Electromagnetic properties of odd Scandium isotopes studied by low-energy Coulomb excitation

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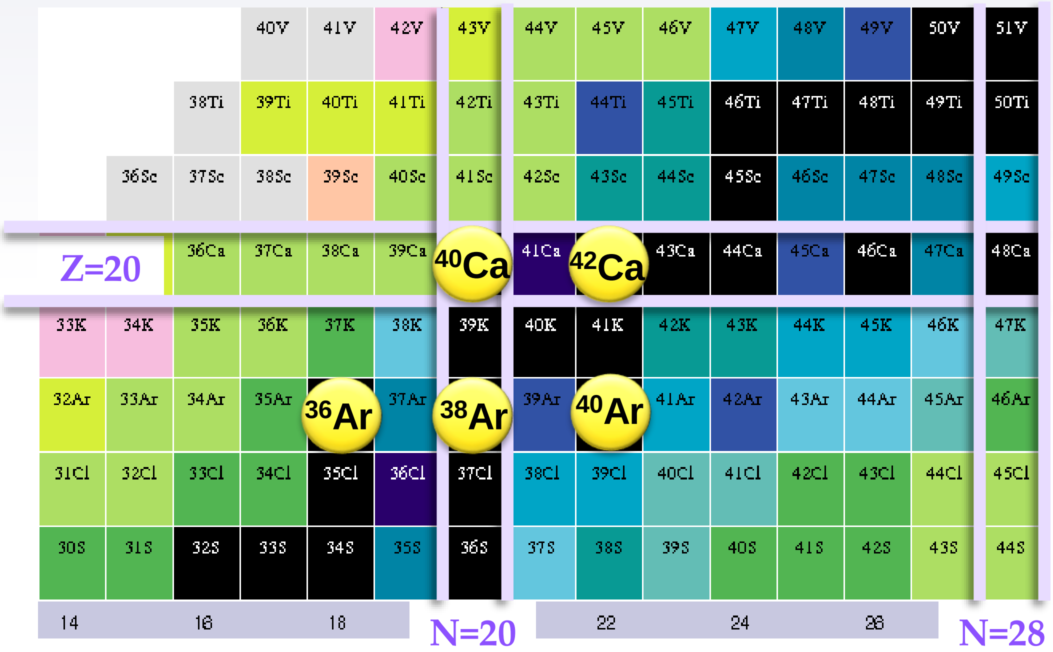
Outline

- Characteristic of odd-Sc isotops
- Motivation to study the ^{45}Sc
- What experimental technique and why?
- Performed measurements
  - HIL UW Warsaw
  - IUAC New Delhi
- Obtained results
- Interpretation
  - Shell-model calculations with the ZBM2 interaction
  - Large-scale mean-field calculation
- Conclusions

Vicinity of doubly-magic ^{40}Ca

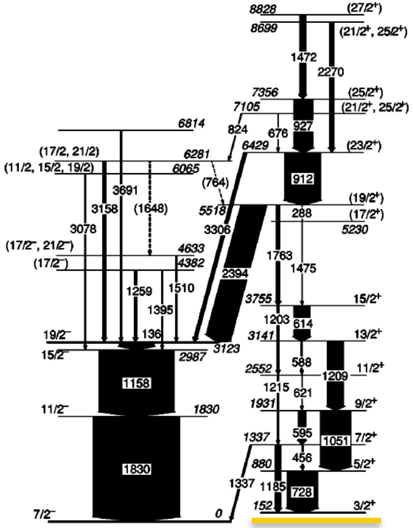


			40V	41V	42V	43V	44V	45V	46V	47V	48V	49V	50V	51V
		38Ti	39Ti	40Ti	41Ti	42Ti	43Ti	44Ti	45Ti	46Ti	47Ti	48Ti	49Ti	50Ti
	36Sc	37Sc	38Sc	39Sc	40Sc	41Sc	42Sc	43Sc	44Sc	45Sc	46Sc	47Sc	48Sc	49Sc
Z=20		36Ca	37Ca	38Ca	39Ca	^{40}Ca	41Ca	^{42}Ca	43Ca	44Ca	45Ca	46Ca	47Ca	48Ca
33K	34K	35K	36K	37K	38K	39K	40K	41K	42K	43K	44K	45K	46K	47K
32Ar	33Ar	34Ar	35Ar	^{36}Ar	37Ar	^{38}Ar	39Ar	^{40}Ar	41Ar	42Ar	43Ar	44Ar	45Ar	46Ar
31Cl	32Cl	33Cl	34Cl	35Cl	36Cl	37Cl	38Cl	39Cl	40Cl	41Cl	42Cl	43Cl	44Cl	45Cl
30S	31S	32S	33S	34S	35S	36S	37S	38S	39S	40S	41S	42S	43S	44S
14		16		18		N=20		22		24		26		N=28

- Sc isotopes - in the vicinity of ^{40}Ca
- p-h excitations across shell gap results in appearance of SD structures
- ^{36,38,40}Ar, ^{40,42}Ca and ^{44}Ti
- LSSM calculations get in general good agreement with experimental data
- Number of active particles and the $p_{3/2}f_{7/2}$ are large enough to allow for the collective motion of nucleons, therefore
- Nuclei in the vicinity of the doubly magic ones are excellent playground for the theoretical models

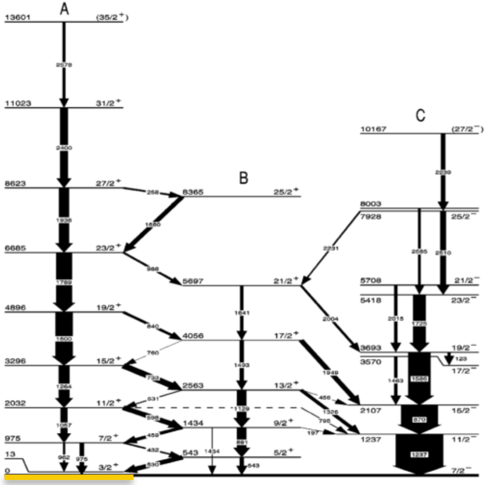
Structure of odd Scandium isotopes

^{43}Sc



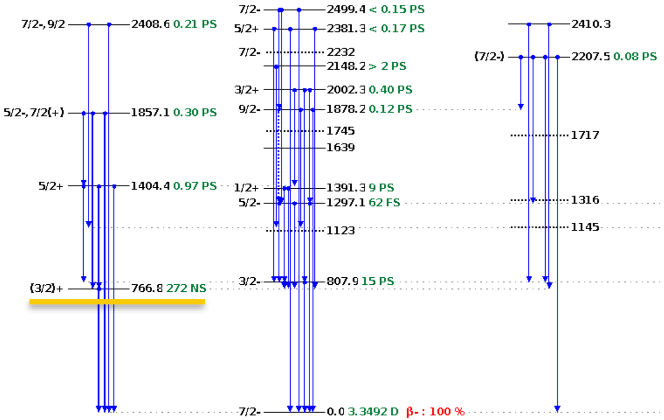
T. Morikawa et al., Phys.Rev.C **70**, 054323 (2004)

^{45}Sc



P. Bednarczyk et al., Eur.Phys.J.A 2, 157 (1998)

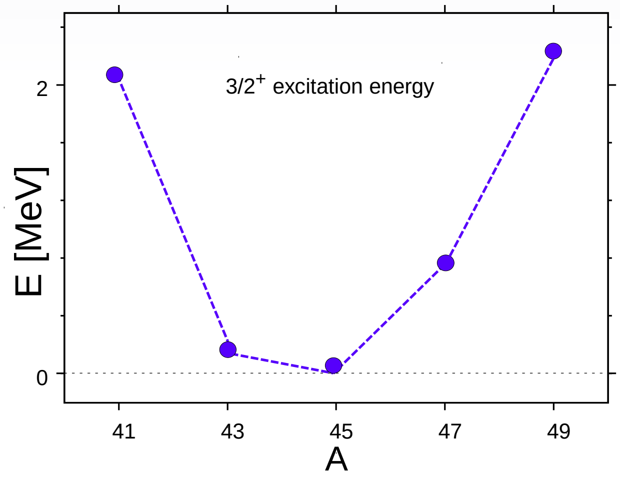
^{47}Sc



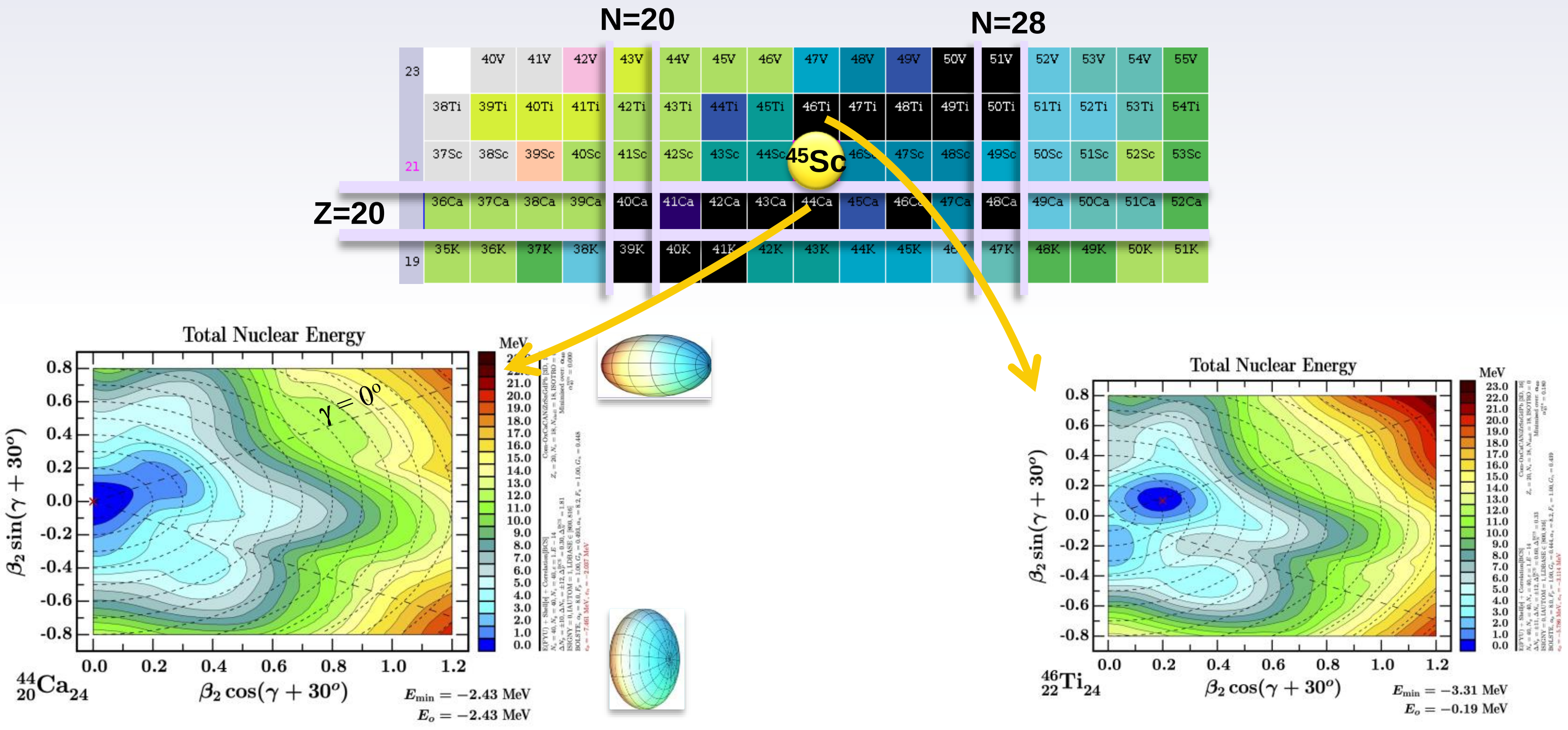
https://www.nndc.bnl.gov/nudat2/

- The structure of odd-mass Sc isotopes is especially interesting because of the coexistence of positive-parity and negative-parity bands near the ground state,
- ^{45}Sc has a degenerated 3/2$^+$ positive-parity state only 12.4 keV above the 7/2- ground state,$T_{1/2}$ = 318 ms isomeric state
- In ^{43}Sc 3/2$^+$ at 152 keV and $T_{1/2}$ = 438 µs, ^{47}Sc 3/2$^+$ at 152 keV and $T_{1/2}$ = 272 ns

Sc isotopic chain

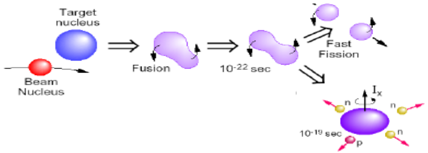


- ✓ $3/2^{+}$ is the first excited state in odd Sc isotopes
- ✓ In the even-even nuclei the evolution of the first 2^{+} state in the given isotopic chain ~ 200 keV



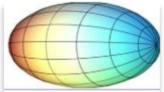
- From the total energy maps we see that ^{45}Sc is exactly where the nuclei have to decide where they stop being spherical and start being prolate-deformed
- There is also a valley near the oblate shape - one may expect prolate-oblate competition in the ^{45}Sc
- Calculation were performed by Irene Dedes (IFJ PAN, Kraków) and Jerzy Dudek (IPHC and CNRS, Strasbourg) using the macroscopic-microscopic method with the realistic phenomenological mean-field Woods-Saxon universal parametrization

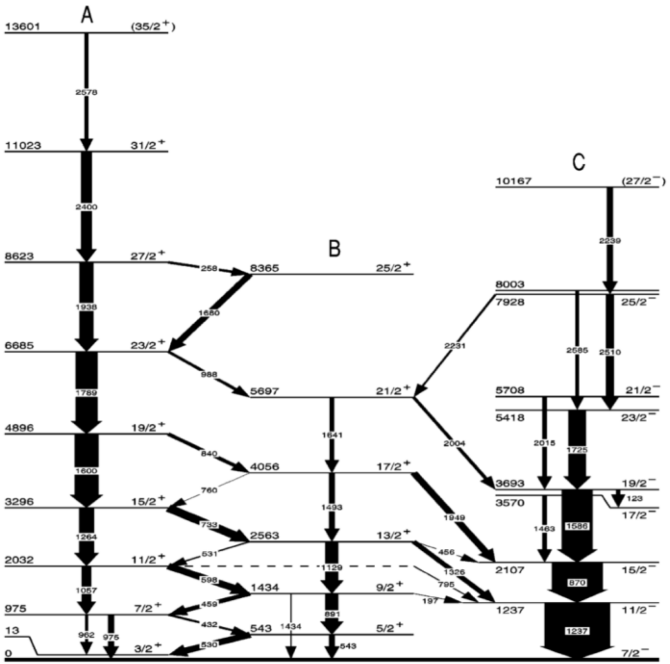
^{45}Sc - comprehensive approach



Fusion-evaporation reaction: 68 MeV ^{18}O + ^{30}Si
Lifetimes up to $11/2^+$ were determined
Assuming rotational model and prolate def.
corresponding elongation β~0.3, rather stable along the band.
P. Bednarczyk, et al., Eur. Phys. J. A 2, 157 (1998)S

Izomeric $3/2^+$ state at 12.4 keV ($T_{1/2}$=318 ms)
From the laser spectroscopy measurement:
Qs = + 0.28(5) b, **prolate** def. β~0.3
M. Avgoulea, et al., J. Phys. G: Nucl. Part. Phys. **38**, 025104 (2011).





P. Bednarczyk, et al., Eur. Phys. J. A 2, 157 (1998)

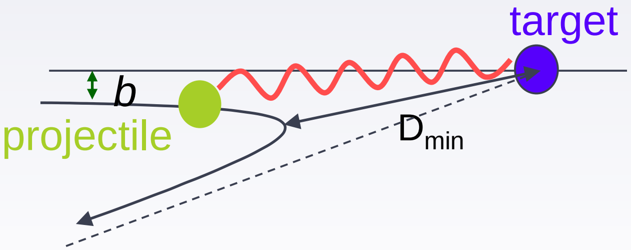
- Coulomb excitation is a unique method allowing to populate low-lying and low-spin nuclear states starting from the ground state. This technique is preferred tool to study low-lying structures.

Motivation

- Investigate electromagnetic structure of ^{45}Sc at low excitation energy
- To obtain complete picture of the deformation along the positive parity band
- Coulomb excitation is used for comprehensive study of low-lying excitations (it allows to extract matrix elements in the model independent way)
- To determine spectroscopic quadrupole moments for the $3/2^+$ state and the ground state, and the deformation parameters – relevant for the possible prolate-oblate competition
- ^{45}Sc - unique case – to compare results obtained in two model independent techniques (Q_s for $3/2^+$ state)
- The odd Sc nuclei exhibit both collective and single-particle characters providing an interesting testing ground for the study of the interplay between the single-particle and collective degrees of freedom in the nuclei near the closed shell

Coulomb excitation

Coulomb excitation is a purely electromagnetic interaction acting between two colliding nuclei due to the Coulomb field



Excitation mechanism – purely electromagnetic

Coulomb excitation requires a distance between the nuclei - ”safe energy” requirement. If the distance of closest approach d_{min} fulfills condition the influence of the strong interaction can be ignored (less than 0.1 %)

$$d_{min} > \left[1.25\left(A_P^{1/3} + A_T^{1/3}\right) + 5\right] fm$$

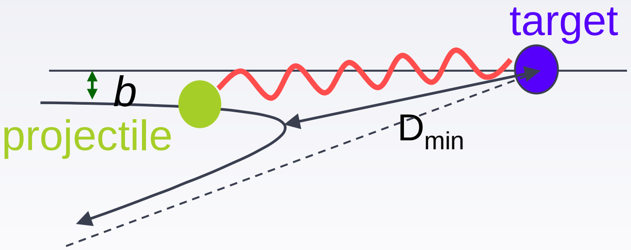
Nuclear structure studied in a model-independent way. Electromagnetic interaction is well known, and no model of the strong interaction is applied.

Coulomb excitation is a precise tool to measure the collectivity of nuclear excitations and in particular nuclear shapes

Bring information on Qs and relative signs of matrix elements – direct distinguish between prolate and oblate shape

It is the only experimental technique that can distinguish between prolate and oblate shape of the nucleus in a short-lived excited state

Coulomb excitation



Solving the time-dependent Schrödinger equation:

$$i\hbar \, d\psi(t)/dt = [H_P + H_T + V(r(t))] \, \psi(t)$$

with $H_{P/T}$ being the Hamiltonian of the projectile and target nucleus

and $V(t)$ being the time-dependent electromagnetic interaction

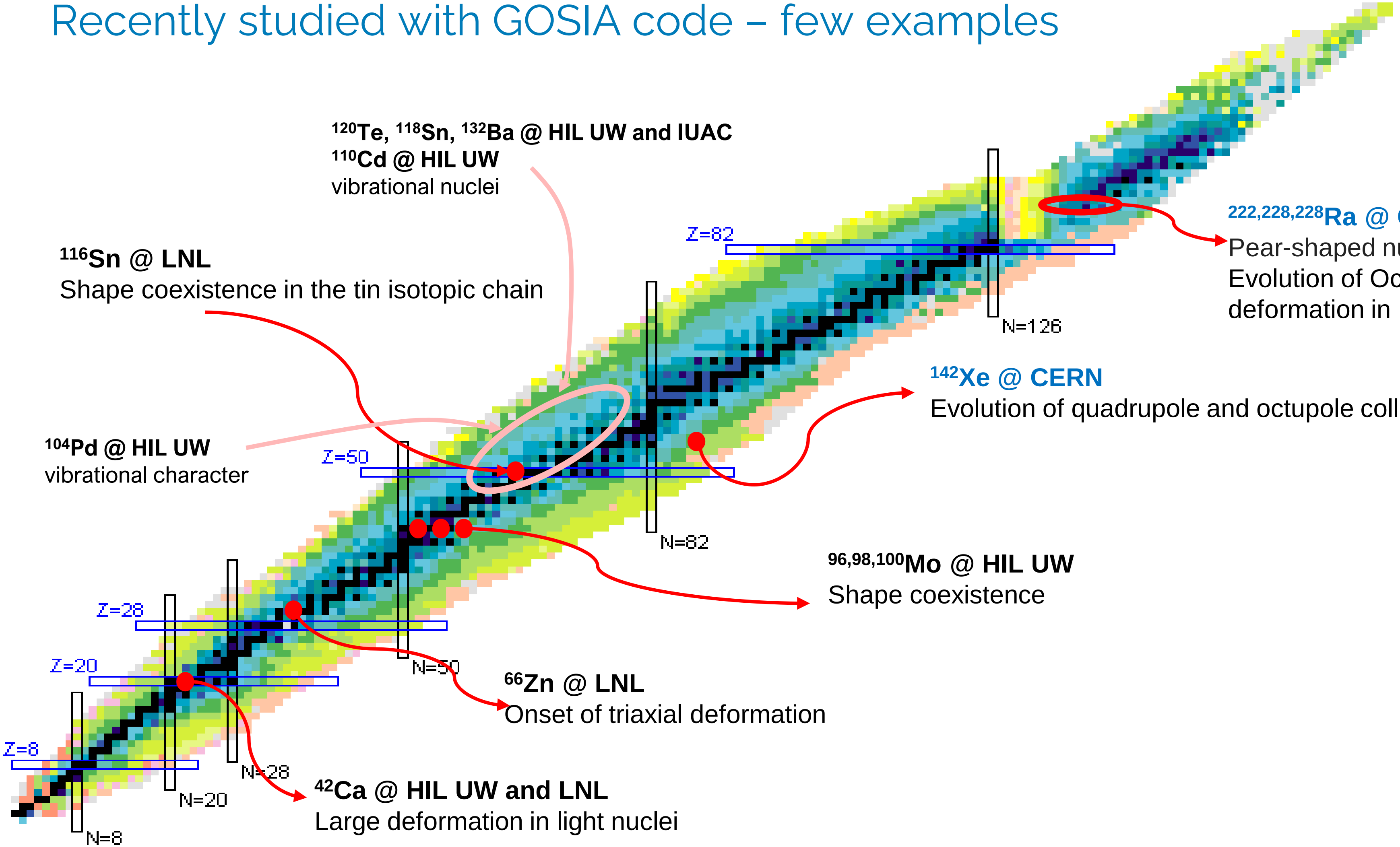
Leads to the excitation probability (stage 1 - excitation).

Information on excitation probability and initial state population (calculated in stage 1)

are used in decay calculation - stage 2

- ✓ GOSIA is a Coulomb excitation code using a two-stage approach and a least-squares search method - complex tool for the "Coulex" data analysis
- ✓ Developments in radioactive ion beam technology led to great interest in studying the nuclear structure via "Coulex"
- ✓ Coulomb excitation at safe energies with RIB is giving the first exploration of excited states in exotic nuclei

Recently studied with GOSIA code – few examples



^{120}Te, ^{118}Sn, ^{132}Ba @ HIL UW and IUAC
^{110}Cd @ HIL UW
vibrational nuclei

^{116}Sn @ LNL
Shape coexistence in the tin isotopic chain

^{104}Pd @ HIL UW
vibrational character

^{222,228,228}Ra @ CERN
Pear-shaped nuclei
Evolution of Octupole deformation in Radium

^{142}Xe @ CERN
Evolution of quadrupole and octupole collectivity

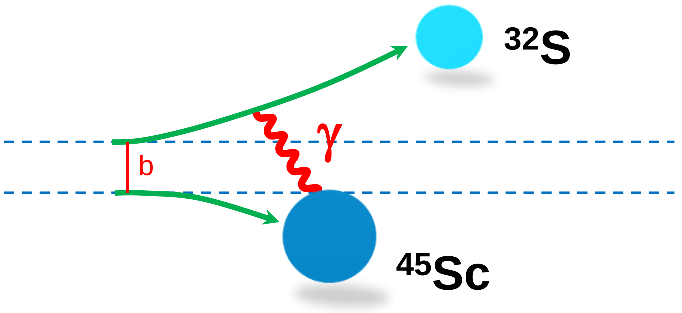
^{96,98,100}Mo @ HIL UW
Shape coexistence

^{66}Zn @ LNL
Onset of triaxial deformation

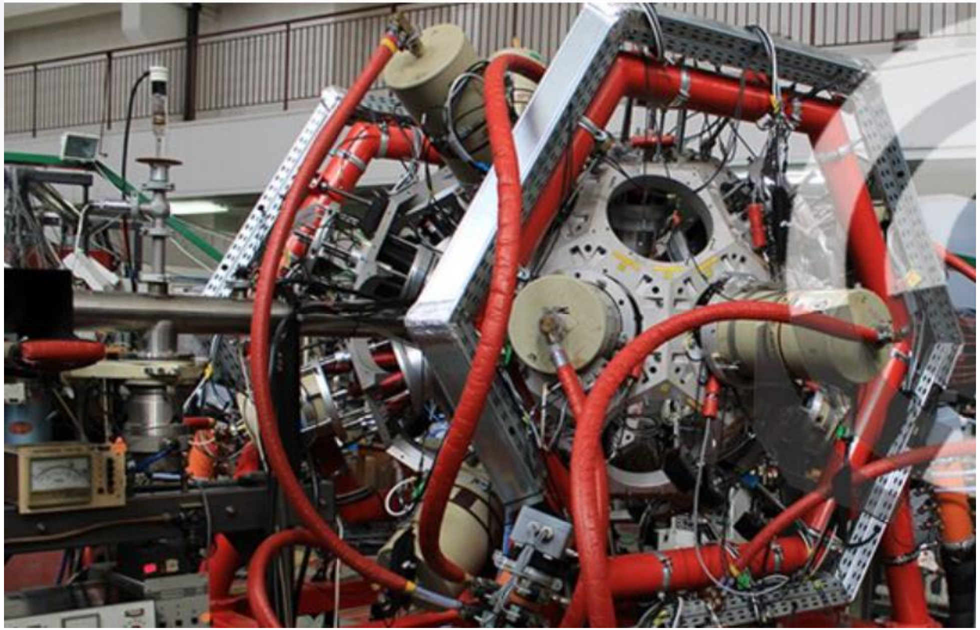
^{42}Ca @ HIL UW and LNL
Large deformation in light nuclei

Coulomb excitation of ^{45}Sc @ HIL UW

- ✓ ^{32}S beam from Warsaw cyclotron
- ✓ 70 MeV ^{32}S + 1mg/cm^2 ^{45}Sc
- ✓ Gamma-rays in coincidence with scattered ions



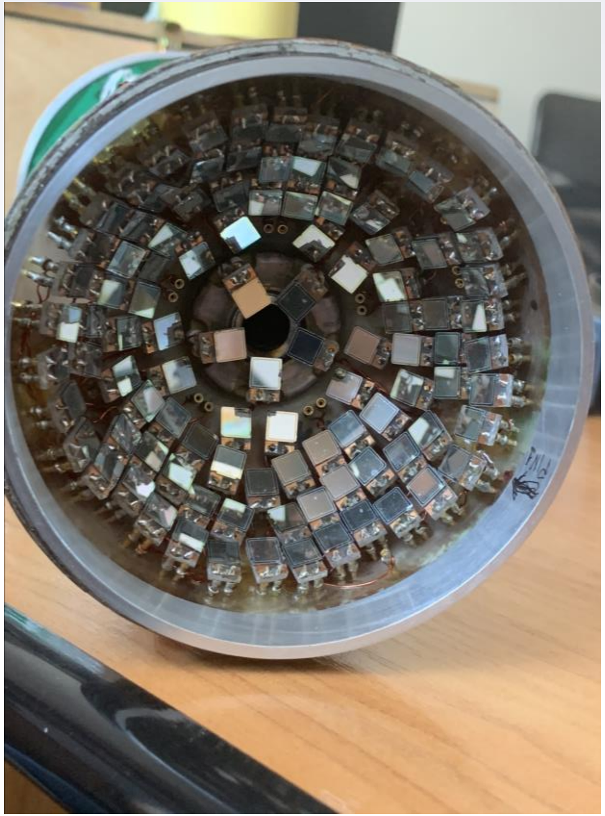
European **A**rray for **G**amma **L**evels **E**valuations at Heavy Ion Laboratory University of Warsaw



γ-ray spectrometer composed of 16 Germanium detectors with ACS
Efficiency @1112 keV is 0.9%

Coulex chamber

- A compact scattering chamber equipped with
- 0.5 x 0.5 cm^2 PIN diodes
- Modular chamber – can hold up to 110 PiN diodes

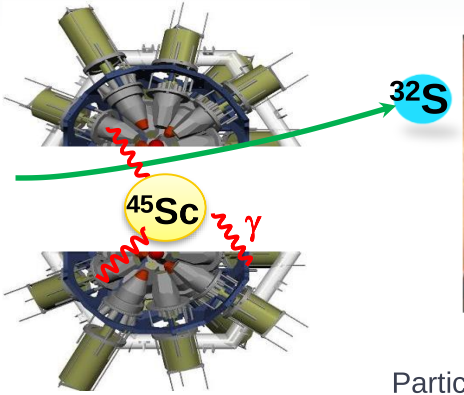


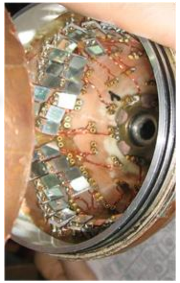
Experimental setup @ HIL UW

70 MeV ^{32}S + 1mg/cm^2 ^{45}Sc

Emax(69^o) = 70 MeV

Emax(49^o) = 78 MeV





48 PiN-Diode HI Detectors

θ_{LAB}: 49 ÷ 69 deg
θ_{CM}: 38 ÷ 111 deg

Particle detector set at forward angles for the very first time! Energy of back-scattered ions - too small to be detected in PIN diodes.

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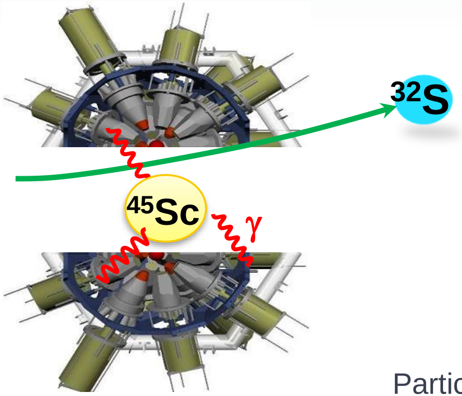

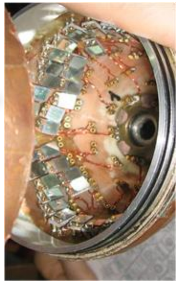

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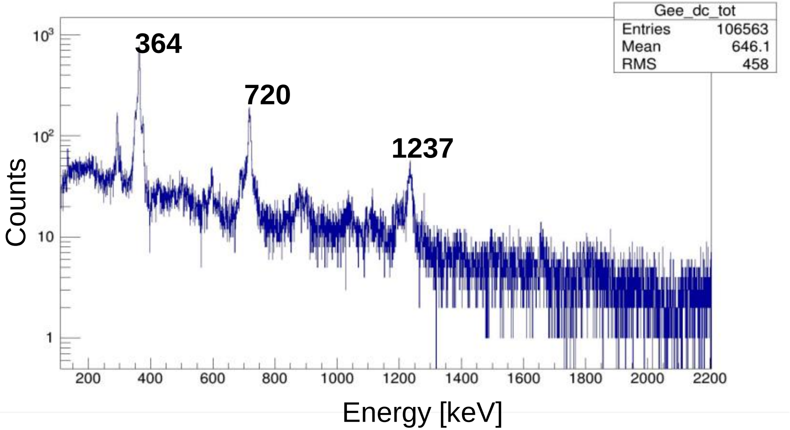
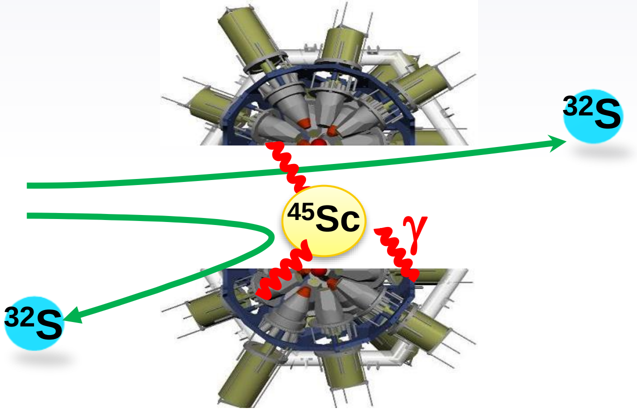


- particle-gamma coincidences
- only 16 hours of data taking

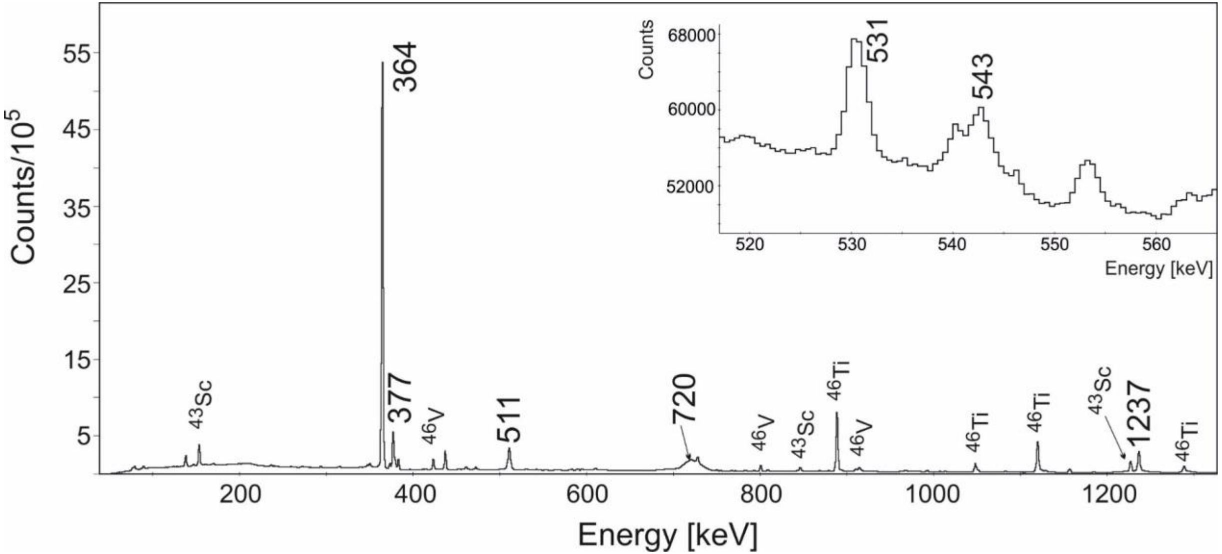
Experimental setup @ HIL UW part 2

Experimental setup @ HIL UW part 2

- Integral measurement
- θ_{CM}: 0 ÷180 deg
- 70 MeV ^{32}S + **15** mg/cm^{2} ^{45}Sc
- Thick target
- Gamma-singles

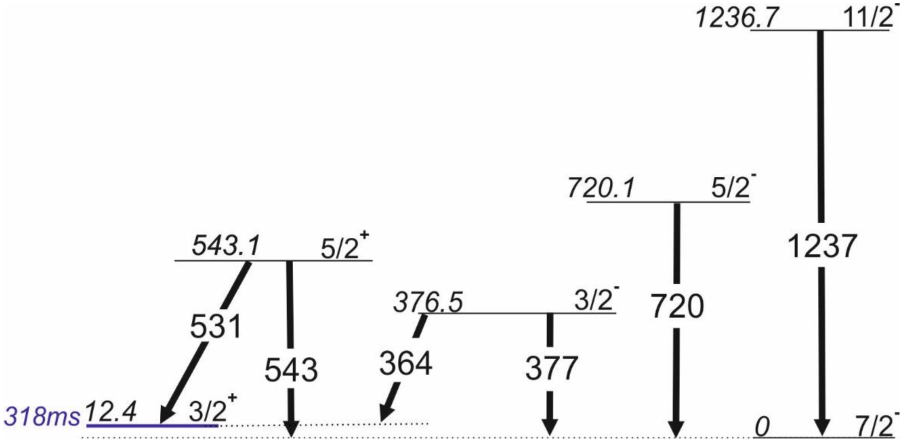


Collected γ-ray energy spectrum



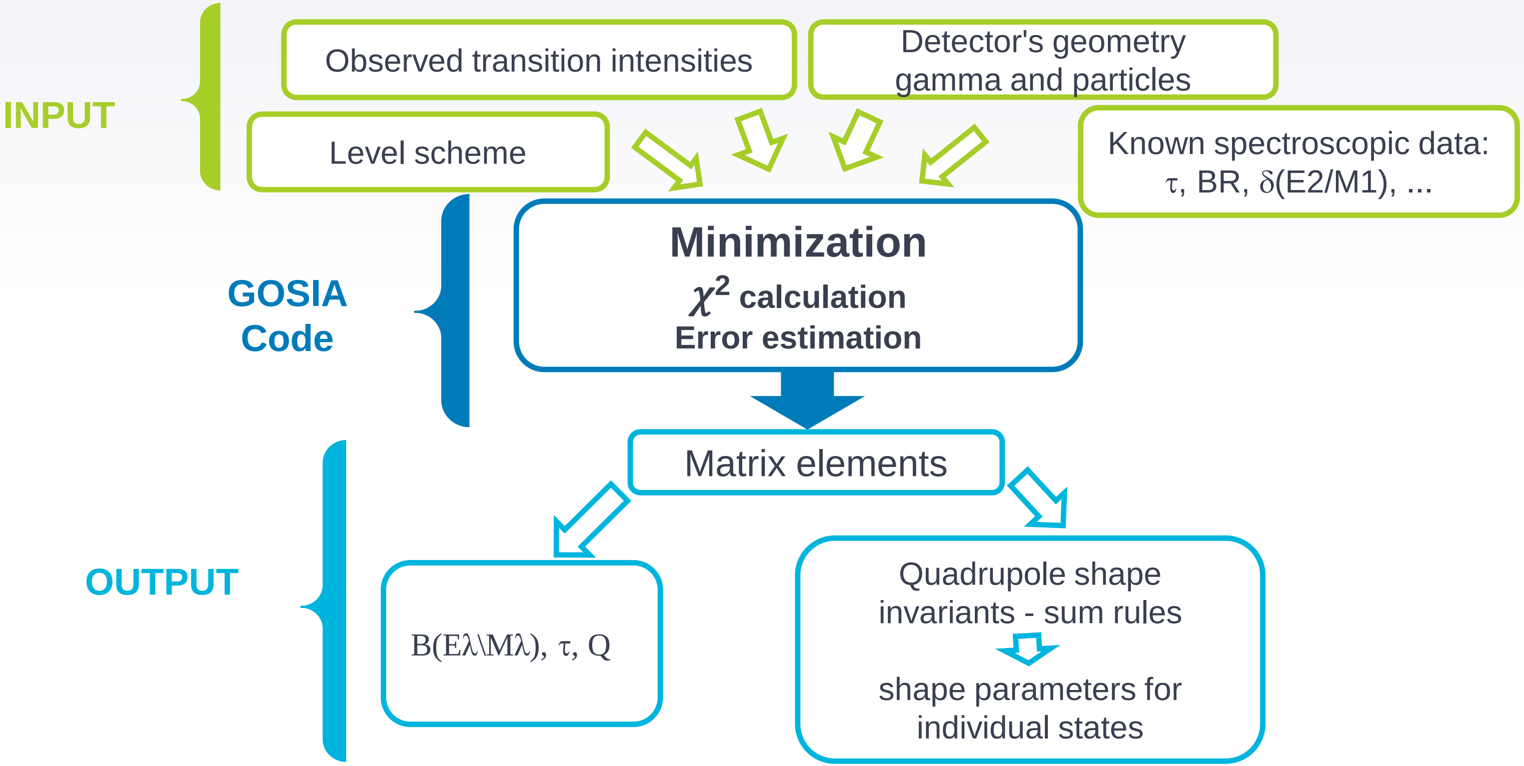
- ✓ 70 MeV ^{32}S beam + thick 15 mg/cm^2 ^{45}Sc target
- ✓ Sum over 16 detectors
- ✓ Lines originating from the reaction products on the target oxidation are marked; i.e., ^{46}Ti, ^{46}V, ^{43}Sc

^{45}Sc level scheme



- ✓ Observation of the 531 and 543 keV confirmed that the positive parity band was populated, and BR confirms identification

GOSIA is a Rochester – Warsaw Coulomb excitation code to reproduce experimentally observed gamma-ray intensities



INPUT

Observed transition intensities

Detector's geometry
gamma and particles

Level scheme

Known spectroscopic data:
τ, BR, δ(E2/M1), ...

GOSIA
Code

Minimization
χ^2 calculation
Error estimation

Matrix elements

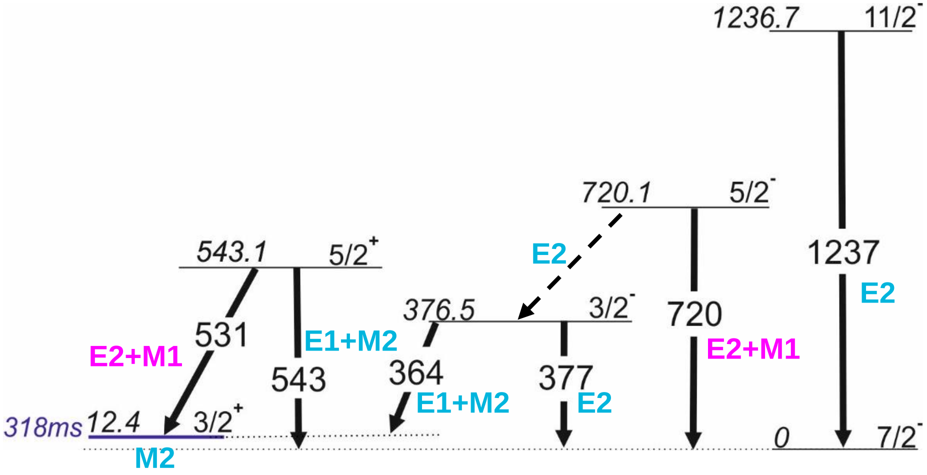
OUTPUT

B(Eλ\Mλ), τ, Q

Quadrupole shape
invariants - sum rules

shape parameters for
individual states

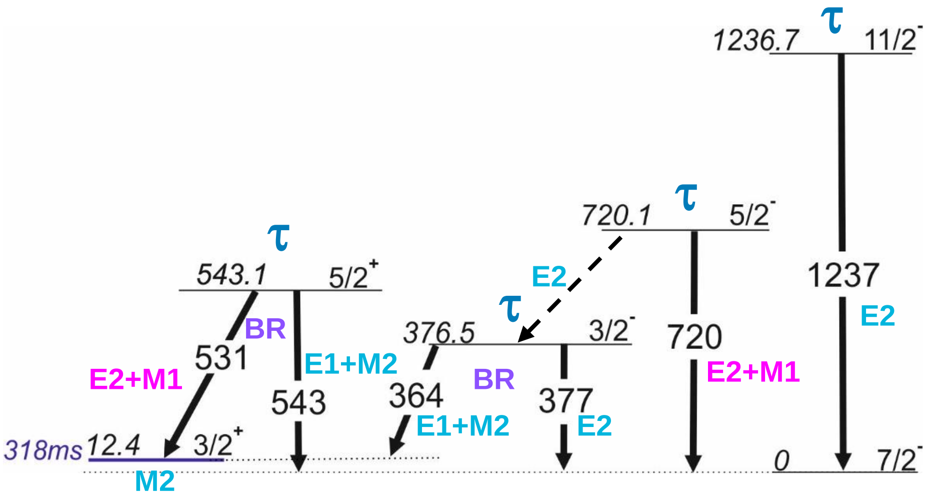
Data analysis



^{45}Sc case:

- 14 matrix elements
- 6 experimental data

Data analysis



^{45}Sc case:

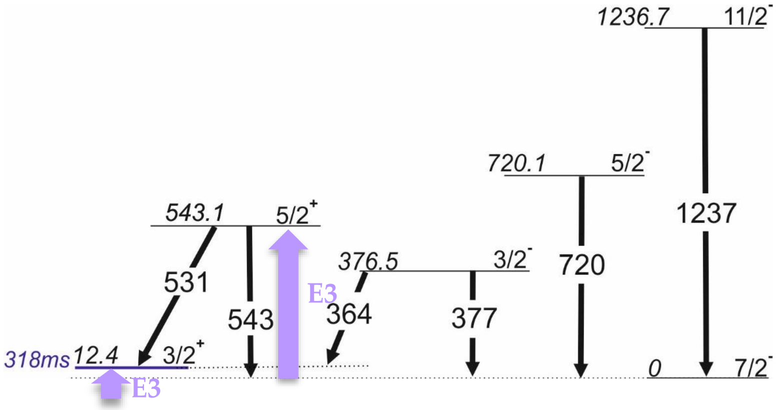
- 14 matrix elements
- 6 experimental data

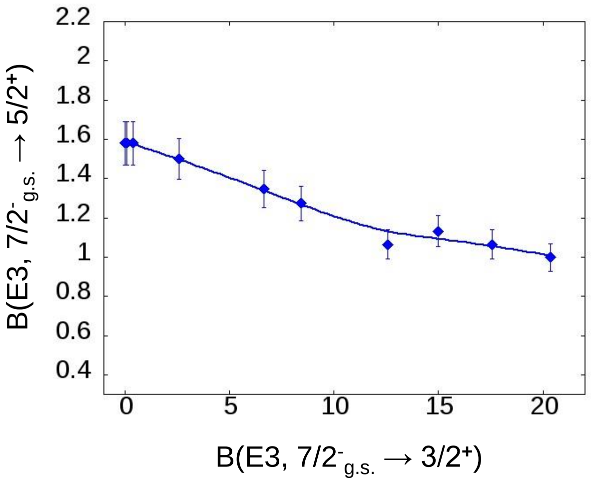
Included into GOSIA calculations:

1) Observed line intensities
2) Additional constrains:
    - Level lifetimes
    - Branching ratios
    - Mixing ratios δ(E2/M1)

The positive-parity, low-lying states in ^{45}Sc were excited via E3 transitions

GOSIA calculations





In the NNDC data base:

B(E3, $7/2^-_{g.s.}$ → $3/2^+$) ≤ 105 e^2fm^6=0.87 W.u.

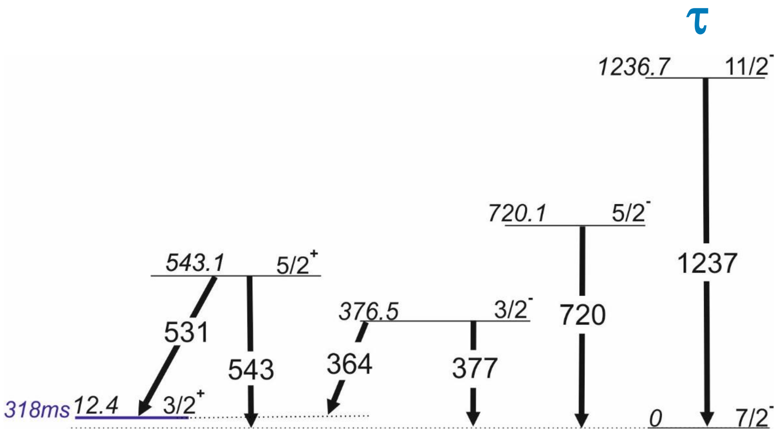
B(E3, $7/2^-_{g.s.}$ → $5/2^+$) was unknown

- ✓ $5/2^+$ can be excited
  via 1 step E3 and/or
  via 2 steps E3+M1/E2

Result: B(E3, $7/2^-_{g.s.}$ → $5/2^+$) ≤ 1.7 W.u.

- ✓ The B(E3, $7/2^-$ → $5/2^+$) have been determined for the first time
- ✓ Because it was integral measurement (over all scattering angles) we could get only an upper limit

GOSIA calculations



Lifetimes for the 11/2$^-$ literature values:

- $T_{1/2}$=0.12 (8) ps from DSAM
- $T_{1/2}$=1.60 *34* ps from (p,p'γ)
- $T_{1/2}$=1.80 *10* ps from (γ,γ), NNDC
- $T_{1/2}$=2.4 (+10, -6) ps from (α,pγ)

- From our data B(E2, 11/2$^-$ → 7/2$^-$) differs from what was already known
- Lifetime of 11/2$^-$ state is longer that the literature value

Without particle-gamma coincidences - difficult analysis …

- Integrate over wide range of scattering angles
- Integrate over wide range of bombarding energies (energy loss in thick target)

- Could not determine both B(E3) excitation probabilities, only limit for the B(E3, $7/2^-_{g.s.} \rightarrow 5/2^+$)
- Information that lifetime of $11/2^-$ state is longer that the literature value

- **Projectile and target combination we were able to populate isomeric band**
- **Spectrum with particle-gamma coincidences we get at the beginning was very promising, number of counts was similar to the simulated one**

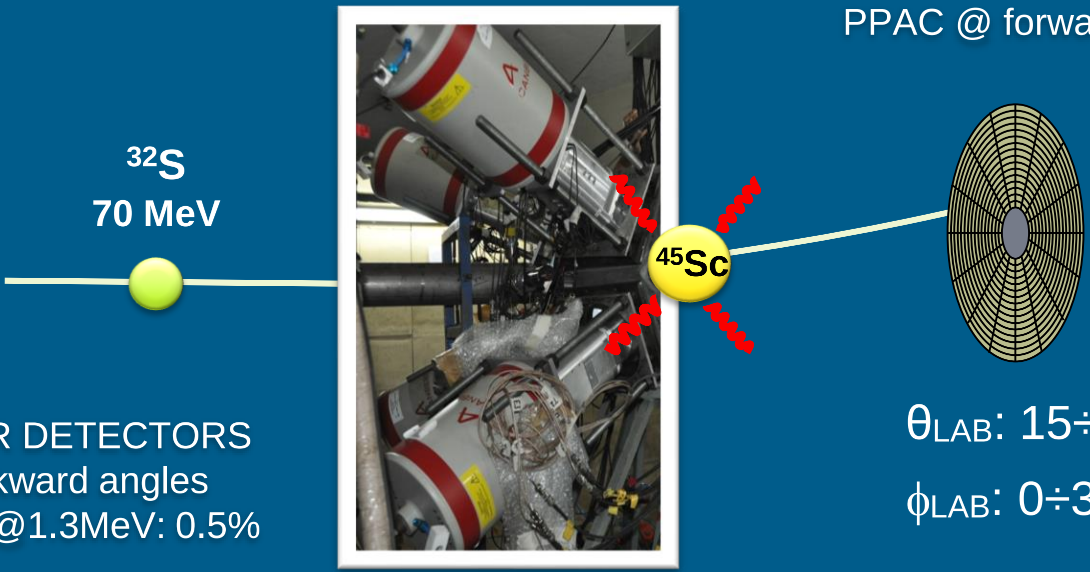
Experiment in the laboratory that has forward particle detector suitable for this kind of measurements …

Inter-University Accelerator Centre (IUAC) in New Delhi

November/December 2017

- 70 MeV ^{32}S beam + 1 mg/cm^2 ^{45}Sc

Particle detector
PPAC @ forward angle



Front: 16 segments (phi)
Back: delay-lines (theta)

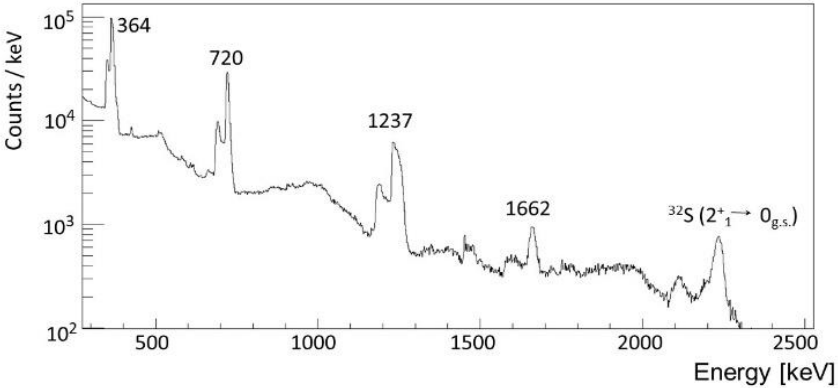
4 CLOVER DETECTORS
@ backward angles
Efficiency@1.3MeV: 0.5%

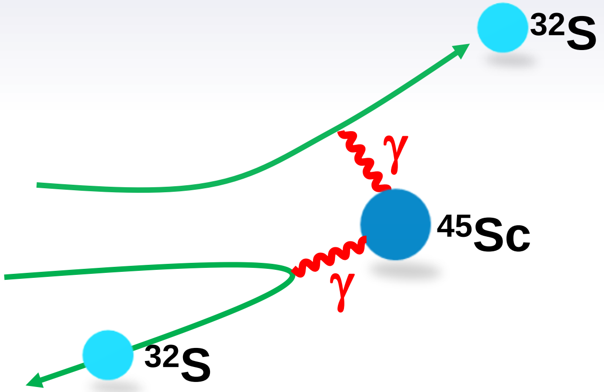
θ_{LAB}: 15÷45 deg

ϕ_{LAB}: 0÷360 deg

IUAC data analysis

Total gamma-ray energy spectrum of ^{45}Sc. Doppler correction applied for the projectile ions registered in APPAC





Double-peak structure - two kinematic solutions were registered

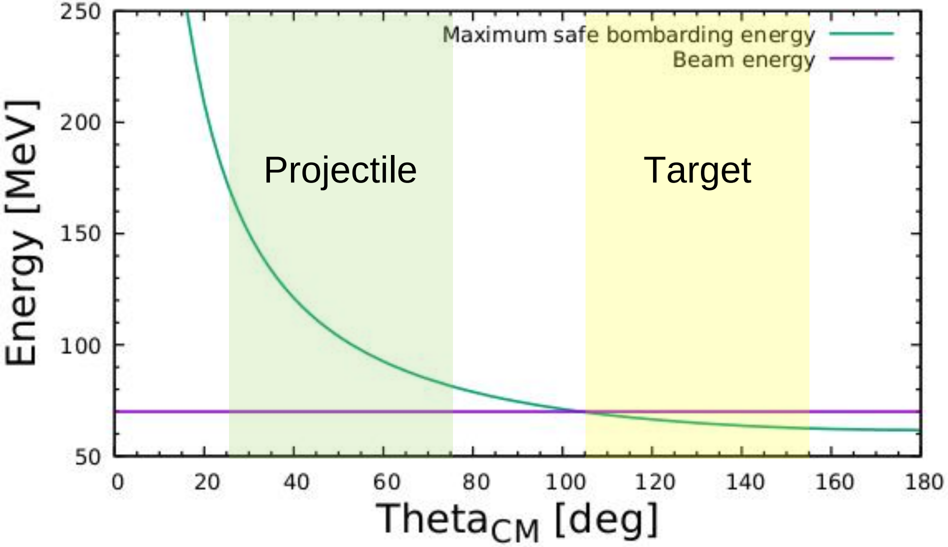
- ✓ Forward scattered beam ions detected in particle detector
- ✓ Beam is backward scattered and recoilnig target nuclei is detected

We have 2 experiments in one data set. Question: Is it advantage or not?

Safe Coulex criterion for the bombarding energy for the ^{32}S projectile and ^{45}Sc target

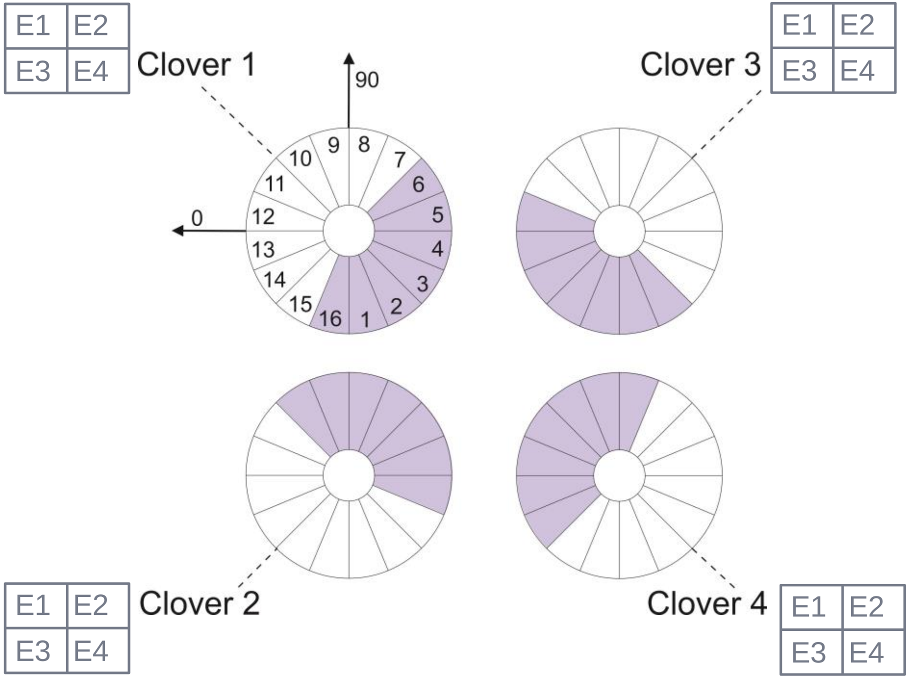
$$d_{min} > \left[1.25\left(A_P^{1/3} + A_T^{1/3}\right) + 5\right] fm$$

$$E_{beam} < 0.72 \cdot \frac{A_P+A_T}{A_T} \cdot \frac{Z_P Z_T}{d_{min}}\left[1 + \frac{1}{\sin(\theta_{CM}/2)}\right] MeV$$

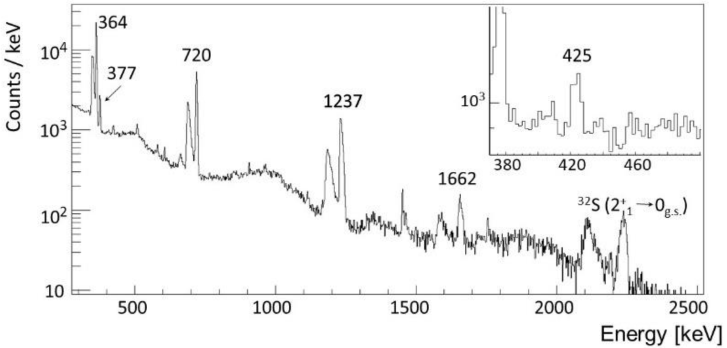


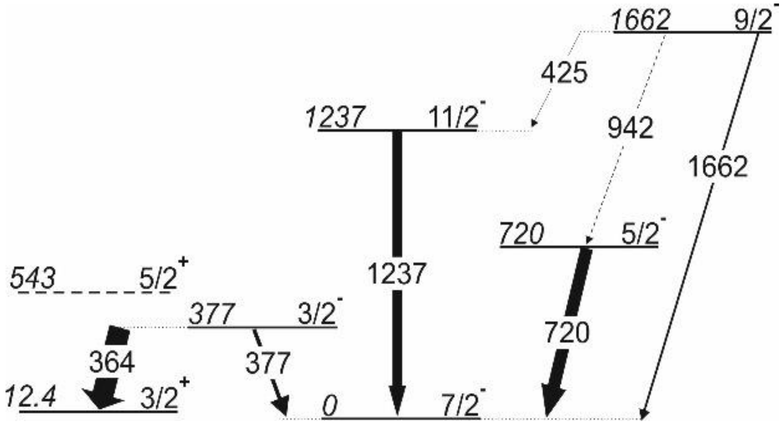
- Particle detector has angular coverage from 15 – 45 degress in laboratory frame, it corresponds to
- θ_{CM} = 25 deg – 75 deg for beam ions
- θ_{CM} = 105 deg – 155 deg for target nuclei

Therefore, to take into account only events resulting from the “safe” Coulomb excitation, we selected those combinations of crystals and APPAC segments in which this double-peak structure is well-separated



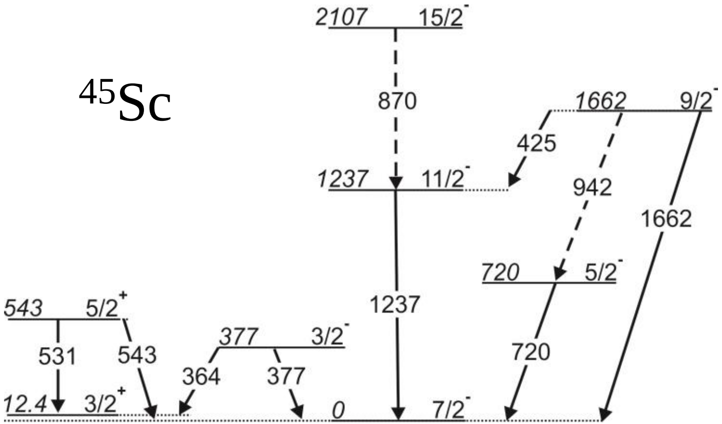
Spectrum for selected segments of particle detector





Level scheme of ^{45}Sc, widths of the arrows correspond to the gamma-ray intensities observed in the IUAC measurement

Data analysis using GOSIA code



State	**Energy (keV)**	**$T_{1/2}$ (ps)**
11/2-	1237	1.80 (10)
5/2-	720	206(16)
3/2+	12.4	318(7)*10^6
5/2+	543	5.5 (6)

Energy (keV)	**Branching ratio**	**Transition**	**δ(E2/M1)**
377/364	0.0911 ± 0.0020	5/2- ->7/2-	0.14 ± 0.05
543/531	0.705 ± 0.009	5/2+ -> 3/2+	-0.55 ± 0.11

A set of electromagnetic matrix elements was extracted from the measured γ-ray intensities. Complementary spectroscopic data were used to constrain the fit:

- **B(E2; 11/2$^-$ → 7/2$^-$) = 74 (5) e^{2}fm^4** and the resulting lifetime for the 11/2$^-$ state at 1237 keV is **τ = 3.83 (0.27) ps**
- **B(E3, 7/2$^-_{\text{g.s.}}$ → 5/2$^+$) ≤ 1.7 W.u.**

Quadrupole deformation from sum rules

Sum rules - method to determine charge distribution parameters (Q,δ) from E2 matrix elements, and (Q,δ) parameters can be transform to β,γ

”Easy” Even-Even Case

In the even-even nucleus intrinsic ground state shape can be determined by a full set of E2 matrix elements linking the ground state to all 2^+ states

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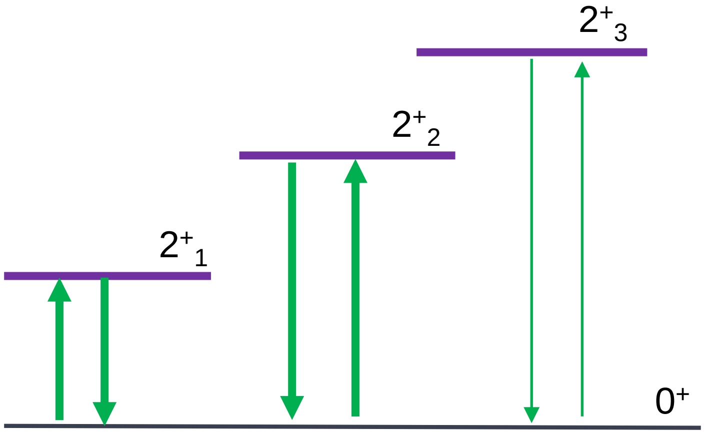
$<Q^2>$: overall deformation parameter – like β



Always positive

$$\left\langle Q^2\right\rangle = \left\langle s\left|[E2\times E2]^0\right|s\right\rangle$$

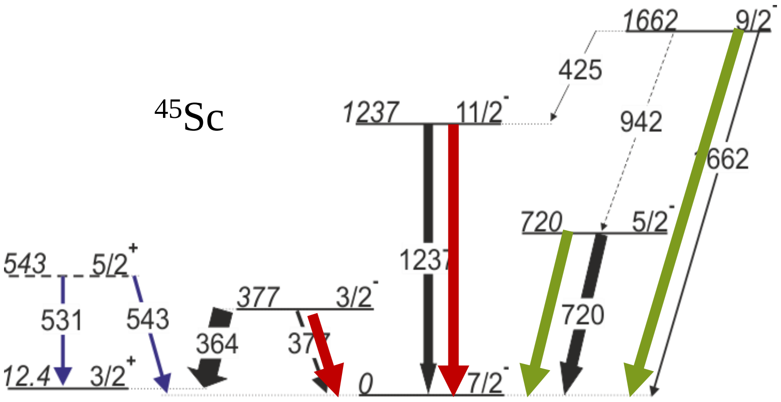
$$= \frac{(-1)^{2I_s}\sqrt{5}}{\sqrt{2I_s+1}}\sum_i \langle s\|E2\|i\rangle\langle i\|E2\|s\rangle \begin{Bmatrix}2 & 2 & 0\\ I_s & I_s & I_i\end{Bmatrix}$$

$$= \frac{(-1)^{2I_s}\sqrt{5}}{\sqrt{2I_s+1}}\sum_i M_{si}M_{is} \begin{Bmatrix}2 & 2 & 0\\ I_s & I_s & I_i\end{Bmatrix}$$

K. Kumar, Phys. Rev. Lett. ***28****, 249 (1972)*
D. Cline, Annu. Rev. Nucl. Part. Sci. ***36****, 683 (1986)*

”Difficult” Odd Case

$$\langle Q^2\rangle = \frac{(-1)^{2I_s}\sqrt{5}}{\sqrt{2I_s+1}}\sum_i M_{si}M_{is}\begin{Bmatrix}2 & 2 & 0\\ I_s & I_s & I_i\end{Bmatrix}$$



$$\begin{Bmatrix}2 & 2 & 0\\ I_s & I_s & I_i\end{Bmatrix} = (-1)^{I_s+I_i}\frac{1}{\sqrt{5}}\frac{1}{\sqrt{2I_s+1}}$$

negative **positive**

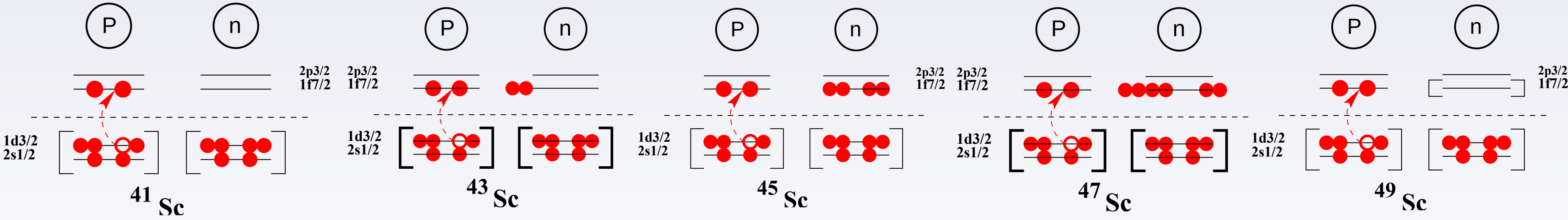
Preliminary:

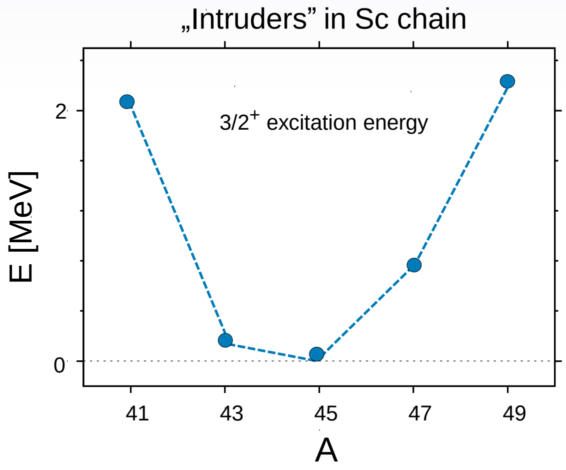
$\langle Q^2\rangle \cong 300\ e^2\mathrm{fm}^4 \Rightarrow \beta \cong 0.2$

$$\langle Q^2\rangle \cong \left(\frac{3}{4\pi}ZR^2\right)^2\beta^2$$

J. Srebrny et al., Nucl.Phys. ***A766****, 25 (2006)*

Shell model calculations



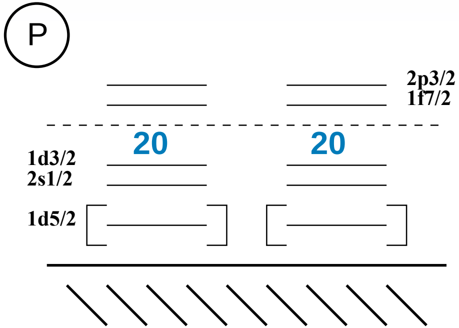


- **It is a great challenge for theory to describe the 2 MeV drop of the 3/2⁺ state with adding only 2 neutrons !**

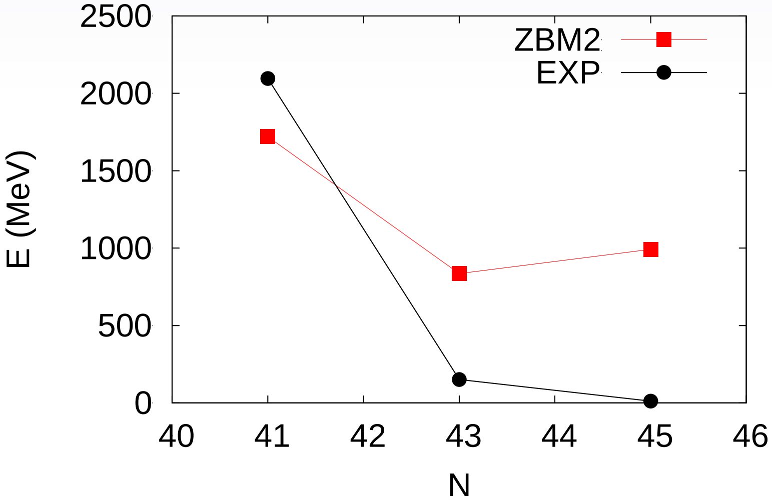
ZBM2-model space and interaction

ZBM interaction was introduced by Zuker, Buck and McGrory to describe properties of ^{16}O and neighboring nuclei

ZBM2 – modified interaction for heavier nuclei

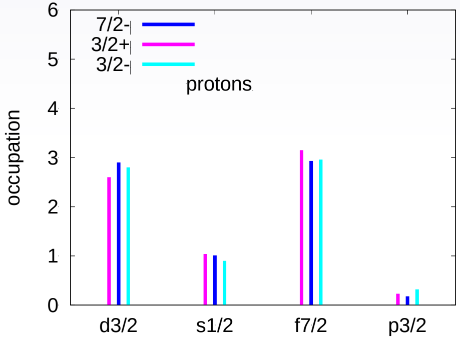


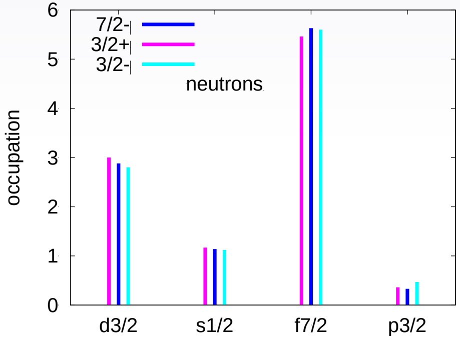
3/2+ energy in Sc isotopes

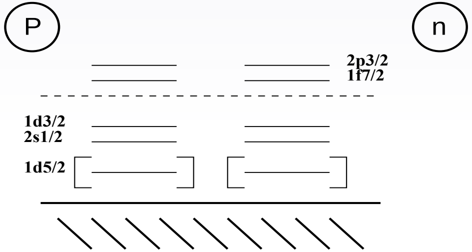


A.P. Zuker, B. Buck and J.B. McGrory Phys. Rev. Lett 21, 39 (1968)

Results with the ZBM2 interaction



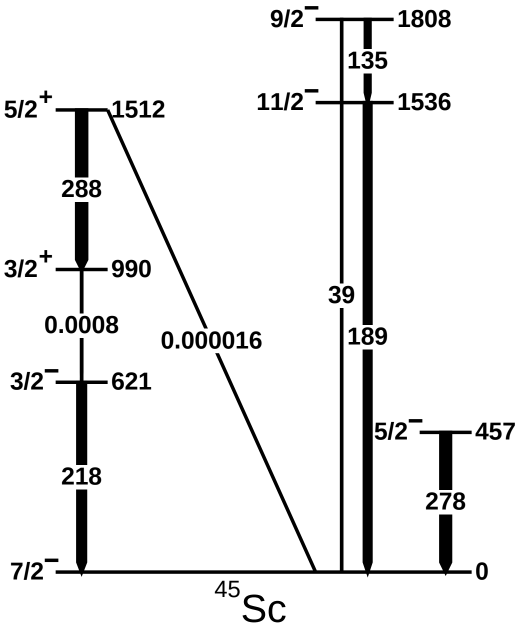


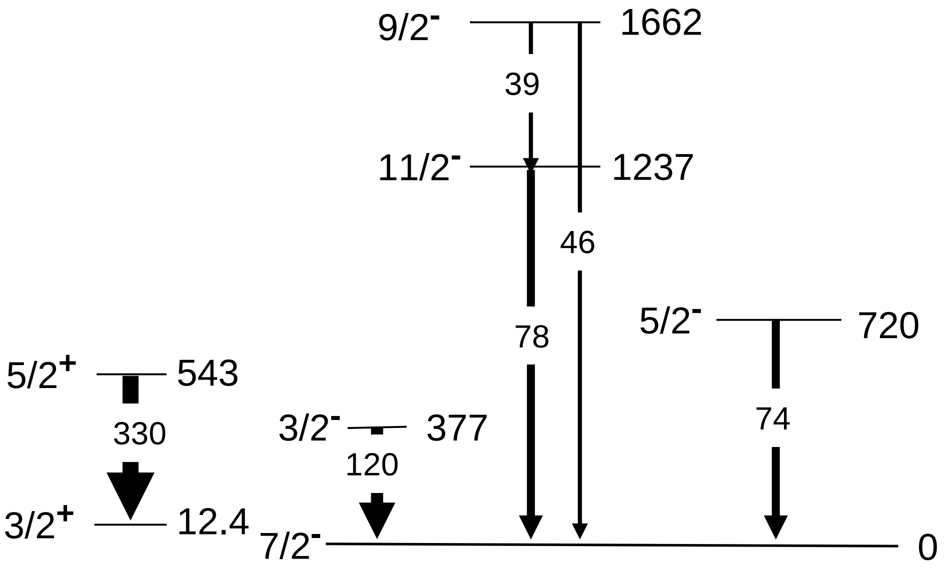


- The occupation of the shown states is almost the same, no clear structure
- It looks that these states are not just simple 1p-1h or 2p-2h excitations
- Calculations in full pf shell are necessary

Results with the ZBM2 interaction

B(E1) e^2fm^2, B(E2) e^2fm^4





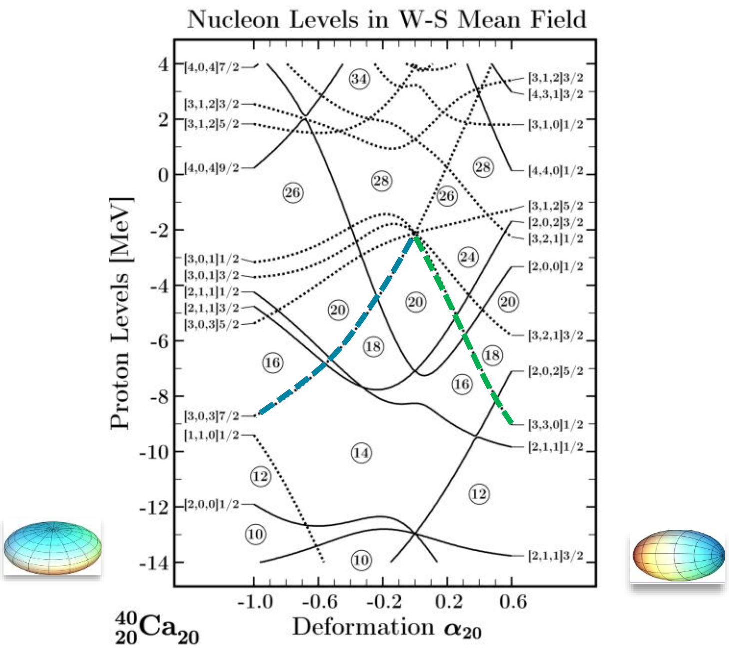
Experiment

- Advantage of the ZBM2 space: tractable numerically
- BUT not enough correlations to describe deformed intruder configurations
- One needs full pf shell to improve the agreement with experiment:
    - 1. full space dimension in ^{45}Sc: $1*10^{12}$
        - currently intractable in Shell Model
        - with the standard method 10^{10} can be diagonalized
        - needs some truncation and study of spectra convergence
    - 2. interaction optimization necessary

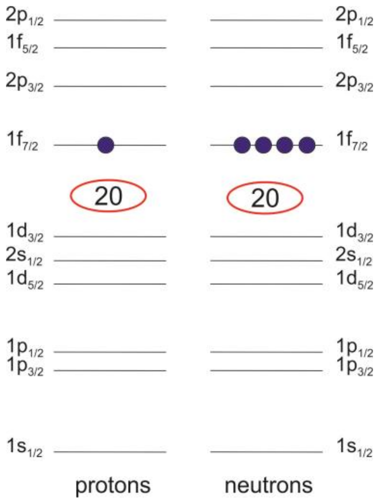
- Kamila Sieja (IPHC and CNRS, Strasbourg) is performing this calculations and work is progress...

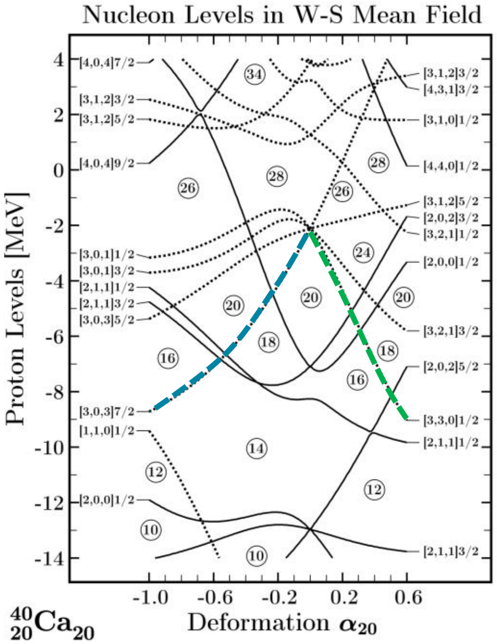
Large-scale mean-field calculations

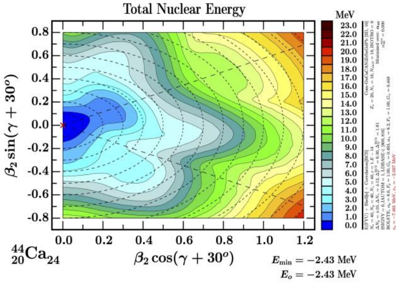
Single particle energies

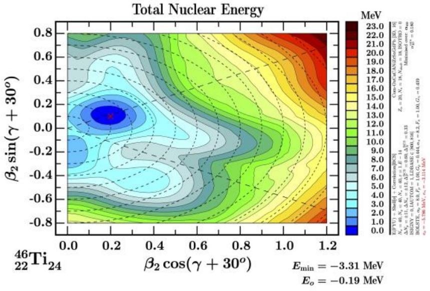


The configuration of the proton and neutron shells for the Sc isotopes









- Large-scale mean-field calculations are being performed to describe properties and structure of ^{45}Sc. To find candidate for the $3/2^+$ isomeric states, configuration etc.…
- This is mean-field approach the universal parametrization is used (12 parameters fixed once for all nuclei)

Summary

- The electromagnetic structure of ^{45}Sc at low excitation energy was investigated via Coulomb excitation at HIL UW and IUAC New Delhi
- A set of reduced E2, E3, and M1 matrix elements was extracted from the collected data
- The B(E3; $7/2^-_{g.s.} \rightarrow 5/2^+$) transition probability have been determined for the first time
- Obtained lifetime for the $11/2^-$ state at 1237 keV is 3.83 (0.27) ps
- We are working to get final deformation parameters (increase sensitivity for diagonal ME)
- Odd nuclei are more difficult and demanding for experimental and theoretical studies
- It is a challenge for theory to reproduce this very low 12.4 keV excitation energy of the $3/2^+$ state
- Results are being interpreted in the terms of Large-Scale Mean-Field approach and Shell-Model calculations

Collaboration

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