & Ren, J Phys: Conf Seri 569, 012044 (2014)

Tan, Ni, Ren, Chin Phys C 41, 054103 (2017)



2. 形变QRPA+真实核子-核子作用

Ni & Ren, J Phys G 41, 125102 (2014)

Ni & Ren, Phys Rev C 89, 064320 (2014)

Ni & Ren, Phys Lett B 744, 22 (2015)

Ni & Ren, Phys Rev C 92, 034324 (2015)

Ni & Ren, Phys Rev C 95, 014323 (2017)

✓ 形变导致能级劈裂，第一禁戒跃迁的贡献（不可忽略）

Thanks for your attention!