Search for chiral doublet in ^{79}Kr with the Hyperball2 array

T. Suzuki,[1,2,3] T. Koike,[3] T. Ahn,[4] T. Endo,[2] M. Fujita,[2] Y.Y. Fu,[5] T. Fukuchi,[6] P. Joshi,[7] S. Kinoshita,[3] Y. Ma,[3] Y. Miura,[3] Y. Miyashita,[2,3] M. Ohguma,[2,3]
G. Rainovski,[4,8] N. Sato,[2,3] T. Shinozuka,[2] K. Shirotori,[3] H. Tamura,[3] M. Tateoka,[2,3] J. Timár,[9] M. Ukai,[2] T. Wakui,[2] and A. Yamazaki[2]

[1]Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka, Japan
[2]Cyclotron and Radio-isotope Center, Tohoku University, Sendai, Japan
[3]Department of Physics, Tohoku University, Sendai, Japan
[4]Department of Physics and Astronomy, SUNY, Stony-Brook, NY, USA
[5]Department of Nuclear Physics, China Institute Atomic Energy, Beijing, China
[6]Center for Nuclear Study, University of Tokyo, Wako, Saitama, Japan
[7]Department of Physics, University of York, UK
[8]St. Kliment Ohridski University of Sofia, Sofia, Bulgaria
[9]Institute of Nuclear Research (ATOMKI), Debrecen, Hungary

Nuclear Chirality (Chiral Doublet)

Three perpendicular angular momenta can be formed into two systems of handedness, the right-handed or the left-handed system.
From S. Frauendorf and J. Meng, Nucl. Phys. A 617, 131 (1997).

For the mass 80 region $\pi g_{9/2} \otimes \nu g_{9/2}^{-1}$

- **1-axis:long axis of the triaxial shape**
  j_n ; neutron-hole in a high-j shell
- **2-axis:short axis of the triaxial shape**
  j_p; proton-particle in a high-j shell
- **3-axis:intermidiate axis of the triaxial shape**
  R ; core rotation

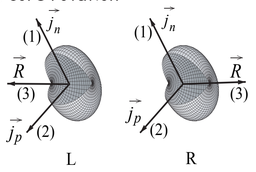
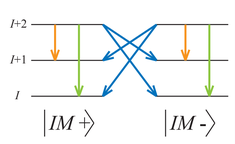


Figure from T. Koike, K. Starosta, and I. Hamamoto, Phys. Rev. Lett. 93, 172502 (2004).

Chiral Symmetry braking in Nuclei
One of spontanious synmmetry breaking in nuclei
Related to time reversal operator

$$[O, H] = 0$$
$$O = TR(\pi)$$



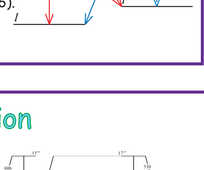
$$H|IR\rangle = \epsilon_R|IR\rangle, \quad H|IL\rangle = \epsilon_L|IL\rangle$$
$$O|IR\rangle = |IL\rangle, \quad O|IL\rangle = |IR\rangle$$
$$\epsilon_R = \epsilon_L$$
$$\begin{cases} |IM+\rangle &= \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle) \\ |IM-\rangle &= \frac{i}{\sqrt{2}}(|L\rangle - |R\rangle) \end{cases}$$
$$H|IM\pm\rangle = \epsilon|IM\pm\rangle$$
$$O|IM\pm\rangle = |IM\pm\rangle$$

two major experimental criteria

(i) the observation of nearly degenerate ΔI = 1 twin bands built on the same single particle configuration

(ii) identical electromagnetic properties --- similar B(E2) and B(M1) values of in-band and inter-band transitions

From C. M. Petrache, G. B. Hagemann, I. Hamamoto, and K. Starosta, Phys. Rev. Lett. 96, 112502 (2006).



Observed candidate chiral doublet

	odd-odd	odd-A
A~130	^{124}Cs, ^{126}Cs, ^{130}Cs, ^{132}Cs, ^{130}La, ^{134}La, ^{132}Pr, ^{136}Pm, ^{138}Eu, ^{140}Eu, ^{134}Pr (lifetime was measured), ^{132}La (lifetime was measured), ^{128}Cs (B(M1) staggering?) $\pi h_{11/2} \otimes \nu h_{11/2}^{-1}$	^{135}Nd (B(M1) and B(E2) values between both twin bands were very similar) $\pi h_{11/2}^{2} \otimes \nu h_{11/2}^{-1}$
A~100	^{100}Tc, ^{102}Rh, ^{106}Rh, ^{104}Rh (lifetime was measured) $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}$	^{105}Rh, ^{107}Ag, ^{103}Rh (lifetime was measured) $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{2}$
A~190	^{198}Tl $\pi h_{9/2} \otimes \nu i_{13/2}^{-1}$	$\pi h_{9/2}^{2} \otimes \nu i_{13/2}^{-1}$
A~80	$\pi g_{9/2} \otimes \nu g_{9/2}^{-1}$	$\pi g_{9/2}^{2} \otimes \nu g_{9/2}^{-1}$

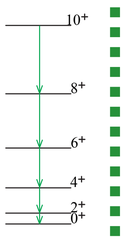
C. M. Petrache et. al. Nucl. Phys. A 597, 106 (1996).
T. Koike et. al. Phys. Rev. C 67, 044319 (2003).
A.A. Hecht et. al. Phys. Rev. C 63, 051302 (2001).
R.A. Bark et. al. Nucl. Phys. A 691, 577 (2001).
S. Zhu et. al. Phys Rev. Lett. 91, 132501 (2003).
A.A. Hecht et. al. Phys. Rev. C 68, 054310 (2003).
C. Vamman et. al. Phys. Rev. Lett. 92, 032501 (2004).
P. Joshi et. al. Phys. Lett. B 595, 135 (2004).
J. Timar et. al. Phys. Lett. B 598, 178 (2004).
P. Joshi et. al. Eur. Phys. J. A 24, 23 (2005).
J. Timar et. al. Phys. Rev. C 73, 011301(R) (2006).
E.A. Lawrie et. al. Phys. Rev. C 78, 021305(R) (2008).
D. Tonev et. al. Phys. Rev. C 76, 044313 (2007).
E. Grodner et. al. Phys. Rev. Lett. 97, 172501 (2006).
S. Mukhopadhyay et. al. Phys. Rev. Lett. 99, 172501 (2007).

Exsample of spontanious symmetry breaking in nuclei

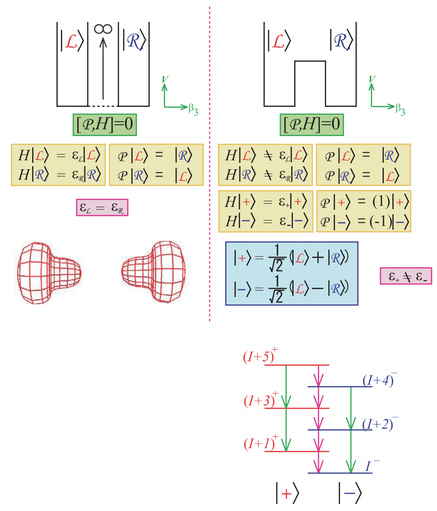
rotational band

$$[R(\Omega), H] = 0$$
$$H|\Psi_0\rangle = \epsilon|\Psi_0\rangle$$
$$|\Psi(\Omega)\rangle = R(\Omega)|\Psi_0\rangle$$
$$H|\Psi(\Omega)\rangle = \epsilon|\Psi(\Omega)\rangle$$

$$|IM\Psi\rangle = \int f(\Omega)|IM\Psi(\Omega)\rangle d\Omega$$
$$H|IM\Psi\rangle = \epsilon|IM\Psi\rangle$$
$$|IM\Psi\rangle = R(\Omega)|IM\Psi\rangle$$

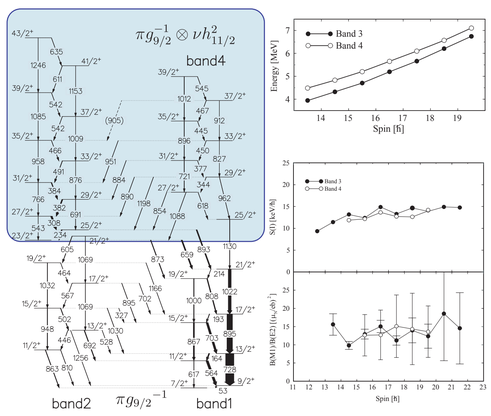


parity doublet



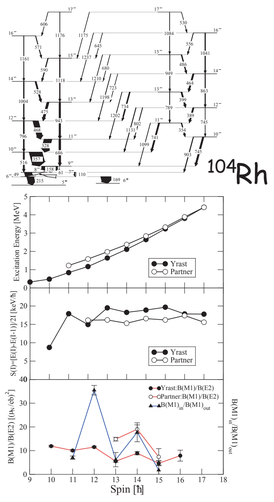
Example; Study of chiral doublet in A~100 region

(i) Observation of nearly degenerate ΔI=1 rotational bands.
(Gammaspere at LBNL experiment)



From J. Timar, C. Vaman, K. Starosta, D. B. Fossan, T. Koike, D. Sohler, I. Y. Lee, and A. O. Macchiavelli, Phys. Rev.C 73, 011301 (2006).

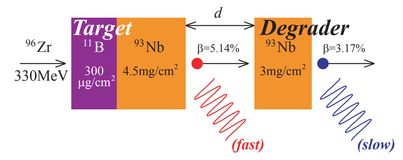
^{103}Rh

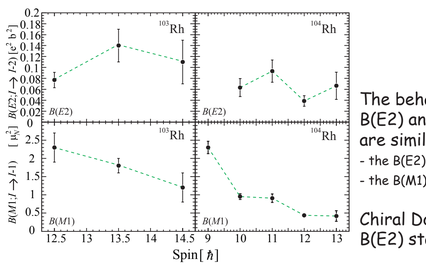


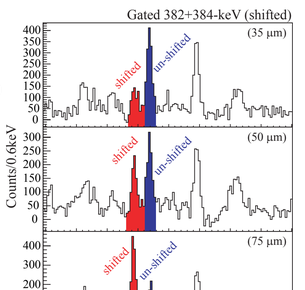
From C. Vaman, D. B. Fossan, T. Koike, K. Starosta, I. Y. Lee, and A. O. Macchiavelli, Phys. Rev. Lett. 92, 032501 (2004).

(ii) identical electromagnetic properties
-- Gammasphere GSFMA169 experiment

New results: T. Suzuki et. al. Phys. Rev. C 78, 031302(R) (2008).
(Lifetime measurement of candidates chiral doublet bands in the ^{103,104}Rh isotopes with the recoil-distance Doppler-shift method in inverse kinematics)





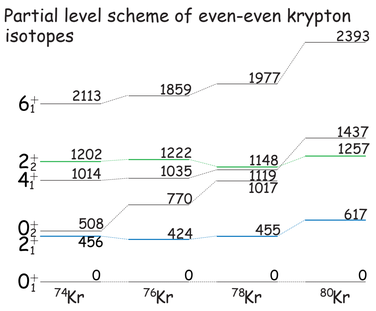


The behavior as well as absolute values of the B(E2) and B(M1) values between the two nuclei are similar;
- the B(E2) values exhibit weak staggering
- the B(M1) values decrease monotonically with increasing spin

Chiral Doublet ⟶ B(M1) staggering
B(E2) staggering ⟶ What causes staggering?

Krypton isotopes

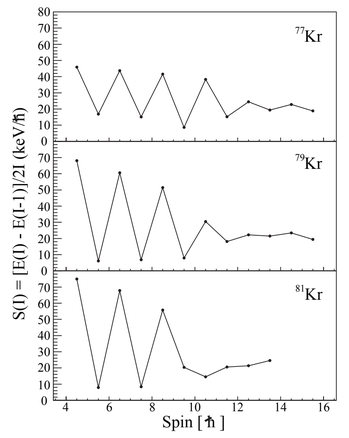
Partial level scheme of even-even krypton isotopes



The triaxial parameter γ is estimated from rigid triaxial rotor model by Davydov-Fillippov.

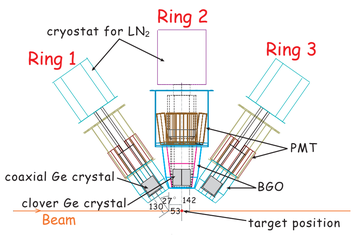
$$\frac{E(2_2^+)}{E(2_1^+)} = \frac{1 + \sqrt{1 - \frac{8}{9}\sin^2(3\gamma)}}{1 - \sqrt{1 - \frac{8}{9}\sin^2(3\gamma)}}$$

	$E(2_2^+)/E(2_1^+)$	γ (deg)
^{74}Kr	2.64	23.8
^{76}Kr	2.88	22.7
^{78}Kr	2.52	24.3
^{80}Kr	2.04	28.4



S(I) of ^{79}Kr is smoothly in 3-qp spin region, and triaxiality is expected.

Array geometry of Hyperball2



-Detectors

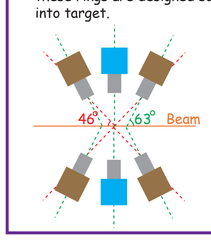
Ring 1, 3
6 coaxial type Compton-suppressed Ge detectors in each ring

Ring 2
6 clovers and 2 co-axial type Compton-suppressed Ge detectors

- Total photo peak efficiency: ~ 5 % @ 1.3 MeV
- Energy Resolution: 2.2 keV @ 1.3 MeV

- Polar angles: 46, 90, 134 deg

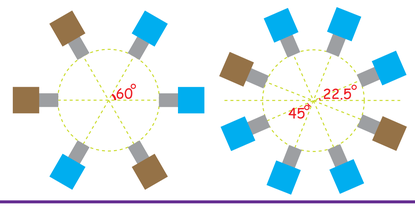
The detecotor center in Ring 1 and 3 sees off-center, 5.3 cm from a target position. The lead collimators of these rings are designed so that Ge detector look into target.



- Azimuthal angles

Ring 1, 3
0, 60, 120, 180, 240, 300 deg

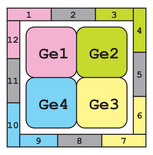
Ring 2
22.5, 67.5, 112.5, 157.5, 202.5, 247.5, 292.5, 337.5 deg

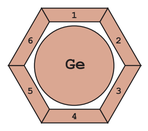


Detector for Hyperball2 and Compton-suppression

Germanium detectors
- normal type (14 detectors)
  crystal: n-type 70mmϕ x 70mm (coaxial)
  relative efficiency: 60%
- clover type (6 detectors)
  crystal: n-type
  each 45mm x 45mm x 71mm (coaxial)
  relative efficiency:
  each 20% or 120% with added-back
- Both detectors have low-gain transister-reset preamplifier.
  threshold level: 150MeV energy deposit
  dead-time due to reset: 20μsec

BGO scintillation counters
- crystal thickness: 19mm
- segmented into 6 and 12 crystals for normal and clover type detectors, respectively.



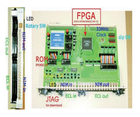


On-line Compton-suppression with Tohoku Universal Logic (TUL) modules

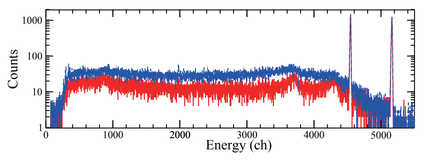
Ge 1 x (BGO1) U (BGO2) U (BGO11) U (BGO12)
Ge 2 x (BGO2) U (BGO3) U (BGO4) U (BGO5)
Ge 3 x (BGO5) U (BGO6) U (BGO7) U (BGO8)
Ge 4 x (BGO8) U (BGO9) U (BGO10) U (BGO11)

BGO 2, 5, 8, 11 are shared!

12 BGO + 1 Ge = 13 TUL IN channels
→78 TUL IN channels for 6 clovers

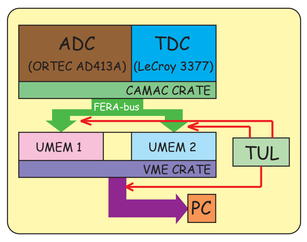


32 ECL IN + 16 NIM IN = 48 IN per TUL



peak/total	BGO OFF	BGO ON
normal type	~ 18 %	~ 32 %
clover (individual)	~ 10 %	~ 15 %
clover (added-back)	~ 20 %	~ 30 %

Double buffer data taking system



Switching of two memory modules controled by TUL
VME universal memory module (UMEM) developed by S. Ajimura from RCNP, Osaka univ.

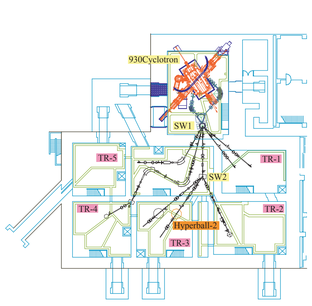
Double buffer mode
When the data are collected onto one module, the another module transports data to a computer.
→ No deadtime for data transfer from UMEM to PC.

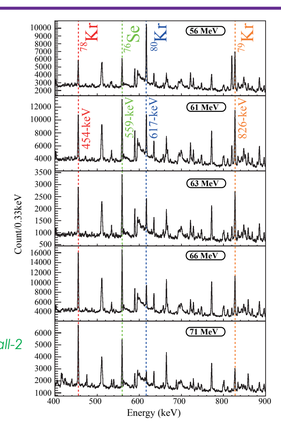
Ex. 1 event data size = 100-byte
FERA ADC&TDC → UMEM:
29 μsec/event
conversion time of ADC : 24 μsec/event
data transfer (20MB/s) : 5 μsec/event
UMEM → PC (5MB/s):
20 μsec/event

In the beam experiments, data are collected 80 % live-time for 4-kHz trigger on 60-byte (30 words) per event with this DAQ system.

The expriment

Reaction: ^{70}Zn(^{13}C, 4n)^{79}Kr
Beam energy: 65 MeV (obtained from 930 cyclotron at Tohoku univ.)
(The beam energy was determined from excitation function measurement at Stony-Brook)
Target: stacks of two 500 μg/cm^2
self supporting enriched (70 %) ^{70}Zn.
γ-ray detection: The Hyperball2 array
Triple or higher coincidence





Intencity of ^{78}Kr, ^{80}Kr, ^{76}Se relative with intencity of ^{79}Kr.