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

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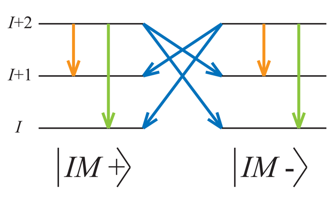
Nuclear Chirality (Chiral Doublet)

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).



$[O, H] = 0$

$O = TR(\pi)$

$|IM+\rangle$ $|IM-\rangle$

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:intermediate axis of the triaxial shape
R : core rotation

$H|IR\rangle = \epsilon_R |IR\rangle, \quad H|IL\rangle = \epsilon_L |IL\rangle$

$O|IR\rangle = |IL\rangle, \quad O|IL\rangle = |IR\rangle$

$\epsilon_R = \epsilon_L$

$$\begin{cases} |IM+\rangle = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle) \\ |IM-\rangle = \frac{i}{\sqrt{2}}(|L\rangle - |R\rangle) \end{cases}$$

$H|IM\pm\rangle = \epsilon |IM\pm\rangle$

$O|IM\pm\rangle = |IM\pm\rangle$

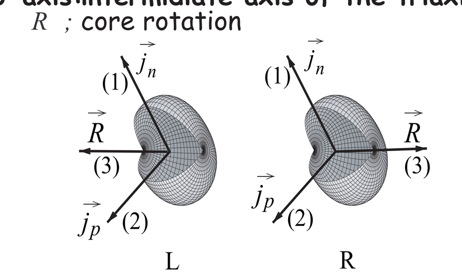


Figure from T. Koike, K. Starosta, and I. Hamamoto, Phys. Rev. Lett. 93, 172502 (2004).

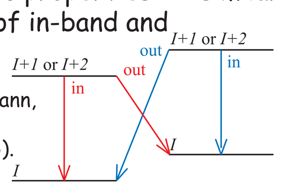
Chiral Symmetry braking in Nuclei
One of spontaneous symmetry breaking in nuclei
Related to time reversal operator

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 $\pi h_{9/2} \otimes \nu i_{13/2}^{-1}$	$\pi h_{9/2} \otimes \nu i_{13/2}^{-2}$
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. Vaman 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

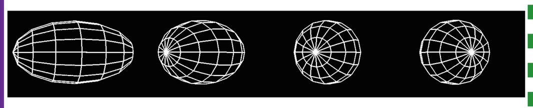
rotational band

$[R(\Omega), H] = 0$

$H|\Psi_0\rangle = \epsilon |\Psi_0\rangle$

$|\Psi(\Omega)\rangle = R(\Omega)|\Psi_0\rangle$

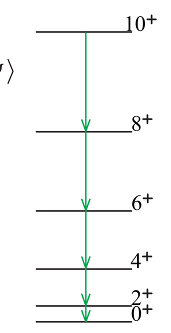
$H|\Psi(\Omega)\rangle = \epsilon |\Psi(\Omega)\rangle$



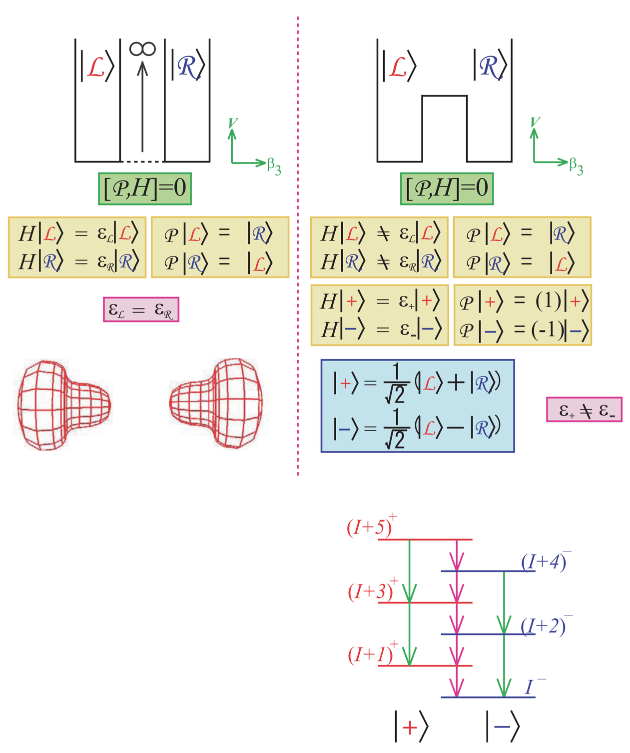
$|IM\Psi\rangle = \int f(\Omega)|IM\Psi(\Omega)\rangle d\Omega$

$H|IM\Psi\rangle = \epsilon |IM\Psi\rangle$

$|IM\Psi\rangle = R(\Omega)|IM\Psi\rangle$

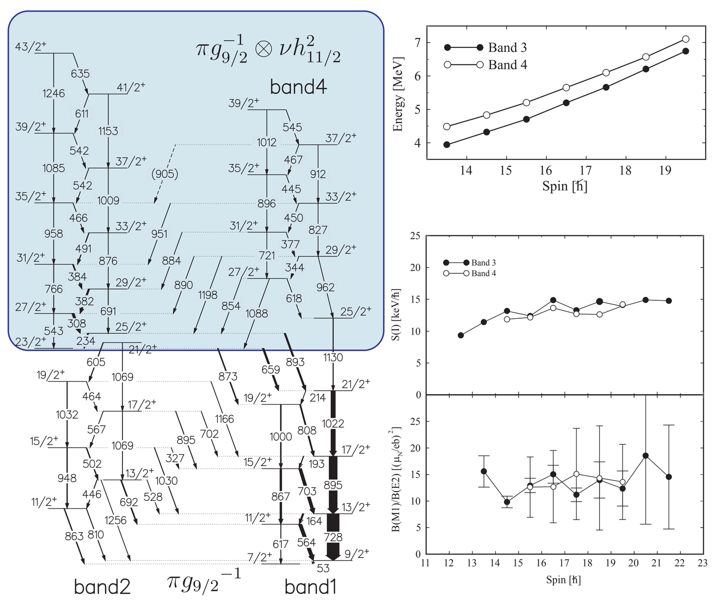


parity doublet



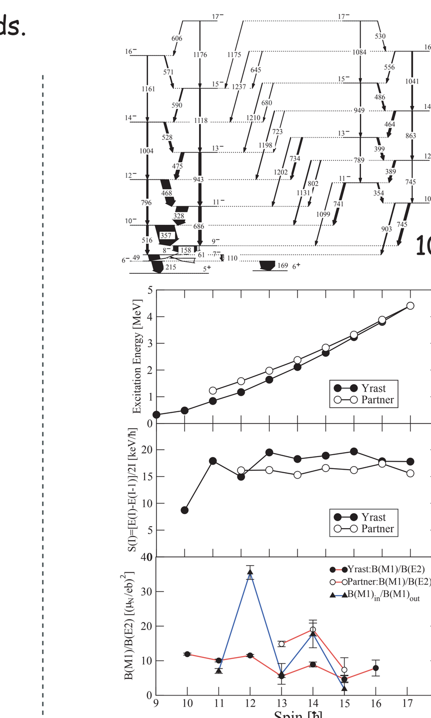
Example; Study of chiral doublet in A~100 region

(i) Observation of nearly degenerate ΔI=1 rotational bands.
(Gammasphere 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

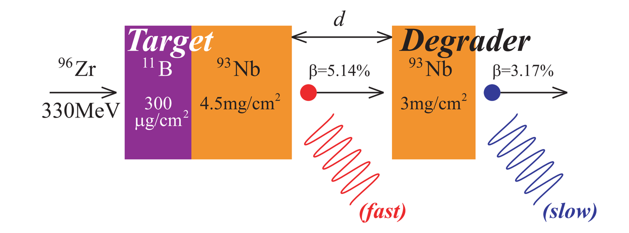


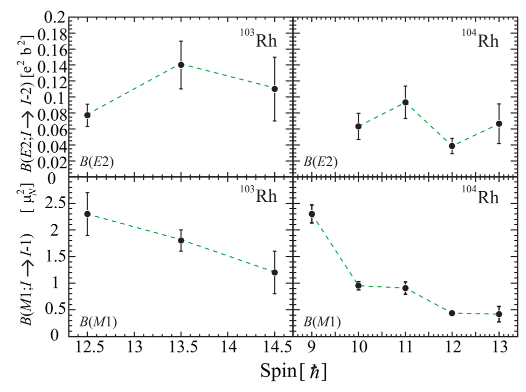
From C. Vaman, D. B. Fossan, T. Koike, K. Starosta, I. Y. Lee, and A. O. Macchiavelli, Phys. Rev. Lett. 92, 032501 (2004).

^{104}Rh

(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)



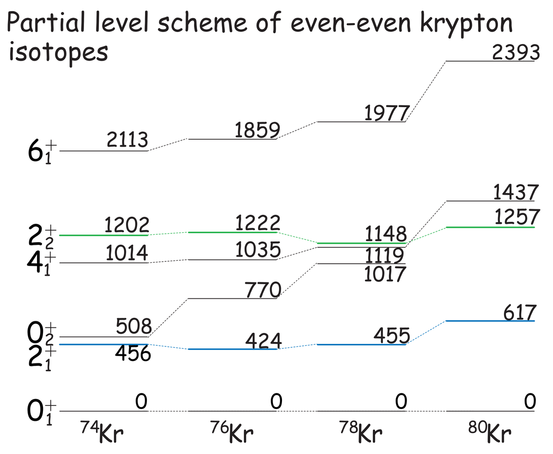


The behavior as well as absolute values of the B(E2) and B(M1) values between the two nuclei are similar;
- the B(E2) values exhibit weak staggering
- the B(M1) values decrease monotonically with increasing spin

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

Krypton isotopes

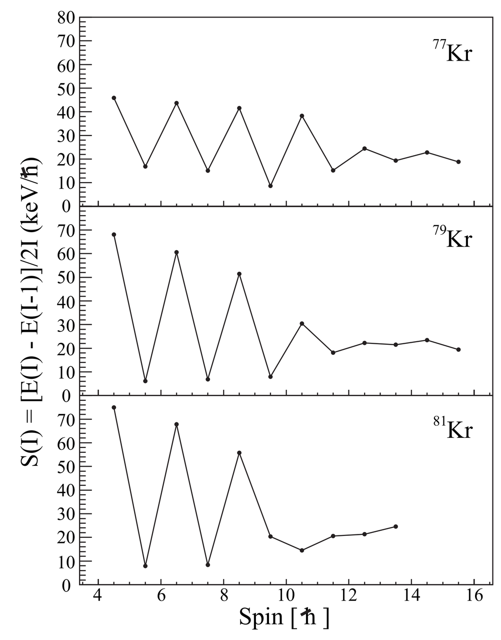
Partial level scheme of even-even krypton isotopes



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

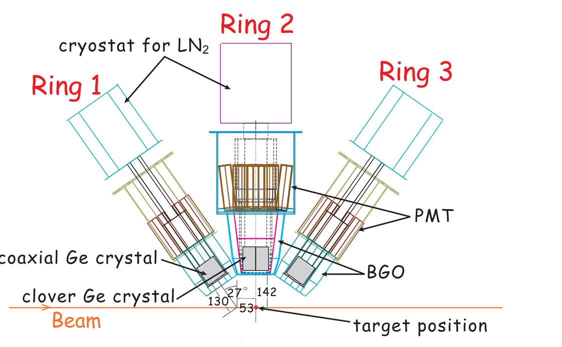
$$\frac{E(2_2^+)}{E(2_1^+)} = \frac{1 + \sqrt{1 - \frac{8}{9}\sin^2(3\gamma)}}{1 - \sqrt{1 - \frac{8}{9}\sin^2(3\gamma)}}$$

	$E(2_2^+)/E(2_1^+)$	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.

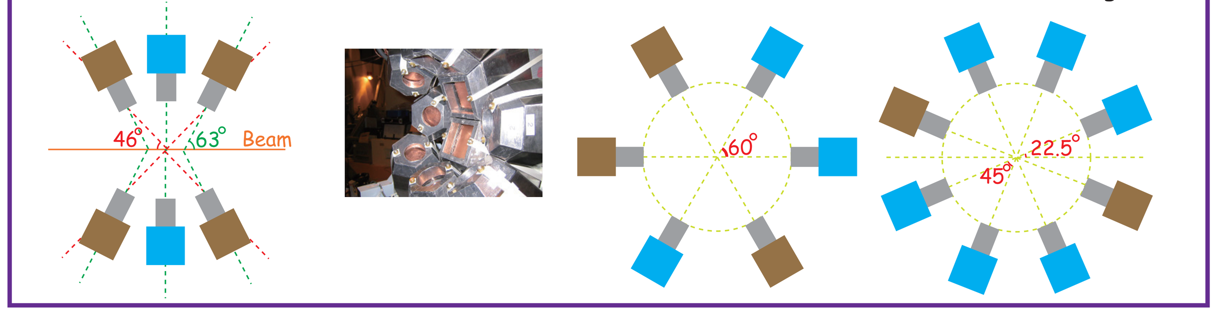
Array geometry of Hyperball2



-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.

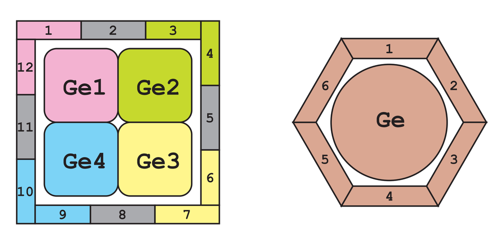
- Azimuthal angles
Ring 1, 3: 0, 60, 120, 180, 240, 300 deg
Ring 2: 22.5, 67.5, 112.5, 157.5, 202.5, 247.5, 292.5, 337.5 deg



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.

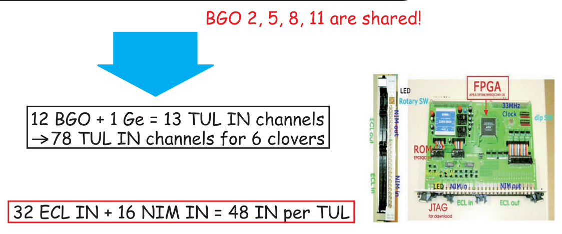


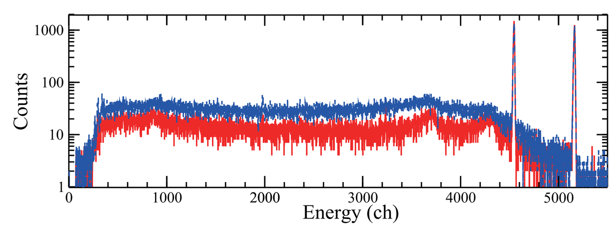
On-line Compton-suppression with Tohoku Universal Logic (TUL) modules

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

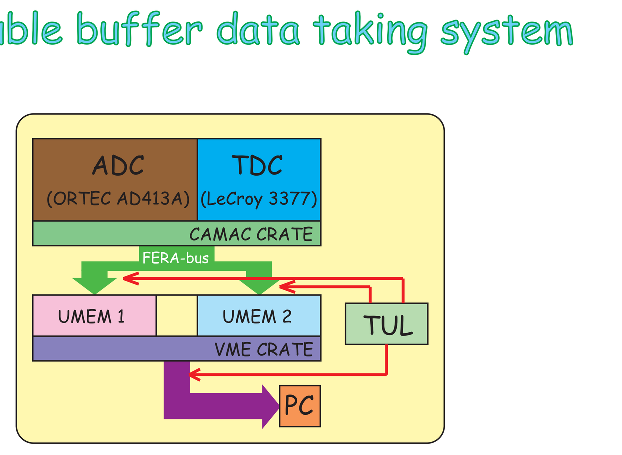
32 ECL IN + 16 NIM IN = 48 IN per TUL





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.

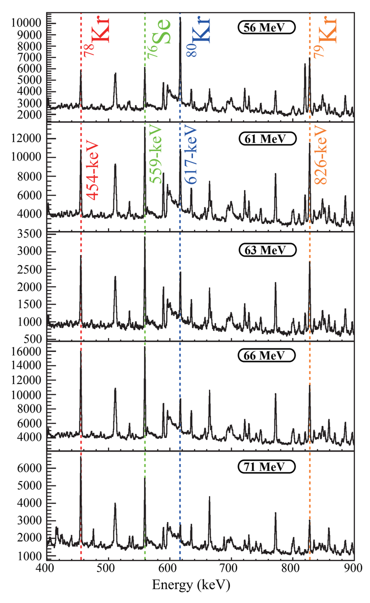
Double buffer mode
When the data are collected onto one module, the another module transports data to a computer.
→ No deadtime for data transfer from UMEM to PC.

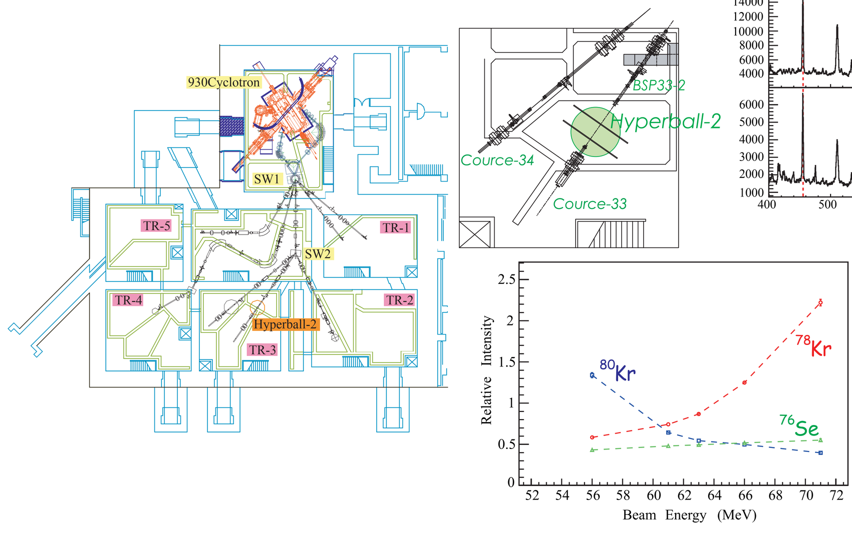
Ex. 1 event data size = 100-byte
FERA ADC&TDC → UMEM:
29 μsec/event
conversion time of ADC : 24 μsec/event
data transfer (20MB/s) : 5 μsec/event
UMEM → PC (5MB/s):
20 μsec/event

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 detector: The Hyperball2 array
Triple or higher coincidence



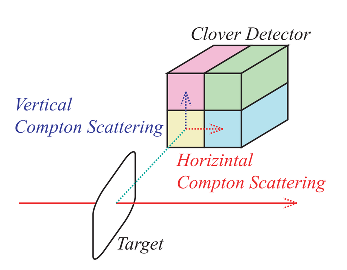


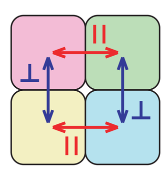
Intencity of ^{78}Kr, ^{80}Kr, ^{76}Se relative with intencity of ^{79}Kr.

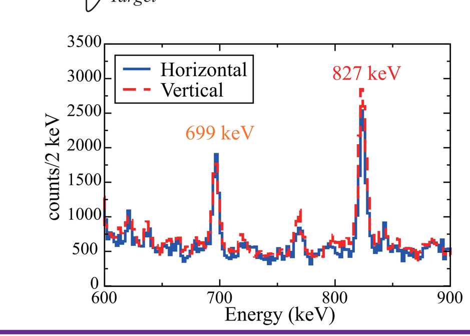
Linear Polarization analysis

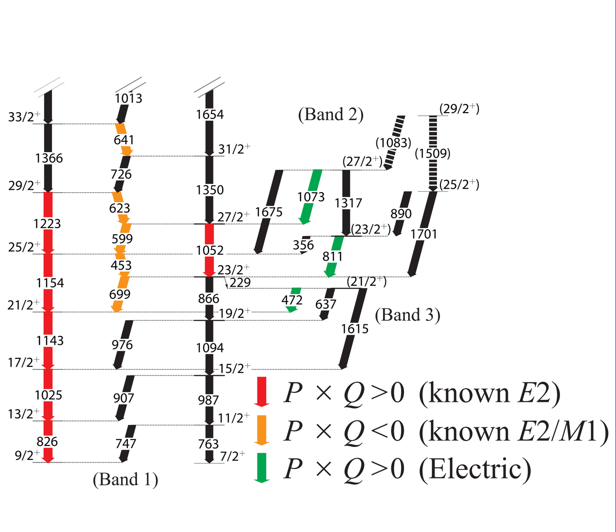
Linear polarization can be extracted with clover detectors to determine whether the transition is electric or magnetic.
(Sign of P can be known without knowing sensitivity Q.)

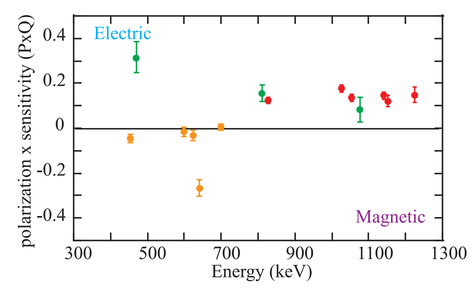
$$P = \frac{1}{Q}\frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}$$









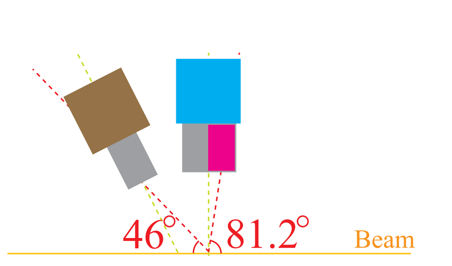


DCO ratios

Directional correlation from oriented states (DCO) can be extracted to determine whether the transition is dipole or quadlepole.

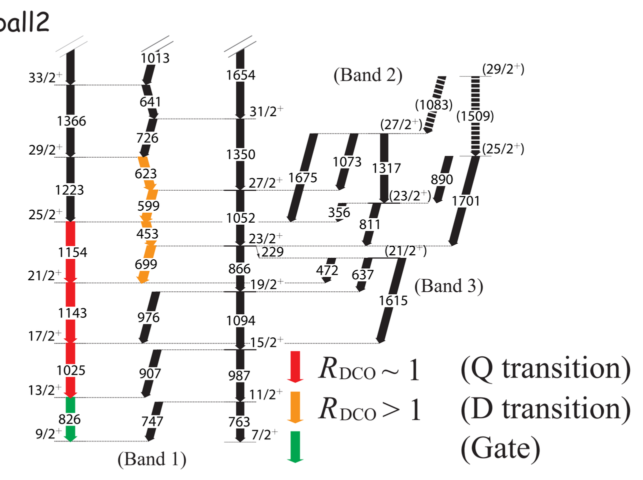
$$R_{DCO} = \frac{I_\gamma\,(\text{at Ring 2}: 90^\circ)\text{ gated by }\gamma_2\,(\text{at Ring 1}: 134^\circ)}{I_\gamma\,(\text{at Ring 1}: 134^\circ)\text{ gated by }\gamma_2\,(\text{at Ring 2}: 90^\circ)}$$

From A. Kramer-Flecken et. al. Nucl. Inst. and Methods in Phys. Res. A 275 333 (1989).

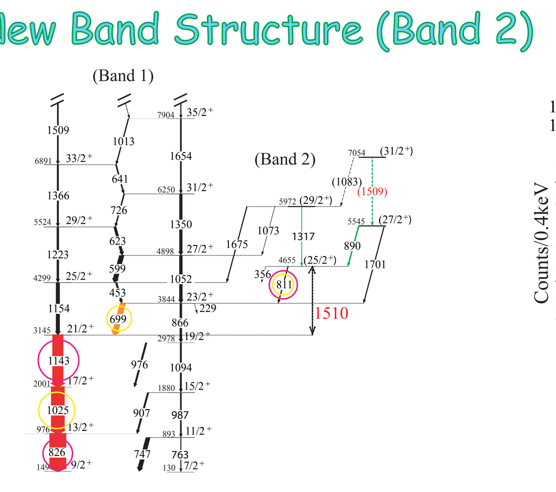


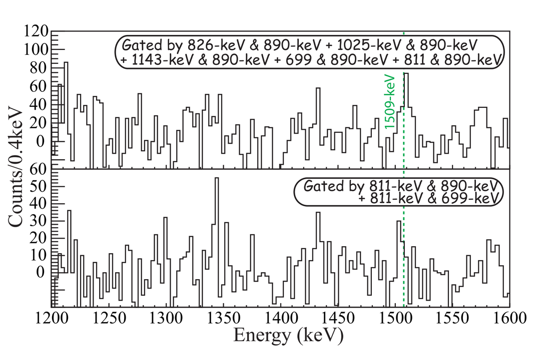
Only two crystals of the clover detectors are used in the same polar angle for obtaining the DCO values.

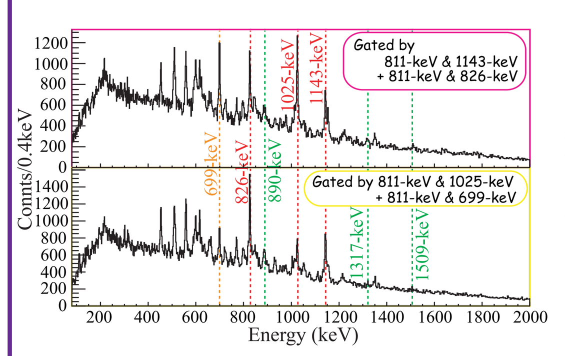
Issues using DCO method for Hyperball2
Small detector-to-target distance
→ less angular sensitivity
Large peak width due to Doppler-broadning

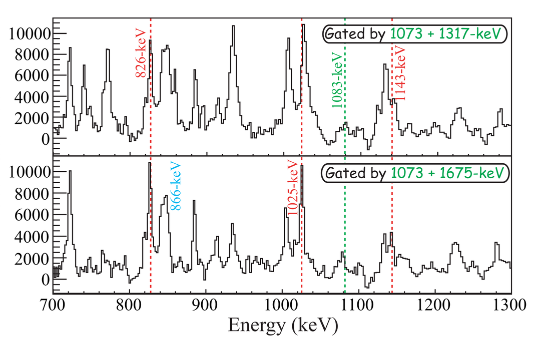


New Band Structure (Band 2)





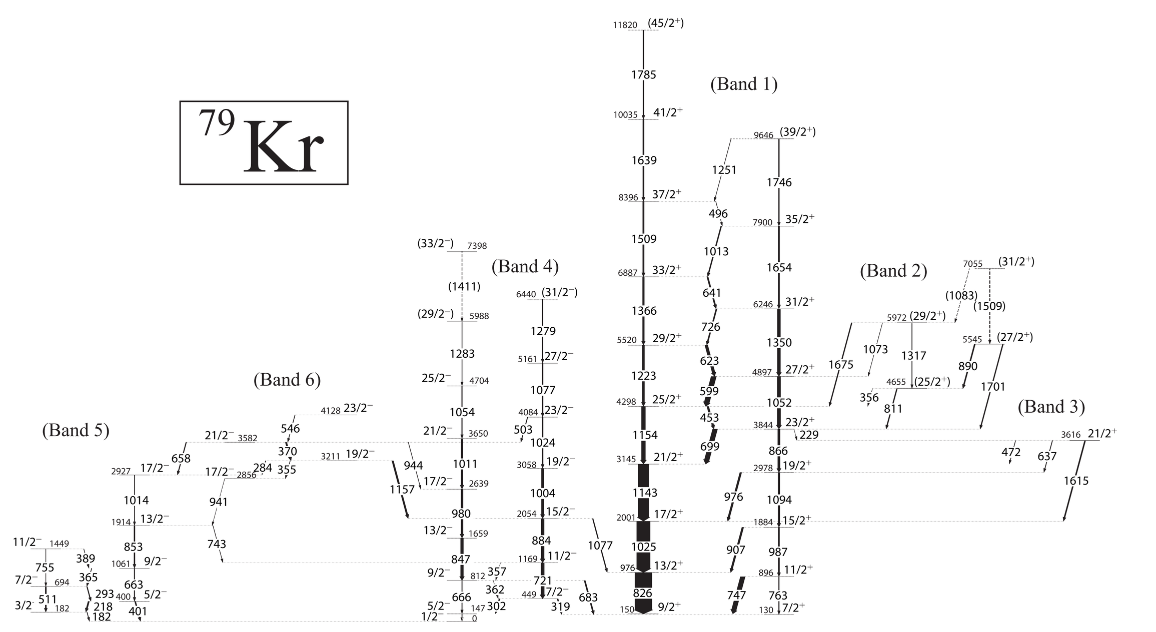




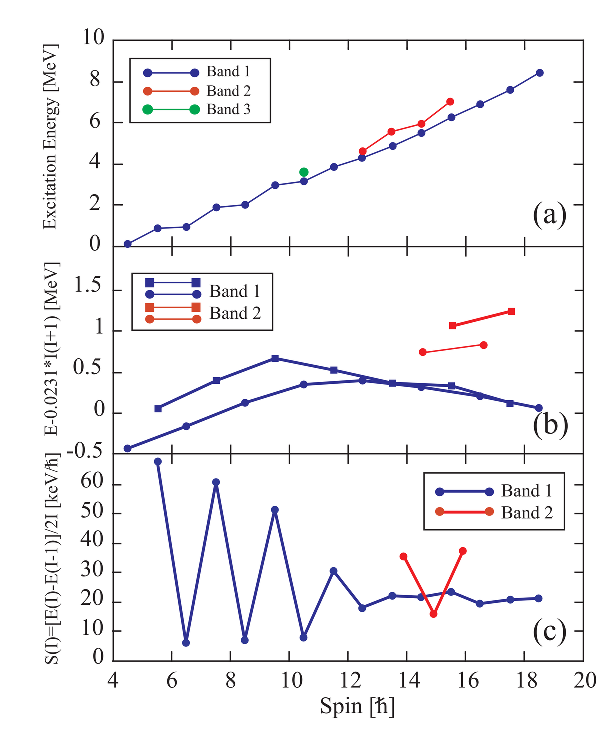
The 1083-keV transition is coincidence with the 1073, 1317 and 1678-keV transitions.

Deduced level scheme

^{79}Kr



Results



	27/2+	29/2+	31/2+	33/2+
E(I)$_b$ - E(I)$_a$ (keV)	356	650	448	805
$\omega_{osc}/\omega_{rot}$	0.79	1.08	0.72	1.11

$\hbar\omega_{rot} = \frac{\partial E_{rot}}{\partial I}, \quad \hbar\omega_{osc} = E_{Band2,3} - E_{Band1}$

Nearly degenerate twin bands?
- other chiral candidates are degenerate less than 300 - 400 keV.
- ^{104}Rh, which is most degerate case, $\omega_{osc}/\omega_{rot}$ is ~ 0.003.
- single particle states are not the same.
- S(I) = [E(I)-E(I-1)]/2I is not smoothly varying.

The current results shows that the side band structures are of non-chiral at this spin regin.