Nuclear Structure Studies through Coulomb Excitations

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Outline of the talk

Introduction

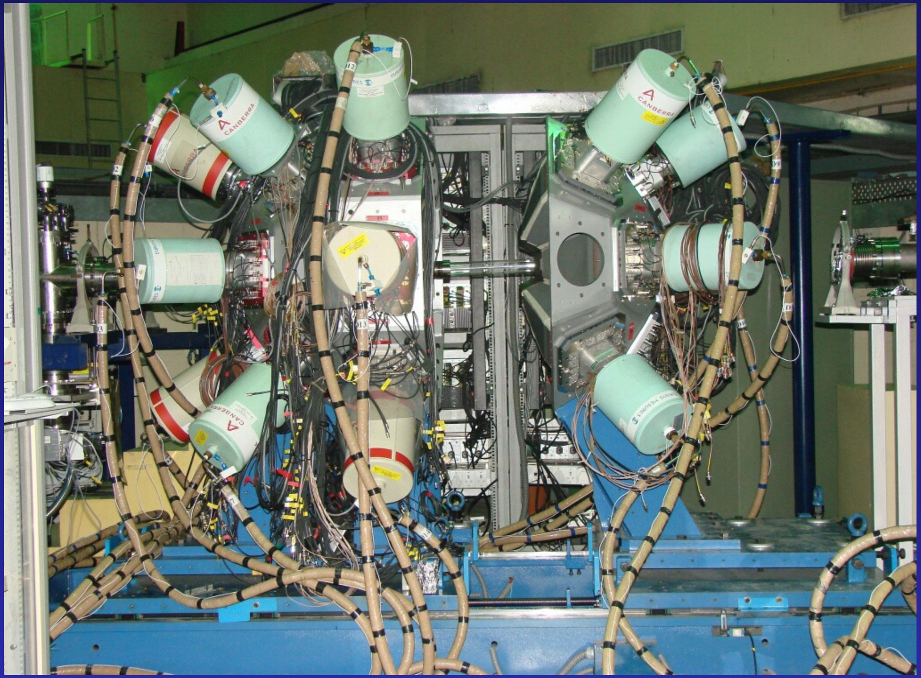
Experiments

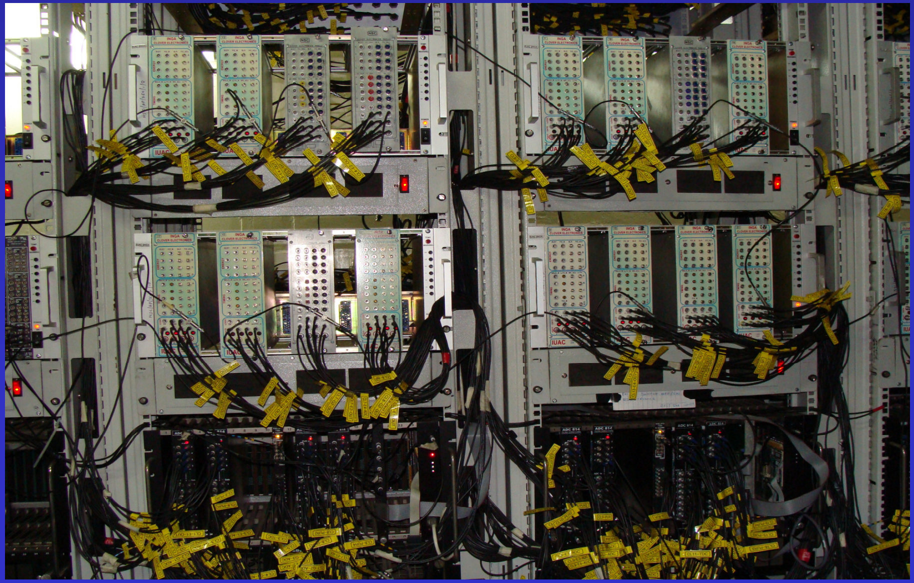
Summary

Inter University Accelerator Centre

(Nuclear Science Centre)

Indian National Gamma Array at IUAC

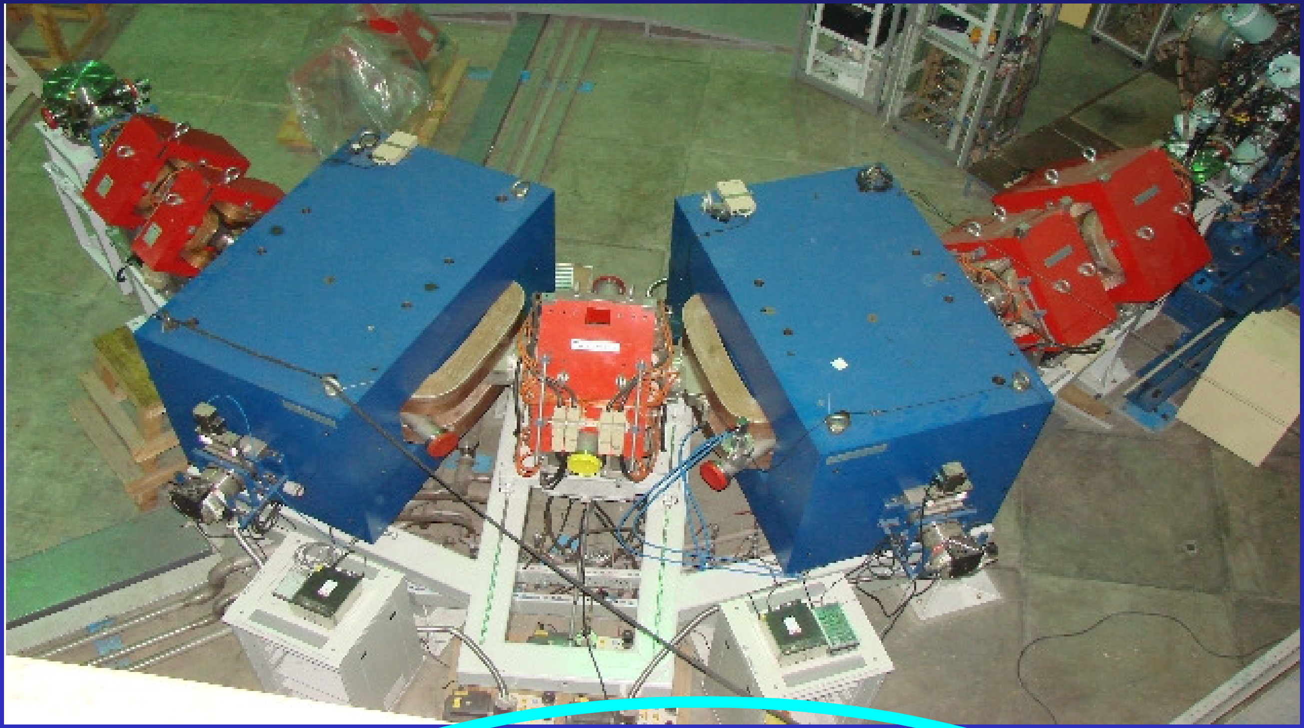




- Compton suppressed Clover detectors
- $\varepsilon_p \sim 5\ \%$
- γ–γ–γ ~ 3-4 k/s
- Indigenous electronics

- Chirality in nuclei
- (Anti)Magnetic Rotations
- Evolution of shell struture
- Octupole Collectivity

Hybrid Reaction Analyser (HyRA)



Gas filled mode:

Higher Eff ~ 20%

A, Z : Recoil decay

Vacuum mode:

ΔM/M ~ 1/300

Eff ~ few percent

X, ΔE, E

Pair Transfers

Fusion cross-section

Spin gated GDR

INGA + HyRA

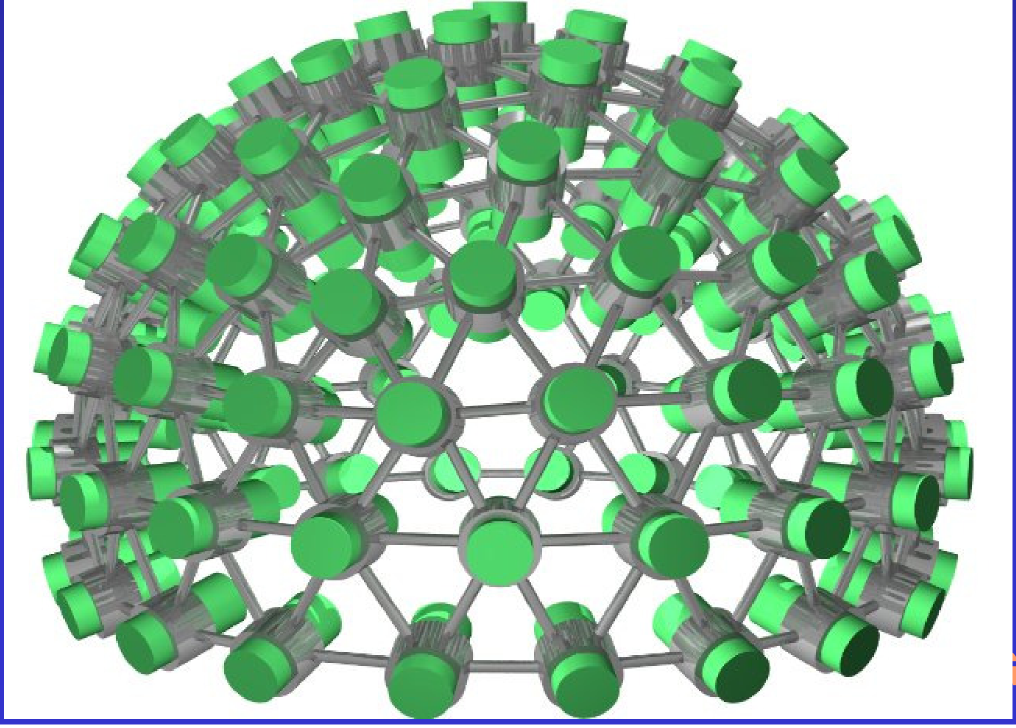
Soon !!

National Array of Neutron Detectors

Heavy ion fusion-fission dynamics : 'n' – multiplicity

Role of Quasi-fission

Neutron Spectrometer of ~ 100 (5”x5”) neutron detectors + High resolution PPACs



Coulomb Excitation Studies

- Started quite early and still very active
- Avoid complications of nuclear intn
- Low lying collective states
- Heavy ions : multiple excitations
- Large detector arrays : High sensitivity

Rough sketch of the Coulex process

'E' well below Coulomb barrier

=> Coulomb intn only

Sommerfeld parameter :

$a/\lambda = Z_1 Z_2 e^2/\hbar v >> 1$

for Heavy ions , low velocities

further $E_{xtn} << E_{bombarding}$

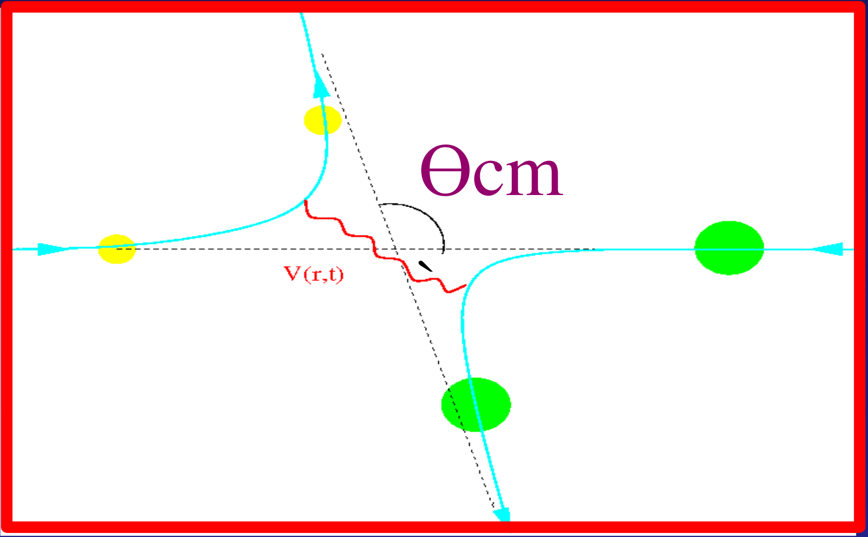
=> Semi-classical

Rutherford scattering formula :

$d\sigma_R = a^2 / 4 \sin^4(\theta/2).d\Omega$

Diff Xtn for excitation:

$d\sigma = P.\, d\sigma_R$



P-probability of excitation

$P = (2Ii+1)^{-1} . \Sigma_{MiMf} |b_{if}|^2$

1st oder perturbation theory

$b_{if} = (i\hbar)^{-1} \int <f|V(t)|i> e^{i\omega t}.dt$

$\omega = (E_f - E_i)/\hbar$

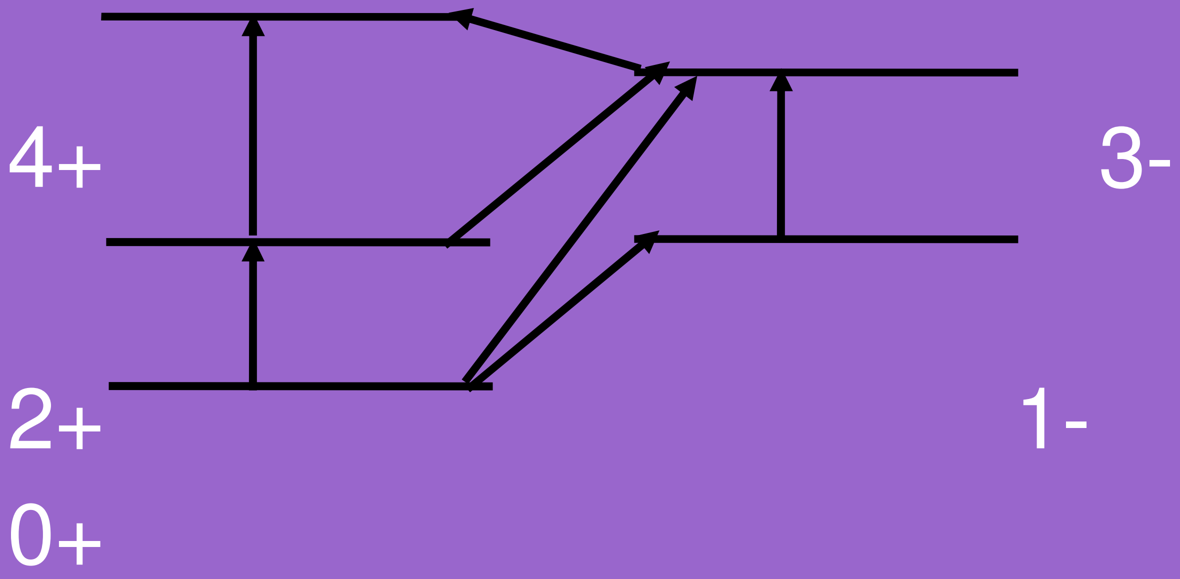
Total Ex. Xtn $\sigma = \int d\sigma$

over all the scatt. angles

$\sigma \sim B(E/M\lambda)$. Orbital integrals

Excitation → Decay Alder et al; RMP(1956)432

$$B(\lambda;I_f \rightarrow I_i) = (2I_i+1)/(2I_f+1).\ B(\lambda;I_i \rightarrow I_f)$$



Selection rules:

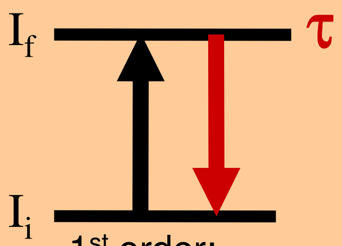
$$|I_i - I_f| \leq \lambda \leq |I_i + I_f|$$

$$\pi_i \pi_f = (-1)^{\lambda} \text{ for } E\lambda$$

$$\pi_i \pi_f = (-1)^{\lambda+1} \quad \text{for } M\lambda$$

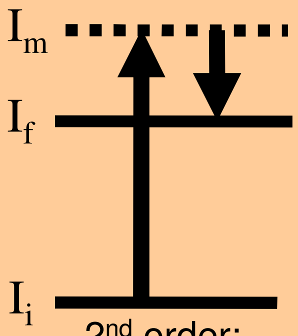
Multi-step Coulex: Many paths : Many matrix elements

Nuclear excitations due electromagnetic field between nuclei



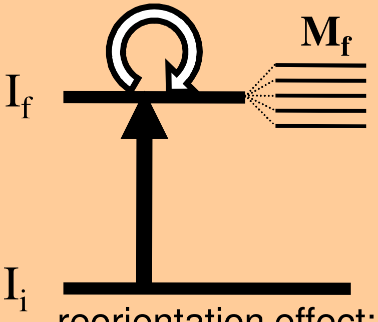
1st order:

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



2nd order:

$$a^{(2)}_{i\to f} \propto \langle I_f \| \mathbf{M}(E2) \| I_m \rangle \langle I_m \| \mathbf{M}(E2) \| I_i \rangle$$



reorientation effect:

$$a^{(2)}_{i\to f} \propto \langle I_f \| \mathbf{M}(E2) \| I_f \rangle \langle I_f \| \mathbf{M}(E2) \| I_i \rangle$$

Codes: Semi-classical , multi-step excitations

COULEX + CEGRY : Winther & Boer, Cline et al:

1st extraction of multiple Coulomb excitation amplitudes from assumed electromagnetic matrix elements

GOSIA : T. Czosnyka et al (Rochester):

model independent extraction of matrix elements :

least square search in multi-dimensional space of

matrix elements : to reproduce experimental data

Collaboration: with group at HIL Warsaw

Experiments

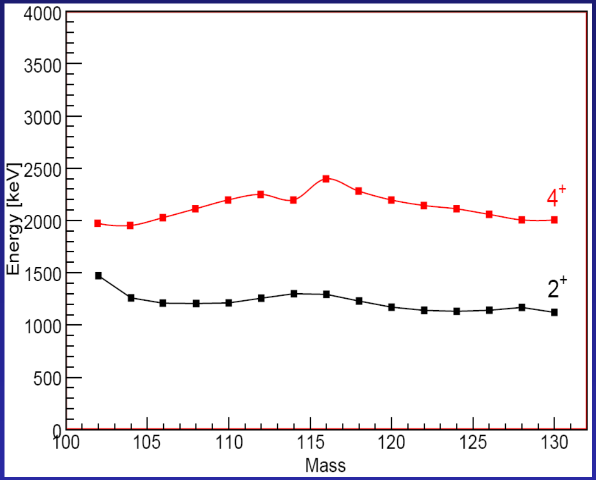
Study of proton rich Sn isotopes

Collaboration with group at GSI

Investigation of Tetrahedral symmetry

Collaboration with LNL,Warsaw,Tetranuc

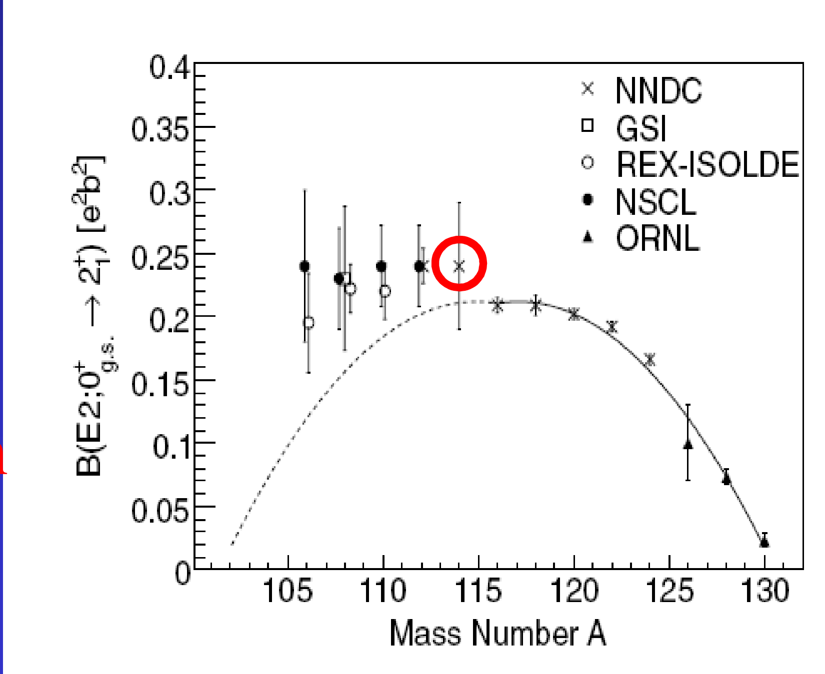
To probe the robustness of Z=50 shell closure between N=50 to N=82



Experimental 2^+ and 4^+ level energies of Sn isotopes

Excitation energies for 2+ almost flat

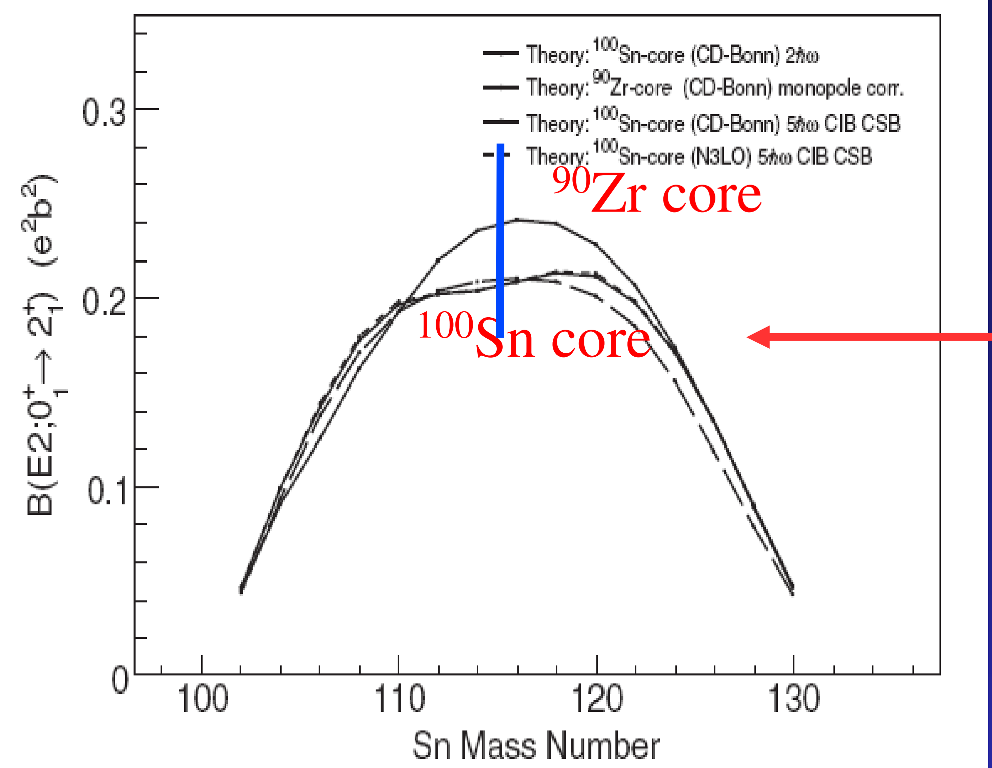
B(E2) sensitive probe of robustness of Z=50 shell closure

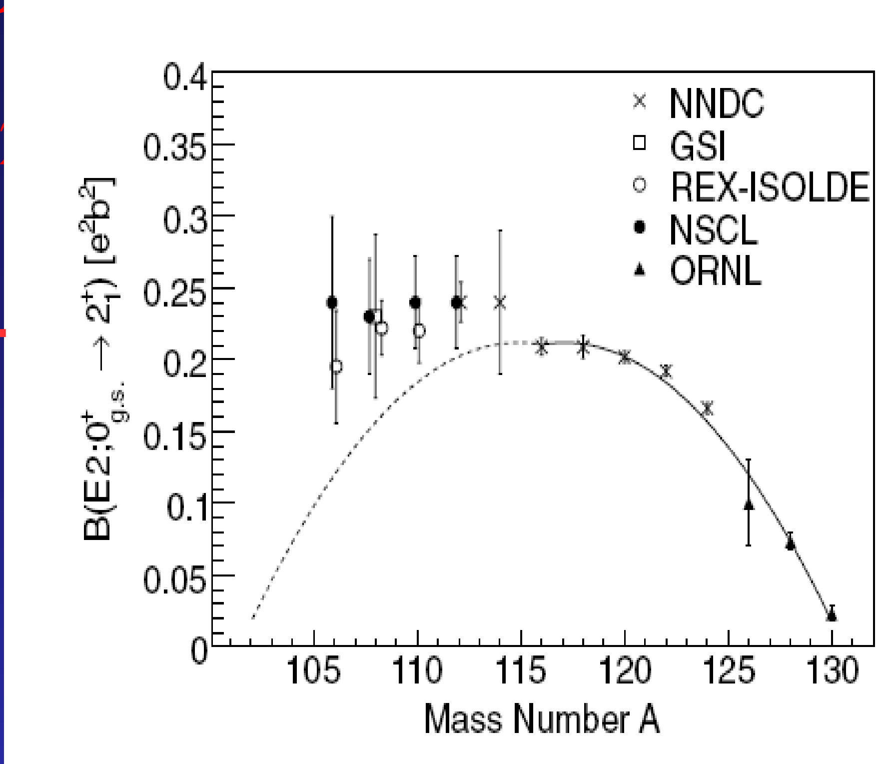


Large errors for the B(E2) for ^{114}Sn

Motivated Coulex measurement to establish crucial data point where B(E2) increases

What does the theory say?



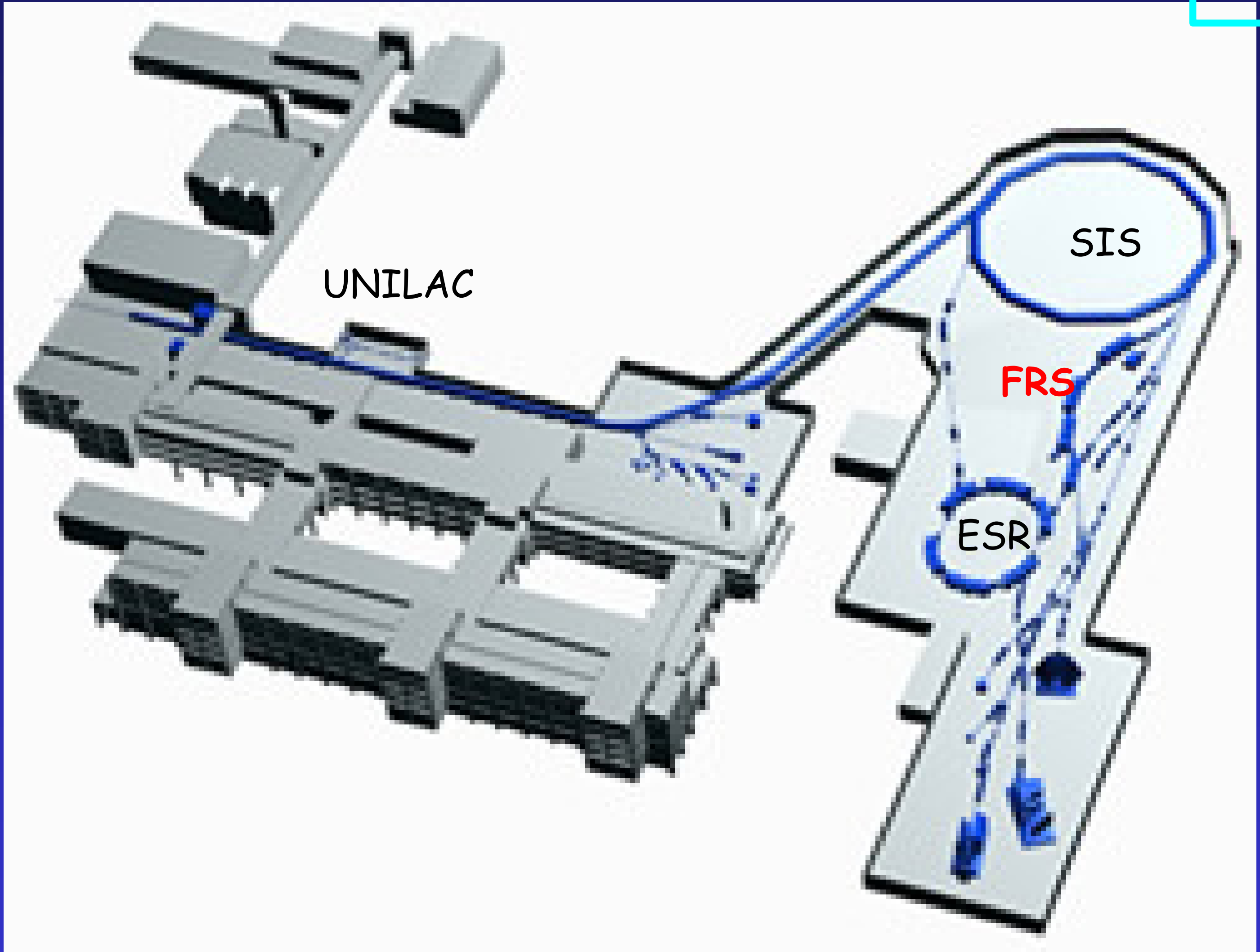


Theoretical B(E2) values for even mass Sn isotopes from large scale shell model calculations

- Previous Coulex measurement used ^{114}Sn as target
- Natural abundance of ^{114}Sn is only 0.65%
- Difficult to separate as 2^+ energy is very close for other isotopes
- **Use ^{114}Sn as beam in inverse kinematics**

GSI accelerator facility

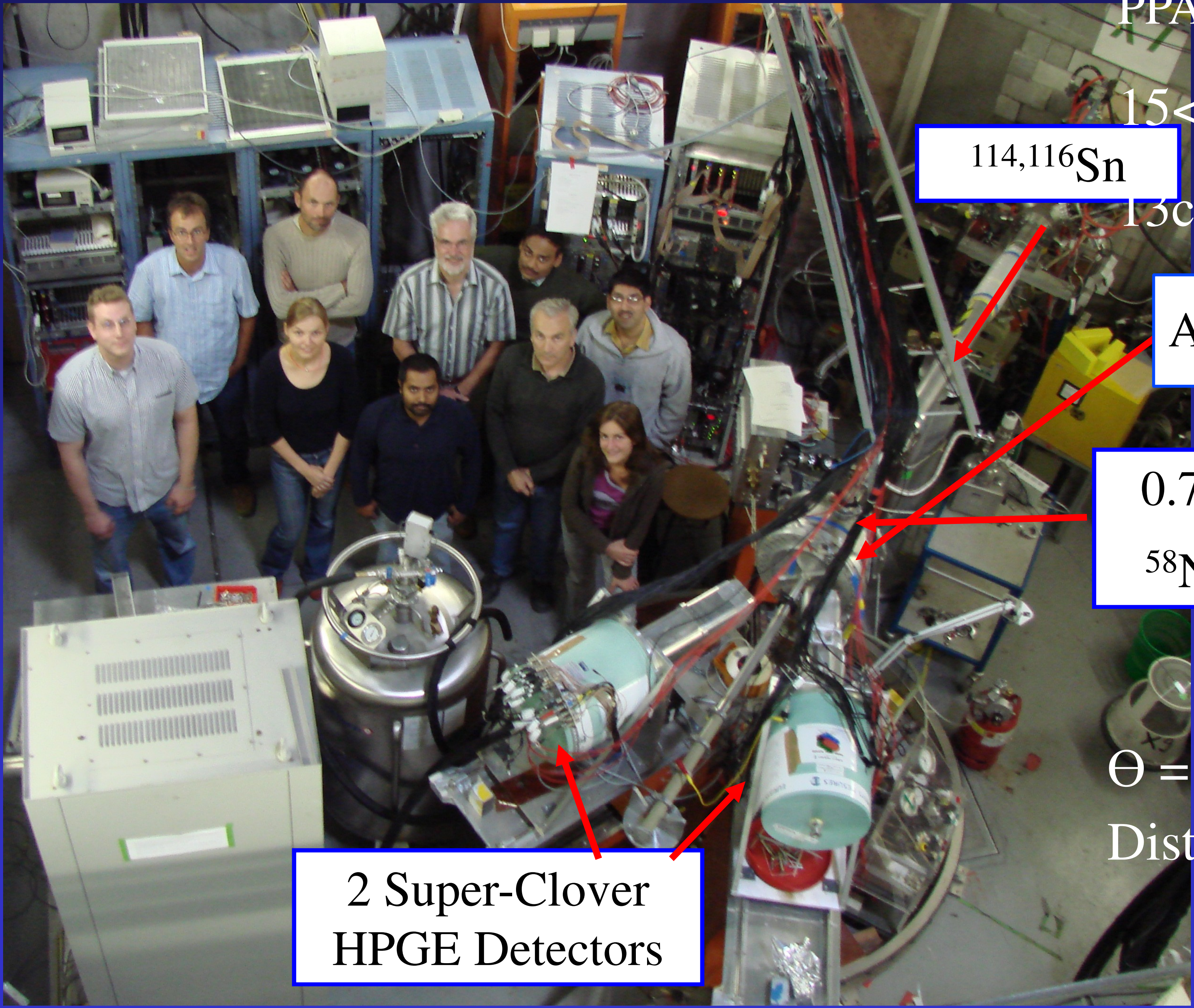
^{114,116}Sn beam on ^{58}Ni



- Sub-barrier beam energies of ~ 3.4 A MeV from UNILAC at GSI
- 99.9% enriched ^{58}Ni target
- Thickness ~0.7mg/cm^2
- 2-Particles-gamma coincidence

In collaboration with GSI

Experimental set-up at GSI



PPAC: 20 seg; 50 rings

$15 < \Theta_{lab} < 45$

^{114,116}Sn

13cms from target

Annular PPAC

0.7 mg/cm^2

^{58}Ni Target

$\Theta = 25^{o}$ w.r.t beam

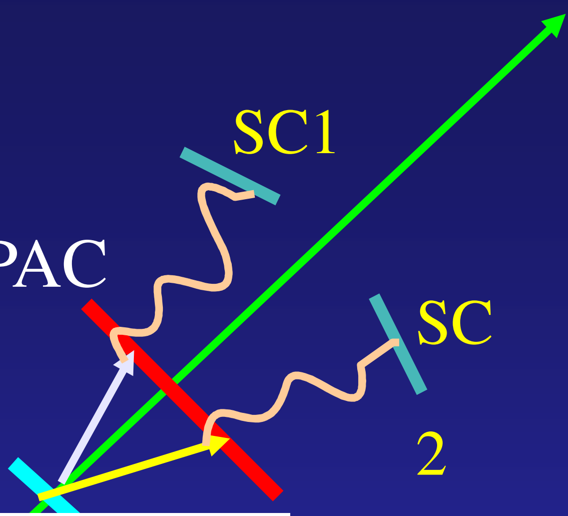
Distance ~ 20cms

2 Super-Clover HPGE Detectors

PPAC split in two independent parts :

coincidence between projectile & ejectile

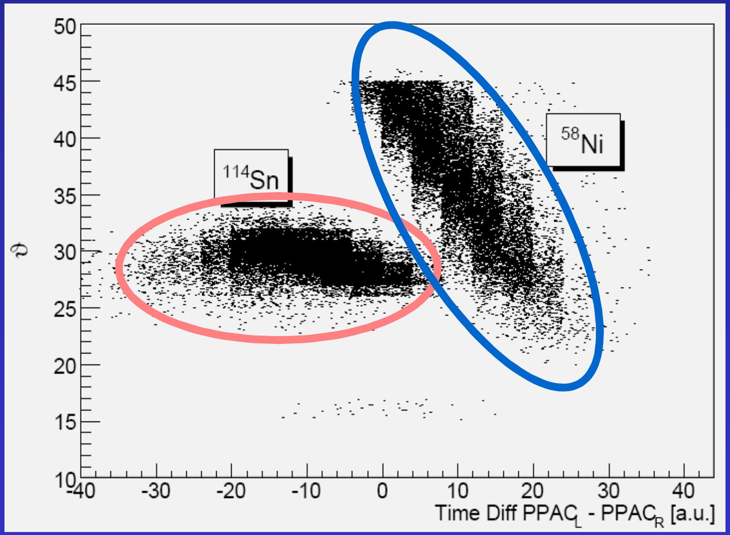
^{58}Ni in PPAC (15° to 45°) ⇒ ^{114}Sn in 24° to 31° in PPAC



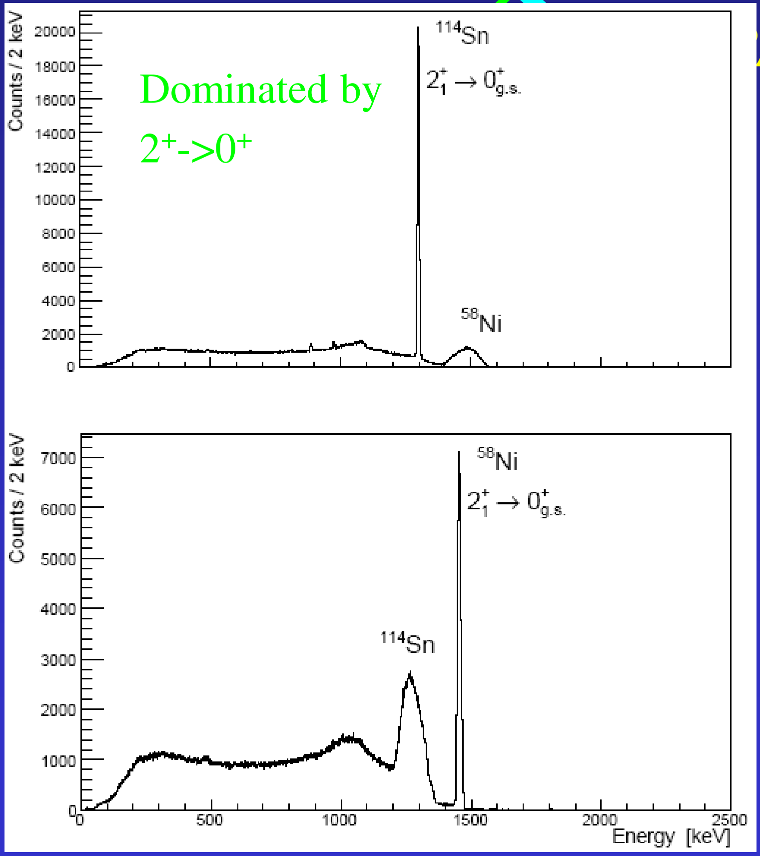
Identification of projectile & target nuclei

by time-of-flight technique

Scattering angle



Time (arb. units)



Doppler Correction for ^{58}Ni and ^{114}Sn

^{116}Sn as reference point

B(E2,↑) value for ^{116}Sn known precisely

Adopted value 0.209(6) from 15 different measurement

Reliable reference point

For same experimental set-up

Coulex measurement repeated for ^{116}Sn on ^{58}Ni

Define Double Ratio of gamma yields:

$$\{I_\gamma(^{114}Sn)/I_\gamma(^{58}Ni)\} \,/\, \{I_\gamma(^{116}Sn)/I_\gamma(^{58}Ni)\} \qquad \text{for } 2_1^+ \rightarrow 0_{gs}^+$$

Systematic errors are excluded and the target excitation

cancels for ^{114}Sn/^{116}Sn γ-ray yield ratio

Feeding from higher states $0_2^+,3_1^-,4_1^+$ (< 4%)

subtracted from 2_1^+ intensity

Using Winther-de Boer Coulex code the double ratio

reproduced and the value of B(E2, $0_{gs}^+ \rightarrow 2_1^+$)

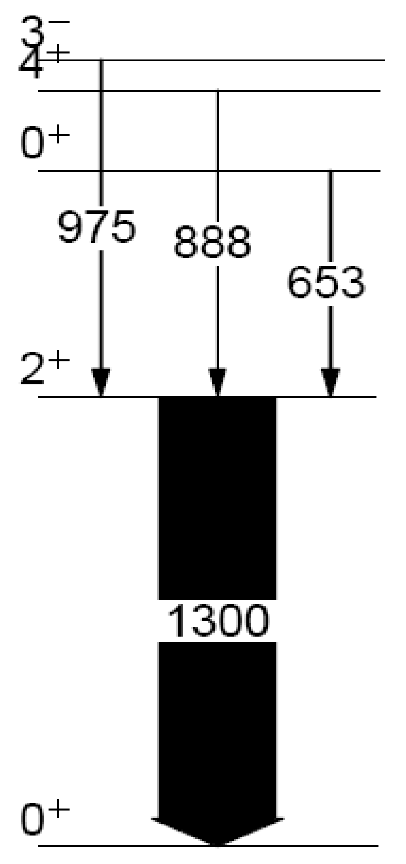
determined to be $0.232(8)e^2b^2$ with good precision;

Doornenbal et al; PRC78('08) 031303(R)

Error in γ-ray intensity ~1%

Error in adopted B(E2) of ^{116}Sn ~3%

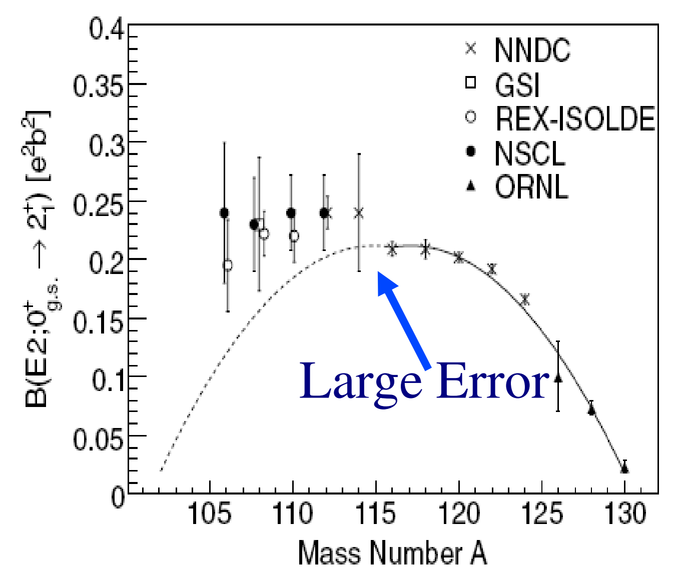
Error in angular acceptance (beam drift,particle eff.)~1%

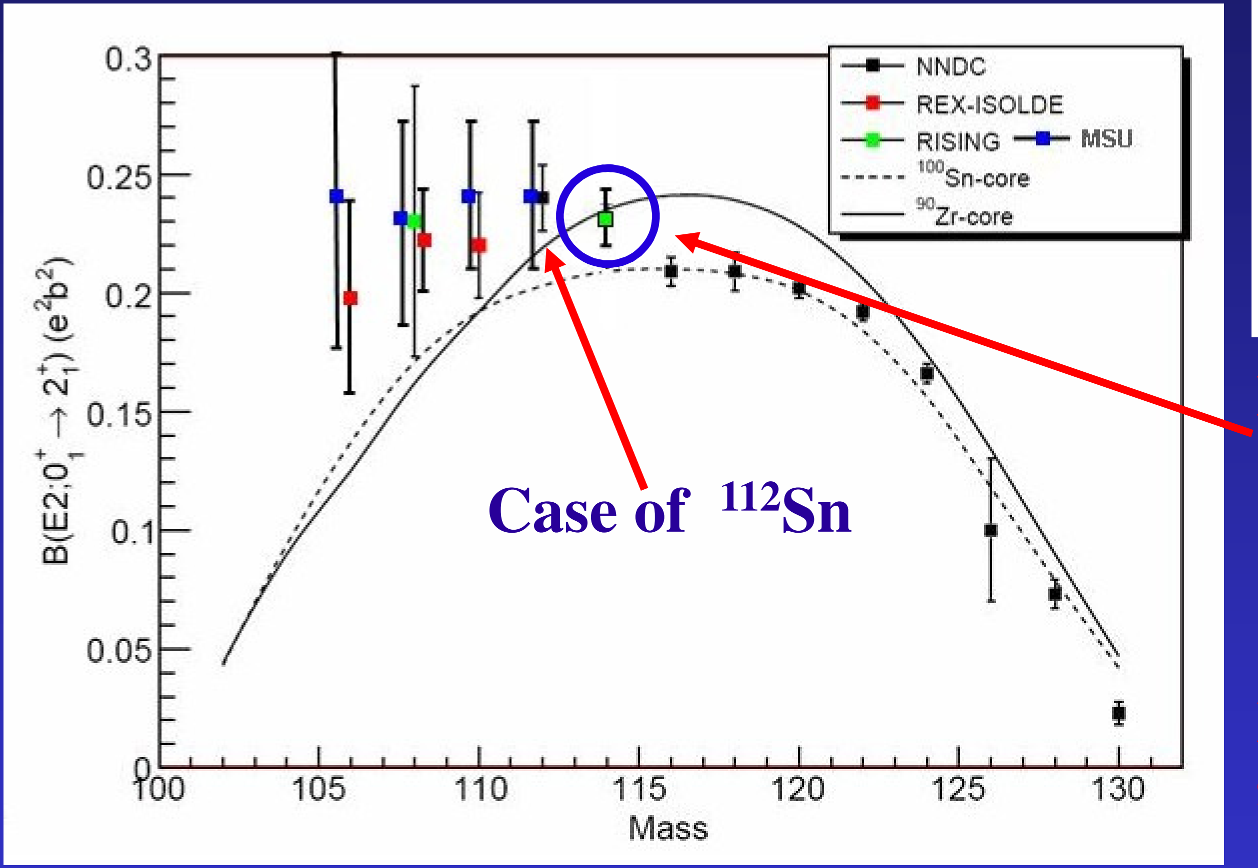


^{114}Sn

B(E2) Systematics for Sn isoto

Doornenbal et al;
PRC78,031303(R)



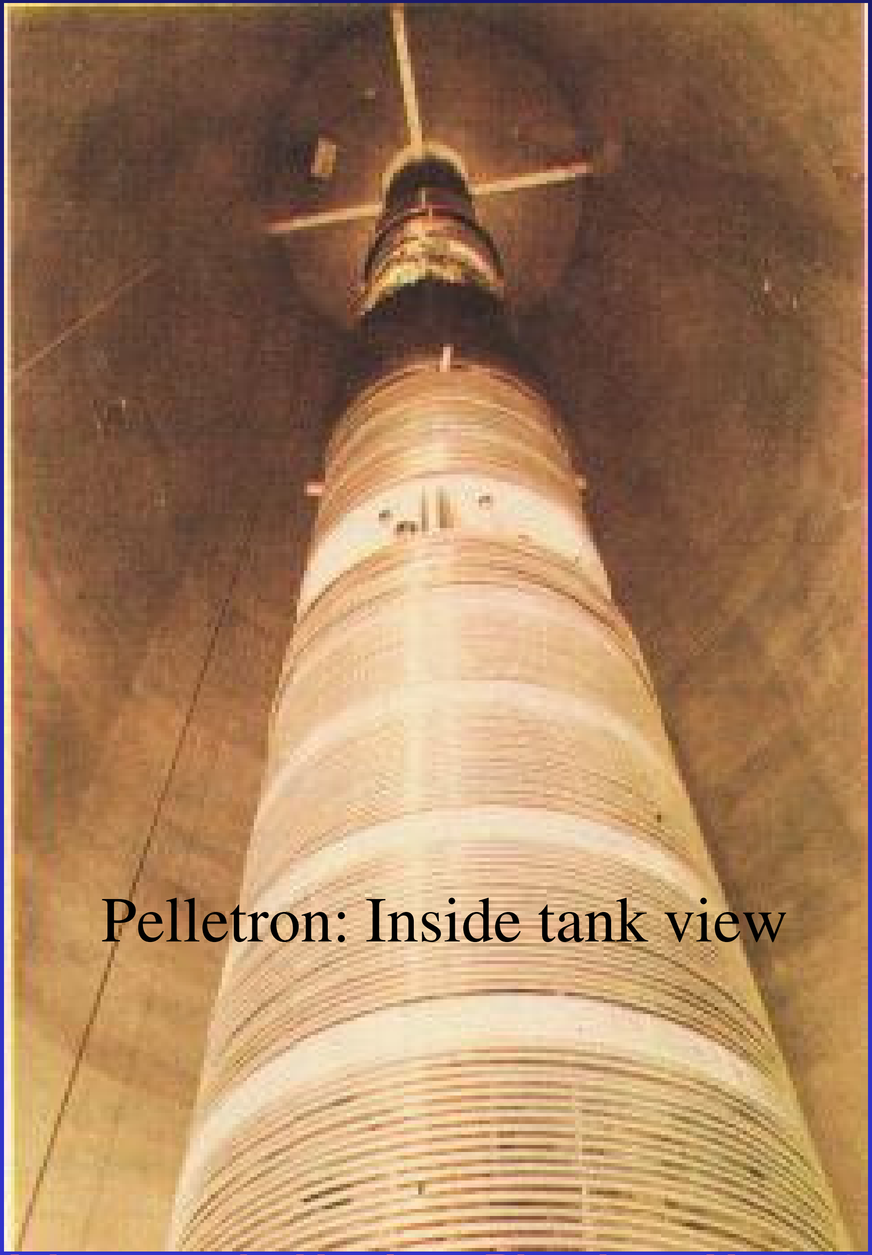


Definite enhancement
^{114}Sn anchor point for
experimental asymmetry

Matches with LSSM with
^{90}Zr as core

Is there enhancement of B(E2) for ^{112}Sn over the LSSM ?
Needs a precise measurement

Measurement of B(E2,2_1^+ -> 0_{gs}^+) in ^{112}Sn



Pelletron: Inside tank view

Experiment with IUAC Pelletron

^{58}Ni used as beam at 175 MeV

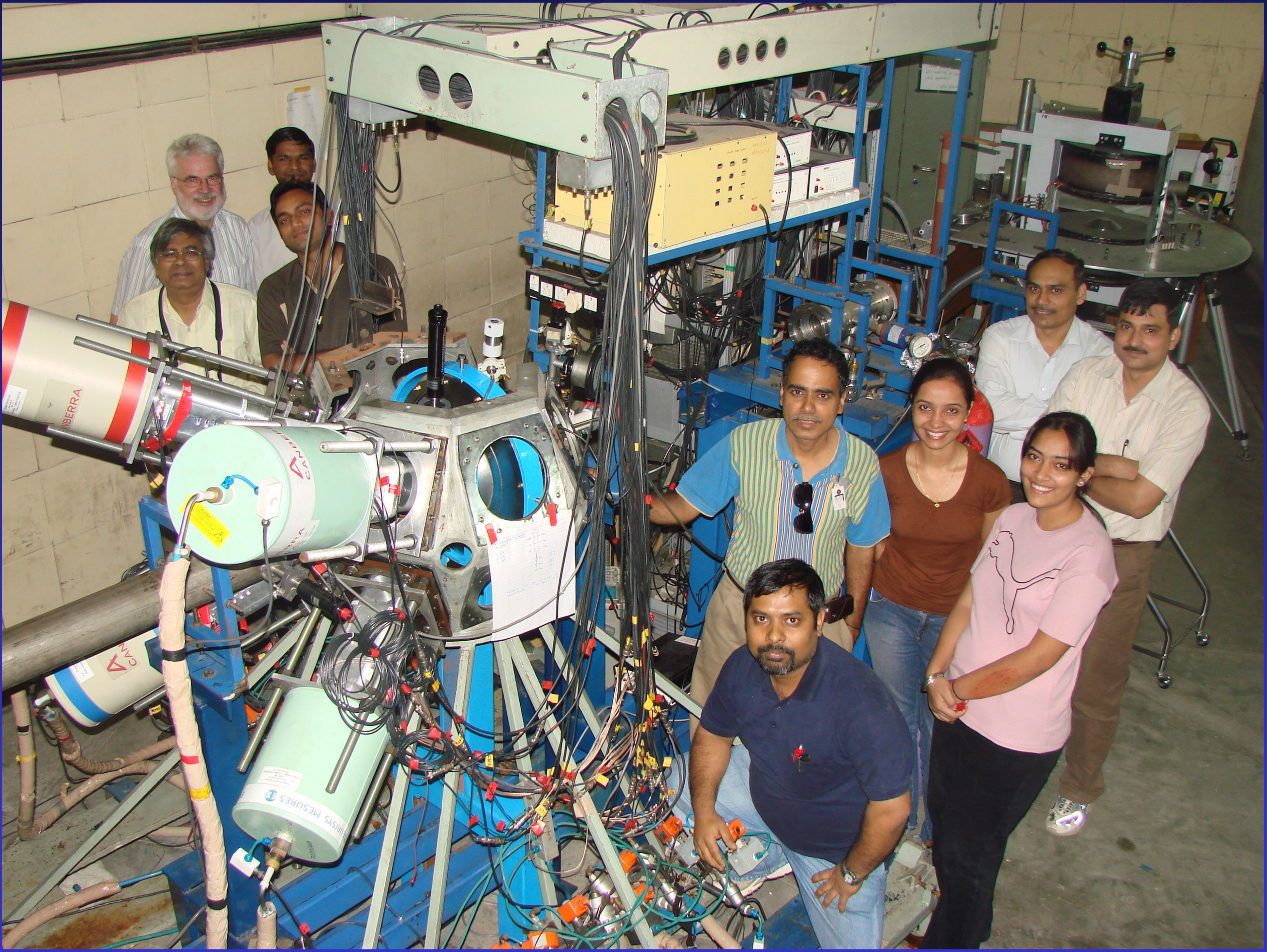
Targets: About 0.5 mg/cm^2

^{112}Sn : 99.5% enriched and

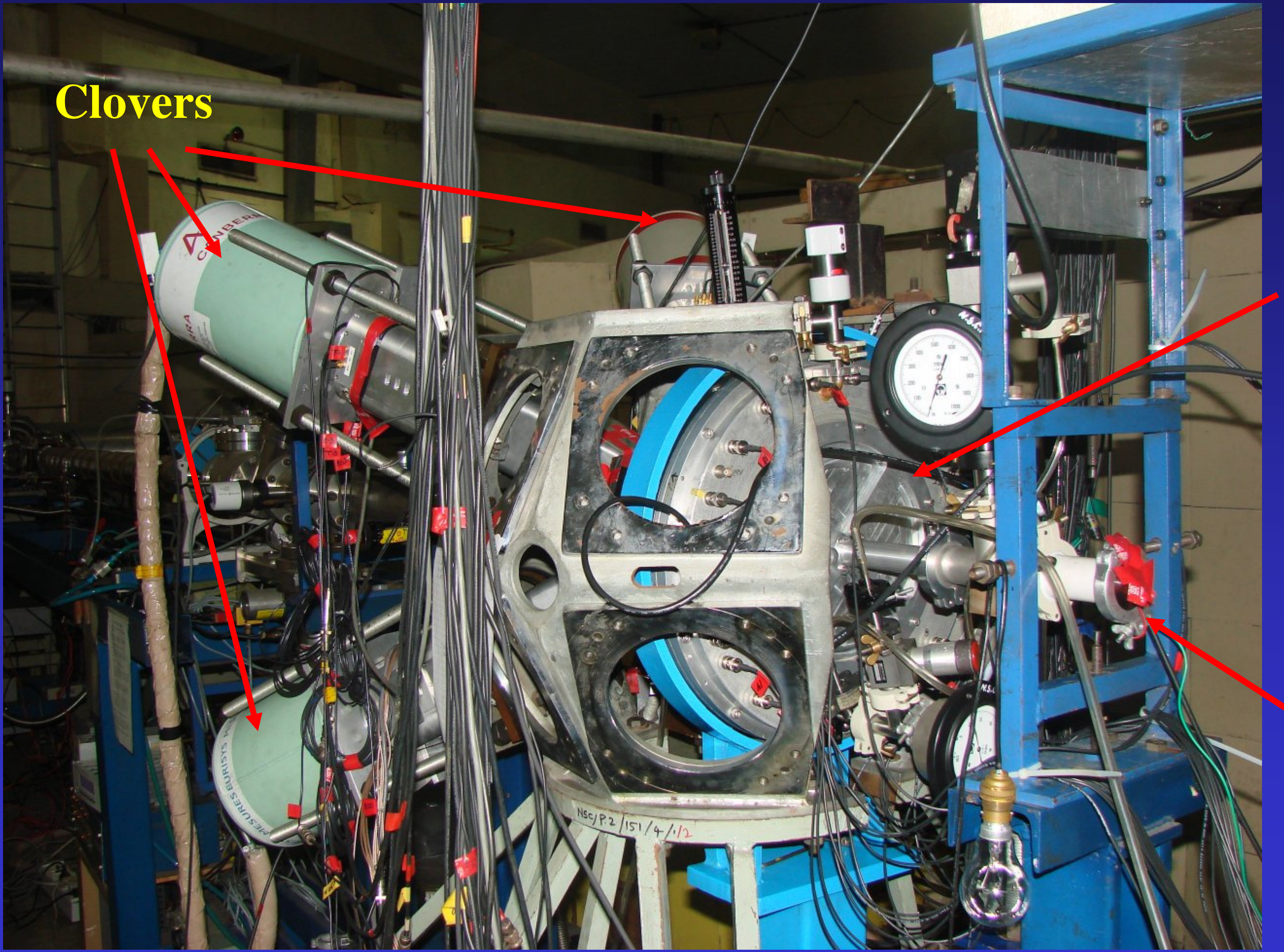
^{116}Sn : 98 % enriched were used

PPAC: 15^o to 45^o

Four normal Clover detectors used



Set-up for Coulomb excitation at IUAC

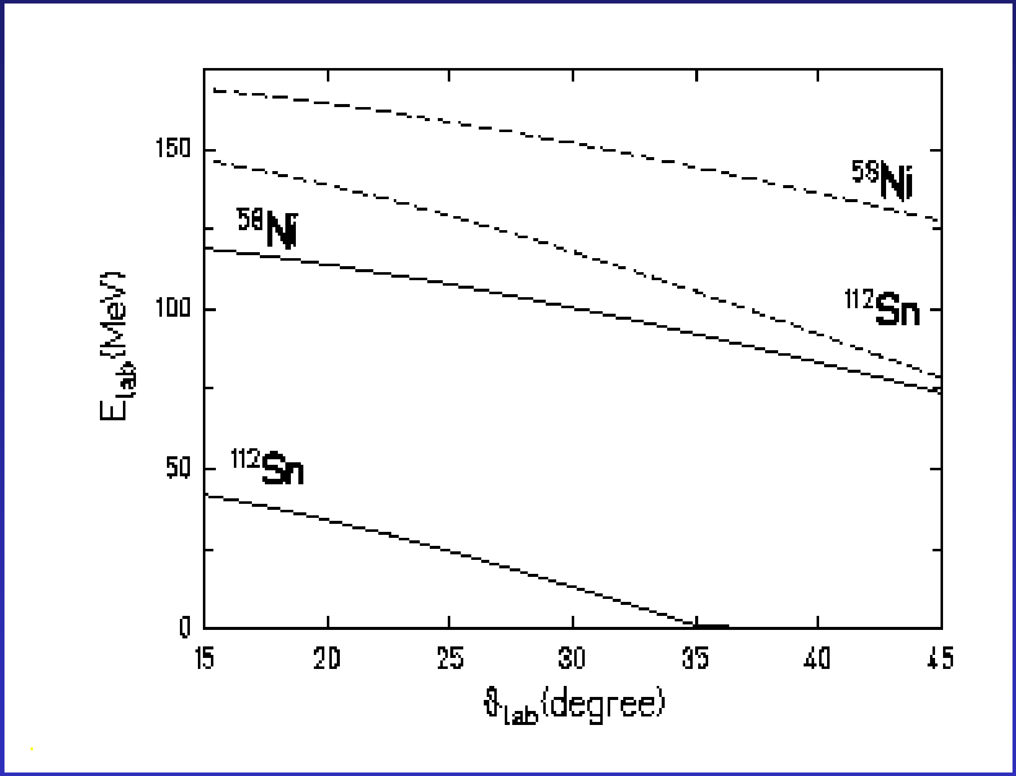


Clovers

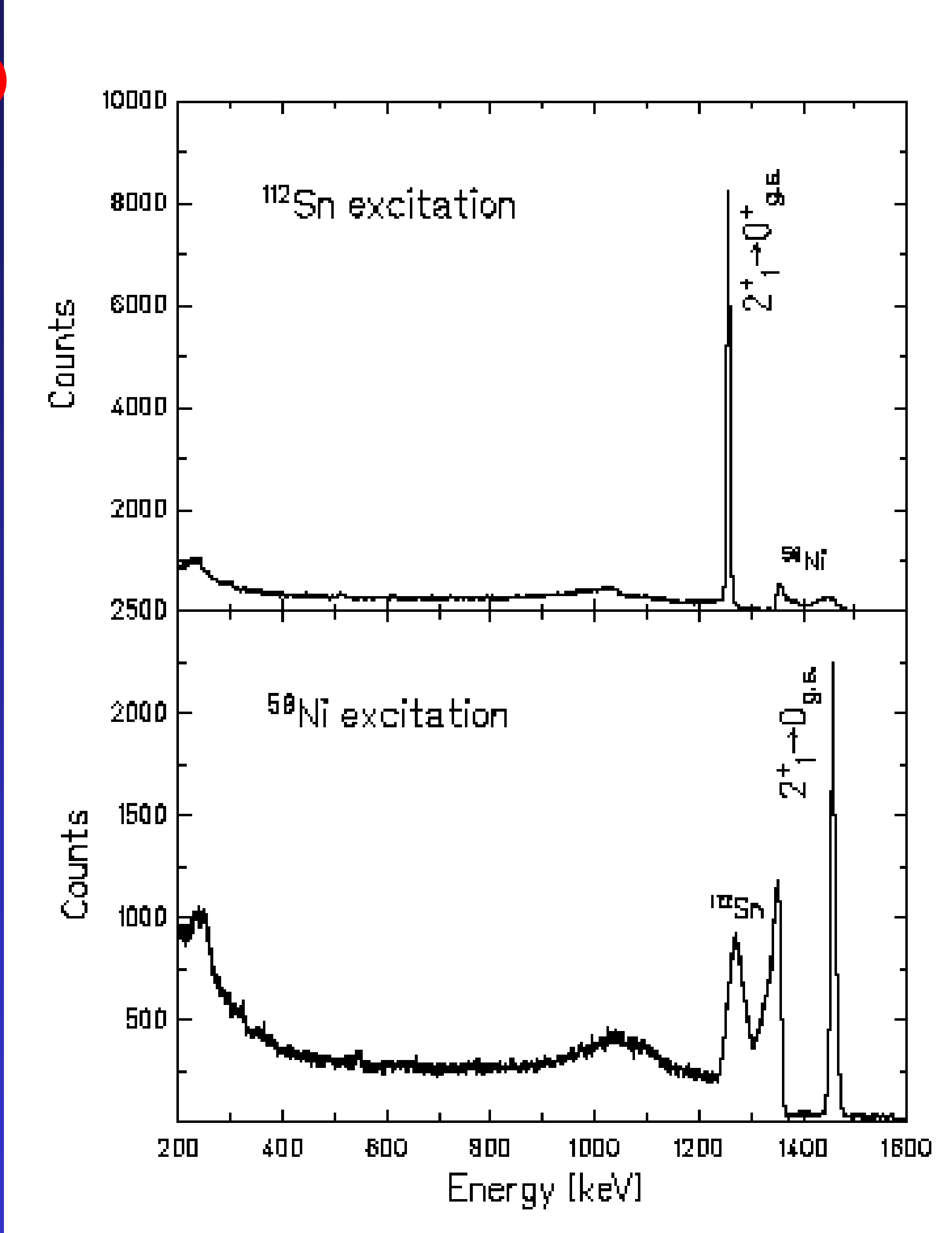
PPAC

Faraday cup

Doppler correction and gamma ray yields R Kumar et al PRC 81(2010)

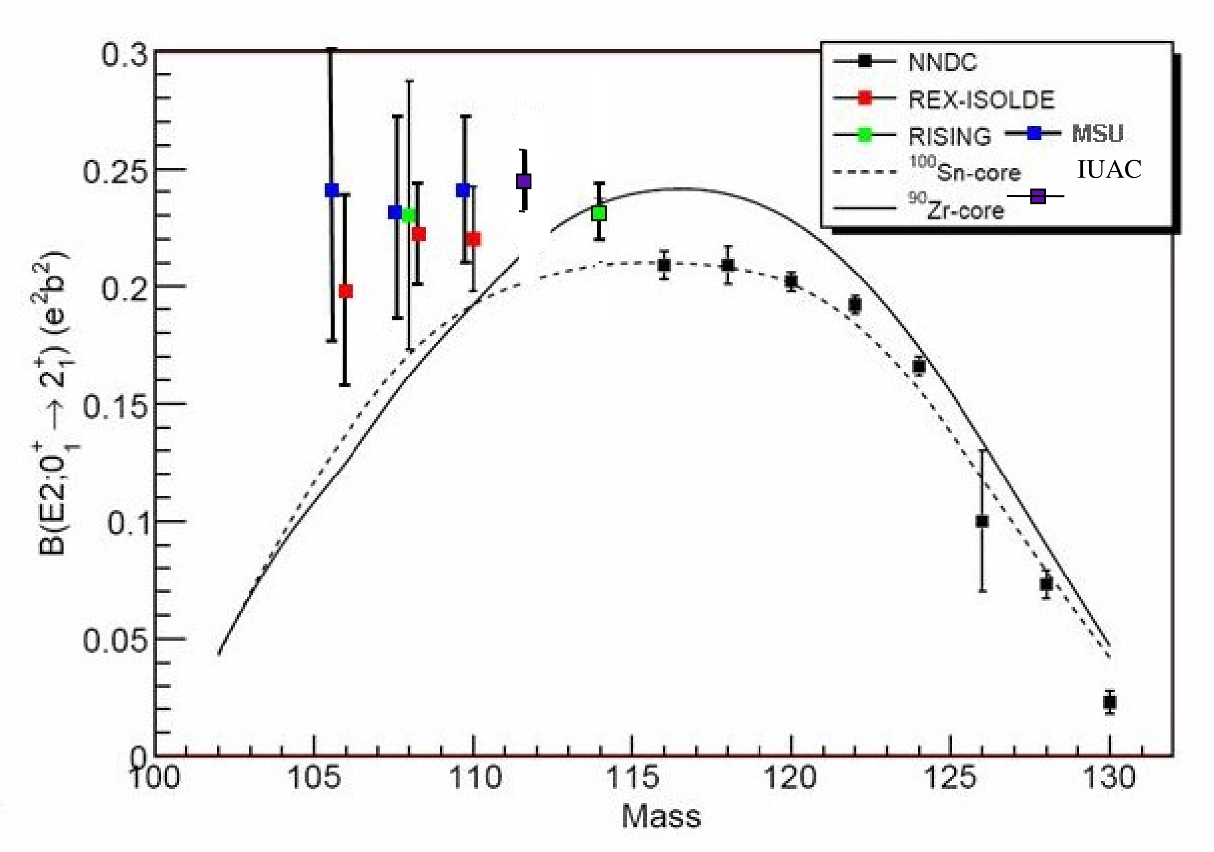


Scattering angle vs E_{lab}



Doppler corrected spectra

Results for ^{114}Sn and ^{112}Sn



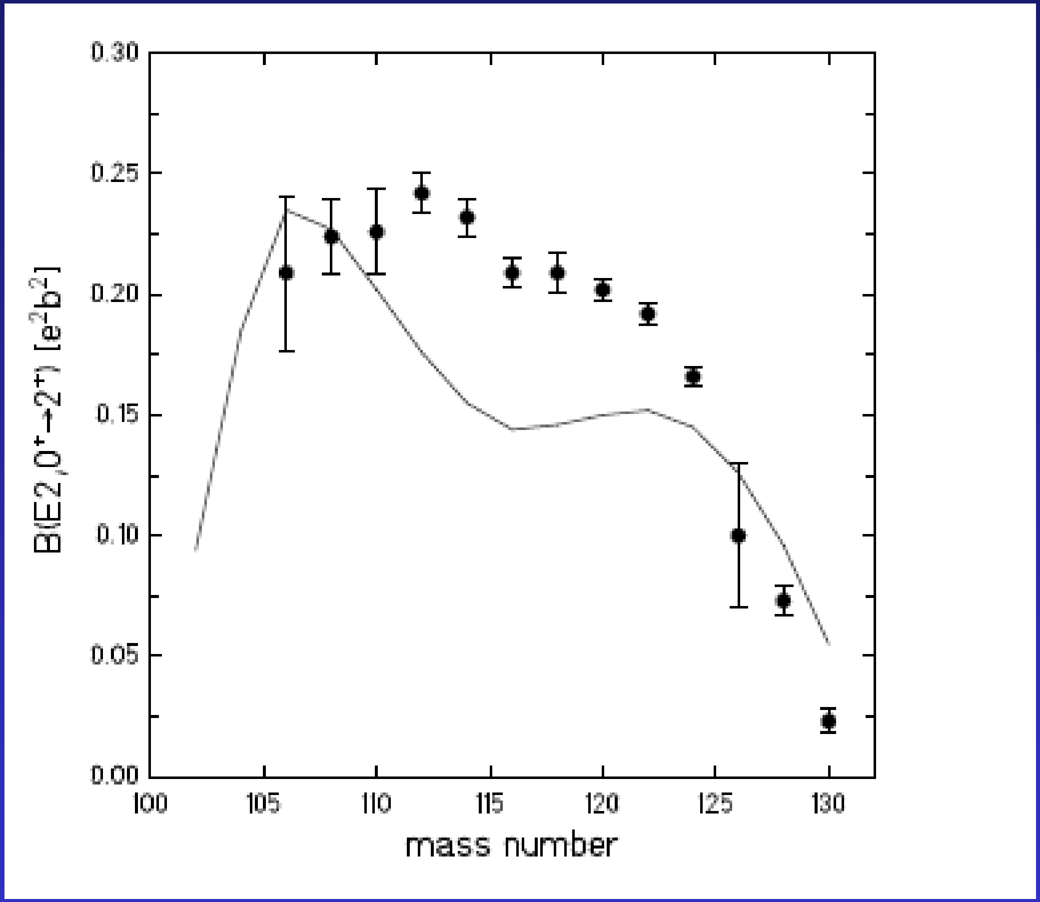
Enhanced B(E2) with ^{114}Sn as turning point

Enhanced B(E2) at ^{112}Sn confirms asymmetrical curve

LSSM calculations fail excitations across N=50 shell α correlations (2p2h), reduction of Z=N=50 shell gaps

Phys. Rev C 81 (2010) 024306

Experimental B(E2) values compared with RQRPA calculations



No inert core

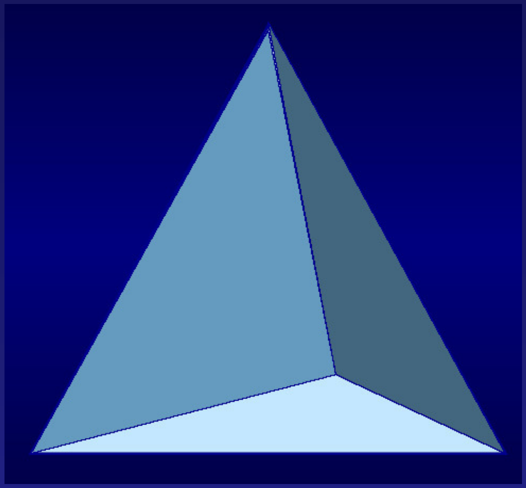
No effective charges

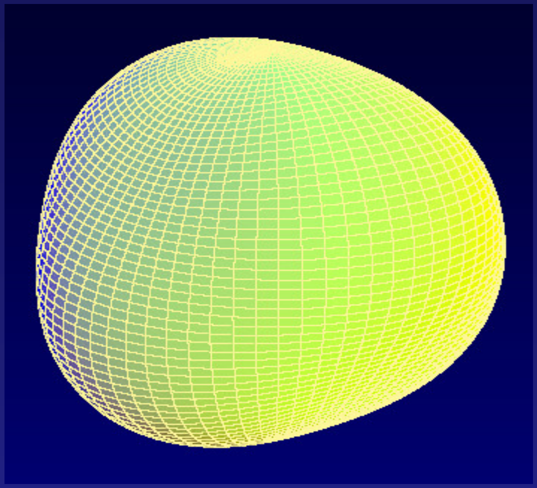
Compares well for Pb

and Ni isotopes also

Kumar et al; Acta Phys Pol. B 42 (2011),

A Ansari et al, Phys. Lett. B623,37(2005)





Investigation of Tetrahedral Symmetry in Nuclei

IUAC,LNL,Lund,Tetranuc and HIL Collaboration

Advances in Nuclear Physiscs Nov-2011

Goa

Skalski et al; Phys. Lett. B274, 1 (1992)

Li et al; Phys. Rev.C 94 (1994)

Takami et al; Phys. Lett. B (1998)

Dudek et al; Phys. Rev. Lett. 88 (2002)

Dudek et al; Phys. Rev. Lett. 97 (2006)

Schunk et al; Int. J. Mod. Phys. E 15 (2006)

……

Zberecki et al; Phys. Rev. C 79 (2009)

Large number of publications based on mean field theories predict existence of Tetrahedral shape in nuclei

Exotic properties

Bearing of stability of nuclei

Identified in Molecules, Metal clusters, Fullerenes

Underlying interaction: Electromagnetic

Single particle energies for tetrahedral

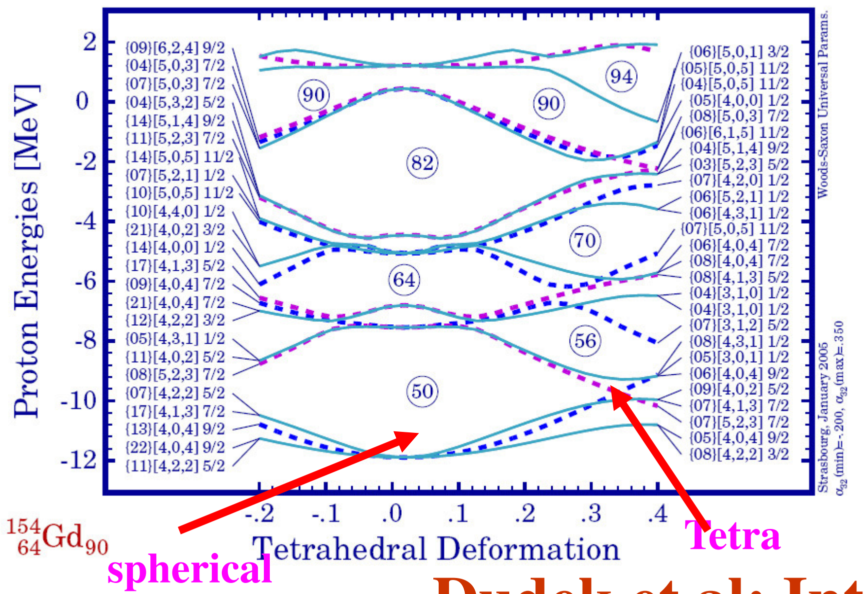


Fig. 2. Single-particle energy levels in function of the tetrahedral deformation for protons. Observe the presence of the four-fold degenerate orbitals marked with full lines and the strong gaps at Z=56, 64, 70, and 90/94 referred to as tetrahedral-magic.

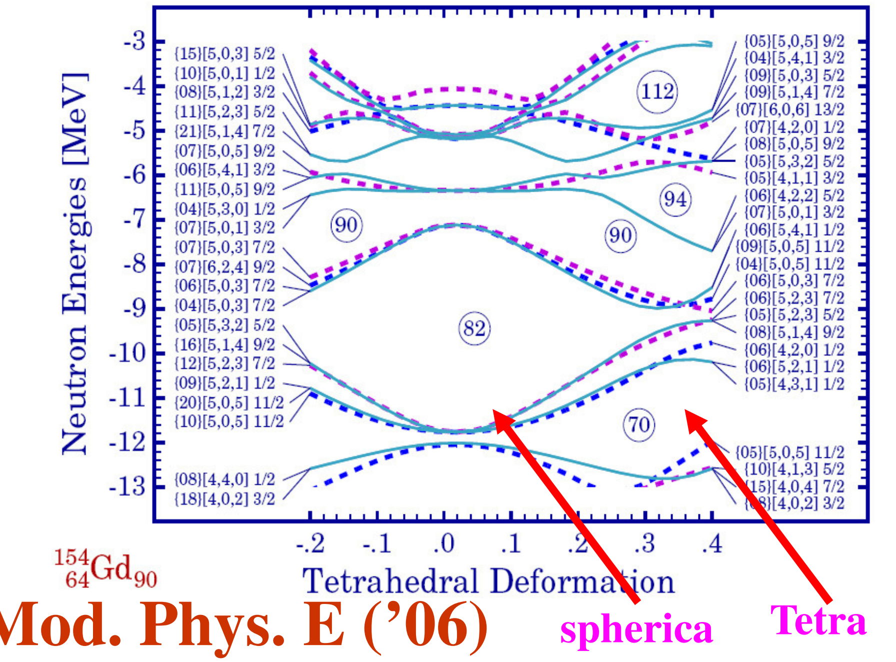


Fig. 3. Single-particle energy levels in function of the tetrahedral deformation for neutrons. Observe strong gaps at N=70, 90/94, and 112.

Dudek et al; Int. J. Mod. Phys. E ('06)

l

Large shell gaps : comparable to Spherical shell Gaps

Four fold degeneracy for some levels (pink)

Can it be confirmed by observation in experiments ?

What to look for ?

1) Find quadrupole moments

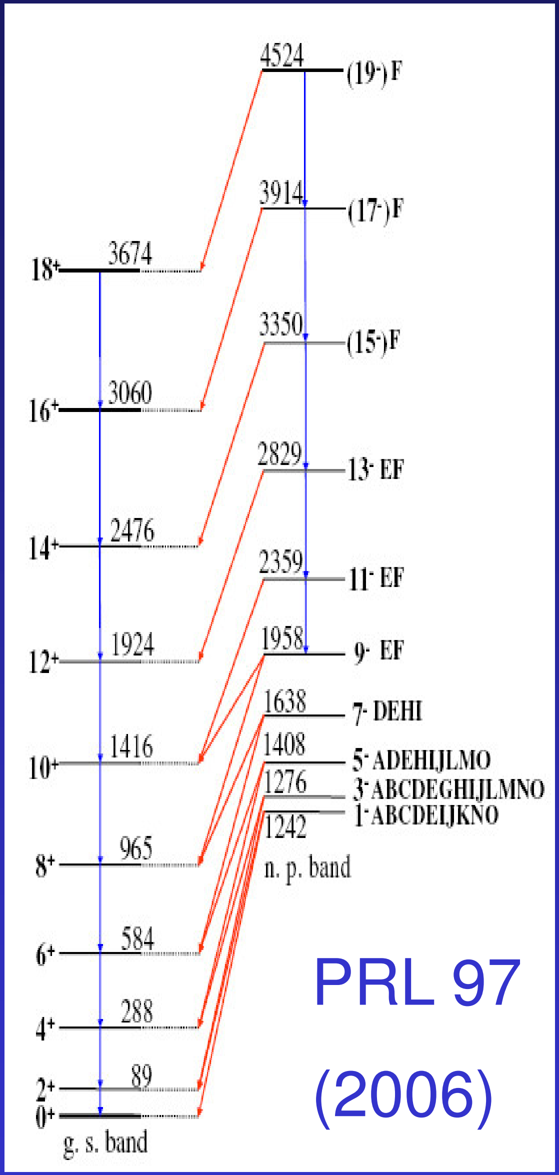
2) Precise branching ratios B(E2)/B(E1)

3) Set a limit on intra-band E2 transitions

4) Measure Lifetimes

^{156}Gd predicted to bit a fit candidate

Dudek et al; Phys. Rev. Lett. 97(2006)

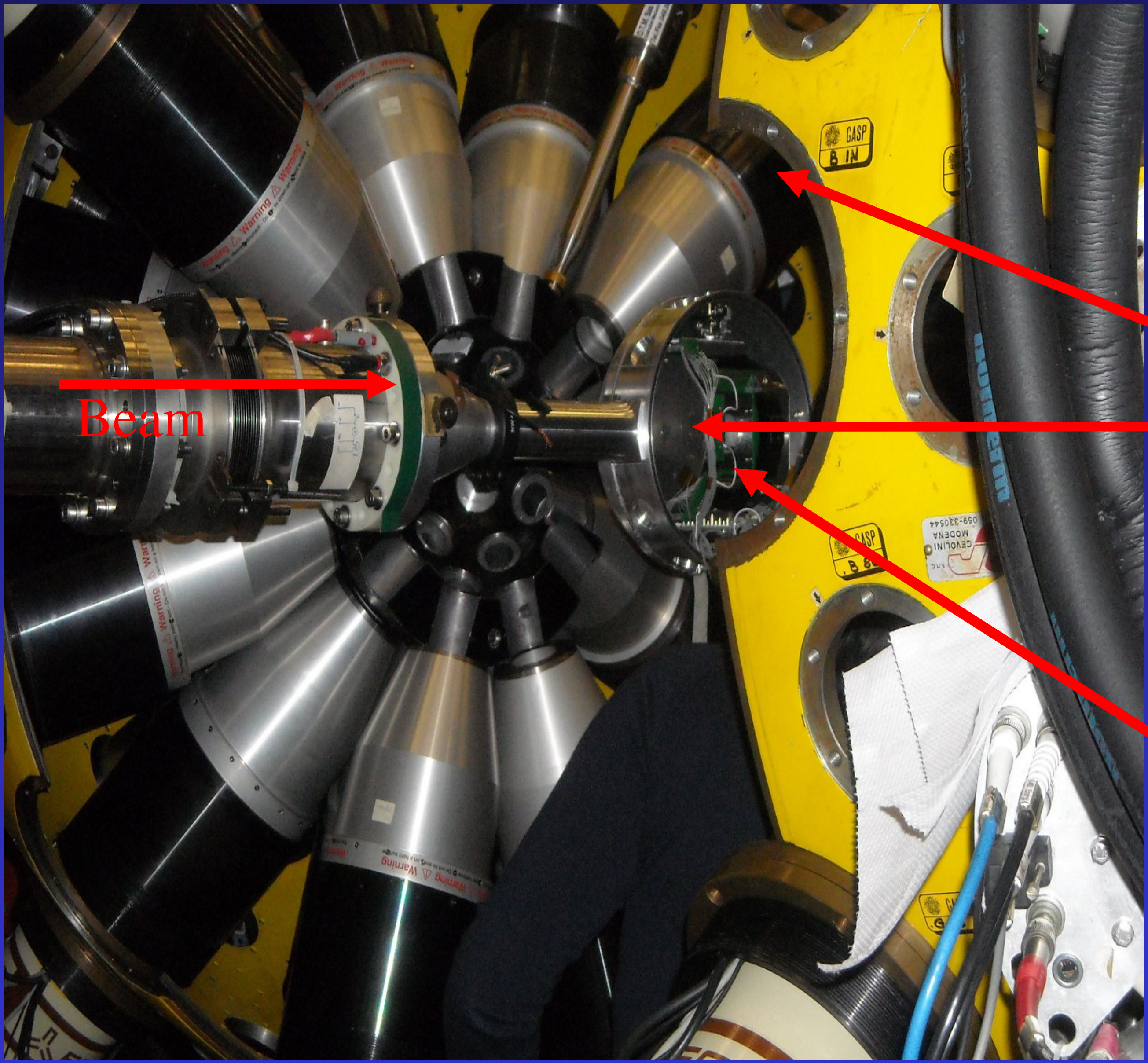


PRL 97

(2006)

Partial level scheme of ^{156}Gd

^{58}Ni beam on ^{156}Gd @ 225 MeV : safe Coulomb excitation



Beam from Tandem at

LNL, Legnaro, Italy

Ge detector array GASP

Annular Si strip detector

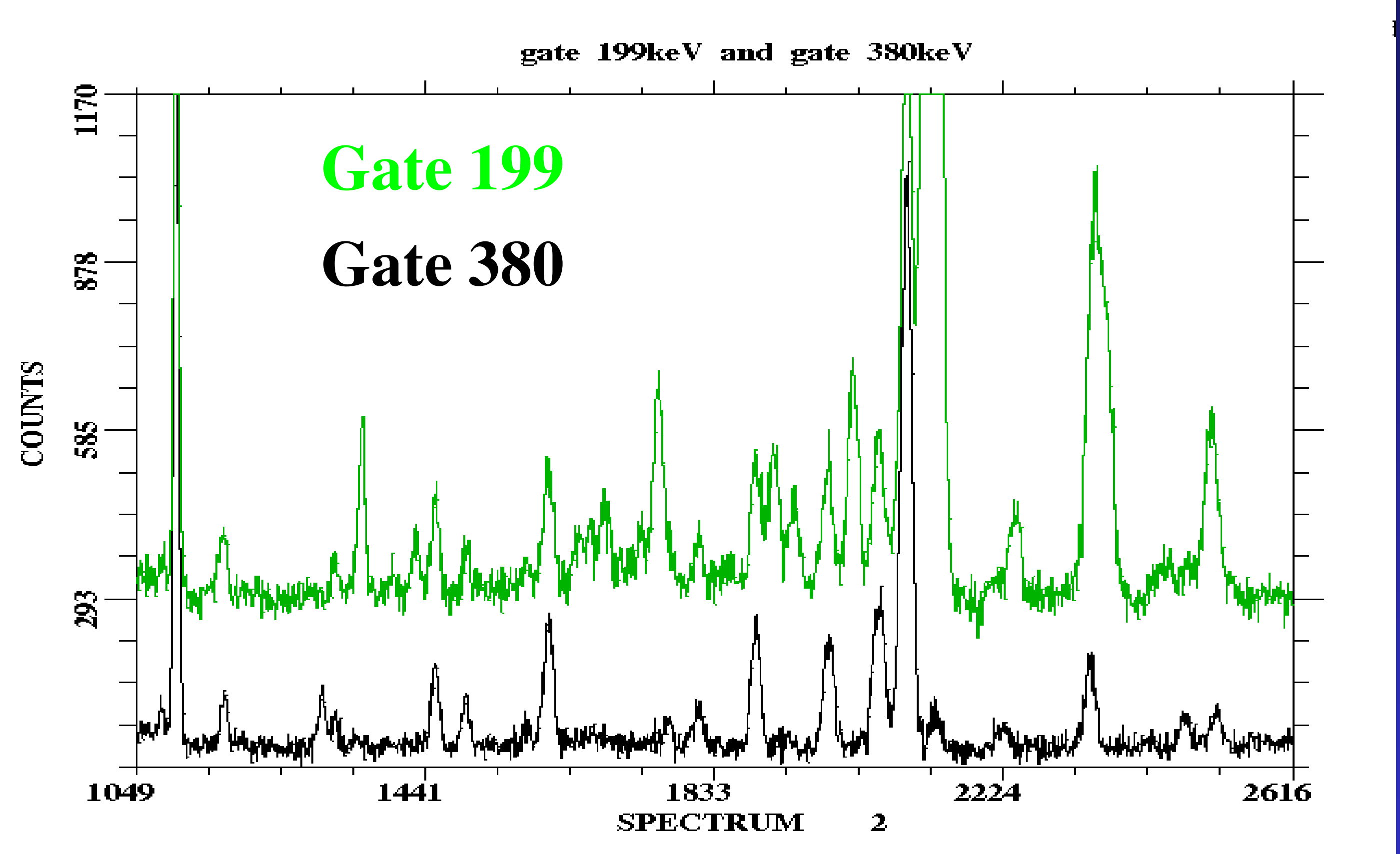
from Lund:

angle range ~137^{o}-170^{o}

Target ~ 1mg/cm^{2}

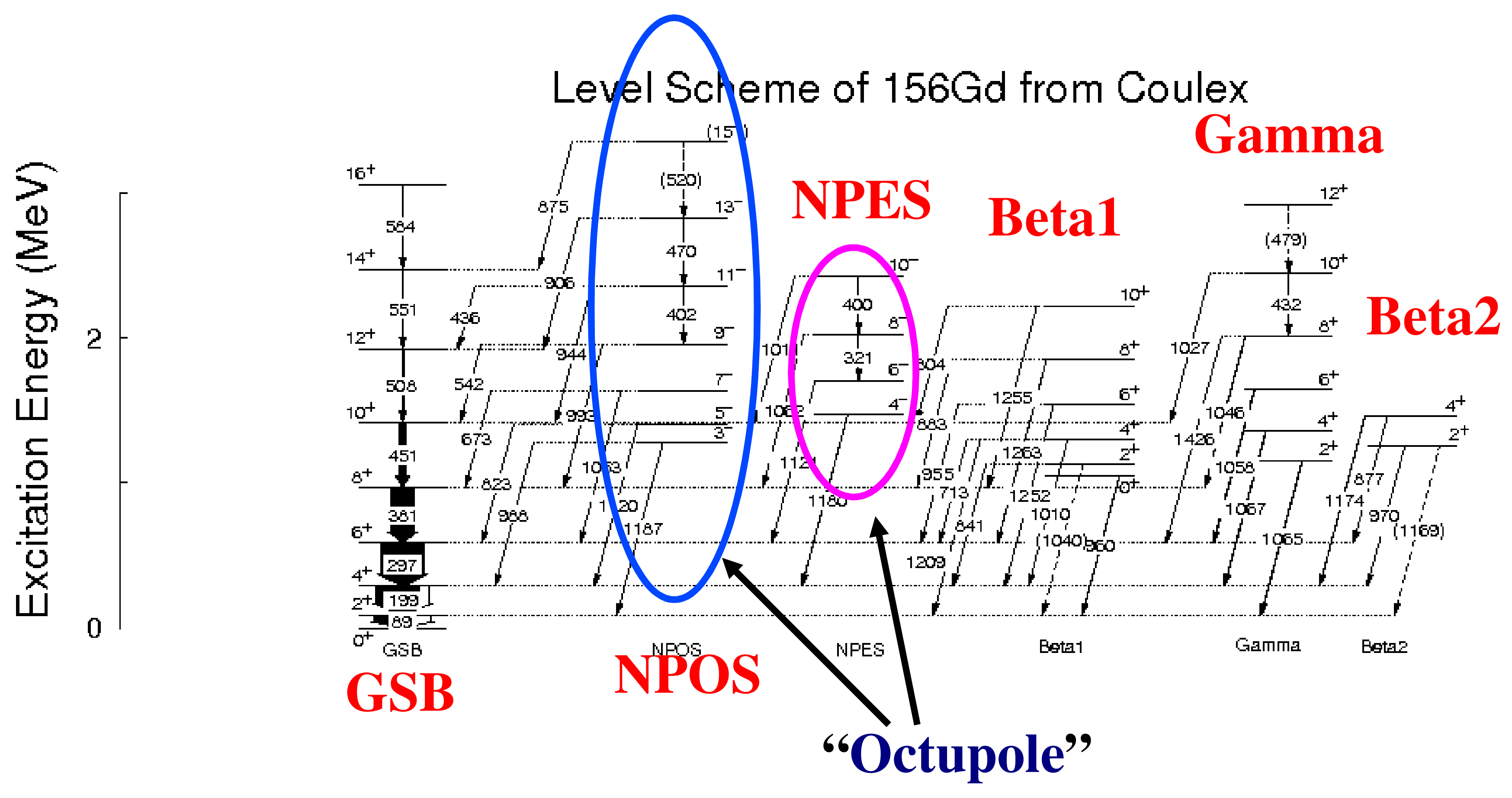
p-γ master trigger 1-2 k

Gamma spectrum from particle-gamma-gamma after Doppler correction



Lines from predicted tetrahedral band ~ 10^3 smaller !!

R P Singh et al (to be published)



Complicated level scheme for Coulomb excitation analysis

B(E2)/B(E1) very different for the even and odd spin "Octupole" bands

I^{π}	B(E2)/B(E1)			I^{π}	B(E2)/B(E1) in $10^6 fm^2$		
	a	b	c		a	b	c
17-	--	16(3)	--	12-	--	--	--
15-	4.5(1.0)	6(2)	< 9	10-	640(100)	240	>132
13-	5.5(0.6)	7(2)	31(13)	8-	330(10)	700	378(164)
11-	< 9	15(7)	27(9)	6-	210(15)	350	---

a, b from Doan et al; Act. Phys. Pol. B40(2009) and refs. there in

c from present work

B(E2)/B(E1) for even spin -ve parity **~ 50 . B(E2)/B(E1) for odd spin -ve parity**

=> Either B(E2) very small or B(E1) very large

Favors Tetrahedral

Bark et al; Phys Rev. Lett. 104 (2010) point out

Difference in hindrance for ΔK=0 and ΔK=1 for E1 transitions

Konijn et al; Nucl. Phys. A352 (1981)

Kocbach et al Phys. Lett. B 32 (1970)

Dracoulis et al; Nucl Phys. A383, 119 (1982)

Not quite conclusive

Detailed analysis based on Coulomb excitations code GOSIA in progress with collaborators at HIL,Warsaw

About 160 matrix elements to be varied to reproduce the yields and other spectroscopic informations

Need to worry about the uniqueness of the solution

Recently reported study Sugwara et al; Phys. Rev C 83 (2011)
~ 20 year old data of Coulex of ^{156}Gd reports
Qo ~ 7eb
No even spin negative pairty band
B(E2)/B(E1) ?

Existence of tetrahedral symmetry in nuclei still a open question

Summary

1. Coulomb excitation is a very useful tool for nuclear structure studies

2. Study of ^{112,114}Sn isotopes through Coulex established enhancement of B(E2;↑) from ^{116}Sn towards lighter Sn isotopes

3. Definite deviation of symmetric trend of B(E2;↑) values with ^{114}Sn as the turning point;

4. The proposed tetrahedral band was populated thro' muti-step Coulomb exciations and the level scheme for ^{156}Gd constructed

5. B(E2)/B(E1) quite different for this band ; Detailed analysis using the code Gosia is being done to get the quadrupole moment of the band

THANKS for your Attention