Multi-phonon vibration mode identified from two complementary fission approaches

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Outline

- Introduction
  - 1 phonon γ vibrational band
  - 2 phonon γ vibrational band

- Motivation
  - Search for odd-odd case: 2 valence nucleons+vibration+rotation

- Experimental setup
  - Spontaneous fission with Gammasphere
  - Induced fission with VAMOS++, AGATA and EXOGAM

- Results and discussion
  - Level scheme, lifetime, systematics, theoretical calculations

- Hybrid detector system at SDU for JUNA and HIAF astrophysics
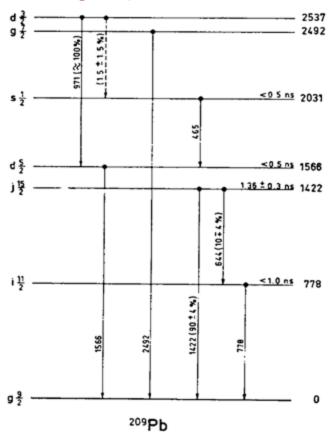
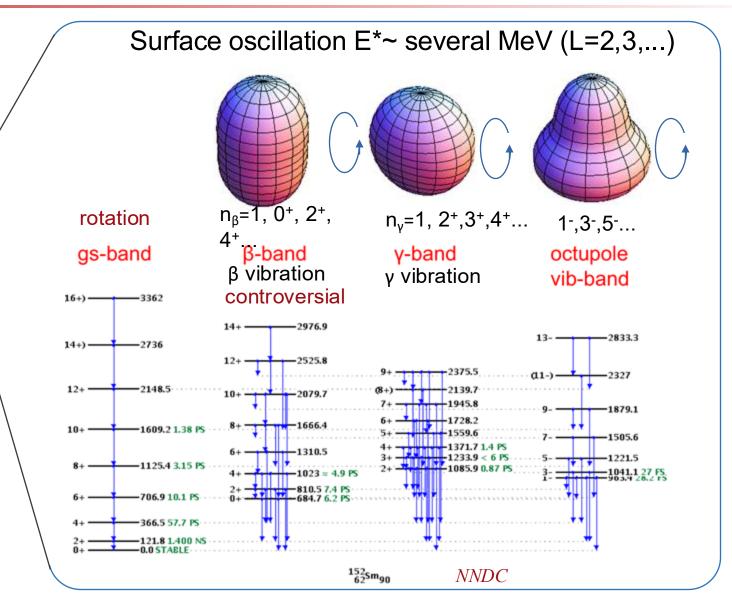- Summary

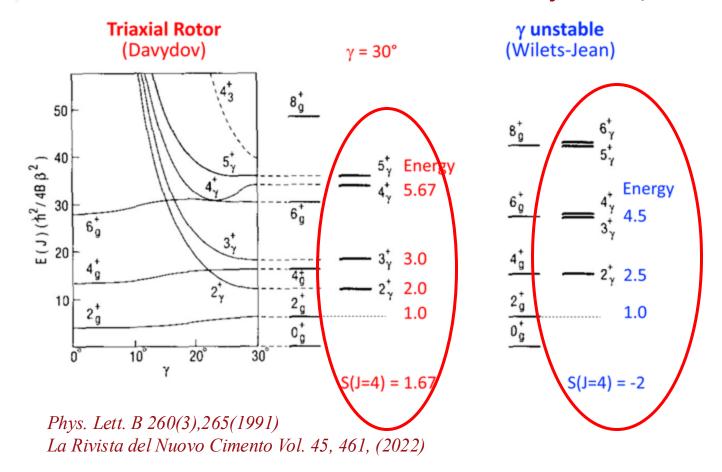# Surface vibration in deformed nuclei

Various nuclear motion
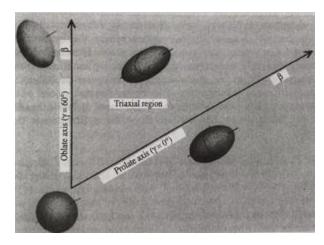
- ### Single particle

Nucl. Phys. A129, 113 (1969)

Surface oscillation E*~ several MeV (L=2,3,...)

rotation	$n_\beta=1$, 0^+, 2^+, 4^+...	$n_\gamma=1$, 2^+,3^+,4^+...	1^-,3^-,5^-...
gs-band	β-band	γ-band	octupole
	β vibration	γ vibration	vib-band
	controversial		

$^{152}_{62}Sm_{90}$ *NNDC*

One phonon γ vibrational band

- Band structure is related to triaxiality and γ softness

Modern atomic and nuclear physics.
F.J. Yang and J. H. Hamilton

Phys. Lett. B 260(3),265(1991)
La Rivista del Nuovo Cimento Vol. 45, 461, (2022)

γ band energy

$$E(2_\gamma^+) \gg E(4_g^+) \qquad \text{axial}$$
$$E(2_\gamma^+) \sim E(4_g^+) \qquad \text{triaxial}$$
$$E(2_\gamma^+) < E(4_g^+) \qquad \text{stiff triaxial}$$

Phonon angular momentum **2** along the symmetry axis
Strong transitions 1γ to 0γ bands *having large E2 component*
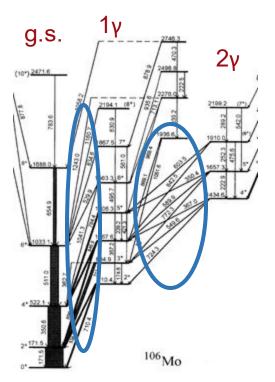
- **First observed in ¹⁶⁸Er (PRL 66, 691).** First harmonic in ¹⁰⁶Mo (PRL 75, 2280). Other regions A~130, 230...
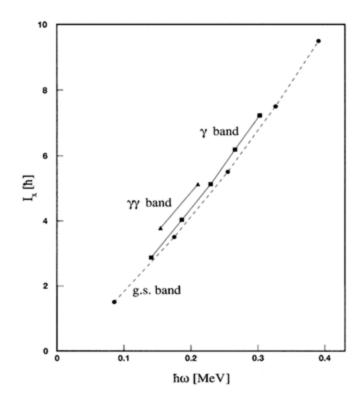
- Fingerprints and identification of 2γ bands

1γ to 0γ, 2γ to 1γ allowed E2
2γ to 0γ forbidden

g.s.   1γ

2γ

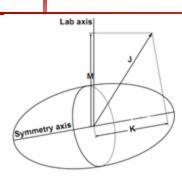Similar inertia $J^{(2)}$ and rotational parameter

$$I_x = \sqrt{(I_a + 1/2)^2 - K^2}$$
$$I_a = (I_i + I_f)/2$$
$$\hbar\omega = (E_i - E_f)/[(I+1)_x - (I-1)_x]$$

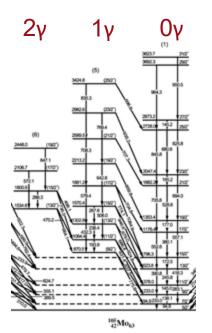$J^{(2)} = \Delta I_x / \Delta\hbar\omega$

¹⁰⁶Mo

PRL 75, 2280

PRL 75, 2280

K: projection on symmetry axis. $K_{1\gamma} = K_{0\gamma} \pm 2$; $K_{2\gamma} = K_{0\gamma} \pm 4$, $K_{0\gamma}$
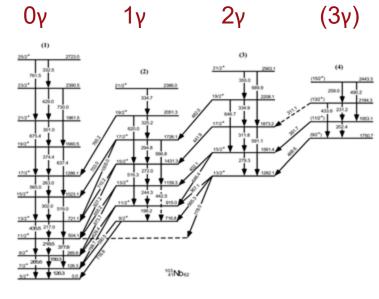$K_{1\gamma} = K_{0\gamma} + 2$; $K_{2\gamma} = K_{0\gamma} + 4$ easy to observe

Multi-phonon γ vibrational bands proposed in 14, extended in 2 nuclei by China-Vanderbilt-Berkeley collaborations from ^{252}Cf SF
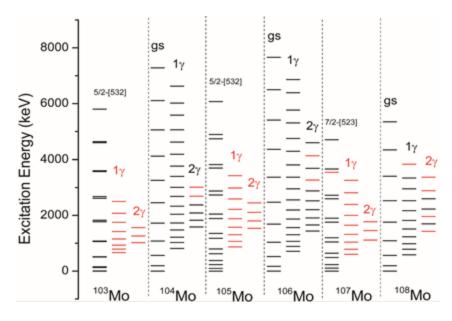
- First odd A: ^{105}Mo
- First odd Z: ^{103}Nb
- Remarkably consistent systematics

Phys Rev C 74, 054301 (2006)

Phys Lett B 675, 420 (2009)

Walter Greiner Memorial Volume, pp. 169 (2018)

How about odd-odd nuclei?

□ 2 phonon γ vibration

○ *3 phonon γ vibration*

^{114}Mo T. Sumikama's talk at INPC

Nb, Tc, Rh are candidates for odd-odd multi-phonon γ vibrational bands
No specific theoretical description currently

How do the valence proton and neutron change the shape of odd-odd nuclei?
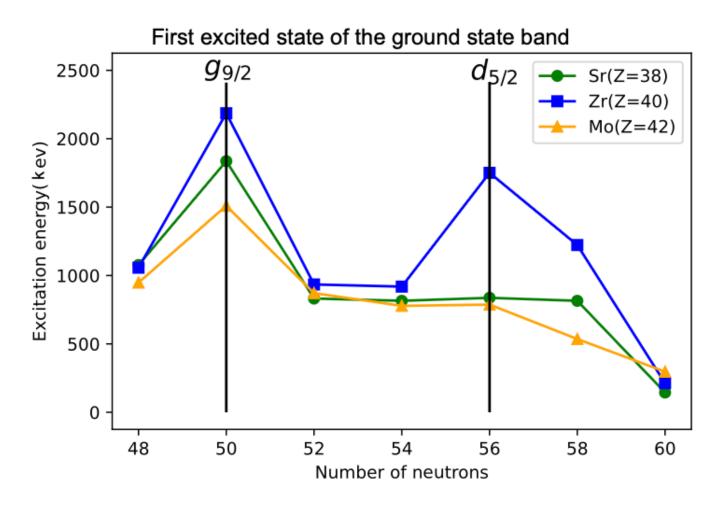*Is it possible to form multi-phonon γ vibrational bands in odd-odd nuclei?*

^{104}Nb is an excellent case

Z=40 and N=60 region gives a remarkable example of sudden nuclear shape transition
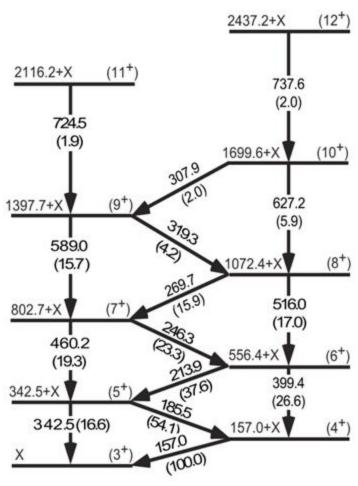
N=58: quasi-spherical shape → N=60 : rigid rotors with large deformation (β=0.4)

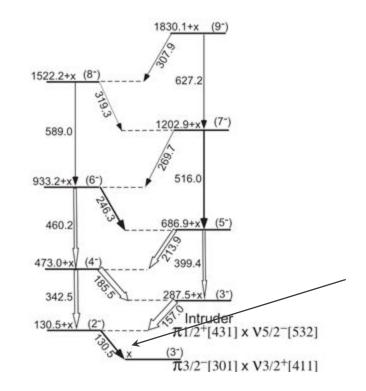First excited state of the ground state band

Spin and parity assignments of the high spin levels
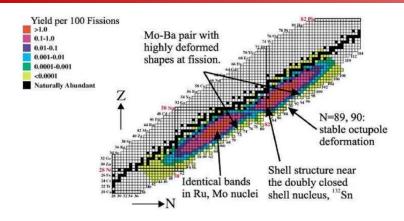

Phys Rev C 78, 014313 (2008)

Proposed ~μs isomeric transition by Luo *et al.*
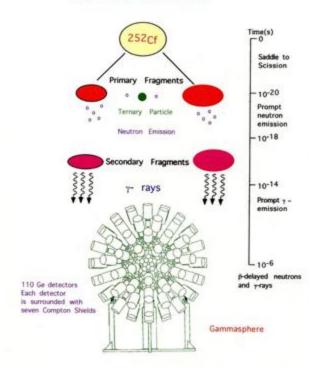
Phys Rev C 89, 044326 (2014)

Spontaneous fission setup

High γ fold
High statistics
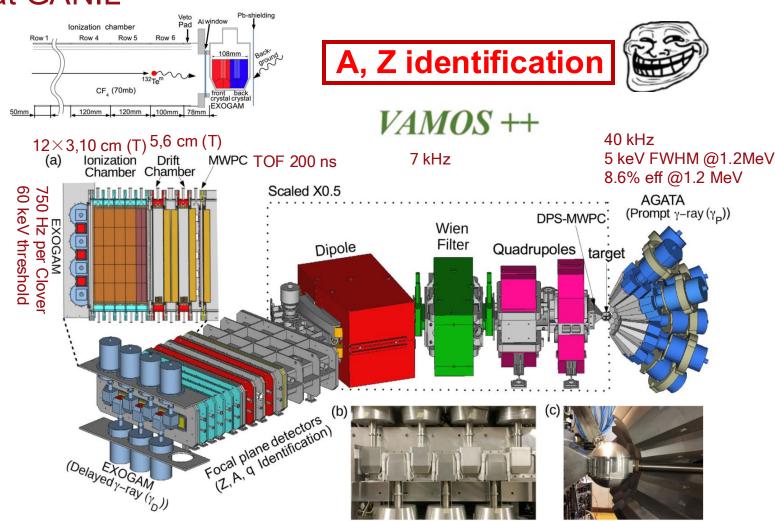*High* angular momentum
High difficulty of data analysis

- ^{252}Cf Source of 62 µCi sandwiched between two 10mg/cm^2 Fe in a 7.62 cm PE ball
- High angular momentum for both fission partners
- Gammasphere Detector Array with 101 HPGe
- ~1µs coincidence time window
- **5.7x10^{11} triple coincidences + 1.9x10^{11} four-fold coincidences**
- γ–γ angular correlation
- Over 3000 γ-rays from hundreds of nuclei
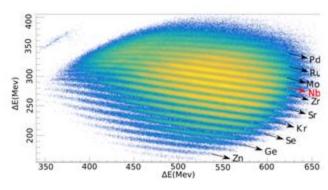
e661 and e680 experiments at GANIL

- Induced fission
  - ^{238}U@ 6.2MeV/u + ^{9}Be (1.85mg/cm^2)

- Experimental setup:
  - AGATA (prompt γ-ray)
  - VAMOS++ (fragments identification)
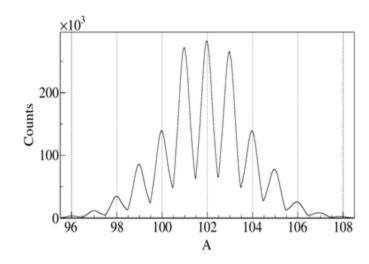 - EXOGAM (delayed γ-ray in 1-200 μs)

A, Z identification

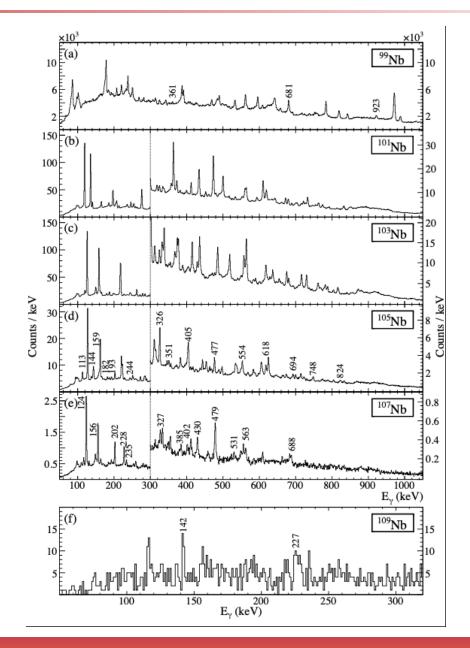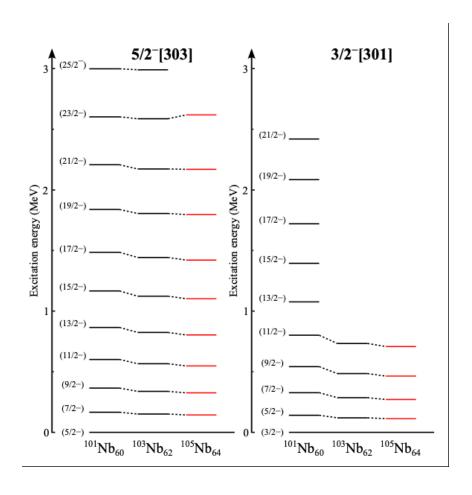*Eur Phys J A 53,1*

Identification of Nb

Z from ΔE/E
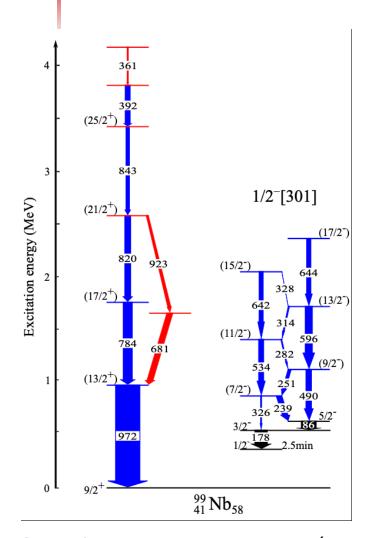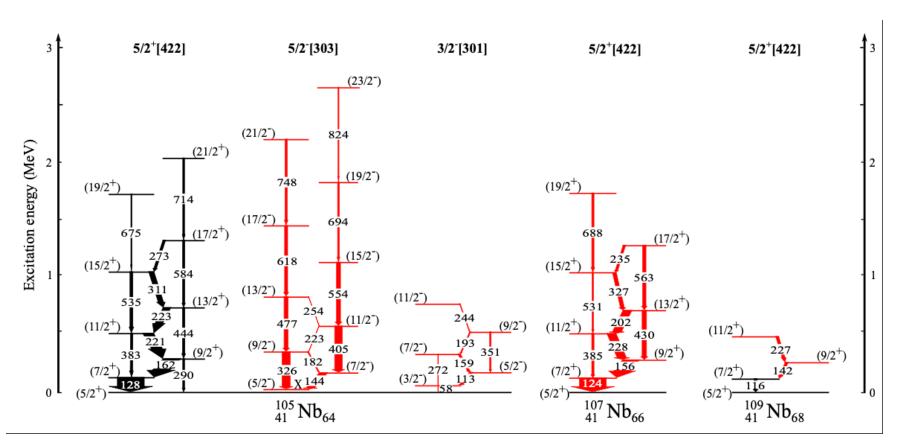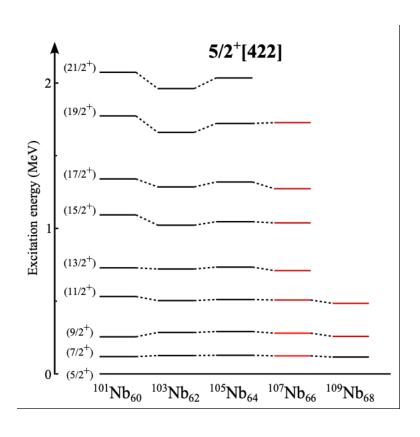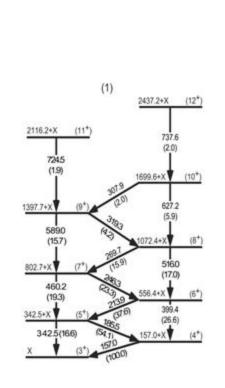
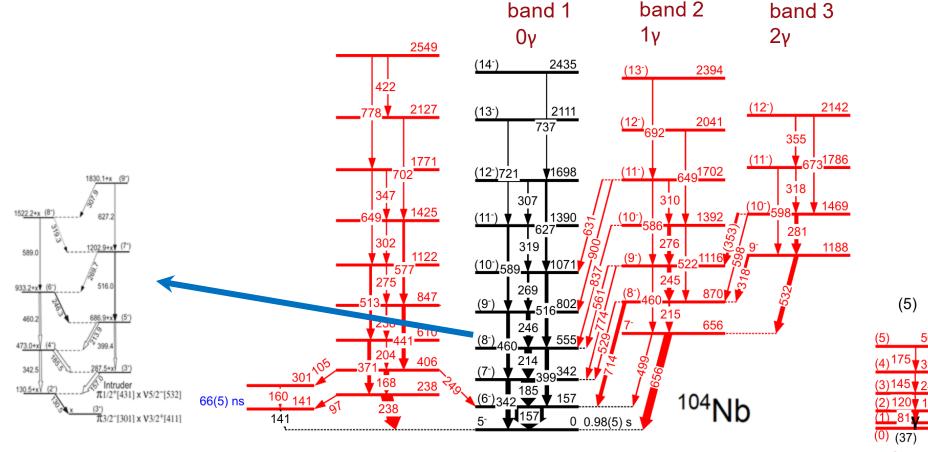**Blue:** Phys. Rev. C 108, 044313 (2023)

New in red

Previous results

New results

Phys Rev C 78, 014313 (2008)

Phys Rev C 89, 044326 (2014)

5$^-$ ground + low spin 10 keV isomer are assigned from
1) Mass measurement, M. Hukkanen *et al.* Phys. Lett. B 856, 138916 (2024)
2) ^{104}Nb β–decay, S. Nandi *et al.* Proc. ISNS-24

Early β-decay

✗ **215(120) keV isomer**
0.94 s high spin

g.s.
4.8 s low spin

NDS 108, 2035 (2007)

Mass measurement

9.8(24) keV isomer

R. Orford, Ph.D thesis 2018

10.0(72) keV isomer low spin

$^{104}Nb^m$ $(0^-, 1^-)$ 4.9(3) s

g.s. high spin

M. Hukkanen, Ph.D thesis 2023

β-decay total absoption
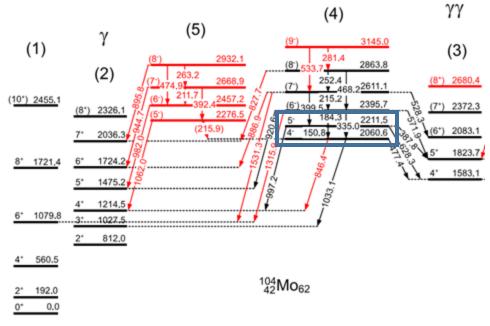
Parent: ^{104}Nb ground (high spin)
$T_{1/2}$=0.94 s; Q(β⁻)=8531
Daughter: ^{104}Mo

← g.s. not isomer

TABLE III. $I_\beta(E)$ for ^{104m}Nb.
low 10^{-3}% were set to 0.

Energy (keV)	Intensity (%)	Error (±)
0	5.6	1.3
192	0	
561	2.9	0.6
812	2.2	0.7
886	0	
1028	0	
1080	0	
1215	0	
1275	0.02	0.06
1469	0.4	0.3
1475	1.7	0.4
1545	0	
1583	1.9	0.3
1607	0	
1611	0	
1624	0.3	0.3
1790	1.0	0.3
1882	0	
2061	28.8	1.5
2317	0	

PRC 103, 035803 (2021)

^{104}Nb I_β=28.8(15) to 2061 keV state in ^{104}Mo
log*ft*~5.20(3)

+

^{252}Cf SF experiment earlier work
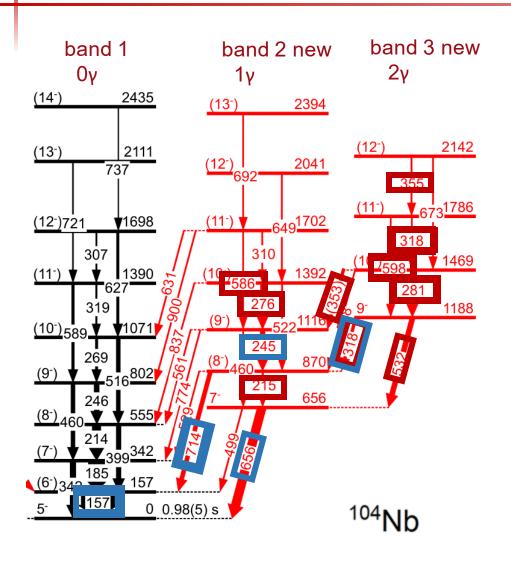
PRC 104, 064318 (2021)
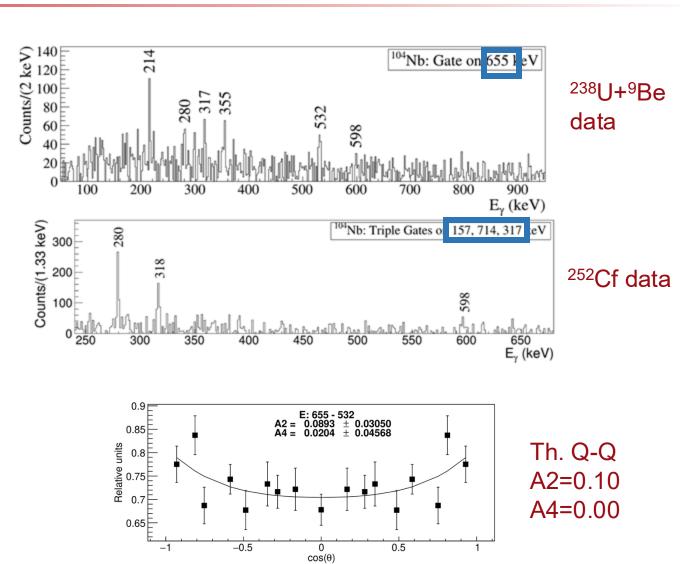
Angular correlations assigned 4⁻ 2061 and 5⁻ 2212 keV states in ^{104}Mo

+

^{104}Nb spin is 5⁻ From ^{104}Nb β–decay, S. Nandi *et al.* Proc. ISNS-24

=
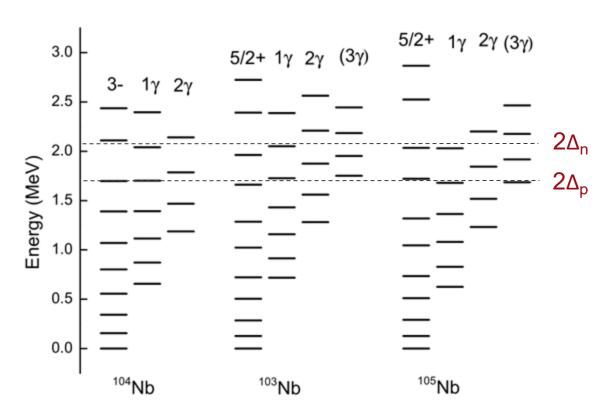
Exp energy levels

Band head energy

	0 phonon	1 phonon	2 phonon	Energy ratio
^{104}Nb	0	656	1188	1.81

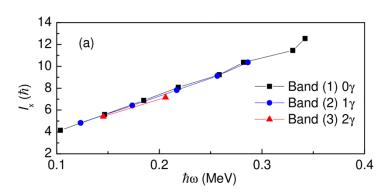| Nucleus	$E_{0\gamma}$ (keV)	$E_{1\gamma}$ (keV)	$E_{2\gamma}$ (keV)	$(E_{2\gamma} - E_{0\gamma})/(E_{1\gamma} - E_{0\gamma})$
^{103}Nb	0.0	716.8	1282.1	1.79
^{105}Nb	0.0	625.9	1231.9	1.97
^{102}Mo	0.0	847.5	1660.4	1.96
^{103}Mo	346.5	1008.6	1370.7	1.55
^{104}Mo	0.0	812.1	1583.3	1.95
^{105}Mo	0.0	870.5	1534.6	1.76
^{106}Mo	0.0	710.4	1434.6	2.02
^{107}Mo	348.3	949.8	1462.5	1.85
^{108}Mo	0.0	586.1	1422.4	2.43
^{107}Tc	137.5	766.2	1499.5	2.17
^{109}Tc	69.6	633.4	1384.2	2.33
^{108}Ru	0.0	708.6	1644.8	2.32
^{110}Ru	0.0	612.7	1618.4	2.64
^{112}Ru	0.0	523.6	1413.6	2.70
^{114}Ru	0.0	563.3	1578.0	2.80

$2\Delta_n \sim 2.1$ MeV, $2\Delta_p \sim 1.7$ MeV, **no 4 qp states**
Exp p and n orbitals with K both up to 5/2
Bands 2 and 3 with K=7 and 9 are not 2qp

IJMPE 26, 1750030 (2017)
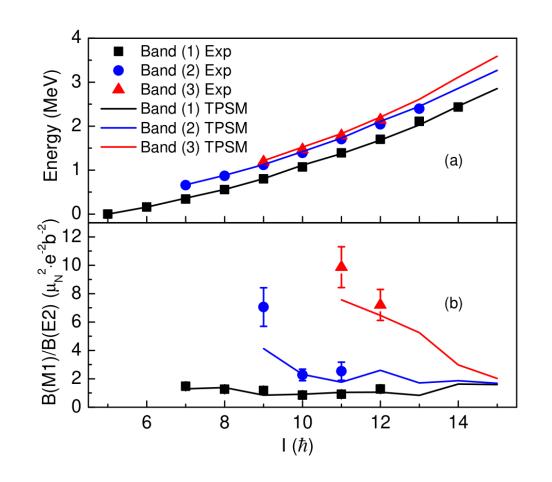
$J^{(2)}$ (slope) are close for 0γ, 1γ and 2γ

α	^{104}Nb	^{103}Nb	^{105}Nb
0γ	18.7	18.2	19.5
1γ	18.4	18.0	19.2
2γ	17.2	18.2	19.3

$$E(I, K) = E_K + \alpha \left[I(I+1) - K^2 \right] + \beta \left[I(I+1) - K^2 \right]^2 \text{。}$$
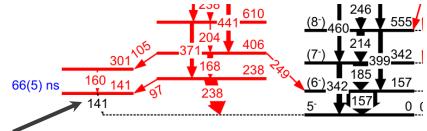

ε=0.32
ε'=0.19

^{238}U+^{9}Be
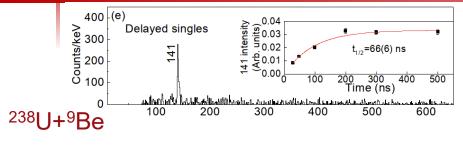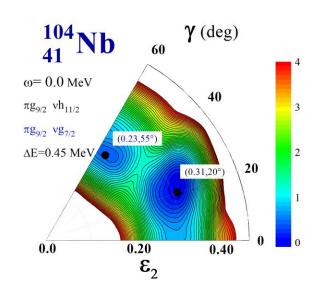
E1 or M1

ICC=0.07(7)
E1=0.04,
M1=0.09

66(5) ns

$^{104}_{41}$Nb

γ (deg)

ω= 0.0 MeV

πg$_{9/2}$ νh$_{11/2}$

πg$_{9/2}$ νg$_{7/2}$

ΔE=0.45 MeV

(0.23,55°)

(0.31,20°)

Cranking model with the shell
correction method

Proton

Neutron
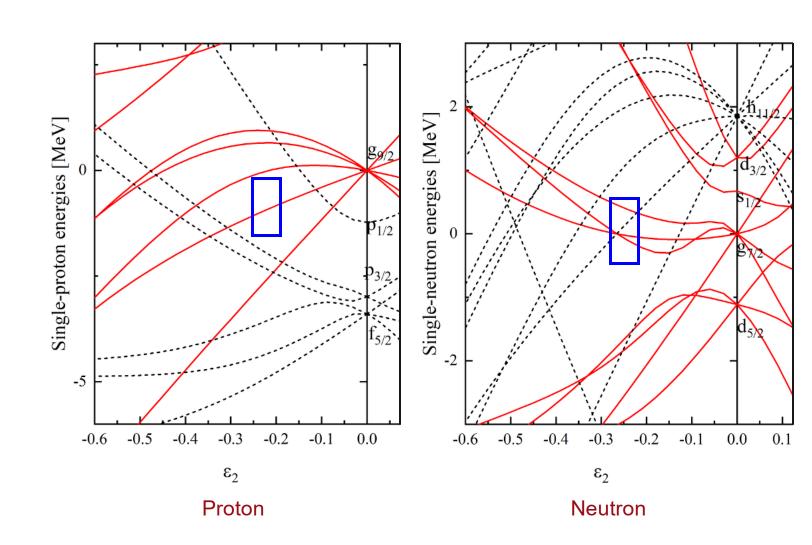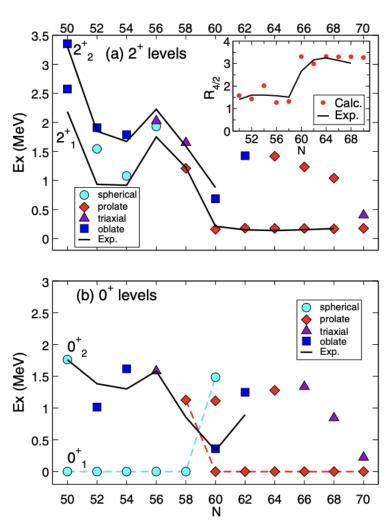
TABLE I. Reduced transition probabilities of the interband transitions in ^{101,103,104}Nb and ^{105}Mo. Halflives, level and transition energies are taken from National Nuclear Data Center website.
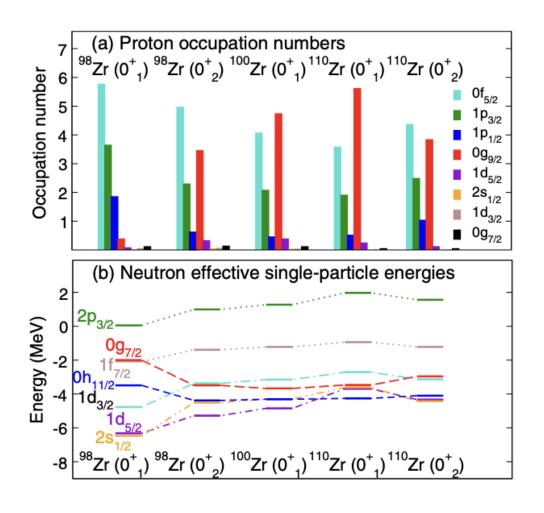
Nucleus	E_i (keV)	$t_{1/2}$ (ns)	E_f (keV)	E_γ (keV)	B(E1) (W.u.)
^{104}Nb[a]	141	66(5)	0	141	$1.7(1)\times10^{-6}$
^{101}Nb	205	1.83(3)	0	205	$1.97(3)\times10^{-5}$
	208	0.80(5)	0	208	$4.3(3)\times10^{-5}$
^{103}Nb	164	5.1(1)	0	164	$1.37(3)\times10^{-5}$
	248	1.25(4)	0	248	$1.62(5)\times10^{-5}$
^{105}Mo	247	0.30(6)	0	247	$7(1)\times10^{-5}$

Nucleus	E_i (keV)	$t_{1/2}$ (ns)	E_f (keV)	E_γ (keV)	B(M1) (W.u.)
^{104}Nb[a]	141	66(5)	0	141	$1.2(1)\times10^{-4}$
^{101}Nb	346	0.024(5)	208	138	$8.5(17)\times10^{-4}$
^{103}Nb	368	0.041(6)	164	204	$2.1(4)\times10^{-3}$
	534	0.018(6)	315	219	$1.1(4)\times10^{-3}$
^{105}Mo	397	0.53(7)	247	150	$6.3(8)\times10^{-3}$

[a] From present work for ^{104}Nb.
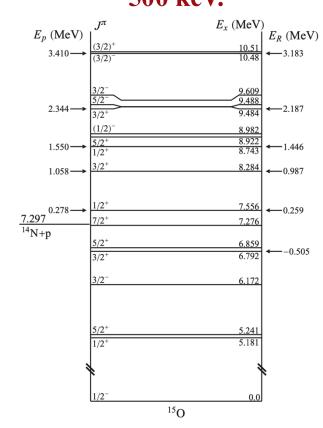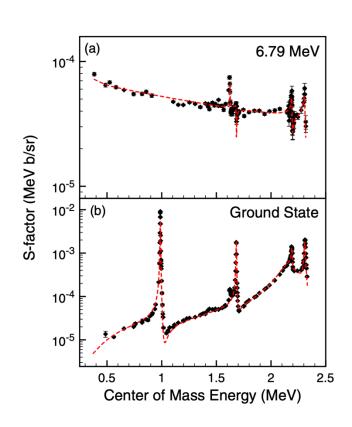
PRL 117, 172502 (2016)

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- Introduction

- Motivation

- Experimental setup

- Results and discussion

- **Hybrid detector system at SDU for JUNA and HIAF astrophysics**
    - ➤ **HPGe and CeBr$_3$ detection array for ^{14}N(p,g)^{15}O reaction angular distribution measurement**

- Summary
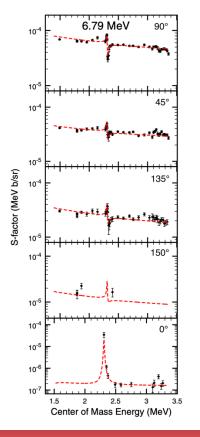
- **The total cross section of this reaction has large contributions from the transitions to 6.79 MeV and the ground state of ¹⁵O.**
- **Due to the cosmic ray background:**
  - **the cross section measurement was only down to 120 keV.**
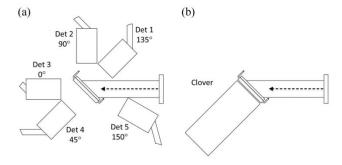 - **the investigation of the angular distributions at low energies is warranted: only went down to 500 keV.**
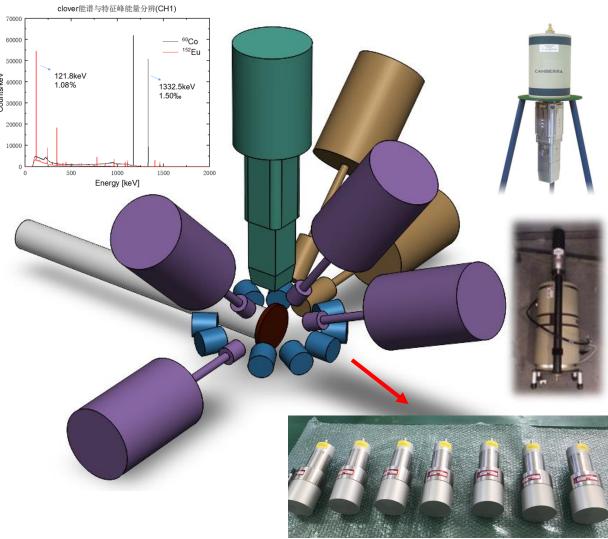
FIG. 2. (a) Detector setups of the angular distribution measurement and (b) of the clover detector.

HPGe and CeBr$_3$ hybrid detection array for angular distribution measurement of gamma-rays

Summary

- Transitions in ^{104}Nb have been unambiguously identified with bands up to high spin

- Lifetimes have been measured; an oblate shape isomer is proposed

- Spins and parities are assigned

- Two new bands are assigned to 1 and 2 phonon γ vibrational bands coupled to the known band

- Triaxial projected shell model calculations well reproduce the multi phonon γ vibrational bands

- The complicated multi quasiparticles + multi phonon vibration + rotation mode needs further self-consistent unified microscopic model description

- Hybrid detector system at SDU will contribute to JUNA and HIAF astrophysics