Shapes and Collectivity of nuclei around Z = 50 by Coulomb excitation

Mansi Saxena
Heavy Ion Laboratory, Warsaw

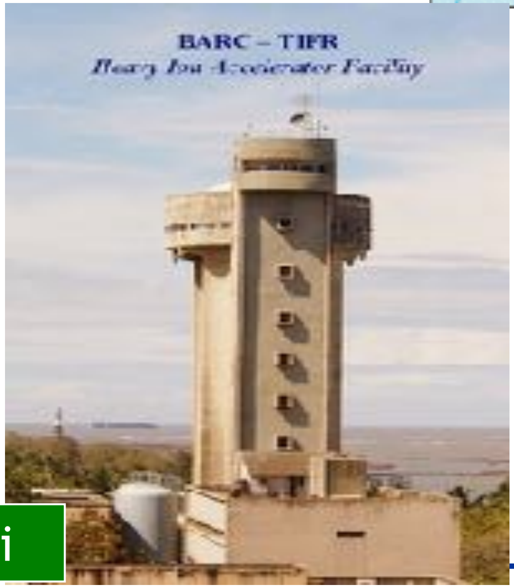
Outline

- Where do I come from
- What I did in my past
- What am I doing at HIL, Warsaw

HIL
Heavy Ion Laboratory

NCN - POLONEZ-1(2015/19/P/ST2/03008).
European Union's Horizon 2020 Research and Innovation Program under the Marie Sklodowska-Curie Grant Agreement No. 665778."

Inter University Accelerator Centre, New Delhi



BARC – TIFR , Mumbai

Variable Energy Cyclotron Centre, Kolkata

The Pelletron Accelerator at IUAC

Tank ht: 26.5 m

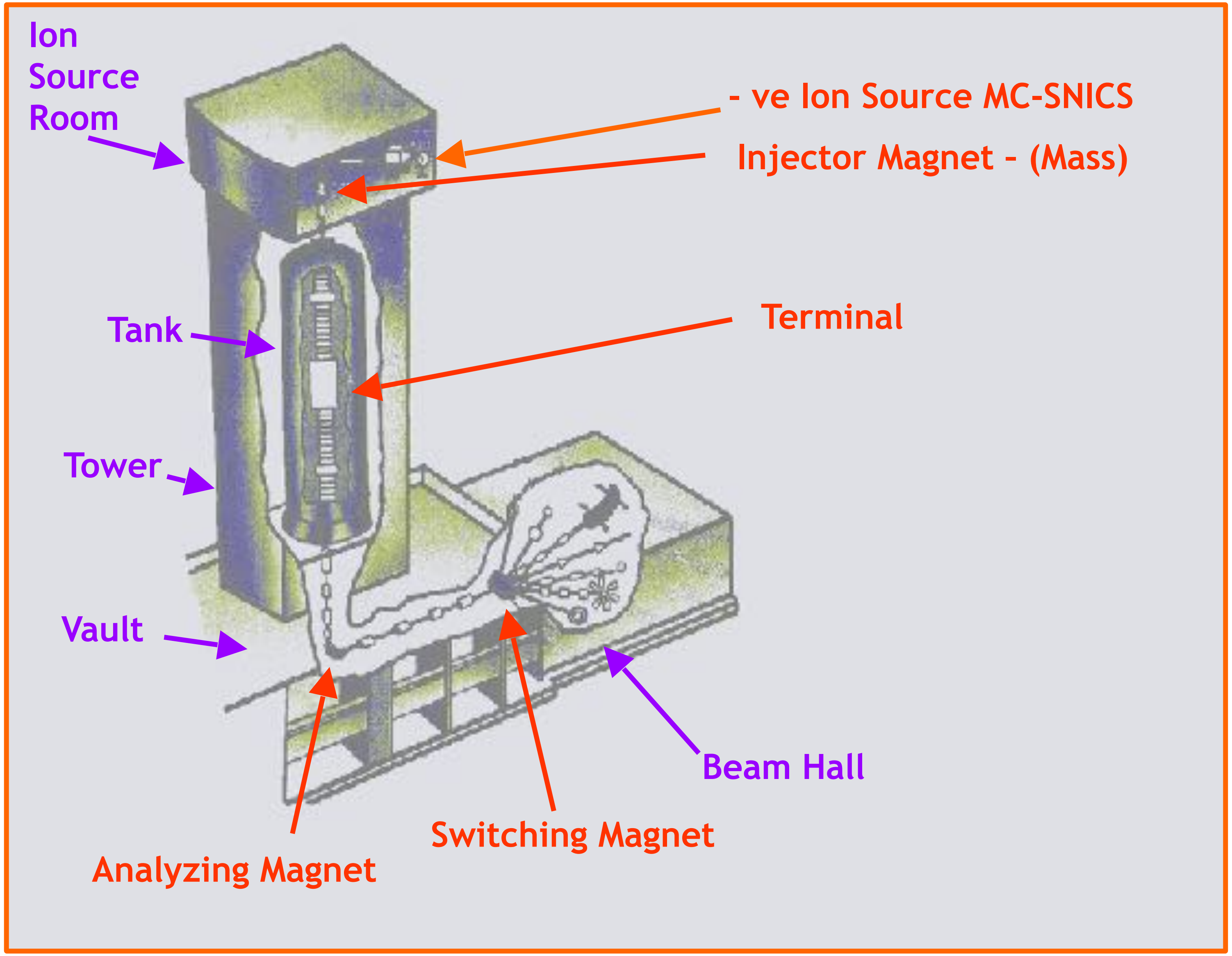
Diameter: 5.5 m

Pressure: 86 PSI of SF_6 gas

Ions accelerated:
H to Au beams

Ion Currents:
Typically
1 - 50 pnA

Energy : 30 - 250 MeV



Ion Source Room

- ve Ion Source MC-SNICS

Injector Magnet - (Mass)

Tank

Terminal

Tower

Vault

Beam Hall

Switching Magnet

Analyzing Magnet

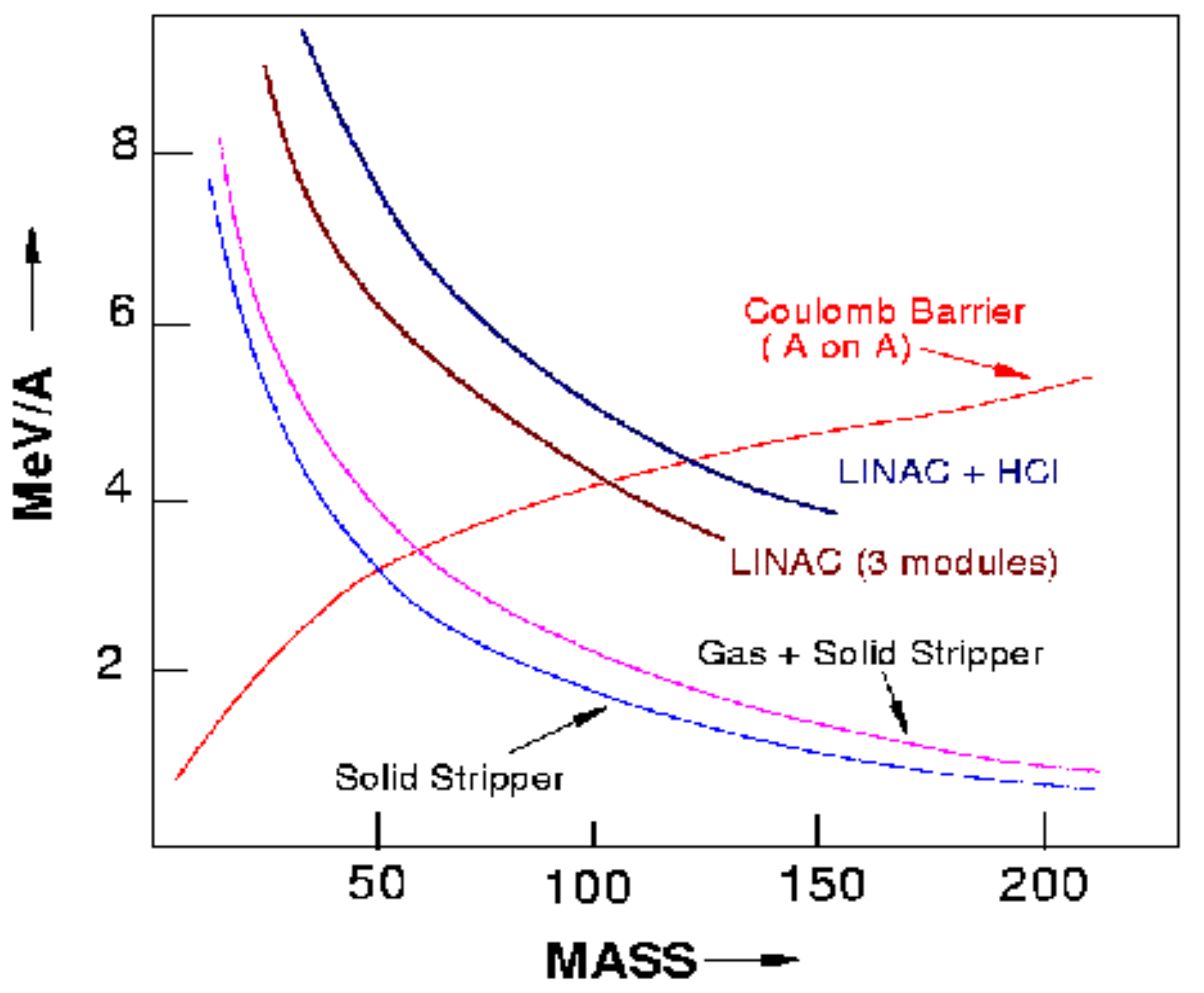
ENERGY AUGMENTATION PROGRAM - LINAC

The maximum energy of ions from the Pelletron

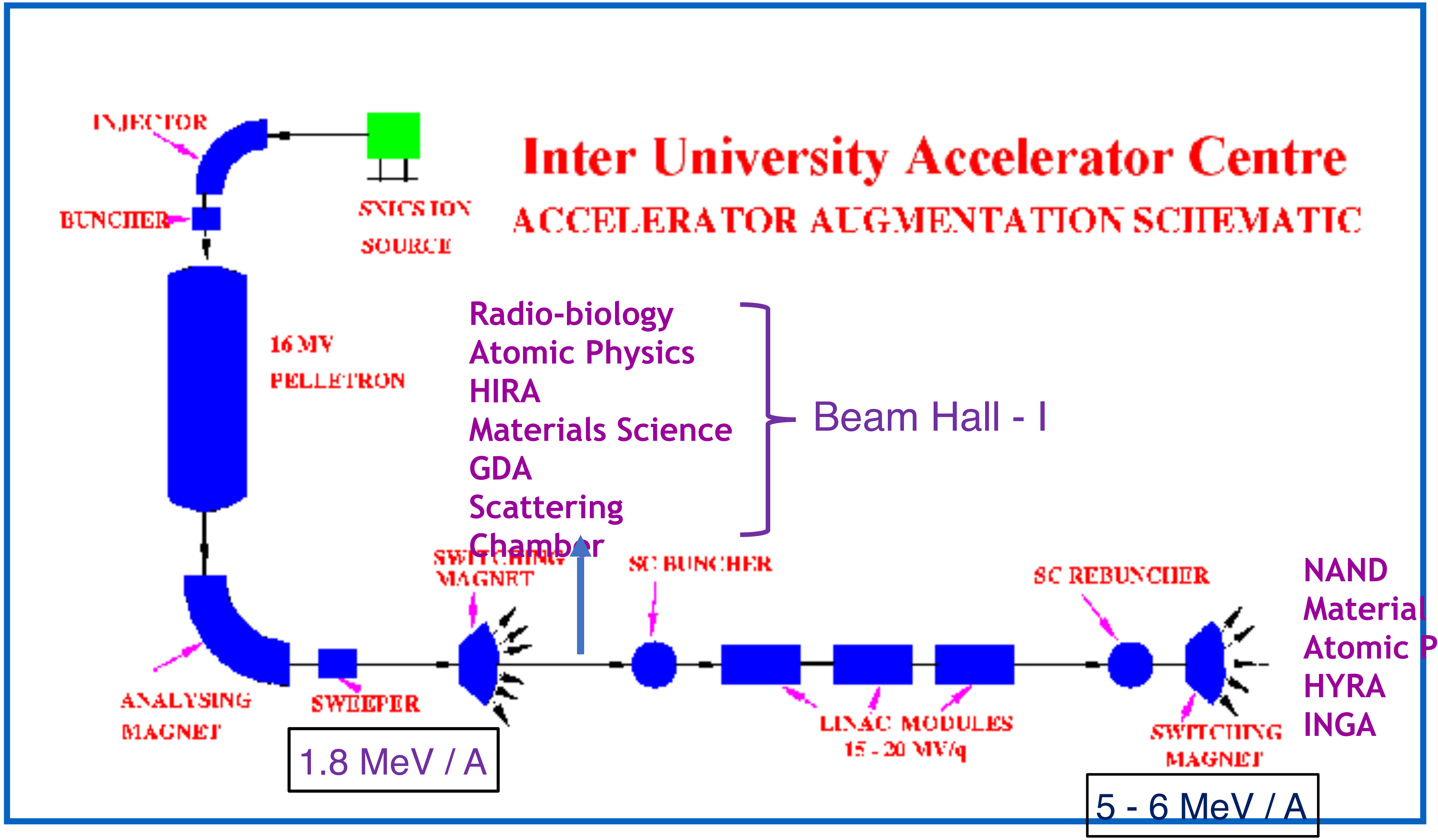
(~ 200-250 MeV) limits the research program for both nuclear physics and materials science.

A superconducting LINAC booster was planned in early 90's for future augmentation of the Pelletron.

The ion energies from the LINAC can be further enhanced by replacing the Pelletron by a high intensity high charged state ion source like ECR



ENERGY BOOSTER LINAC



Radio-biology
Atomic Physics
HIRA
Materials Science
GDA
Scattering
Chamber

Beam Hall - I

1.8 MeV / A

NAND
Material Science
Atomic Physics
HYRA
INGA

Beam Hall -

5 - 6 MeV / A

A/q	Type of Beam	Electrical current (eμA)	RF power (Watts)
6.0	C^{2+}	2000	600 W/57 W
5.33	O^{3+}	1273	193 W /28 W
6.66	Ne^{3+}	1500	391 W/33 W
5.71	Ar^{7+}	617	488 W/8 W *
6.14	Xe^{21+}	39	552 W/44 W *
6.2	Ta^{29+}	5	476 W/11 W *
5.96	Au^{33+}	7.3	398 W/56 W *
6.7	Pb^{31+}	7.7	777 W/57 W *

Advantages of HCI

- ✓ High current
- ✓ High Mass Ion Species
- ✓ Accelerate Noble gases

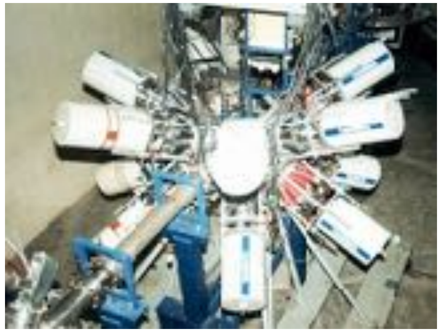
D. Kanjilal, G. Rodrigues, P.Kumar, A. Mandal, A. Roy, Performance of First High Temperature Superconducting ECRIS, ***Rev. Sci.Instrum.*, (2006)**

Under-Development !

Major Nuclear Physics Facilities at IUAC

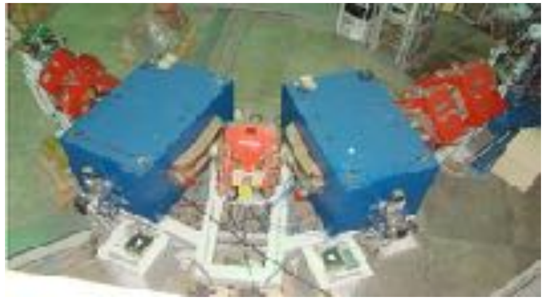
- **Gamma arrays**
  S. Muralithar (murali@iuac.res.in)

  Gamma detector array (GDA)
  Indian National Gamma Array (INGA)



- **Recoil separators**
  N. Madhavan (madhavan@iuac.res.in)

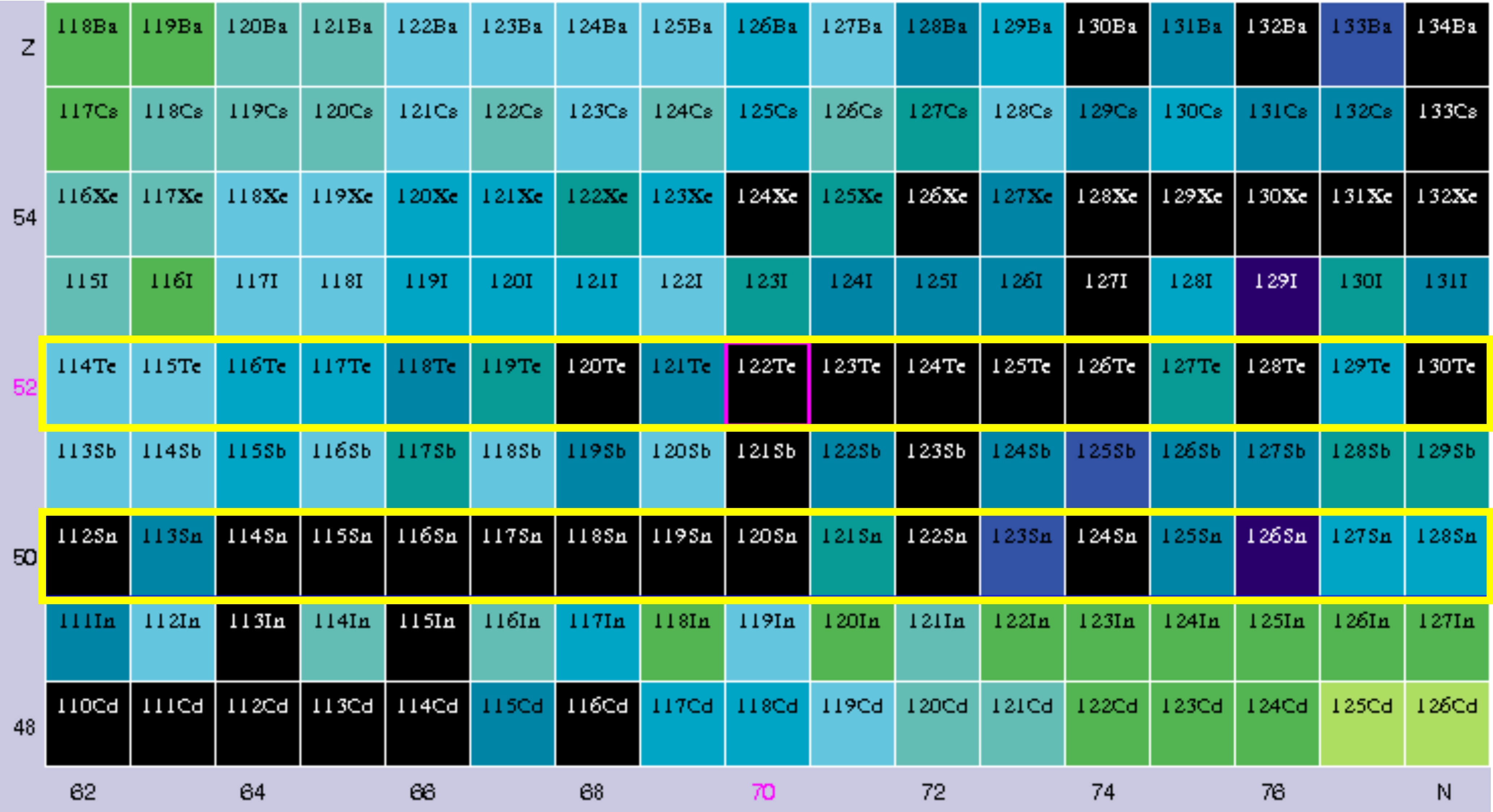
  Heavy Ion Reaction Analyzer (HIRA)
  Hybrid Recoil mass Analyzer (HYRA)



- **Scattering chamber / Neutron array**
  Dr. P. Sugathan (sugathan@iuac.res.in)

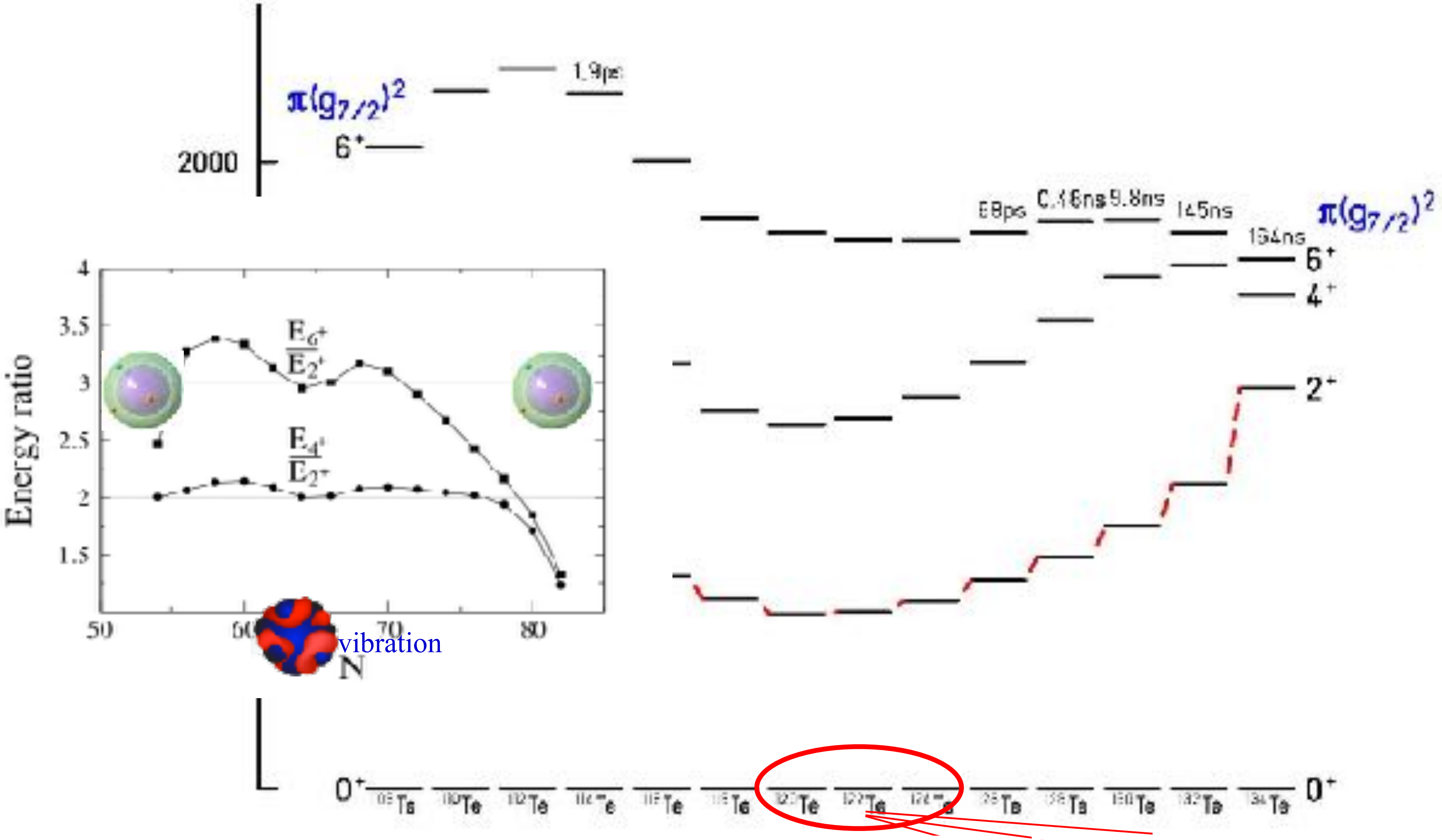
  General Purpose Scattering Chamber (GPSC)
  National Array of Neutron Detectors (NAND)

Recent Activities @ IUAC &



Z	118Ba	119Ba	120Ba	121Ba	122Ba	123Ba	124Ba	125Ba	126Ba	127Ba	128Ba	129Ba	130Ba	131Ba	132Ba	133Ba	134Ba
	117Cs	118Cs	119Cs	120Cs	121Cs	122Cs	123Cs	124Cs	125Cs	126Cs	127Cs	128Cs	129Cs	130Cs	131Cs	132Cs	133Cs
54	116Xe	117Xe	118Xe	119Xe	120Xe	121Xe	122Xe	123Xe	124Xe	125Xe	126Xe	127Xe	128Xe	129Xe	130Xe	131Xe	132Xe
	115I	116I	117I	118I	119I	120I	121I	122I	123I	124I	125I	126I	127I	128I	129I	130I	131I
52	114Te	115Te	116Te	117Te	118Te	119Te	120Te	121Te	122Te	123Te	124Te	125Te	126Te	127Te	128Te	129Te	130Te
	113Sb	114Sb	115Sb	116Sb	117Sb	118Sb	119Sb	120Sb	121Sb	122Sb	123Sb	124Sb	125Sb	126Sb	127Sb	128Sb	129Sb
50	112Sn	113Sn	114Sn	115Sn	116Sn	117Sn	118Sn	119Sn	120Sn	121Sn	122Sn	123Sn	124Sn	125Sn	126Sn	127Sn	128Sn
	111In	112In	113In	114In	115In	116In	117In	118In	119In	120In	121In	122In	123In	124In	125In	126In	127In
48	110Cd	111Cd	112Cd	113Cd	114Cd	115Cd	116Cd	117Cd	118Cd	119Cd	120Cd	121Cd	122Cd	123Cd	124Cd	125Cd	126Cd
	62		64		66		68		70		72		74		76		N

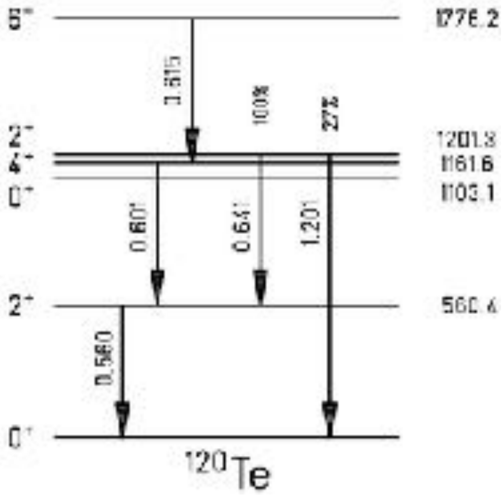
Systematics of Te isotopes (Z=52)



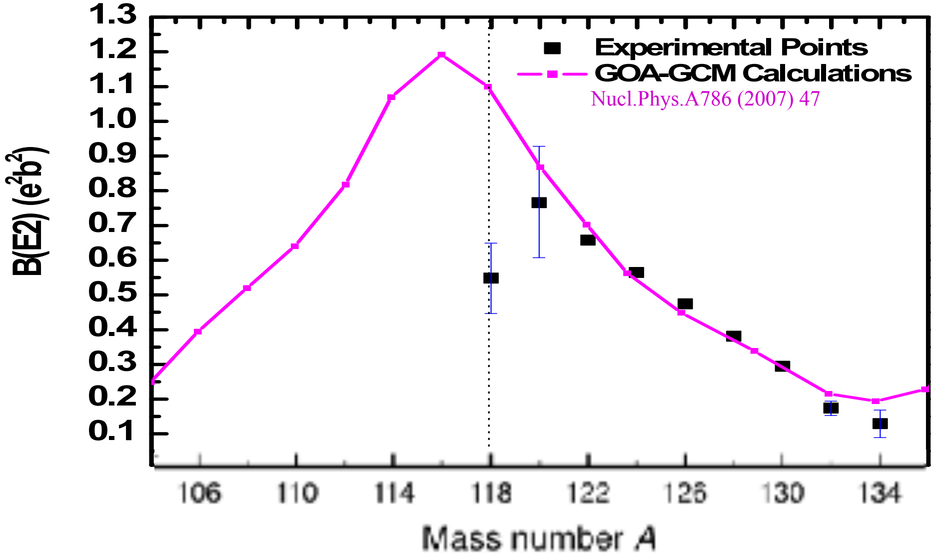
Z=52

Z=50

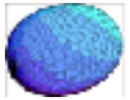
Collectivity of Te isotopes (Z=52)



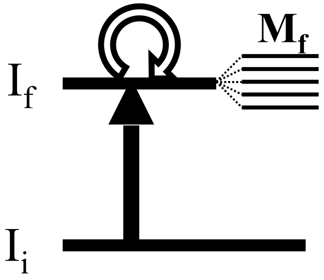
vibrational structure



Nucl.Phys.A786 (2007) 47



Coulomb excitation / Re-orientation Effect



two unknowns:
- ➢ B(E2; $0^+ \rightarrow 2^+$)
- ➢ $Q_s(2^+)$ **= 0 !**

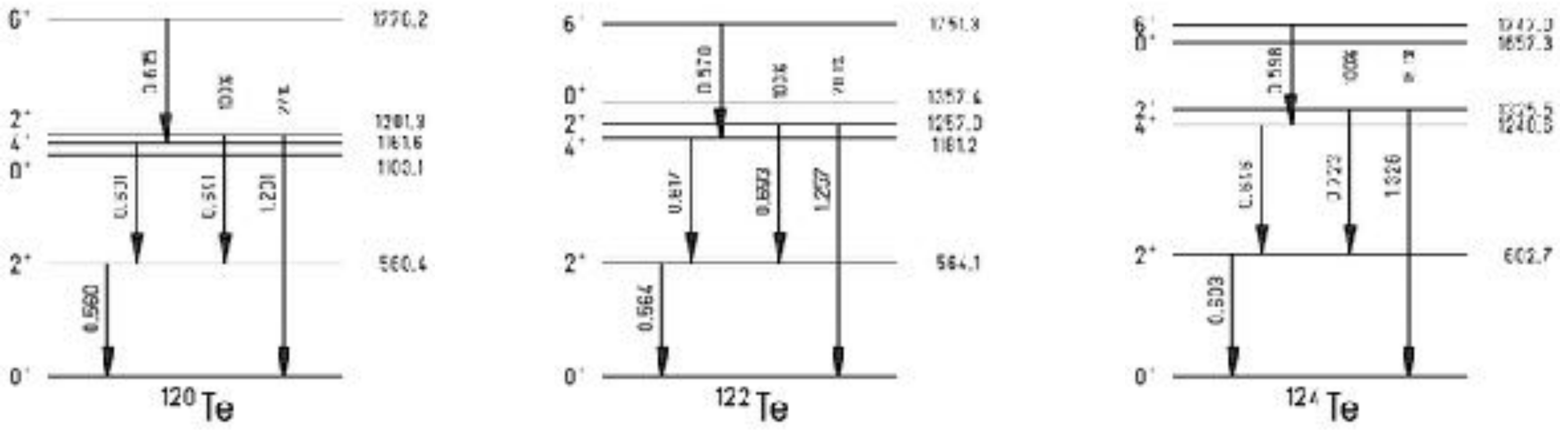
Isotope	**Q_{2+}(eb)**
^{120}Te	
^{122}Te	**-0.47±0.03**
^{124}Te	**-0.45±0.04**
^{126}Te	**-0.23±0.04**
^{128}Te	**-0.22±0.03**
^{130}Te	**-0.12±0.04**

large **quadrupole moments** compared to rotor with γ=0⁰

$$B\left(E2;0^+ \rightarrow 2^+\right) = \frac{5}{16\pi} Q_0^2$$

$$Q_{2^+} = -\frac{2}{7} \cdot Q_0$$

Motivation !!!!



- To study the nuclear structure of ^{120,122,124}Te nuclei

- To measure the B(E2; $0^+ \rightarrow 2^+$) value for ^{120}Te to a much higher precision !

- To measure the reduced transition probabilities of higher lying states !

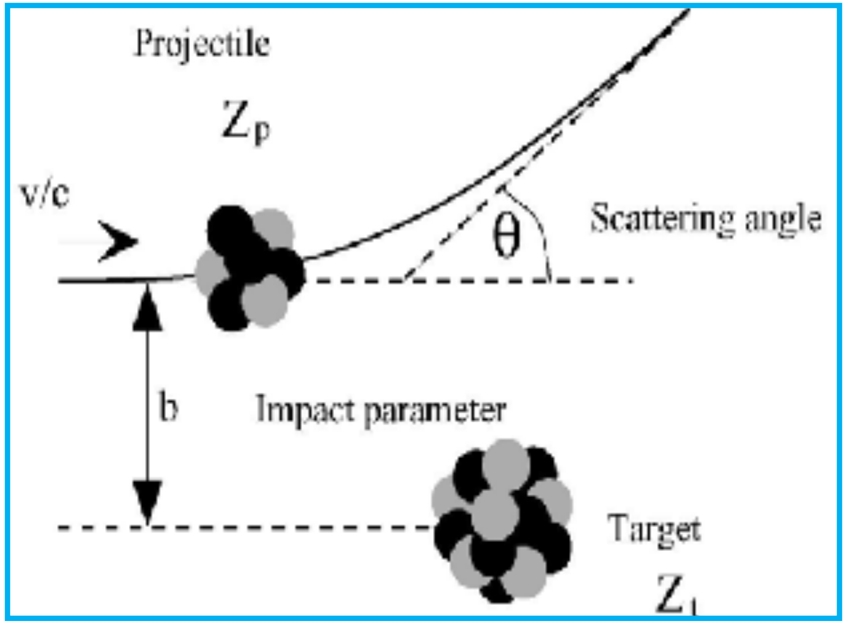
Why Coulomb Excitation ???

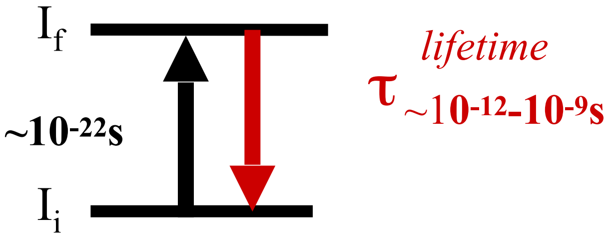
Coulomb Excitation – the most powerful and direct experimental method to study nuclear collectivity and shapes.

Nuclei excited by electromagnetic interaction only, no nuclear interaction
Distance of closest approach > $r_p + r_T$

"<u>safe energy</u>" criterion:
purely electromagnetic interaction if the distance between nuclear surfaces is greater than 5 fm ;

$$d > 1.25 \cdot (A^{1/3}_p + A^{1/3}_t) + 5.0\ [\mathrm{fm}]$$





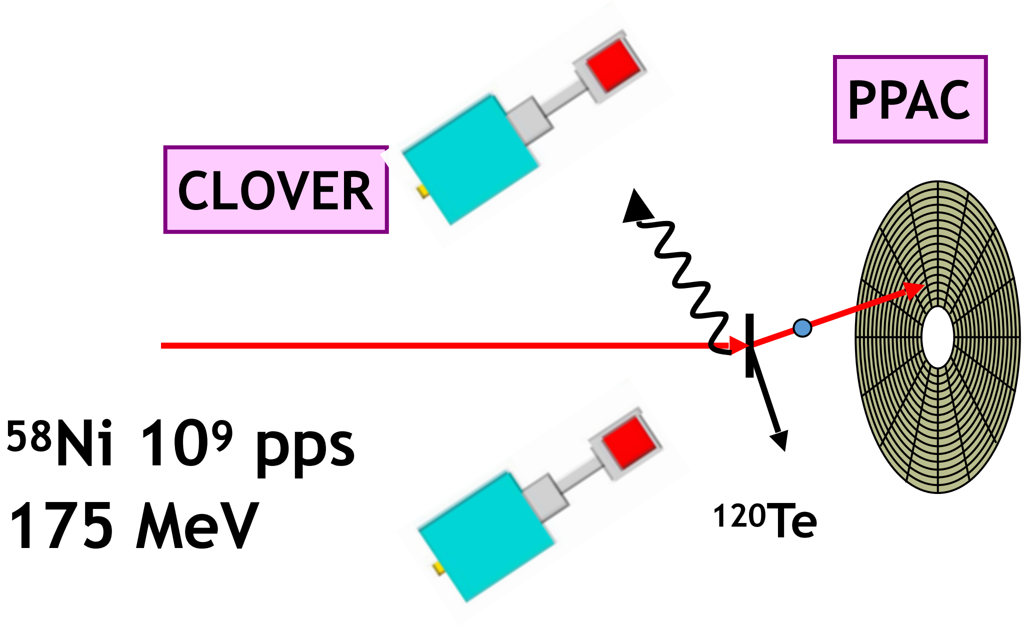
1st order: $a^{(1)}_{i\to f} \propto \langle I_f \| \mathbf{M}(E2) \| I_i \rangle$

Sommerfeld parameter
strength of the Coulomb interaction

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v} >> 1$$

^{58}Ni(175 MeV) on ^{120}Te η~117

Experimental Set up @ IUAC, New Delhi

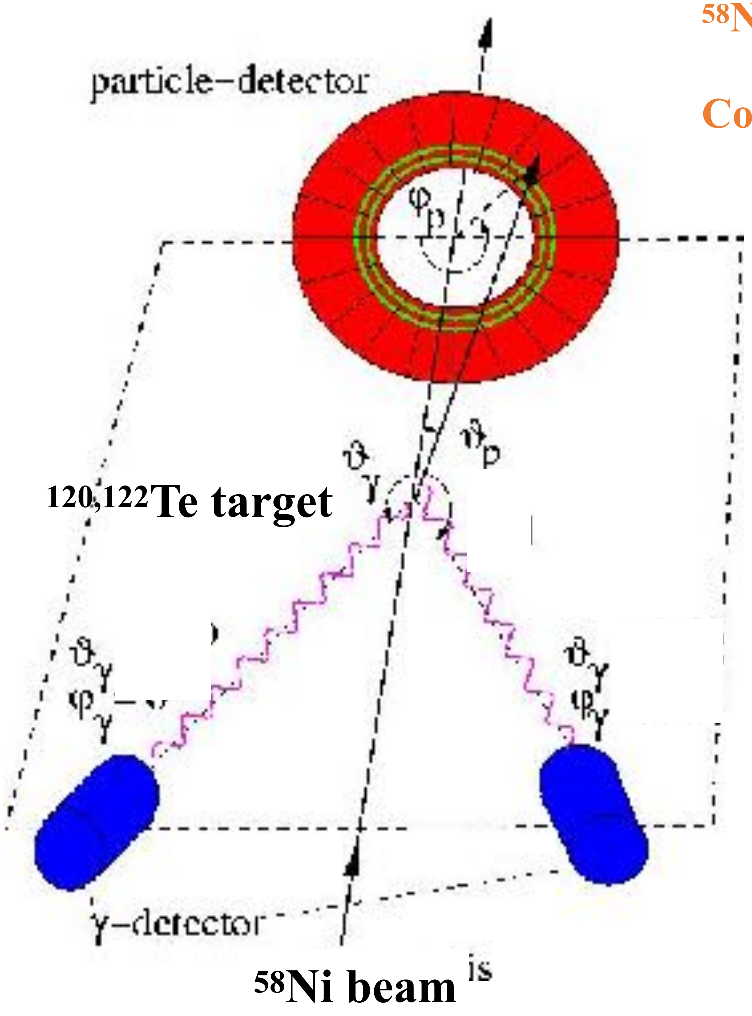


^{58}Ni → ^{120,122,124}Te (~ 0.15 mg/cm^2 thickness) @ 175MeV

Coulomb barrier ~ 240 MeV (lab frame)

IUAC, New Delhi

Experimental Set up @ IUAC, New Delhi



^{58}Ni → ^{120,122,124}Te (~ 0.15 mg/cm^2 thickness) @ 175MeV

Coulomb barrier ~ 240 MeV (lab frame)

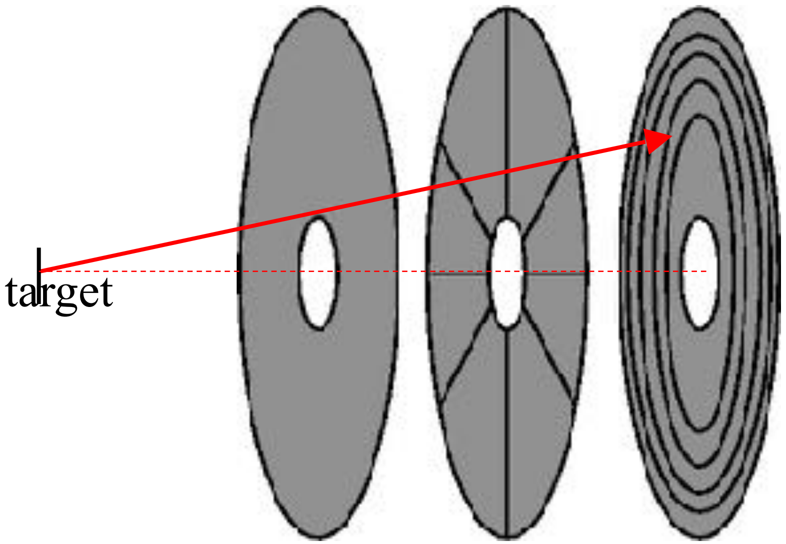
- Scattered projectiles and recoils are detected in an annular gas-filled parallel-plate avalanche counter (PPAC), subtending the angular range ϑ_{lab} = 15° - 45°

  in the forward direction.

  20 azimuthal segments with $\Delta\Phi=18^0$.

- De-excitation γ -rays are detected in four clover detectors mounted at $\vartheta_\gamma \sim 135^\circ$ with respect to the beam direction.
- Data was collected in particle – γ coincidence AND.

Particle Detector - PPAC

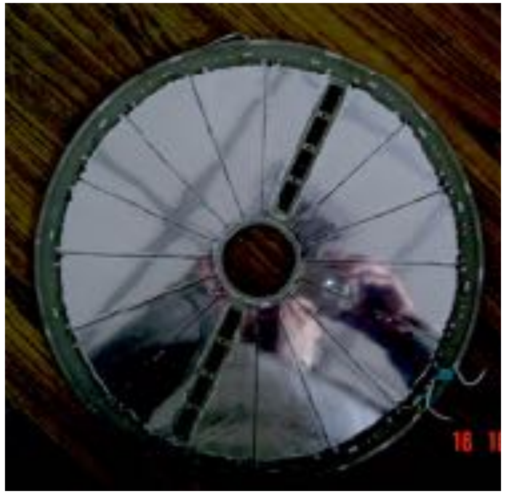


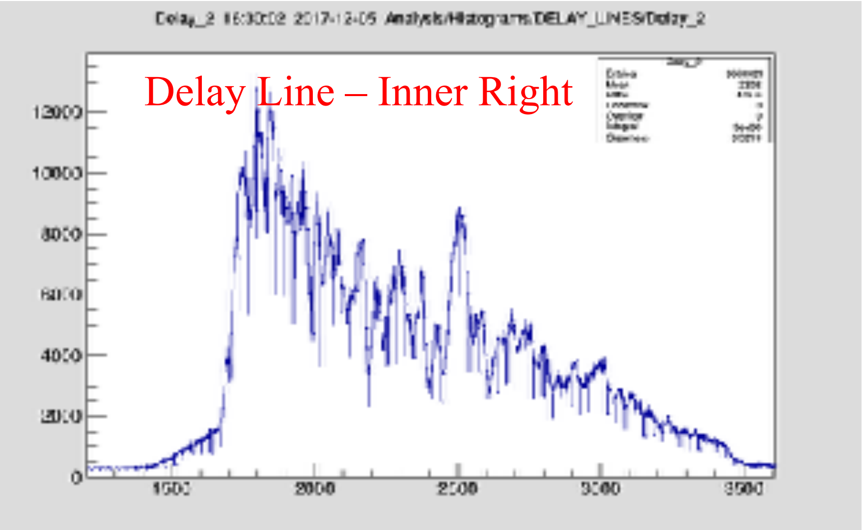
$V_0 \sim -500$ V

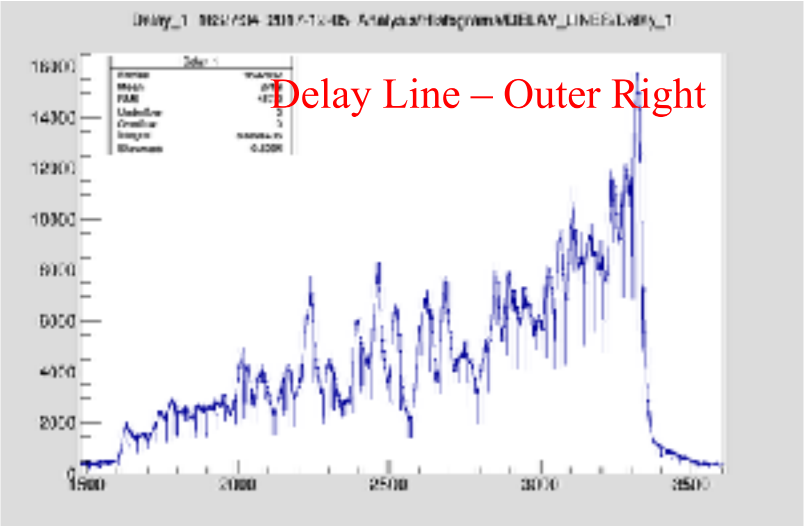
$p = 5\text{-}10$ mbar

entrance window $\sim \varphi_{lab}$ $\sim \tan\vartheta_{lab} \approx$ delay inner – delay outer

Front → ϕ-information



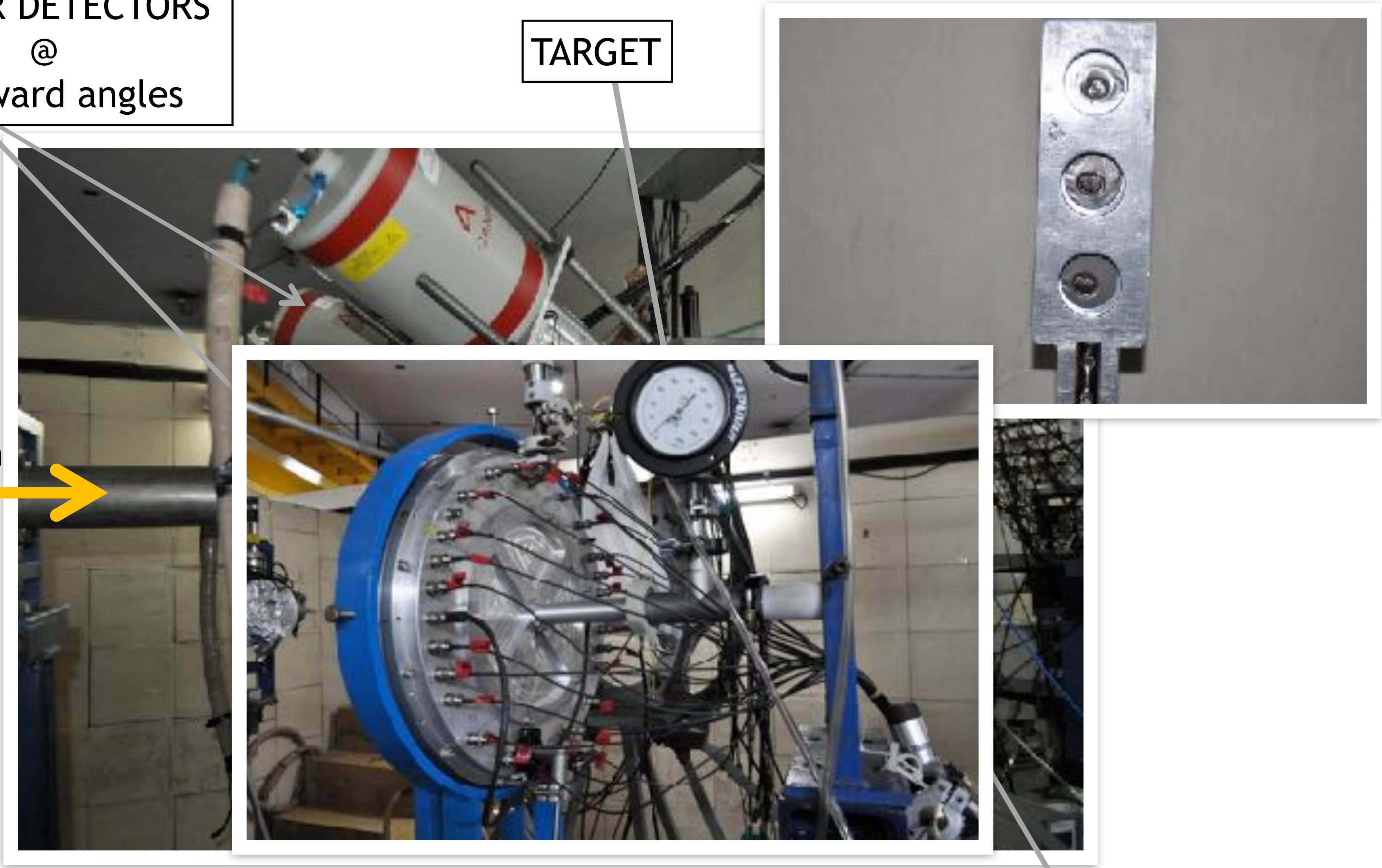




Back→ θ-information

A. Jhingan, Proc of DAE-BRNS Symp on Nucl Physics 61 (

Experimental Set up



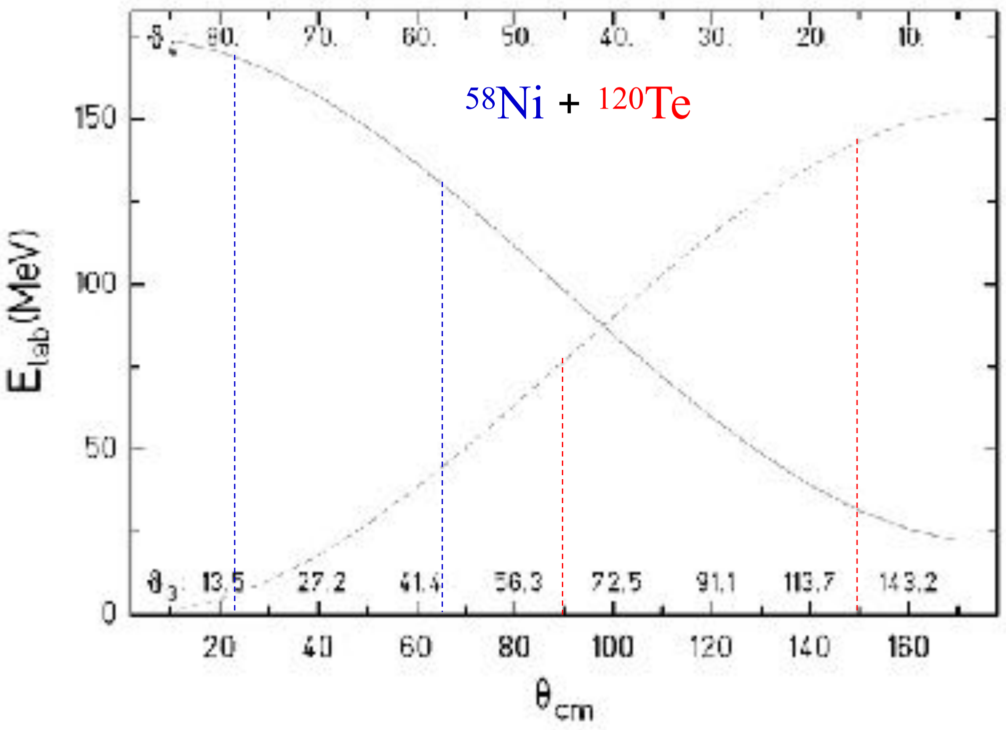
CLOVER DETECTORS
@
backward angles

TARGET

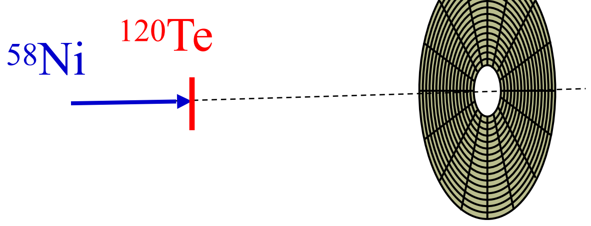
Beam Direction

PPAC @ forward angle

Analysis & Results of ^{58}Ni + ^{120}Te Experiment

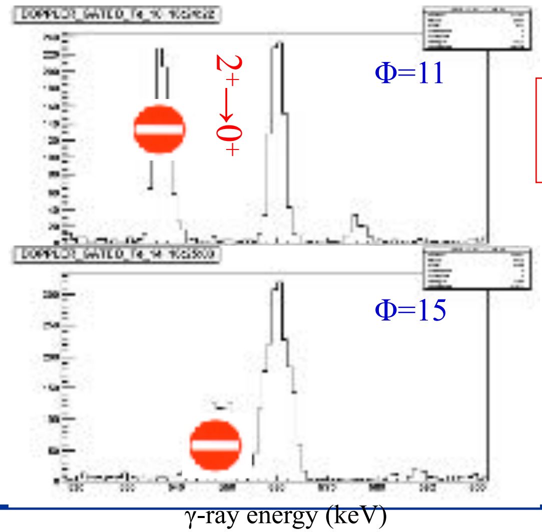


Φ segmentation

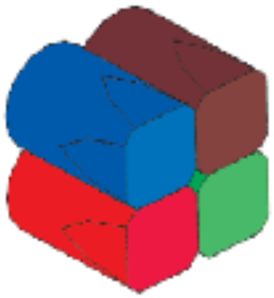


projectile and target nucleus are measured in PPAC

^{58}Ni in PPAC: distant collisions



2 γ-rays for same decay



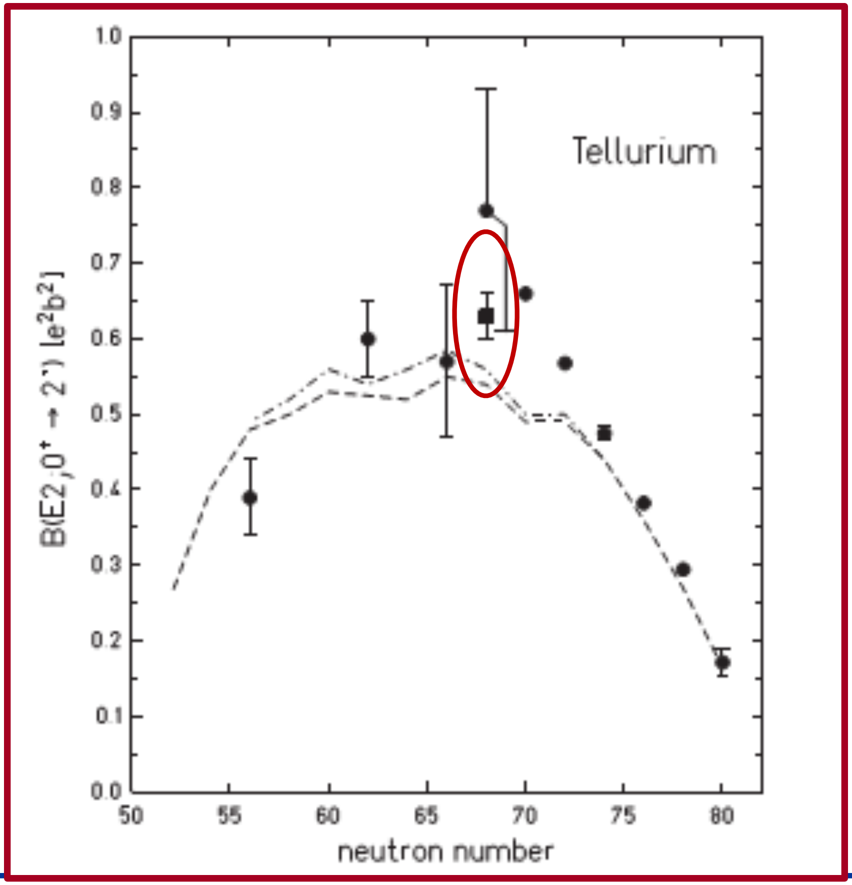
clover Ge-detector

Results: ^{58}Ni + ^{120}Te Experiment

DOUBLE RATIO : $$B\left(E2,\ ^{120}Te\right) = B\left(E2,\ ^{122}Te\right)\frac{\sigma_{^{122}Te}}{\sigma_{^{120}Te}}\left\{\frac{I_\gamma\left(^{120}Te\right)}{I_\gamma\left(^{58}Ni\right)}\right\}\left\{\frac{I_\gamma\left(^{58}Ni\right)}{I_\gamma\left(^{122}Te\right)}\right\}$$

^{120}Te + ^{58}Ni : ⟶ $$\left\langle 2^+ \left\| M(E2) \right\| 0^+ \right\rangle = 0.816(5)$$

$$B(E2; 0^+ \rightarrow 2^+) = 0.666(20)e^2b^2$$



Comparison with LSSM calculations

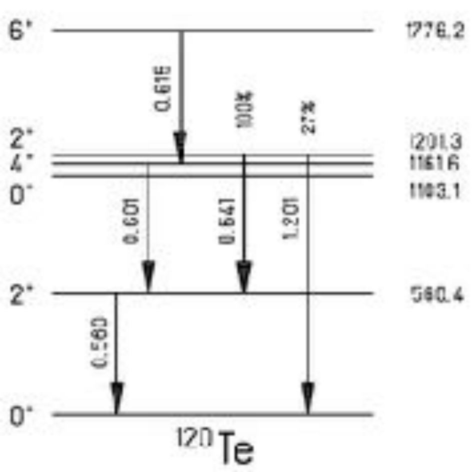
✓ Effective charge used were $e_\nu = 0.8e$, $e_\pi = 1.5e$

✓ SM calculation bottom dashed line with $d_{5/2}$ $g_{7/2}$ inverted

✓ Model space ($g_{7/2}$, $d_{5/2}$, $d_{3/2}$, s, $h_{11/2}$ was used. The model space was limited for midshell nuclei ,allowing excitation of four neutrons in the $h_{11/2}$ sub shell

Phys.Rev.C 84 (2011)041306

Experimental Results of ^{120,122,124}Te



PHYSICAL REVIEW C 90, 024316 (2014)

Rotational behavior of ^{120,122,124}Te

M. Saxena,[1] R. Kumar,[2] A. Jhingan,[2] S. Mandal,[1] A. Stolarz,[3] A. Banerjee,[1] R. K. Bhowmik,[2] S. Dutt,[4]
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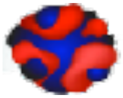
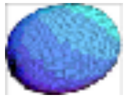
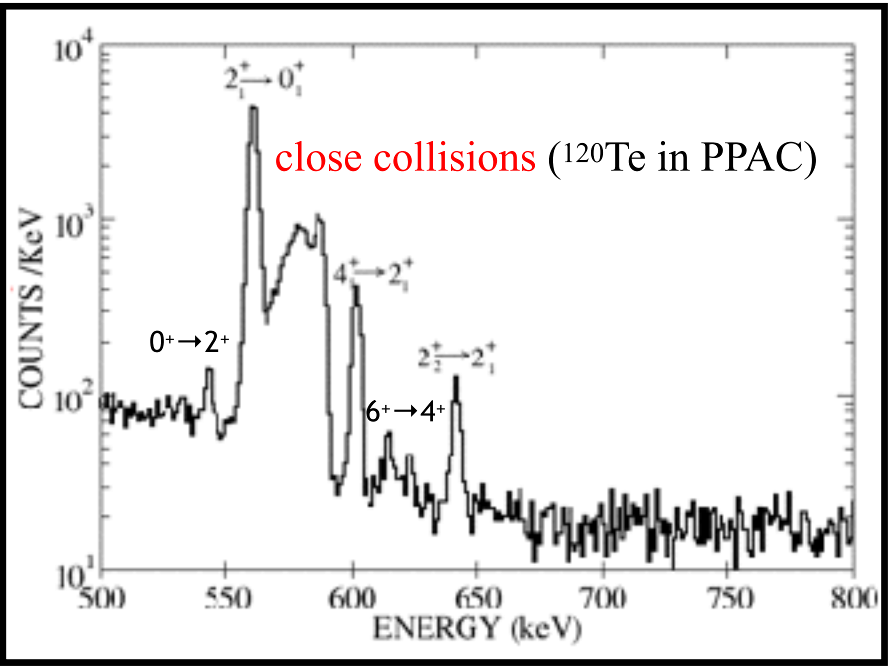


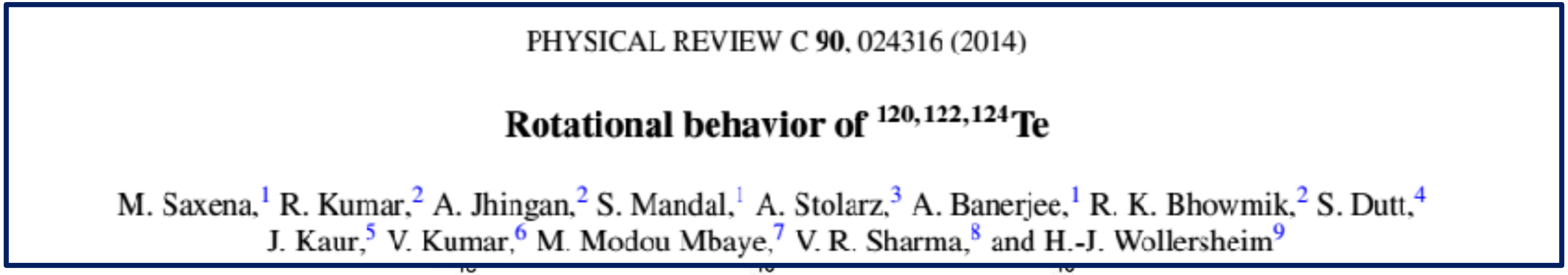




close collisions (^{120}Te in PPAC)

	Experiment	Vibrator	Asymmetric Rotor (γ = 27.5)	IBA-2
$\frac{B(E2;4^+ \to 2^+)}{B(E2;2^+ \to 0^+)}$	1.640(33)	2.0	1.426	1.514
$\frac{B(E2;6^+ \to 4^+)}{B(E2;2^+ \to 0^+)}$	2.37(58)	3.0	1.781	1.82
$\frac{B(E2;2^+_2 \to 2^+)}{B(E2;2^+ \to 0^+)}$	1.215(50)	2.0	0.906	1.560
$\frac{B(E2;2^+_2 \to 2^+)}{B(E2;2^+_2 \to 0^+)}$	82.9(47)		20.42	105

Conclusions of the Experiment



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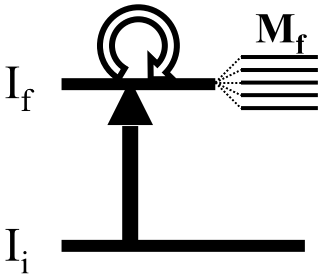
- ❑ B(E2; $0^+ \rightarrow 2^+$) well described by the shell model
    - quadrupole deformation β= 0.18

- ❑ Experimental excitation energies and transition probabilities can be described by triaxial rotor model.

- ❑ IBM - 2 calculations were also performed and ^{120,122,124}Te were found close to the O(6) limit of IBM-2.

Current Coulex Campaign at HIL, Warsaw

Study of static quadrupole moments in ^{120}Te



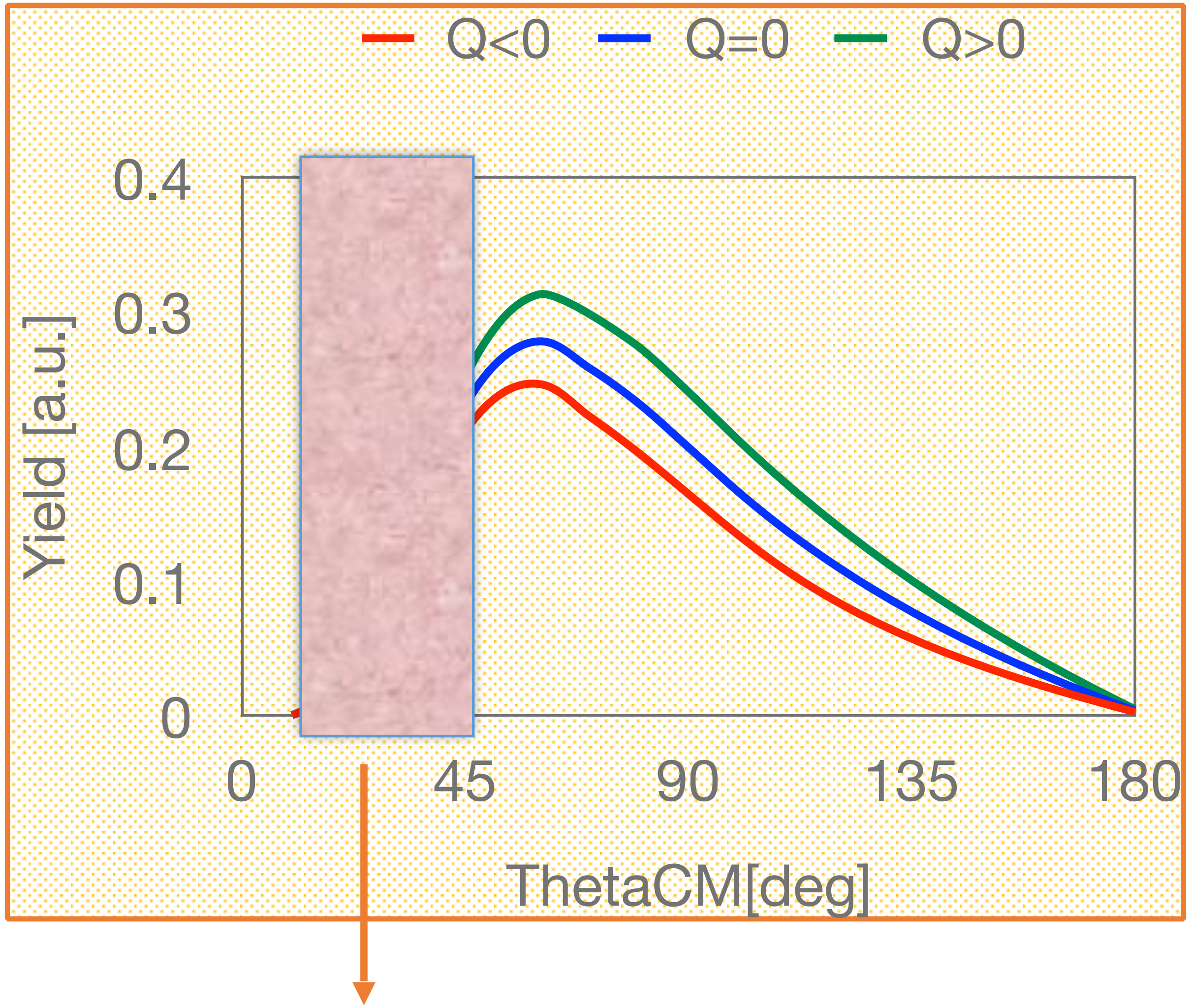
- ➢ In the recent COULEX experiment at IUAC, We had estimated the BE2 value for ^{120}Te to a high precision.
- ➢ For ^{120}Te the quadrupole moments (Q_{2+}) are not known experimentally.
- ➢ Quadrupole moments (Q_{2+}) for ^{120}Te will further give us information about the deformation in this nuclei.

Sensitivity of $Q(2^+)$

- Excitation probability depends on:
  - projectile scattering angle interaction strength,
  - sign of quadruple moment
- Gamma yields are experimental observable

$$P^{(2)}_{0\to 2}(\theta,\xi) = P^{(1)}_{0\to 2}\,(\theta,\xi)\cdot\left[1+\sqrt{\frac{7}{2\pi}\frac{5}{4}}\cdot\frac{A_p}{Z_p}\cdot\frac{\Delta E}{1+{}^{A_p}/_{A_t}}\cdot Q_2\cdot K(\theta,\xi)\right]$$

$$Q(2^+) = -\sqrt{\frac{2\pi}{7}\frac{4}{5}}\cdot\langle 2\|M(E2)\|2\rangle$$



I.U.A.C, Delhi

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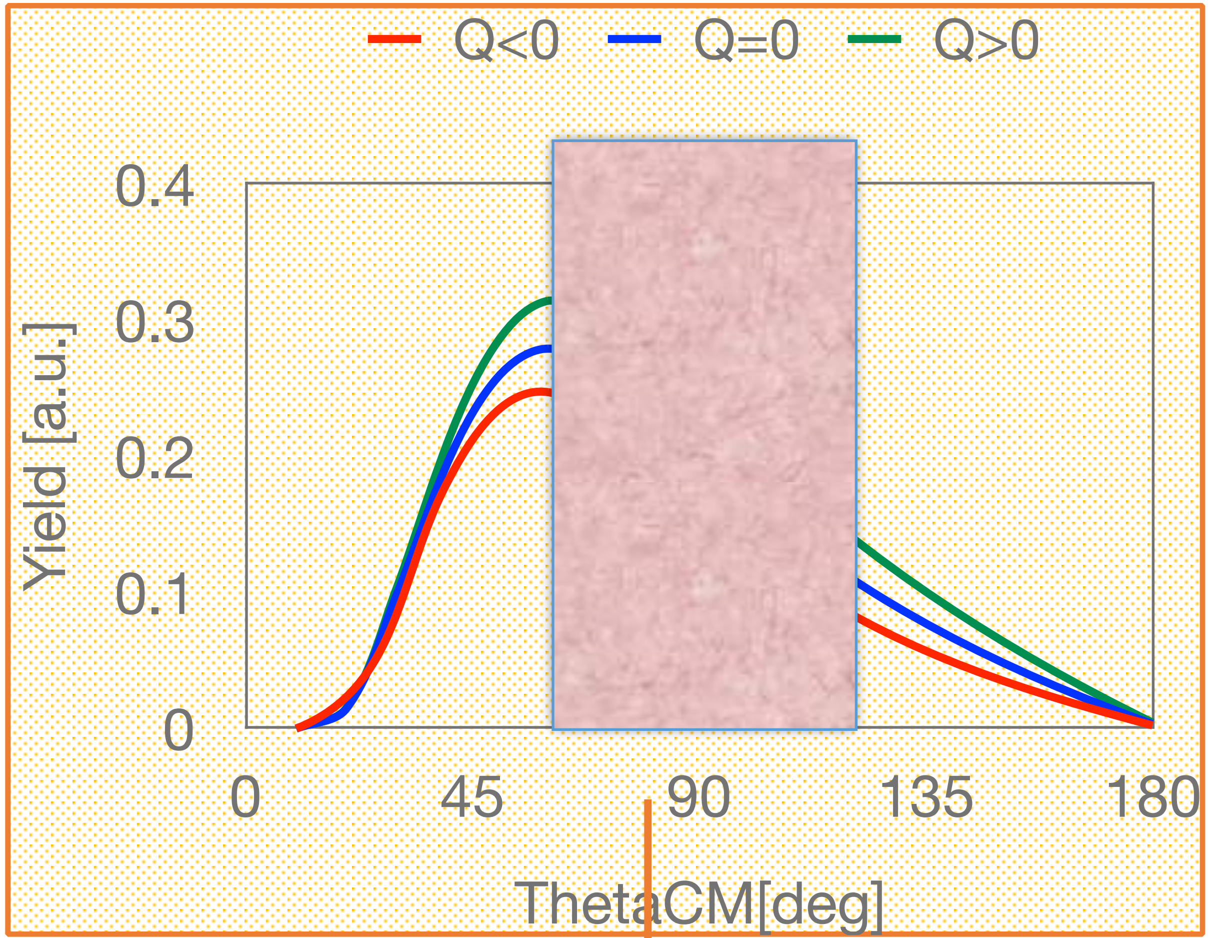


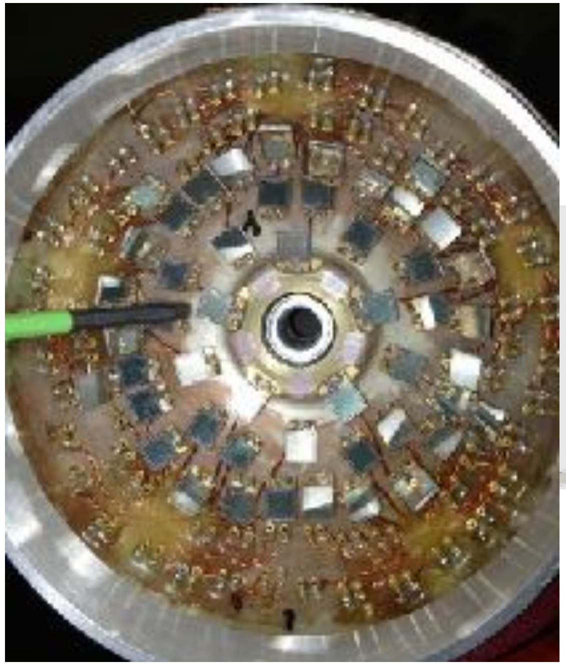
Complementary measurements at Delhi & Warsaw !!

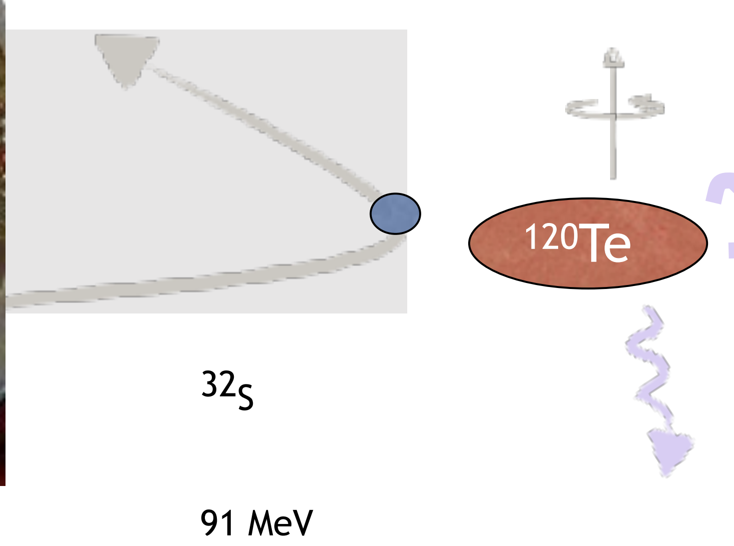
HIL, WARSAW

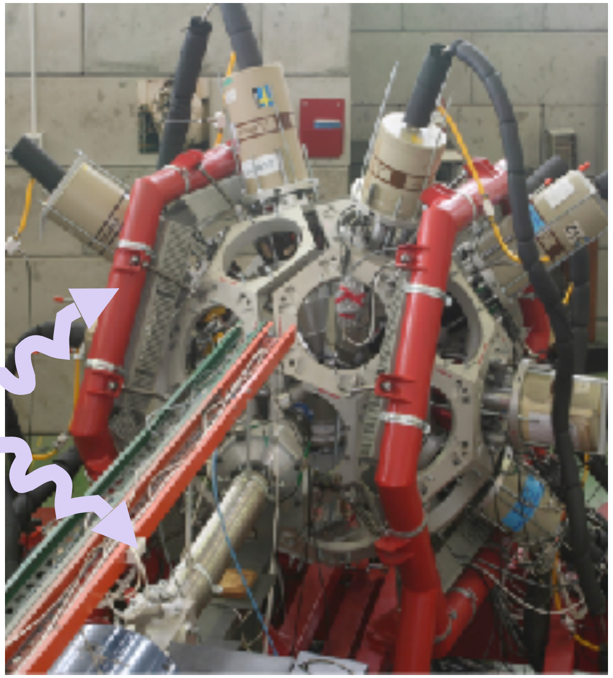
Experimental Set Up at HIL, Warsaw

$^{32}S \rightarrow {}^{120}Te$ (~ 0.15 mg/cm² thickness) @ 91 MeV

Coulomb barrier ~ 125 MeV (lab frame)







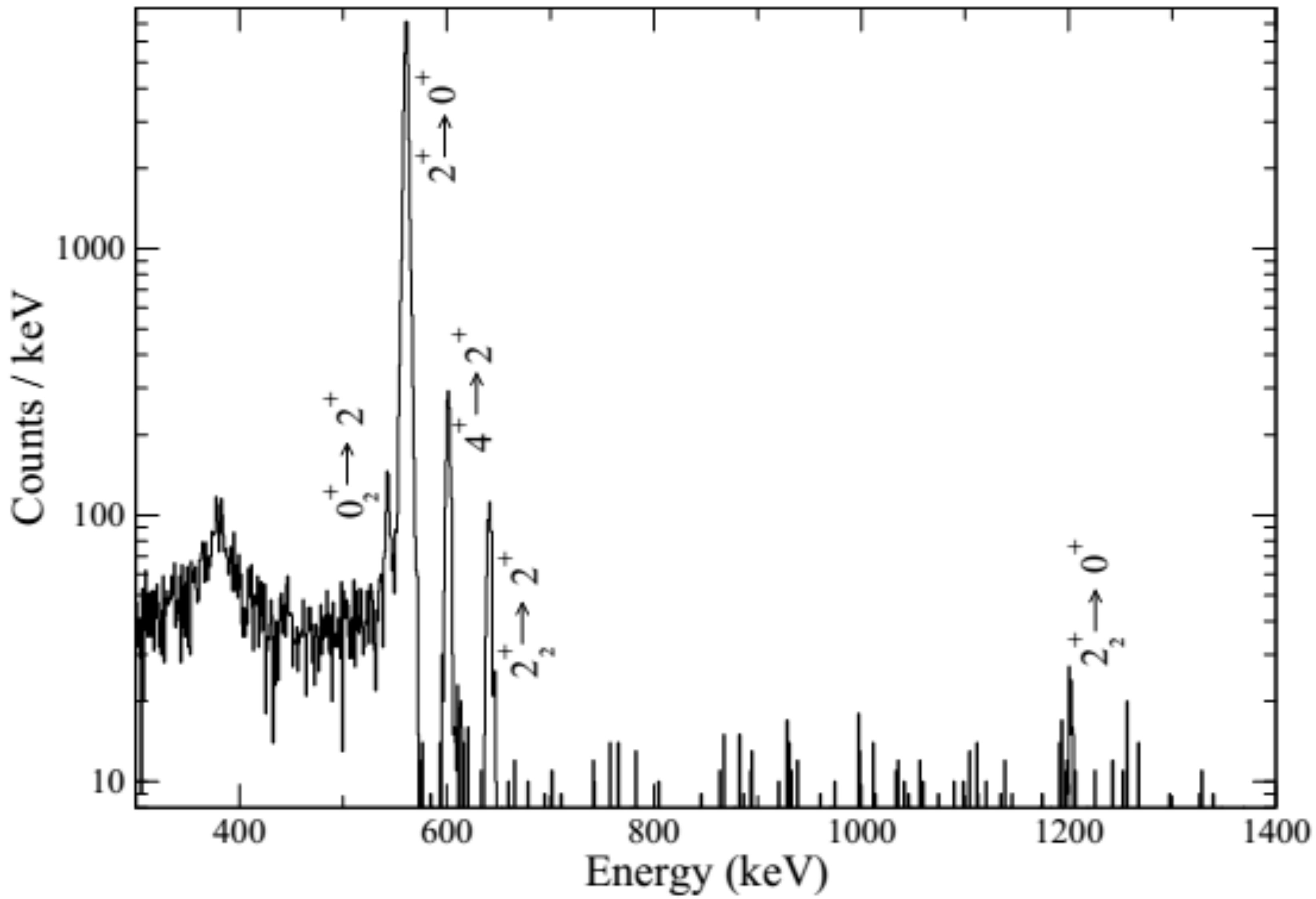
48 PiN-Diode HI Detectors

θ_{LAB}: 100÷170 deg

15 HPGe & ACS

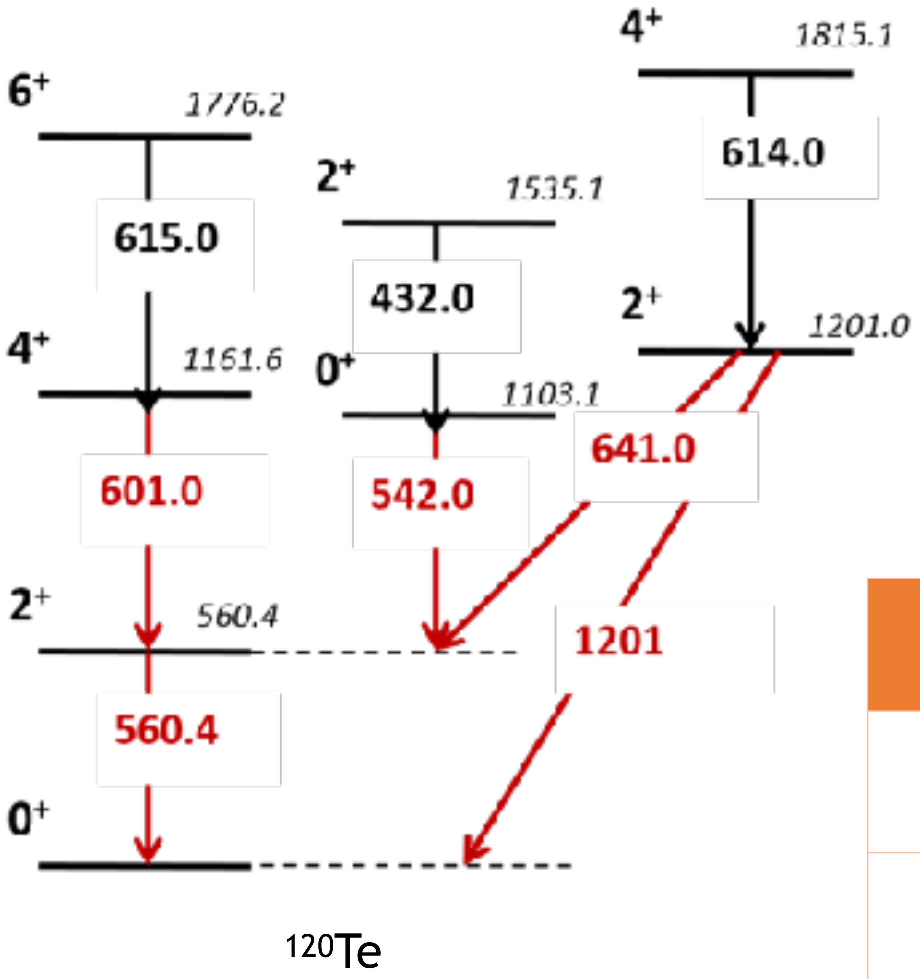
Efficiency@1.3MeV: 0.5%

Doppler Corrected γ-ray Spectrum



Experimental Results

GOSIA – Coulomb Excitation least squares search code



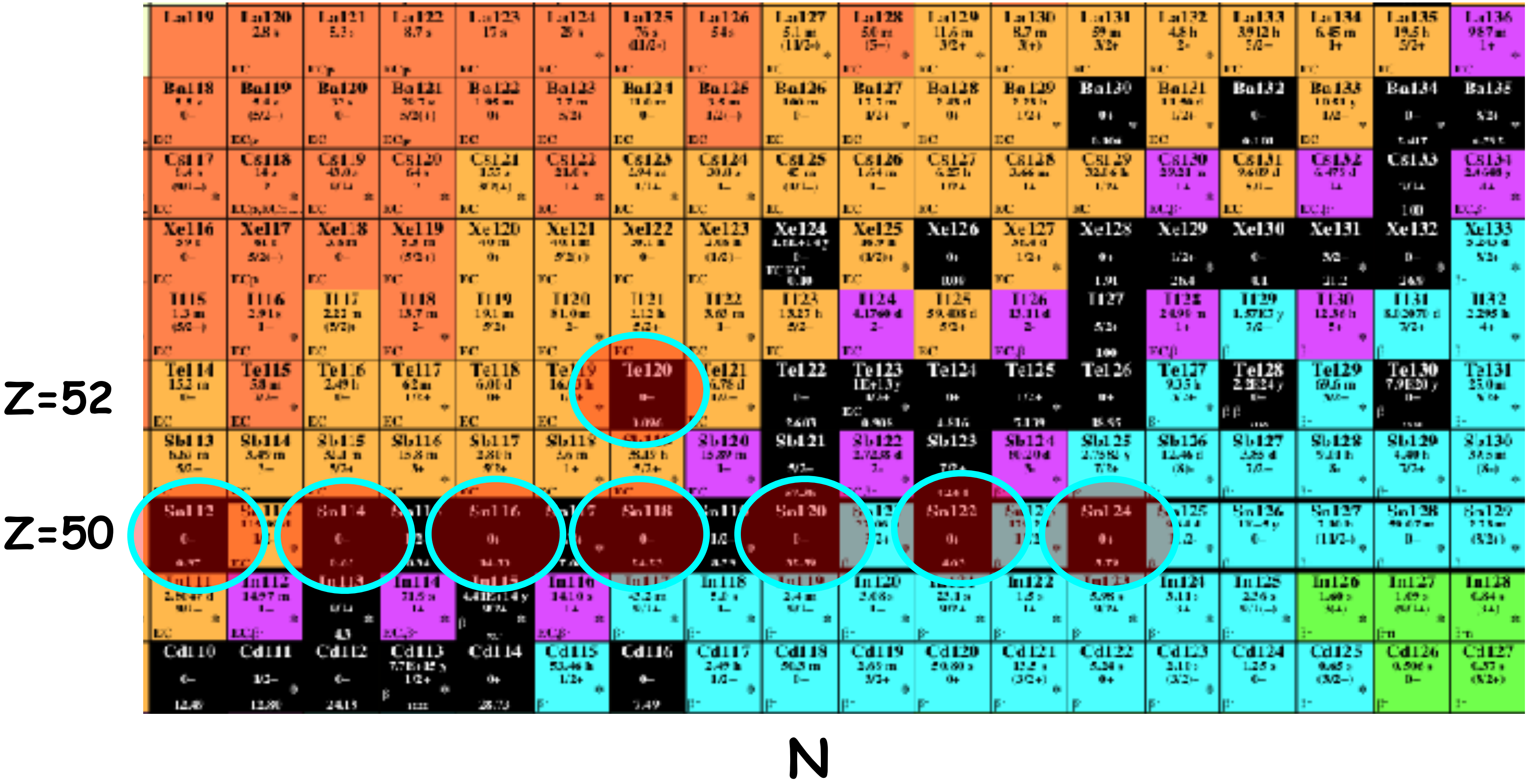
Transition $I_i \rightarrow I_f$	$\vert\langle I_f \Vert E2 \Vert I_i \rangle\vert$ (Exp)	B(E2) ↓ (e^2b^2)
$2_1^+ \rightarrow 0_1^+$	0.778±0.014	0.121±0.004
$4^+ \rightarrow 2_1^+$	1.342±0.019	0.200±0.006
$2_2^+ \rightarrow 2_1^+$	0.955±0.020	0.183±0.009
$2_2^+ \rightarrow 0_1^+$	0.161±0.011	0.0052±0.0008

State (I)	$\langle I \Vert E2 \Vert I \rangle$ (Exp)	Qs (eb)
2_1^+	-0.55±0.04	-0.41±0.03
4_1^+	-1.02±0.25	-0.77±0.19

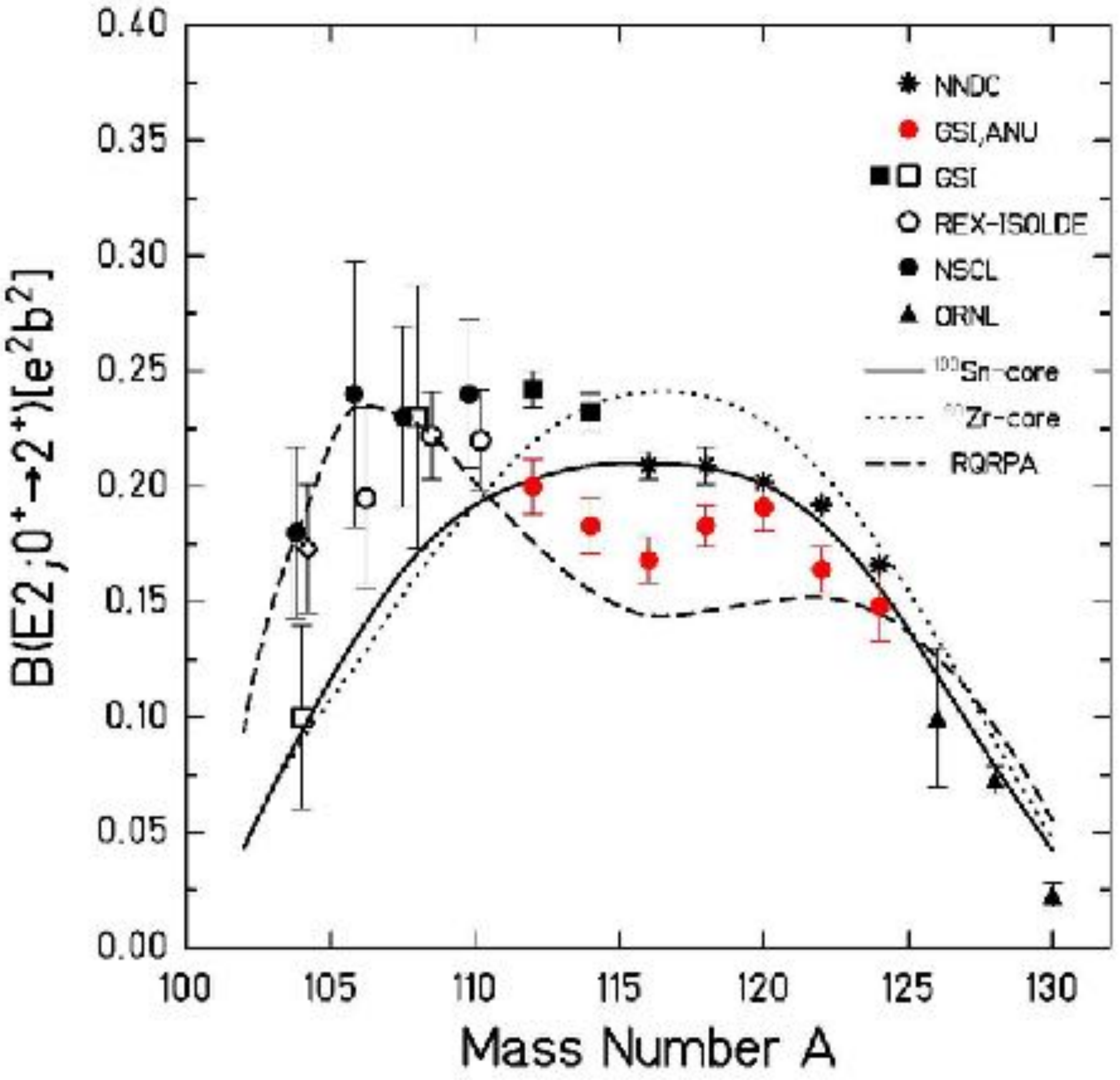
First Experimental hint at prolate like shape of ^{120}Te nucleus in the 2^+ state !!

- Acta Physica Polonica Submitted

Re-measurement of B(E2) for Stable Sn-



Evidence for reduced collectivity in Sn isotopes



A recent Doppler Shift attenuation (DSA) measurement yield, however low B(E2↑) values (up to 20%) than previously found in the literature .

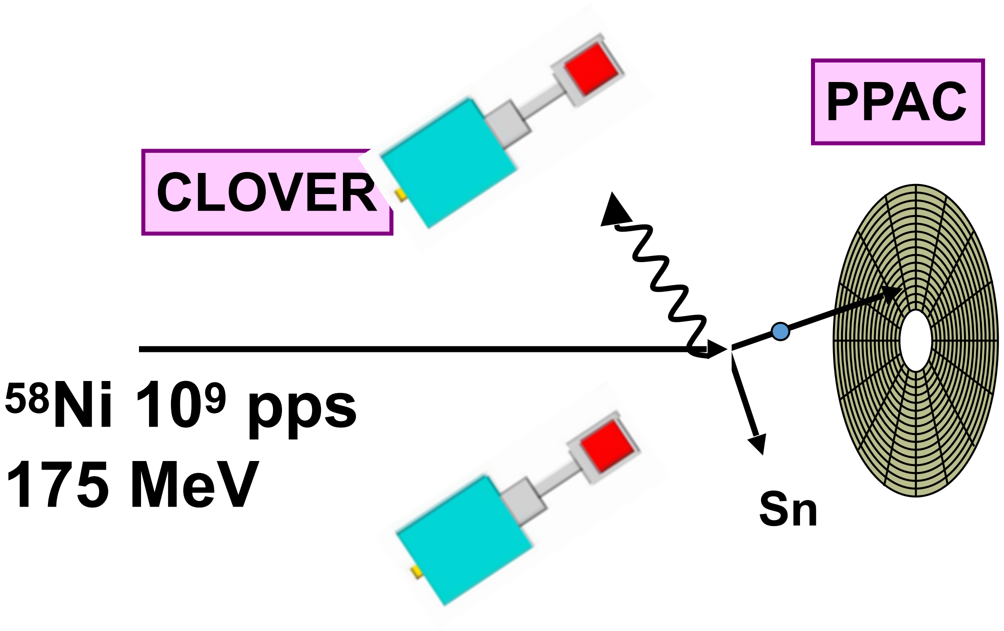
A.Jungclaus et al. Phys. Lett. B 110, 695 (2011)

To draw firm conclusions on the B(E2↑) pattern for Sn isotopes, Coulomb excitation of all stable isotopes using a relatively heavy beam (e.g. ^{58}Ni) was necessary.

Coulomb Excitation of $^{112-124}$Sn

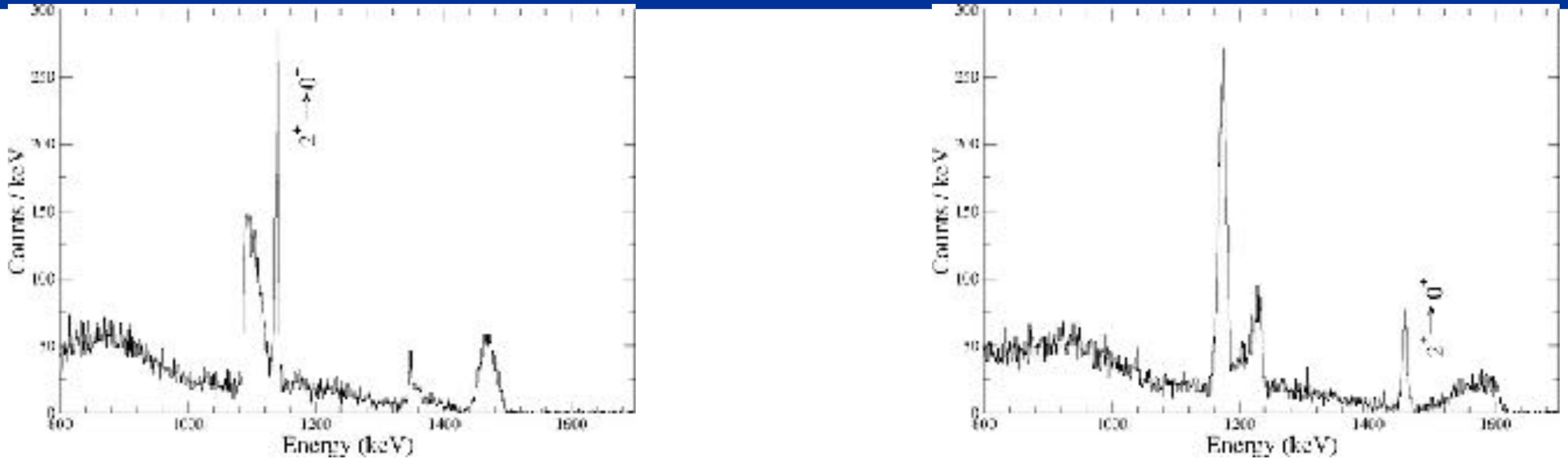
$^{58}\mathrm{Ni} \rightarrow {}^{112,116,118,120,122,124}\mathrm{Sn}$ at 175MeV

Experimental setup at IUAC



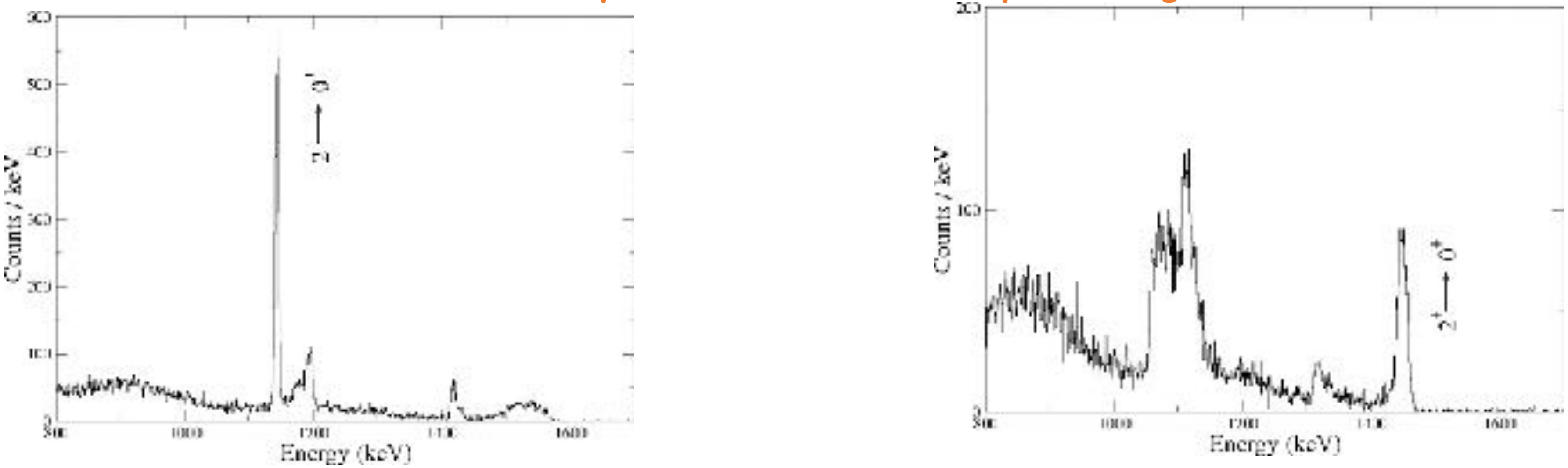
IUAC, New Delhi

Doppler shift corrected γ-spectra emitted from the ^{122}Sn target nuclei and the ^{58}Ni projectiles at 175 MeV



For distant collision (22.1° ≤ θ_{cm} ≤ 64.6°) ^{58}Ni detected in PPAC,

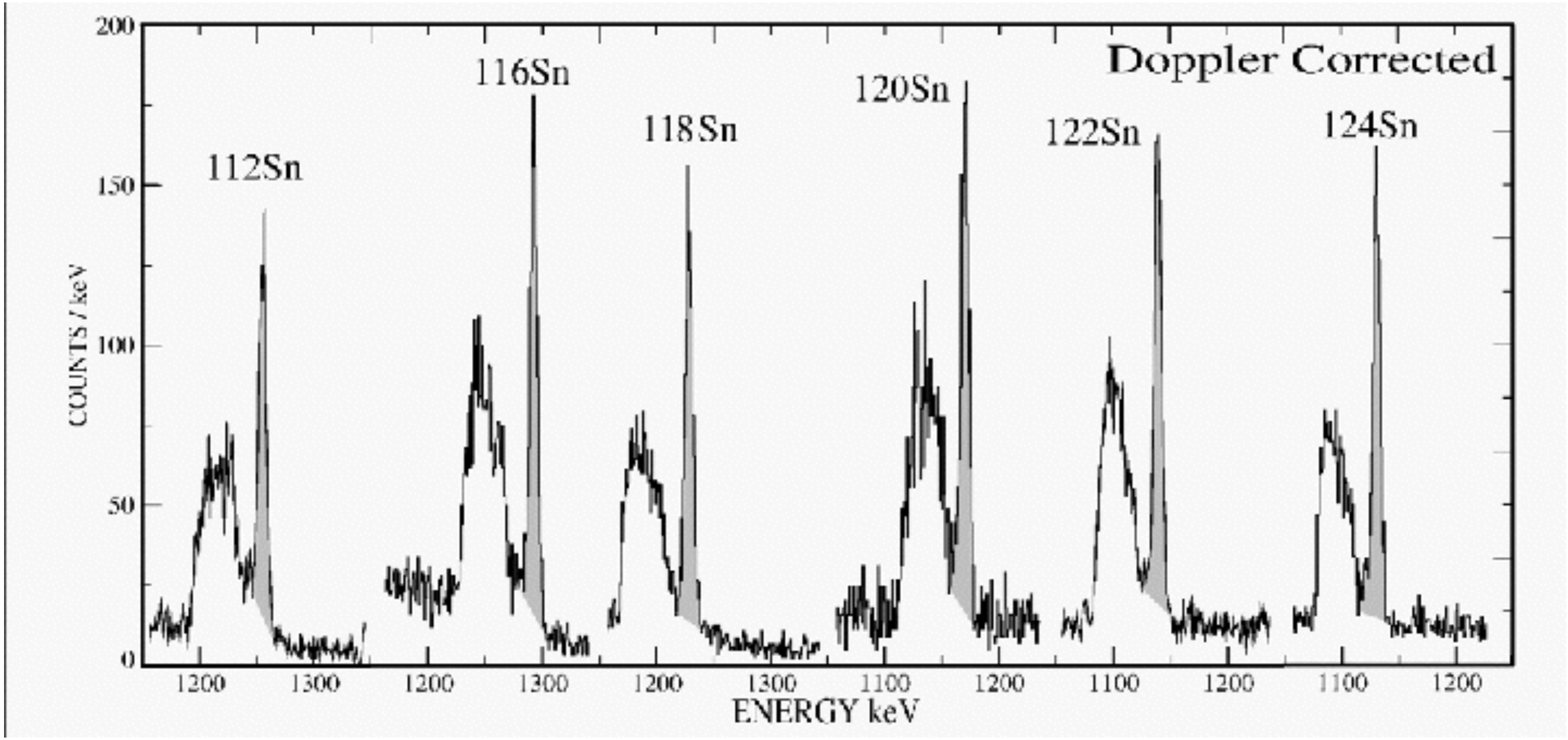
The corrected ^{122}Sn spectra left and ^{58}Ni spectra right



For close collision (90° ≤ θ_{cm} ≤ 150°) ^{122}Sn detected in PPAC,

The corrected ^{122}Sn spectra left and ^{58}Ni spectra right

Energy Spectra from Sn Targets



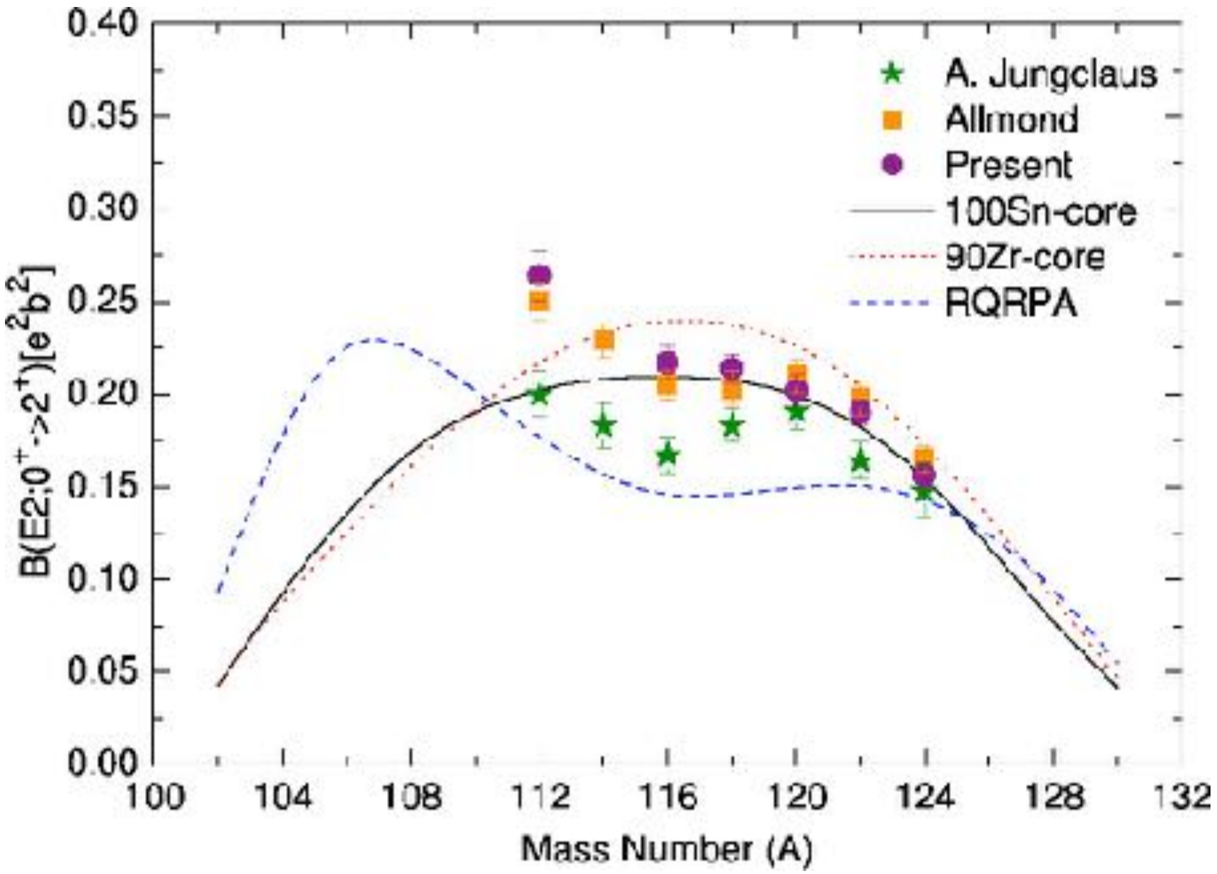
Data from one Ge detector only (out of 16)

PHYSICAL REVIEW C 96, 054318 (2017)

No evidence of reduced collectivity in Coulomb-excited Sn isotopes

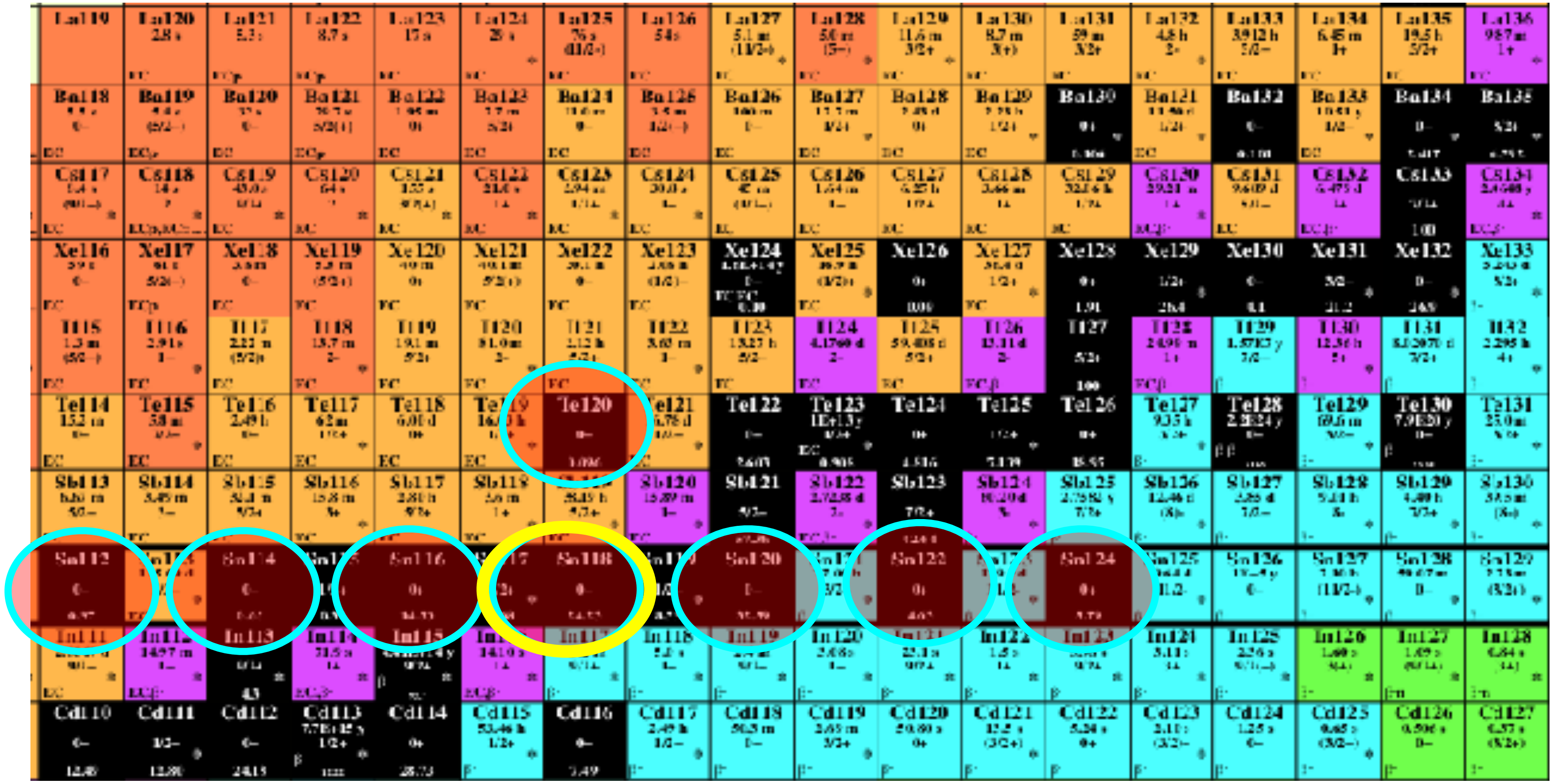
R. Kumar,[1] M. Saxena,[2] P. Doornenbal,[3] A. Jhingan,[1] A. Banerjee,[4] R. K. Bhowmik,[1] S. Dutt,[5] R. Garg,[1] C. Joshi,[6] V. Mishra,[7]
P. J. Napiorkowski,[2] S. Prajapati,[8] P.-A. Söderström,[3] N. Kumar,[4] and H.-J. Wollersheim[9]

A	B(E2;0⁺ →2⁺) Previous	B(E2;0⁺ →2⁺) A. Jungclaus	B(E2;0⁺ →2⁺) Present
112	0.242(8)	0.200(12)	0.242(8)
114	0.232(8)	0.183(12)	0.222(14)
116	0.209(6)	0.167(10)	0.200(7)
118	0.209(8)	0.183(9)	0.198(6)
120	0.202(4)	0.191(10)	0.188(7)
122	0.192(4)	0.164(10)	0.175(5)
124	0.166(4)	0.148(15)	0.144(4)



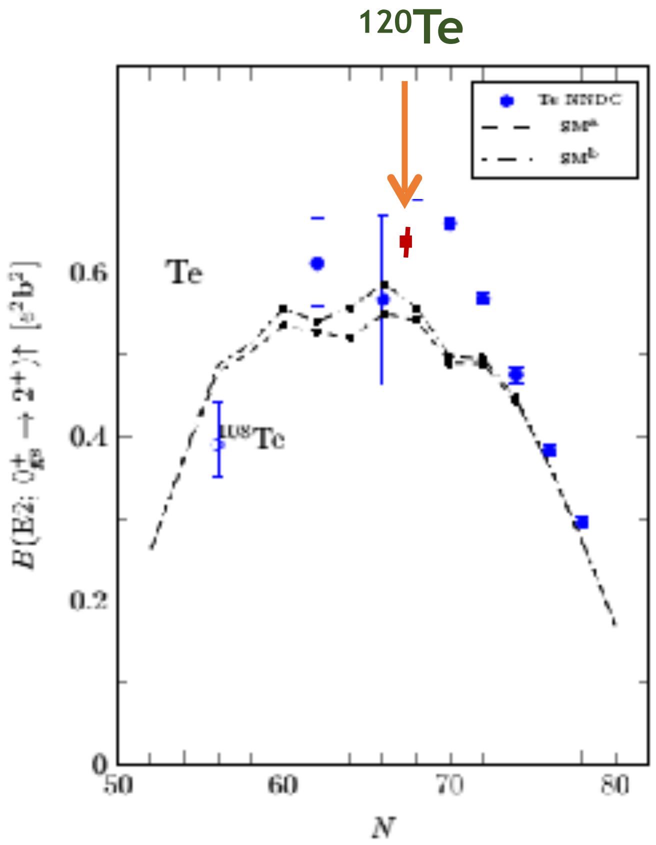
Coulomb Excitation of ^{118}Sn @ HIL, Warsaw

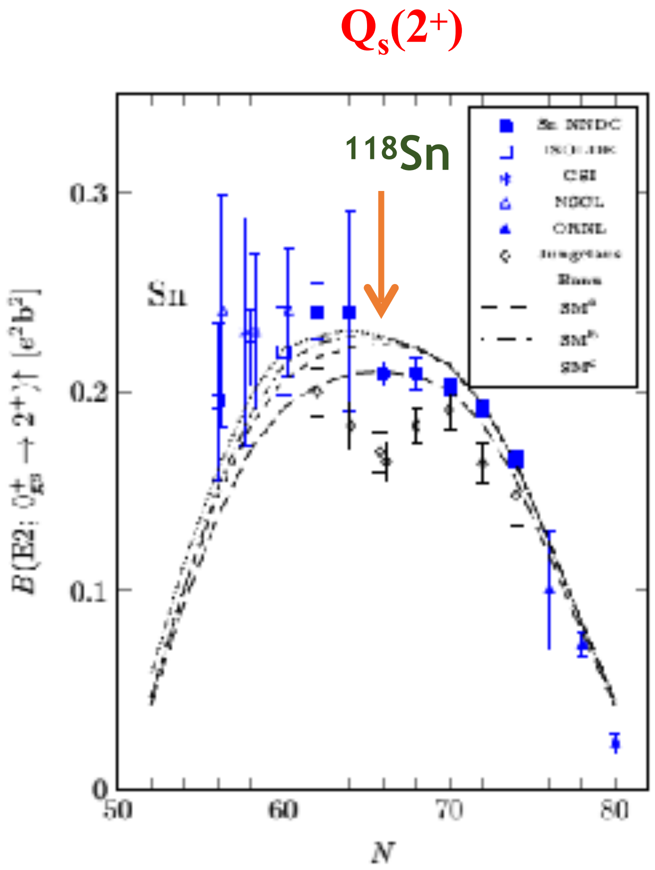
- $^{100}_{50}Sn_{50}$ is a doubly magic nucleus with spherical shape
- How does the nuclear deformation evolves by adding neutrons and protons?



La119	La120	La121	La122	La123	La124	La125	La126	La127	La128	La129	La130	La131	La132	La133	La134	La135	La136
Ba118	Ba119	Ba120	Ba121	Ba122	Ba123	Ba124	Ba125	Ba126	Ba127	Ba128	Ba129	Ba130	Ba131	Ba132	Ba133	Ba134	Ba135
Cs117	Cs118	Cs119	Cs120	Cs121	Cs122	Cs123	Cs124	Cs125	Cs126	Cs127	Cs128	Cs129	Cs130	Cs131	Cs132	Cs133	Cs134
Xe116	Xe117	Xe118	Xe119	Xe120	Xe121	Xe122	Xe123	Xe124	Xe125	Xe126	Xe127	Xe128	Xe129	Xe130	Xe131	Xe132	Xe133
I115	I116	I117	I118	I119	I120	I121	I122	I123	I124	I125	I126	I127	I128	I129	I130	I131	I132
Te114	Te115	Te116	Te117	Te118	Te119	Te120	Te121	Te122	Te123	Te124	Te125	Te126	Te127	Te128	Te129	Te130	Te131
Sb113	Sb114	Sb115	Sb116	Sb117	Sb118	Sb119	Sb120	Sb121	Sb122	Sb123	Sb124	Sb125	Sb126	Sb127	Sb128	Sb129	Sb130
Sn112	Sn113	Sn114	Sn115	Sn116	Sn117	Sn118	Sn119	Sn120	Sn121	Sn122	Sn123	Sn124	Sn125	Sn126	Sn127	Sn128	Sn129
In111	In112	In113	In114	In115	In116	In117	In118	In119	In120	In121	In122	In123	In124	In125	In126	In127	In128
Cd110	Cd111	Cd112	Cd113	Cd114	Cd115	Cd116	Cd117	Cd118	Cd119	Cd120	Cd121	Cd122	Cd123	Cd124	Cd125	Cd126	Cd127

Collectivity in semi magic Sn & Te isotopes





- ✓ B(E2)-values are a measure of the deformation and collectivity
- ✓ Large B(E2)-values mean more nucleons take part in the excitation

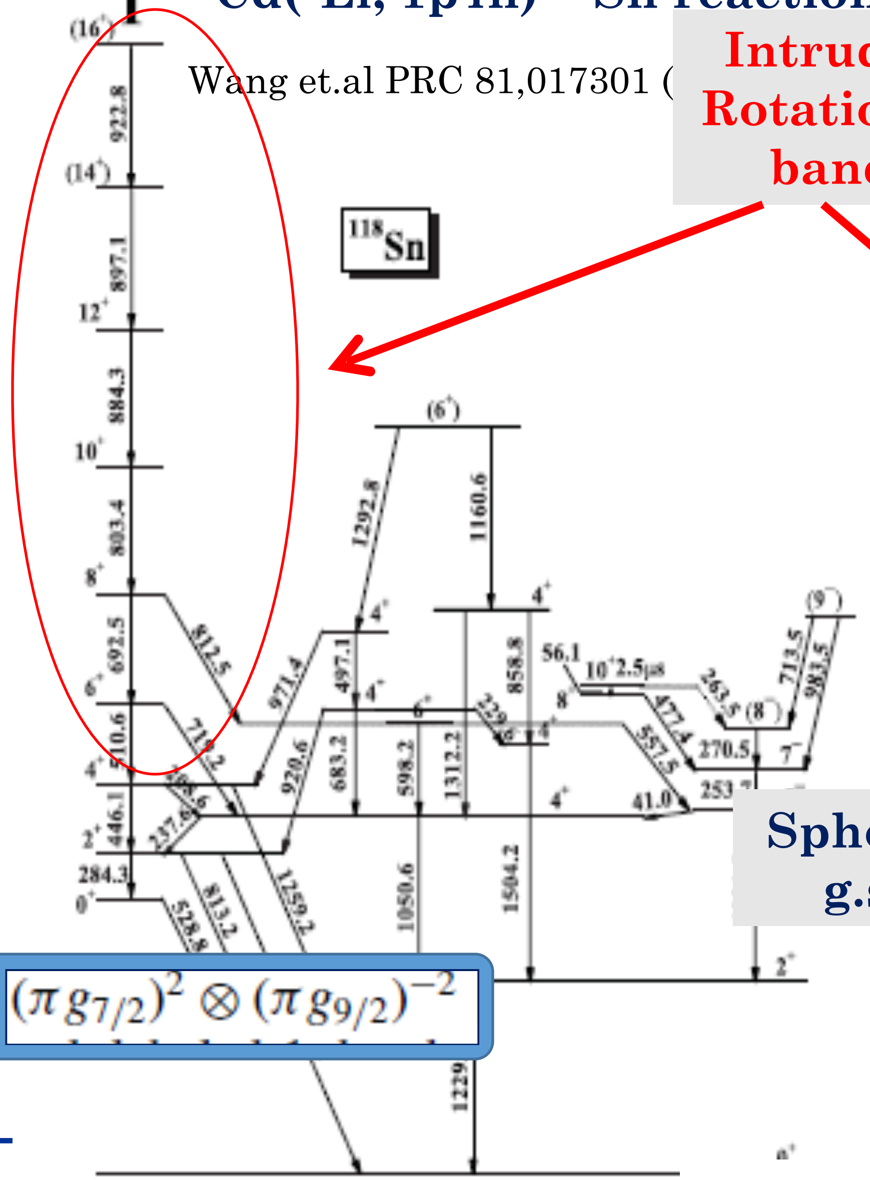
T. Back , Phys Scr. T150 014003(2012)

- ❖ Additional protons will shed light on the interplay between particle and collective degrees of freedom
- ❖ $^{118}_{50}Sn_{68} \leftrightarrow ^{120}_{52}Te_{68}$(isotone)

^{118}Sn - Shape Co-existence

^{116}Cd(^{7}Li, 1p4n)^{118}Sn reaction

Wang et.al PRC 81,017301 (

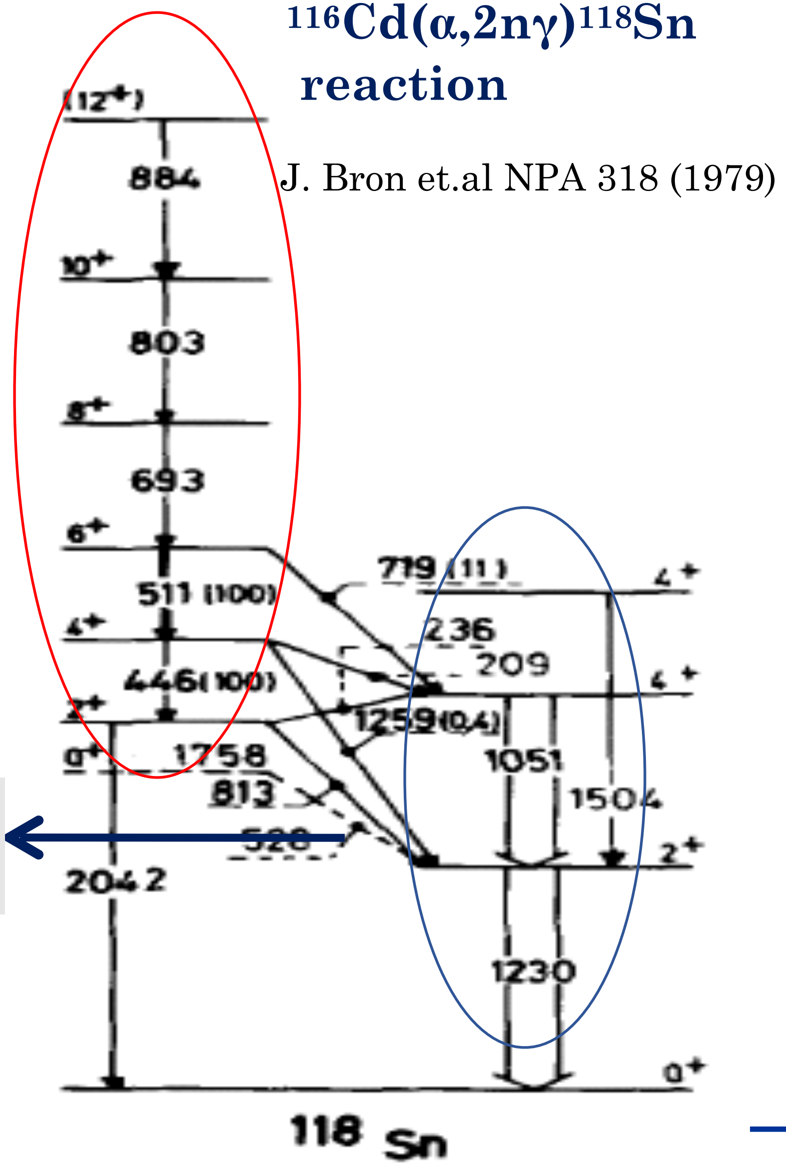


Intruder Rotational band

$(\pi g_{7/2})^2 \otimes (\pi g_{9/2})^{-2}$

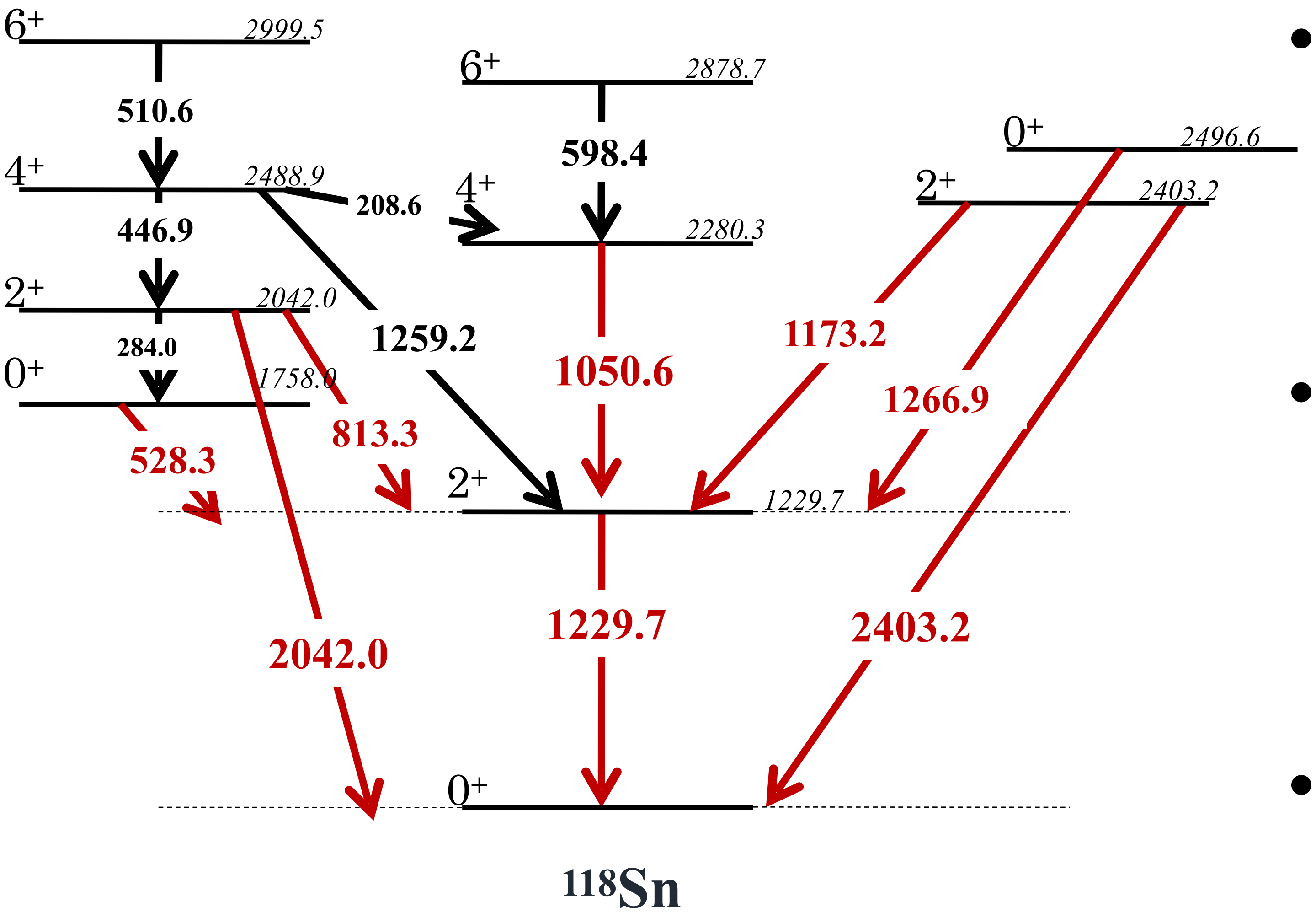
^{116}Cd(α,2nγ)^{118}Sn reaction

J. Bron et.al NPA 318 (1979)



Spherical g.s.b.

Coulomb Excitation of ^{118}Sn



γ-rays expected to be observed in the proposed Coulex of ^{118}Sn .

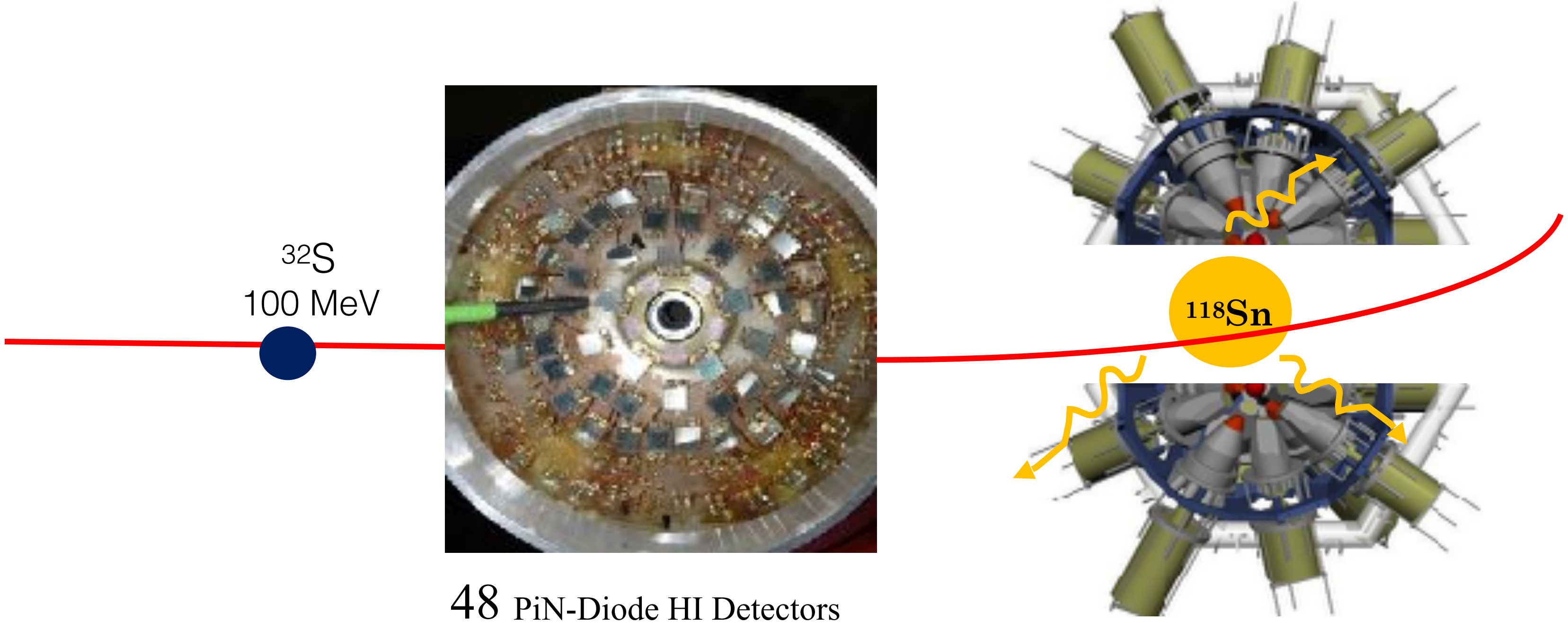
- determine the signs and the magnitudes for the diagonal matrix elements 2^+_2 and 2^+_3 states at 2042 keV, and 2403.2 keV respectively, 4^+ state and reduced transition probabilities for 0^+_3 state decay.
- also determine the relative signs and magnitudes of transitional electromagnetic matrix elements between the low-lying states inside the ground state band and the intruder rotational band to validate the shape co-existence scenario.
- Re-measure the quadrupole moment of the first excited 2^+ with an improved precision.

Experimental Set Up for ^{118}Sn

100 MeV ^{32}S + 1mg/cm^2 ^{118}Sn

Coulomb Barrier = 126 MeV
T safe Energy = 106 MeV

EAGLE γ-ray spectrometer



48 PiN-Diode HI Detectors

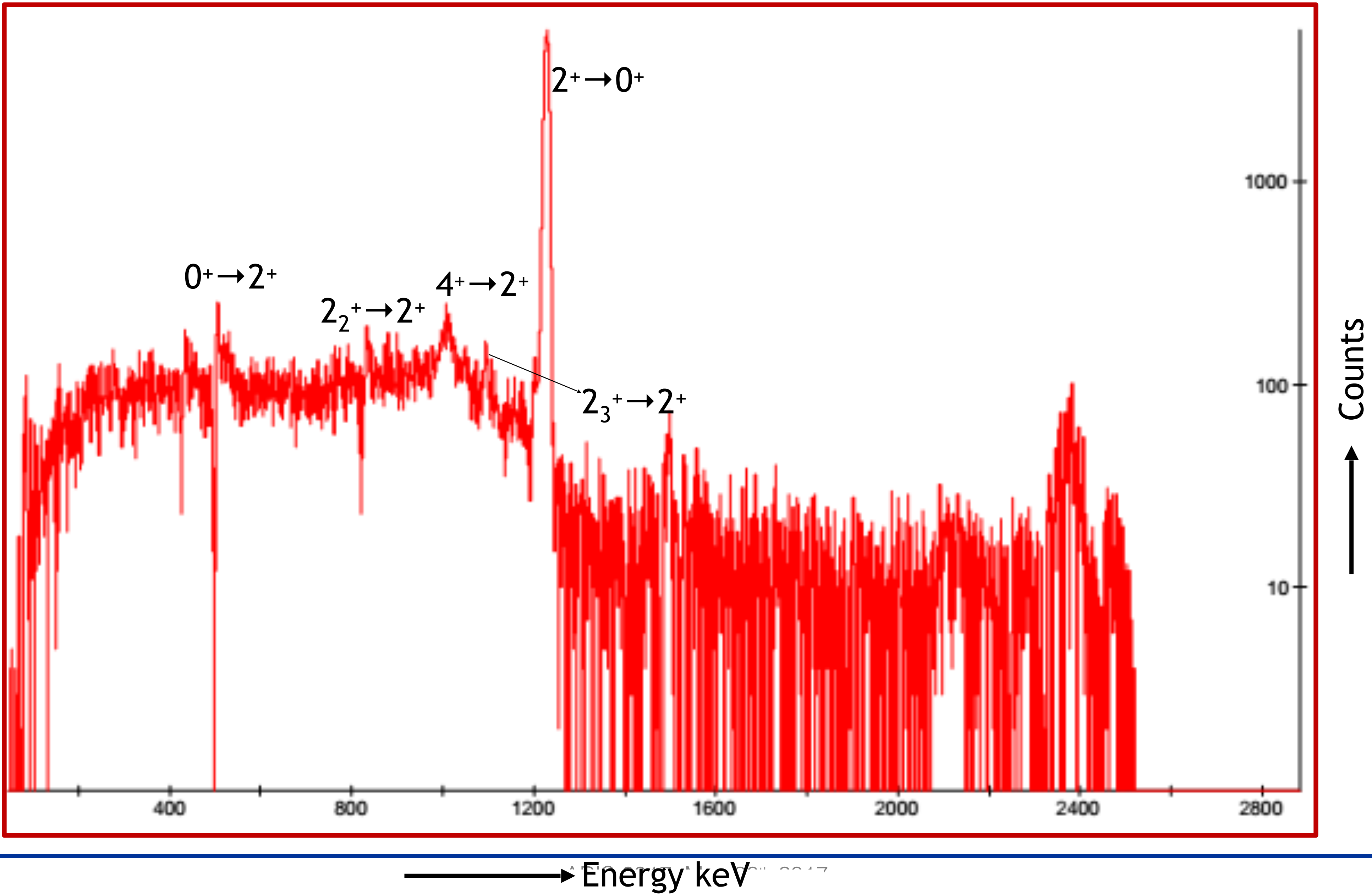
θ_{LAB}: 108° - 167°

15 HPGe & ACS
Efficiency@1.3MeV: 0.5%

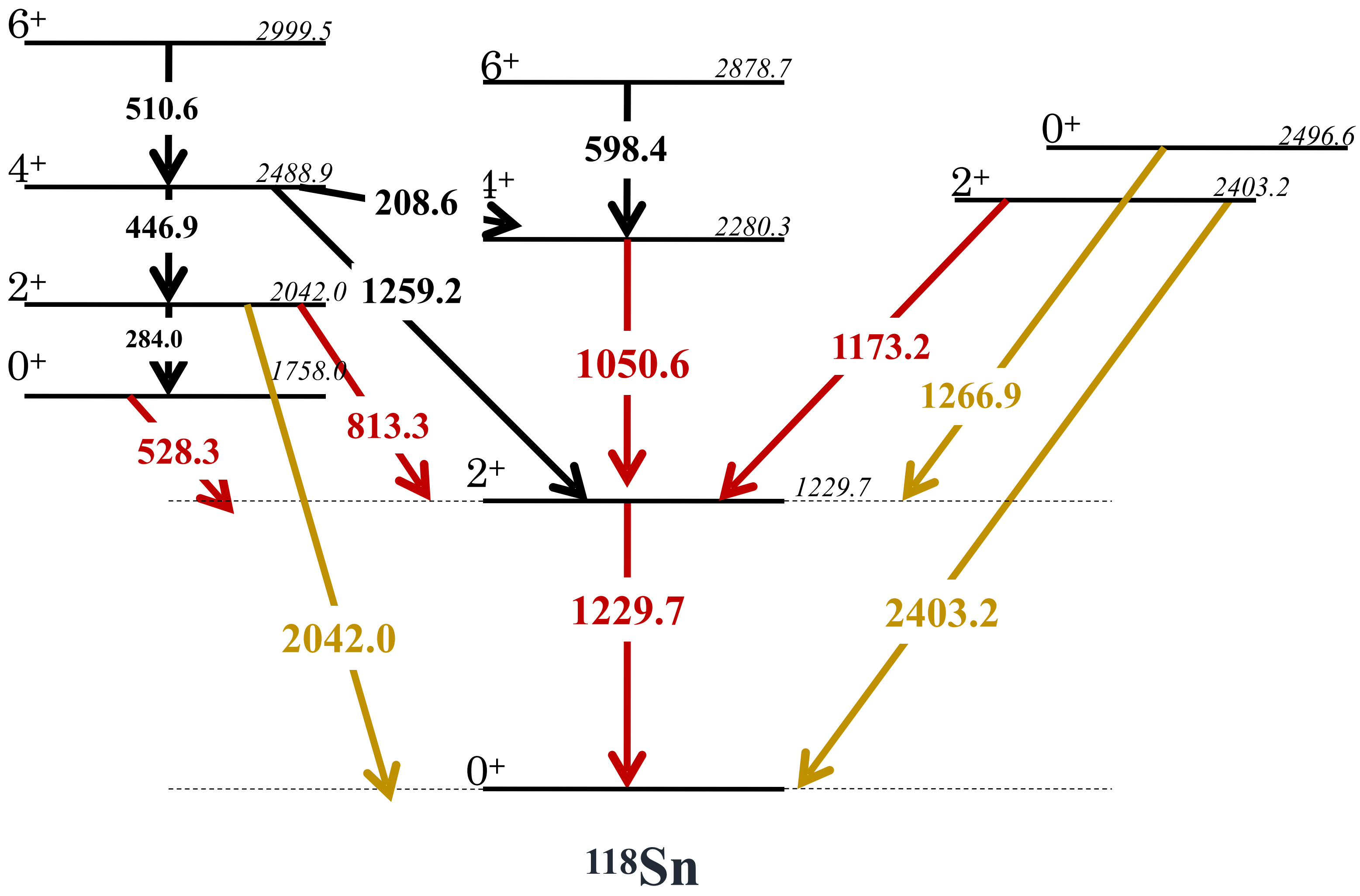
p-ɣ coincidence measurement !

7 GammaPool HPGe Detectors

Preliminary Spectra - ^{118}Sn



Partial level scheme - ^{118}Sn



5 Days of data taking (^{32}S beam) in particle gamma coincidence mode !

SUMMARY

- ❑Two experiments were performed to measure different observables in ^{120}Te nuclei.
- ❑Experimental excitation energies and transition probabilities can be described by triaxial rotor model.
- ❑Magnitudes with relative signs of the transitional states of the low-lying states in ^{120}Te were determined using GOSIA.
- ❑First experimental measurement for the quadrupole moment in ^{120}Te.

- ❑ Coulomb excitation measurement performed for ^{112,116,118,120,122,124}Sn using ^{58}Ni projectiles.
- ❑ No evidence of reduced collectivity found in even – even stable Sn isotopes.
- ❑ Nuclear structure of ^{118}Sn (isotone of ^{120}Te) investigated – Analysis Ongoing !

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Thank you for your kind attention