Innovative Detector Developments for Nuclear Science

Pete Jones
iThemba Laboratory for Accelerator Based Sciences
Cape Town, South Africa

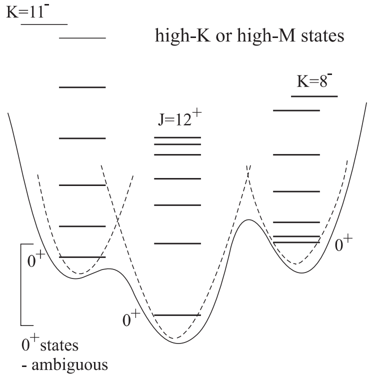
Outline

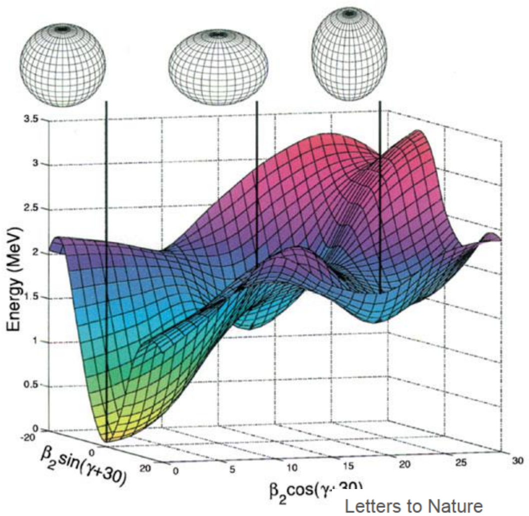
- Introduction to 0^+ states
- Spectroscopic observables
- Conversion electron spectroscopy in A ~ 70 nuclei
  - Spectrometer
  - Results
- Internal pair spectroscopy of A ~ 50 nuclei
  - Spectrometer upgrades
  - Simulations
  - Results
- Joint South Africa – JINR collaboration project
- Future innovation platform at iThemba LABS

Excited 0^+ states are the least understood of any low-energy degree of freedom in nuclei.

E0 transition strengths are a measure of the off-diagonal matrix elements of the mean-square charge radius operator.

Mixing of configurations with different mean-square charge radii produces E0 transition strength.



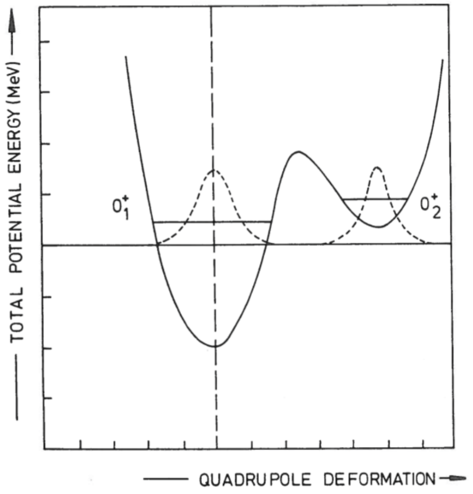


Letters to Nature

Nature **405**, 430-433 (25 May 2000) | doi:10.1038/35013012; Received 20 December 1999; Accepted 3 April 2000

A triplet of differently shaped spin-zero states in the atomic nucleus ^{186}Pb

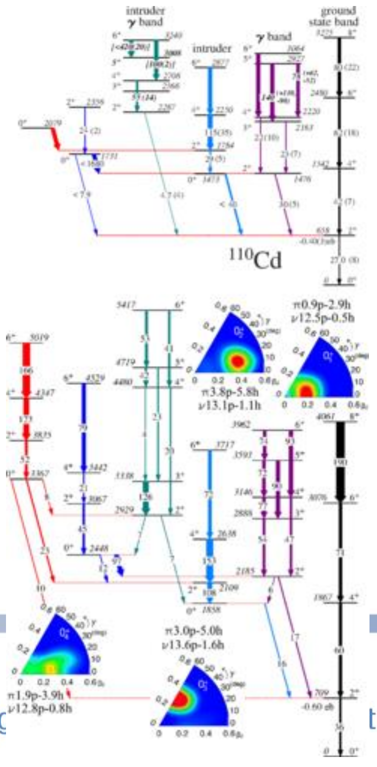
A. N. Andreyev[1], M. Huyse[1], P. Van Duppen[1], L. Weissman[1], D. Ackermann[2], J. Gerl[2], F. P. Hessberger[2], S. Hofmann[2], A. Kleinböhl[2], G. Münzenberg[2], S. Reshitko[2], C. Schlegel[2], H. Schaffner[2], P. Cagarda[3], M. Matos[3], S. Saro[3], A. Keenan[4], C. Moore[4], C. D. O'Leary[4], R. D. Page[4], M. Taylor[4], H. Kettunen[5], M. Leino[5], A. Lavrentiev[6], R. Wyss[7] & K. Heyde[8]



Wave functions must overlap for a transition to occur

solid line—schematic potential
dashed line—schematic wave function

J.L. Wood, E.F. Zganjar, C. De Coster, K. Heyde, Nucl. Phys. A 651 (1999) 323.

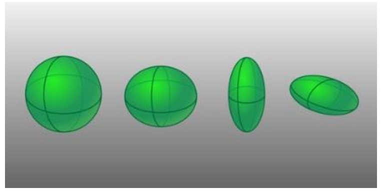


PHYSICAL REVIEW LETTERS **123**, 142502 (2019)

Editors' Suggestion | Featured in Physics

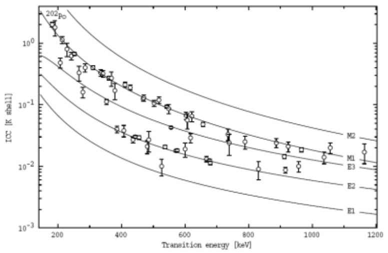
Multiple Shape Coexistence in ^{110,112}Cd

P. E. Garrett,[1,2] T. R. Rodríguez,[3] A. Diaz Varela,[1] K. L. Green,[1] J. Bangay,[1] A. Finlay,[1] R. A. E. Austin,[4] G. C. Ball,[5] D. S. Bandyopadhyay,[1] V. Bildstein,[1] S. Colosimo,[4] D. S. Cross,[6] G. A. Demand,[1] P. Finlay,[1] A. B. Garnsworthy,[5] G. F. Grinyer,[7] G. Hackman,[5] B. Jigmeddorj,[1] J. Jolie,[8] W. D. Kulp,[9] K. G. Leach,[1,*] A. C. Morton,[5,†] J. N. Orce,[2] C. J. Pearson,[5] A. A. Phillips,[1] A. J. Radich,[1] E. T. Rand,[1,‡] M. A. Schumaker,[1] C. E. Svensson,[1] C. Sumithrarachchi,[1,†] S. Triambak,[2] N. Warr,[8] J. Wong,[1] J. L. Wood,[10] and S. W. Yates[11]



Internal conversion electrons

$$\alpha^{tot} = \frac{I_{ce}}{I_\gamma} = \alpha_K + \alpha_L + \alpha_M + \ldots$$



L sensitivity

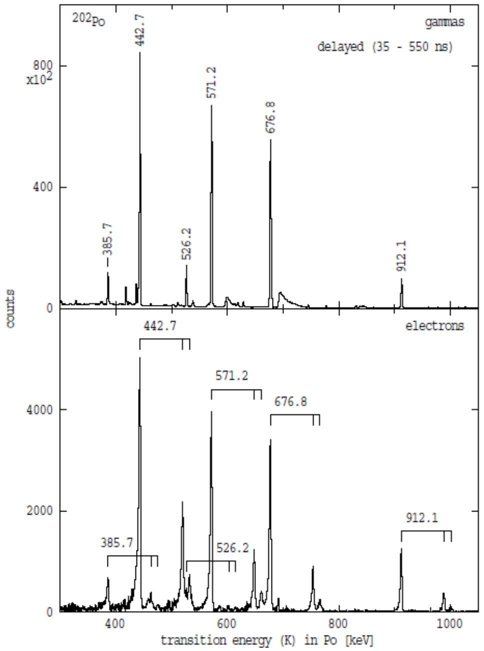
$$I_i^{\pi_i} \quad E_i$$

$$L$$

$$I_f^{\pi_f} \quad E_f$$

$$E_\gamma = E_i - E_f$$

$$E_i = E_\gamma - B_i, i = K, L, \ldots$$



Intensity ratio

oo	E0
1	Low energy isomers
10^{-1} <	50< Z
10^{-2} - 10^{-3}	30<Z < 50
10^{-4} - 10^{-5}	Z < 30

$$\alpha_K(EL) \propto Z^3 \left(\frac{L}{L+1}\right)\left(\frac{2m_e c^2}{E}\right)^{L+5/2}$$

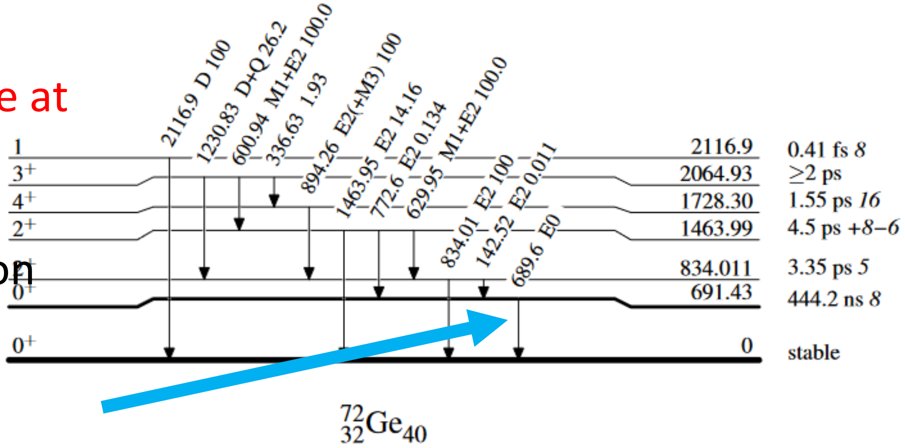
Important for heavy nuclei, where inner electron shells are closer to the nucleus

Important for low-energy transitions

Non photon emission for de-excitation

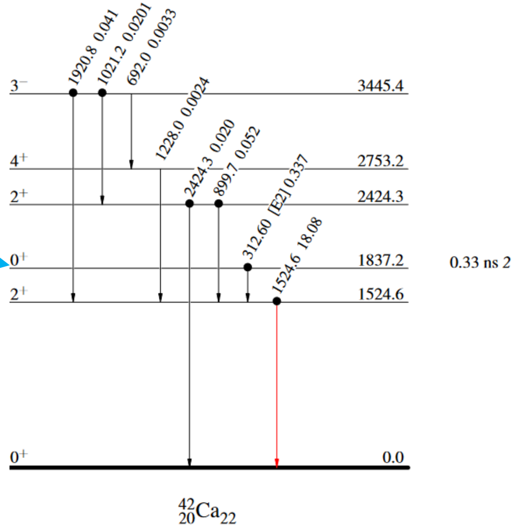
J = 0 → 0 transitions cannot take place by photon emission

- Photon has spin and therefore must remove at least one unit of angular momentum



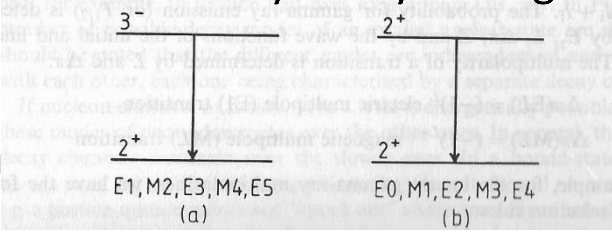
If no change in parity in 0 → 0 transition deexcitation occurs by other means

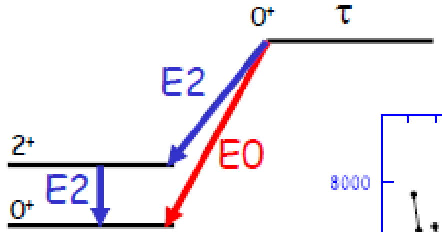
- Emission of an internal conversion electron
  - ^{72}Ge, ^{214}Po
- Simultaneous emission of an electron-positron pair (E > 1.022 MeV)
  - ^{16}O, ^{42}Ca



Transitions between two J=0 states of opposite parity cannot take place by any first-order process

Transitions between J → J also may decay through E0





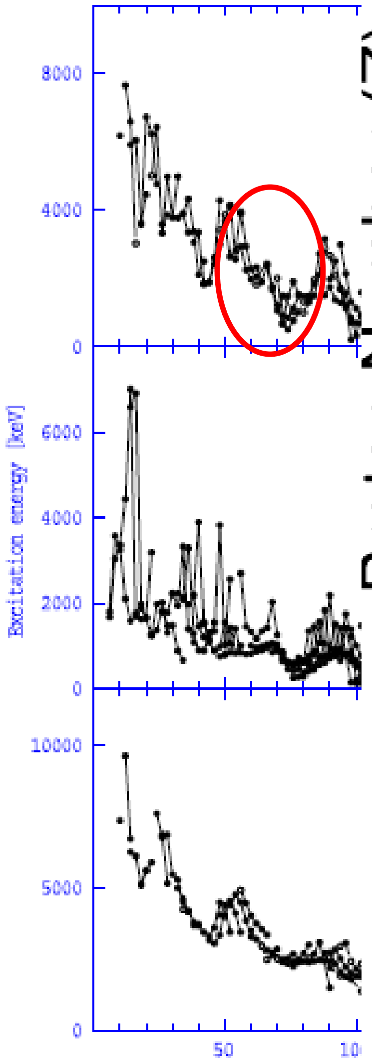
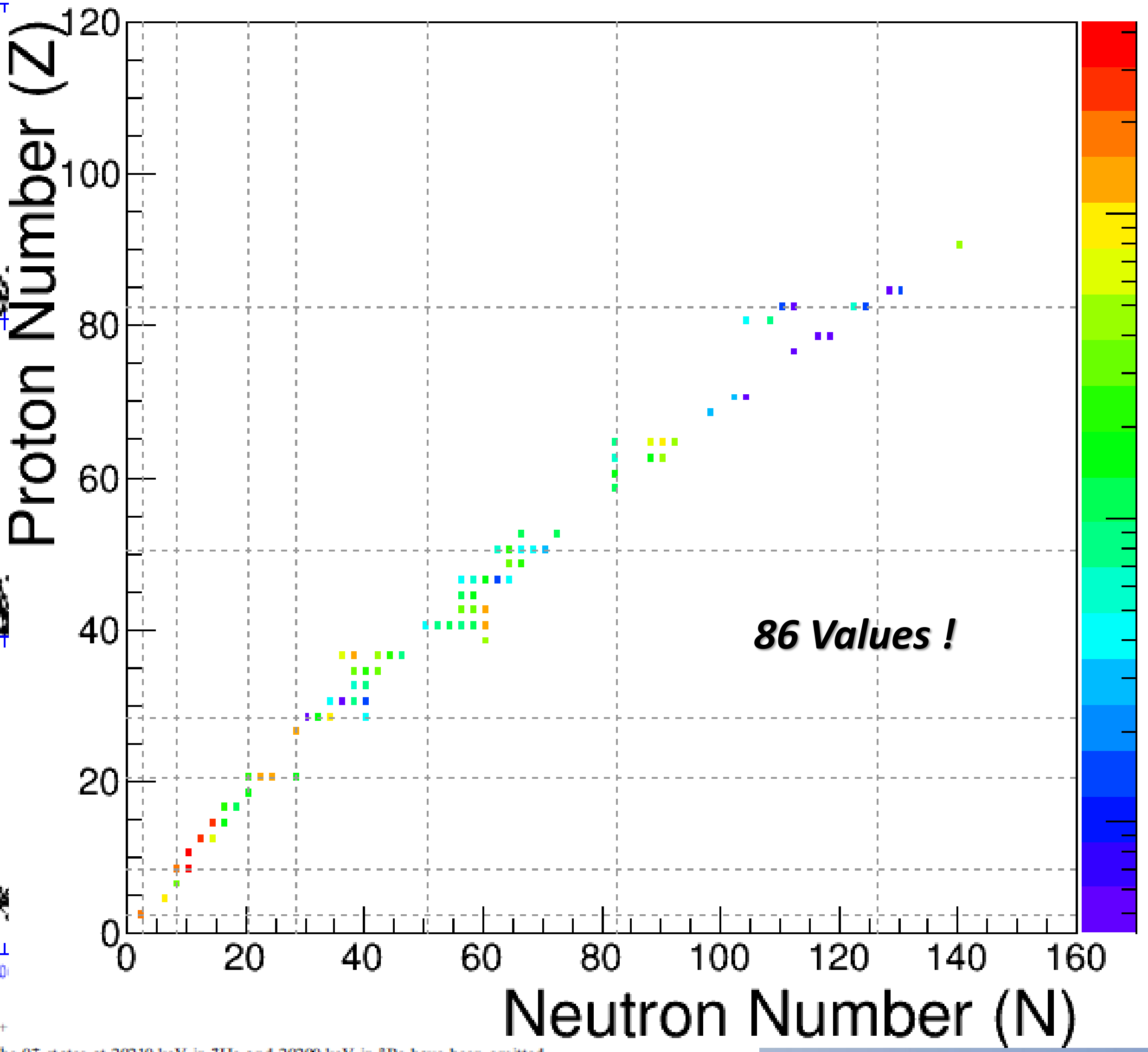
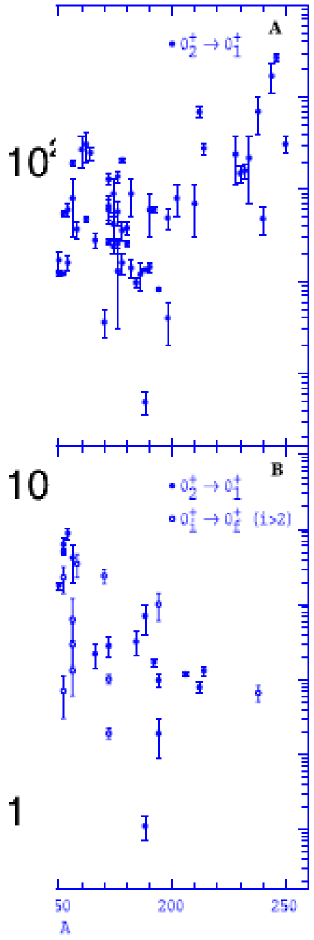


Fig. 1. Excitation energy of the first excited 0^+ isotopes. In order to avoid scale distortion, the 0_2^+ states at 20210 keV in ^{4}He and 20200 keV in ^{8}Be have been omitted.

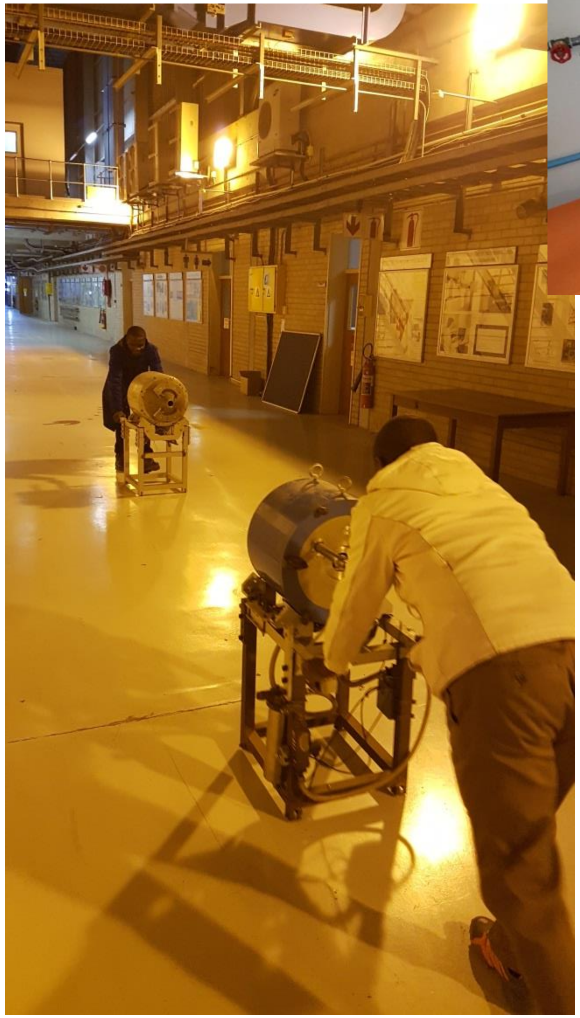
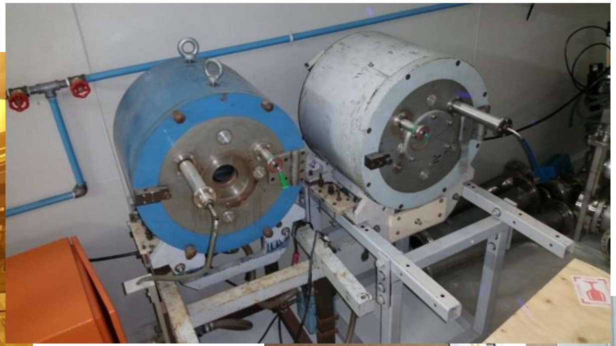
Measured ρ^2 (E0 : $0_2^+ \rightarrow 0_1^+$) ($\times 10^3$) values

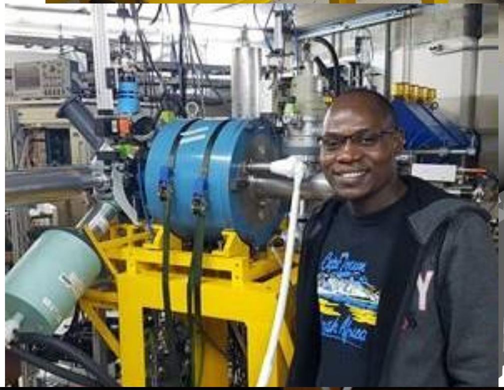
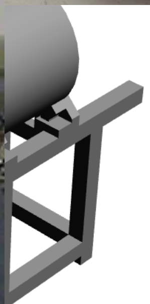


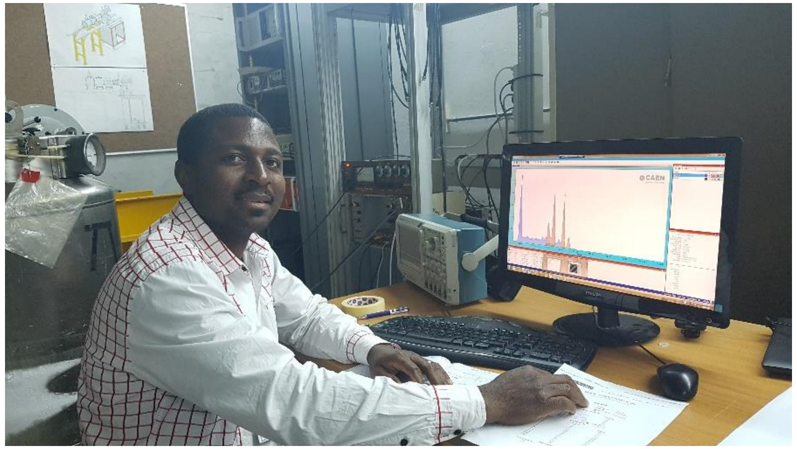


0_1^+ transitions; and (B) $10^3\rho^2$(E0) for $0_2^+ \rightarrow 0_1^+$ transitions (filled nly limits are known (see Table 1) have been omitted. The data omitted.

Electron spectrometer project 2016-

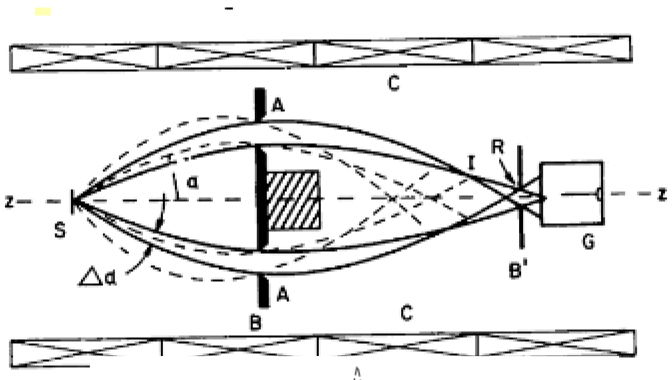



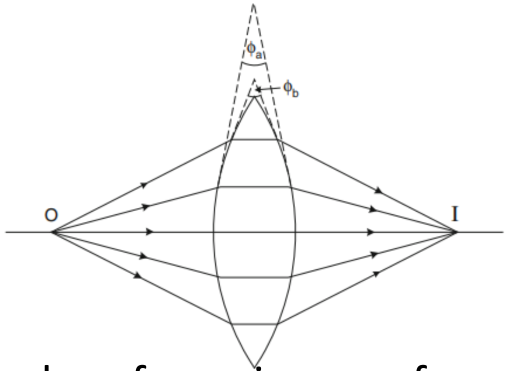




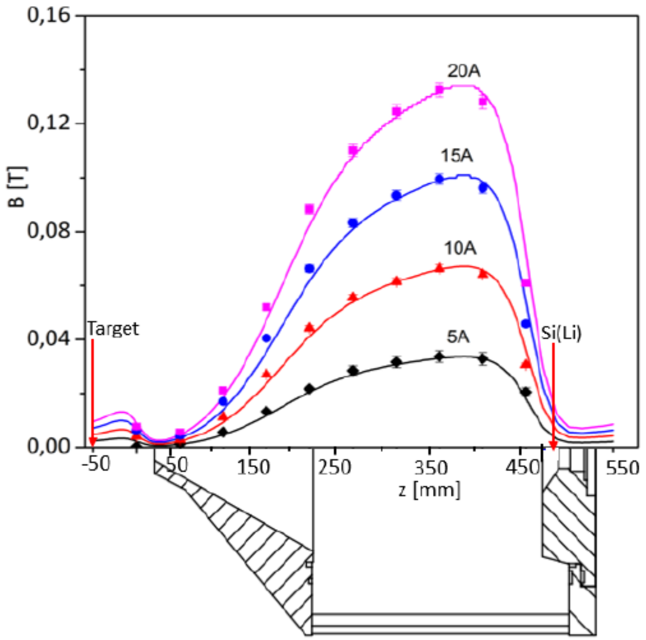

Spectrometer Characterisation

- An axial field possesses dispersion and focussing properties which make its use possible as a spectrometer [2]





Convex lens focussing rays from an object to an axial image point[3]



Axial magnetic field profile of the Solenoid

- **Transmission T:** The ratio of the total absorption peak count rate to the rate of emission of electrons with corresponding energy form the source [4]
- **Resolution** (width of momentum window): $R = \frac{\Delta p}{p} = \frac{\Delta B_\rho}{B_\rho}$
- **Sweeping efficiency:** $\varepsilon(p) \approx \frac{\Delta p}{p_2 - p_1} T$
- **Magnetic rigidity** Bρ of the solenoid magnetic lens is related to kinetic energy, mass and charge of an electron by the expression $B_\rho = \frac{A\sqrt{E^2 + 2mc^2 * E}}{m_0 c^2}$

[2] Fay Ajzenberg-Selove (1960) Nuclear Spectroscopy.

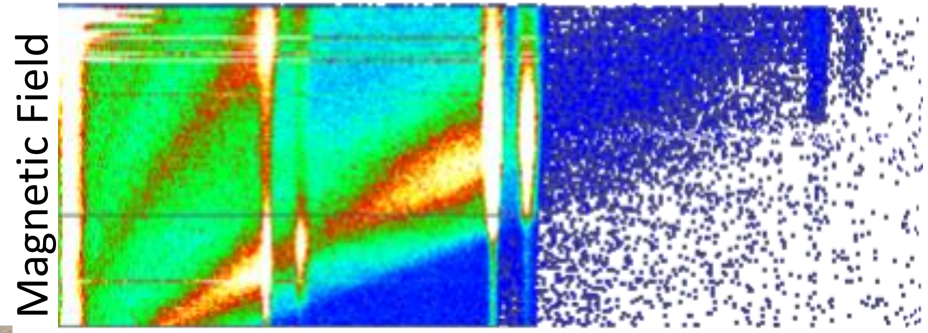
[3] Egerton, R.F.(2005),Physical Principles of Electron Microsc

[4] Kantele *et al* (1975). *Nucl. Inst. And Meth*. 130 467-474

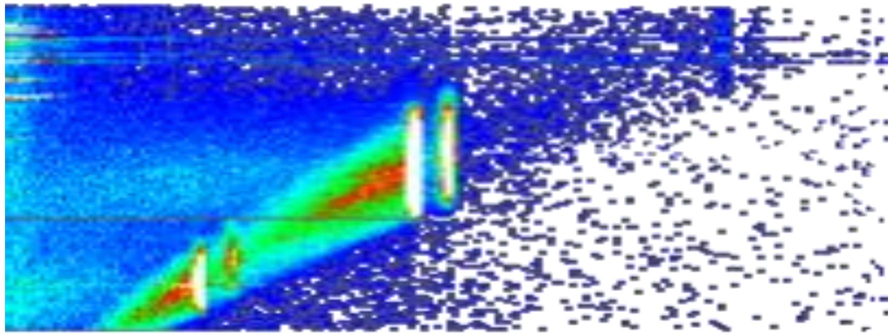
Spectrometer Bρ evaluation

^{207}Bi source

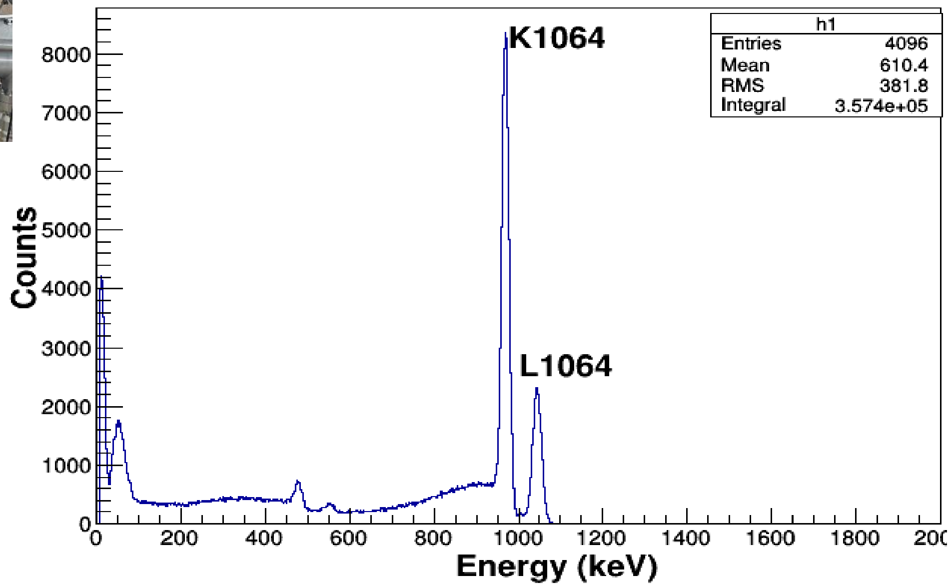
Empty with Baffle



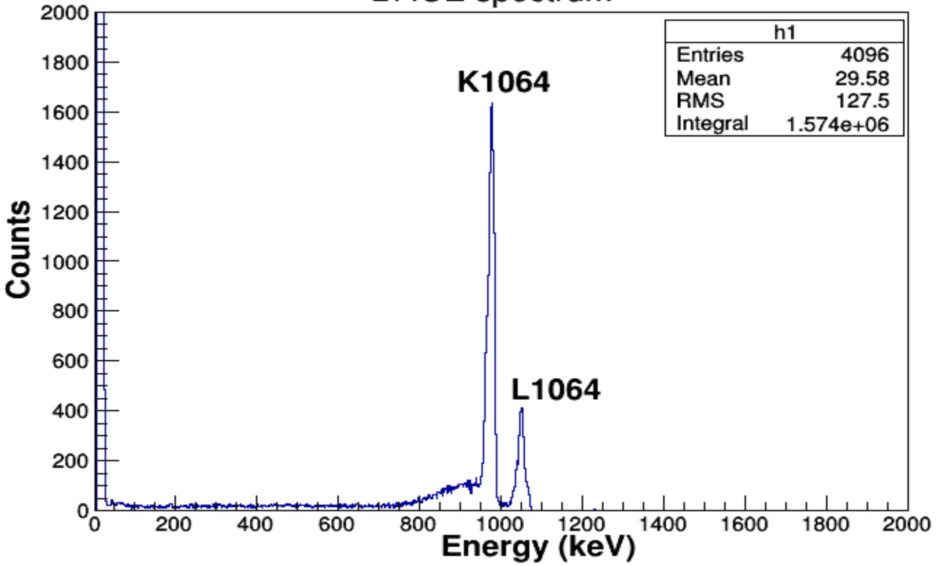
Lens with Baffle



^{207}Bi ICE spectrum

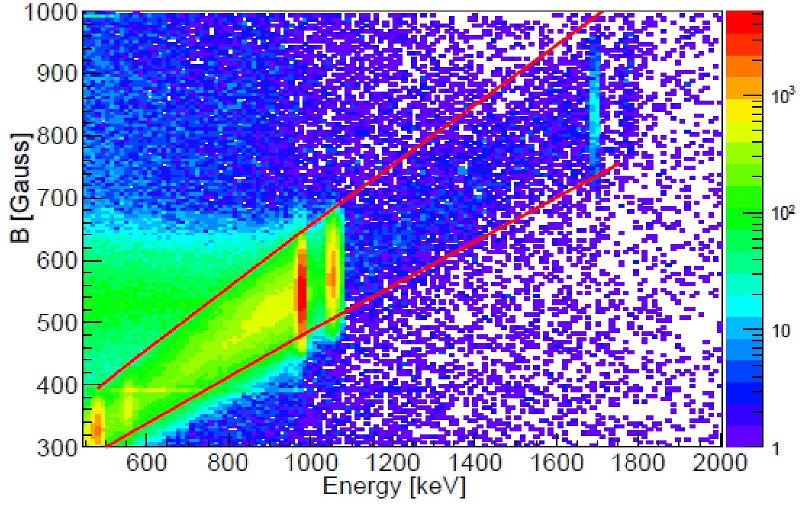


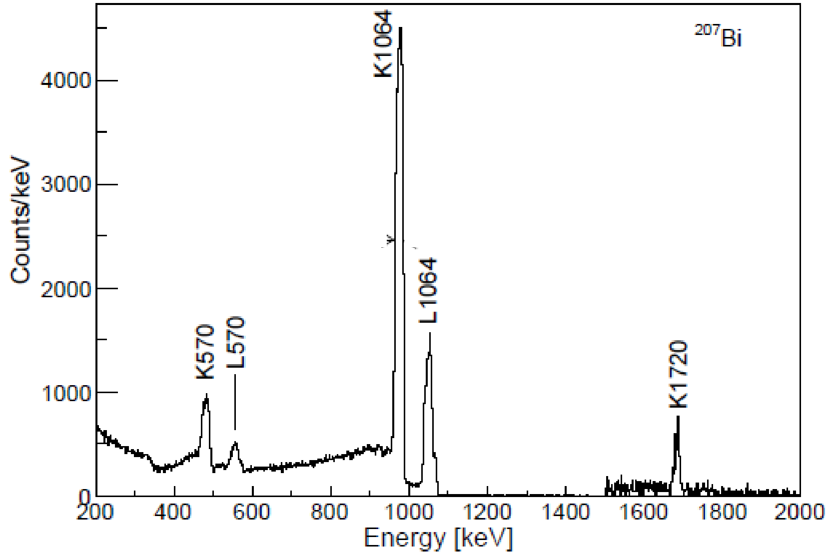
^{207}Bi ICE spectrum

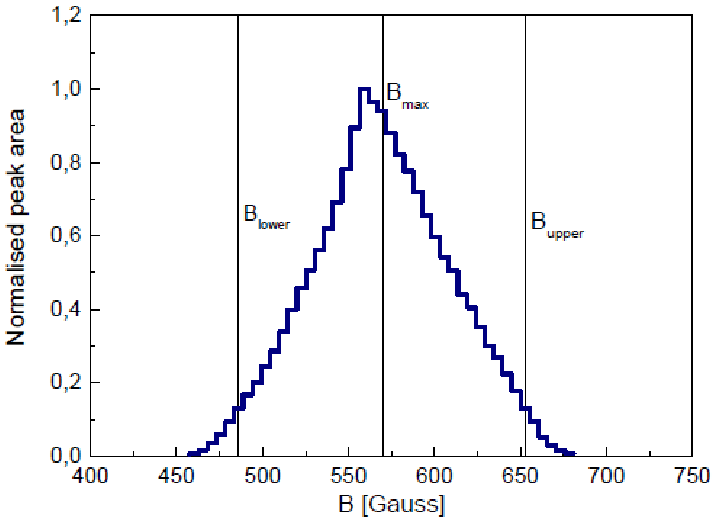


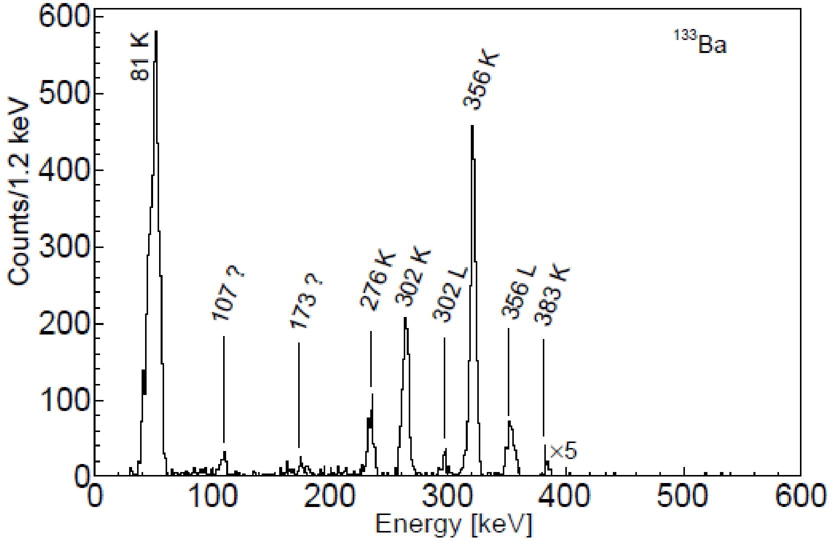
A.A. Avaa, University of the Witwatersrand / iThemba LABS

Spectrometer Bρ evaluation

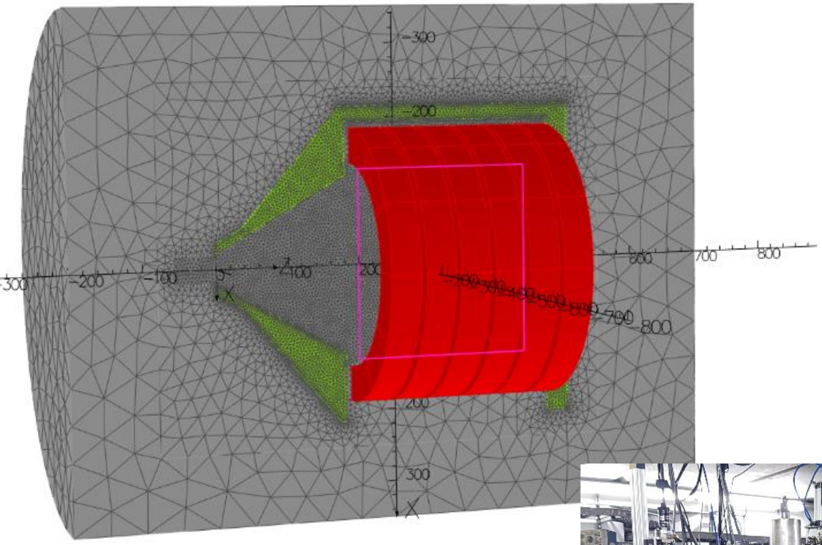


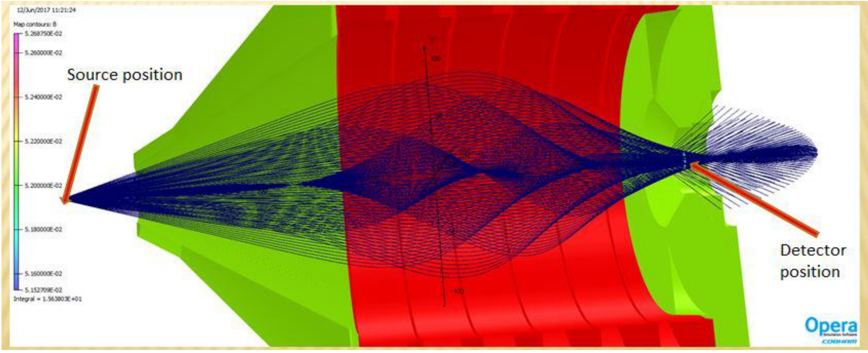


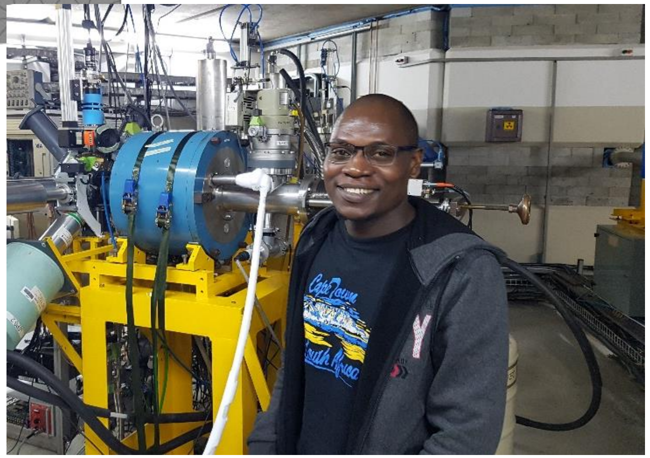


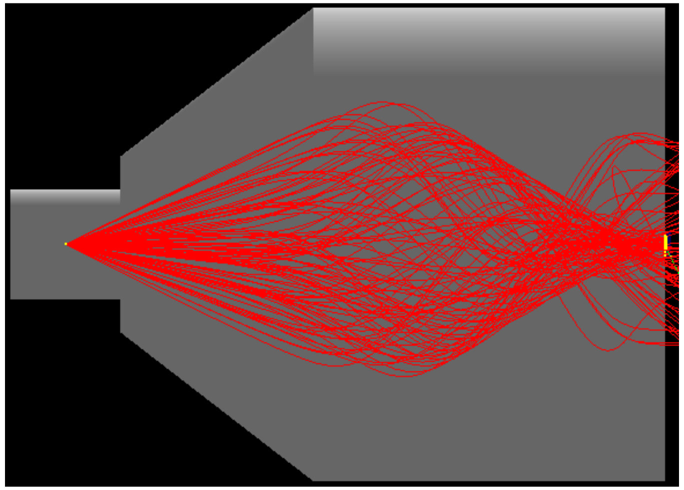


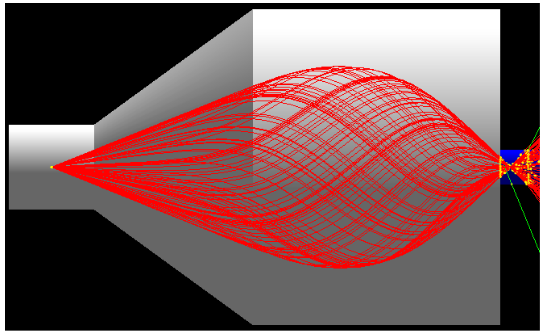
Simulations: Opera / Geant 4

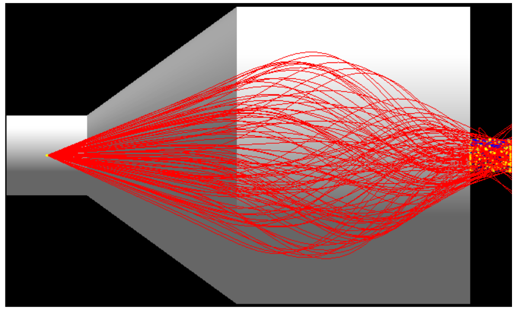






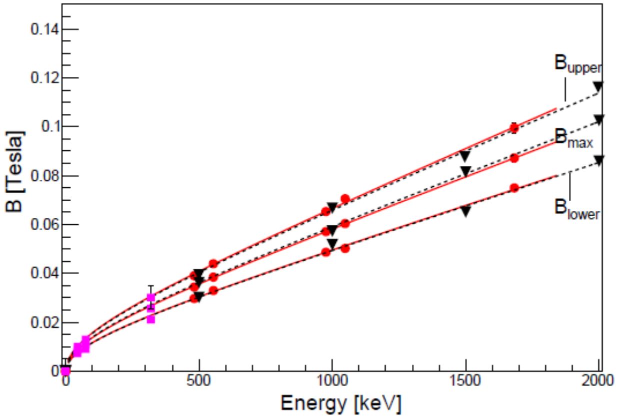


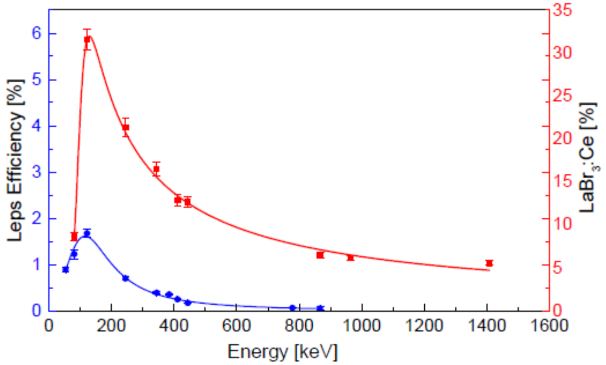




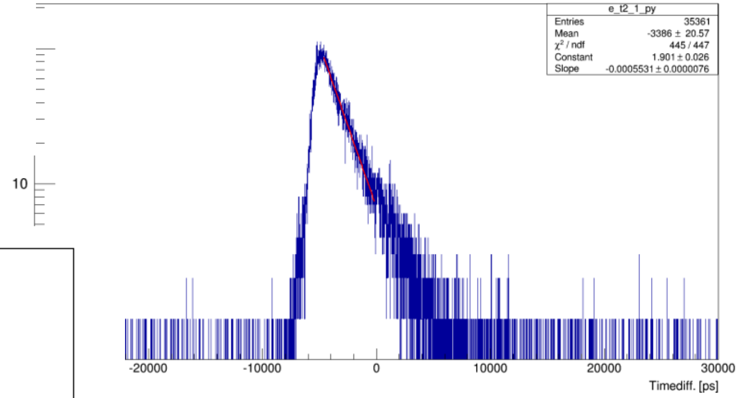
M.V. Chisapi, University of Stellenbosch / iThemba LABS

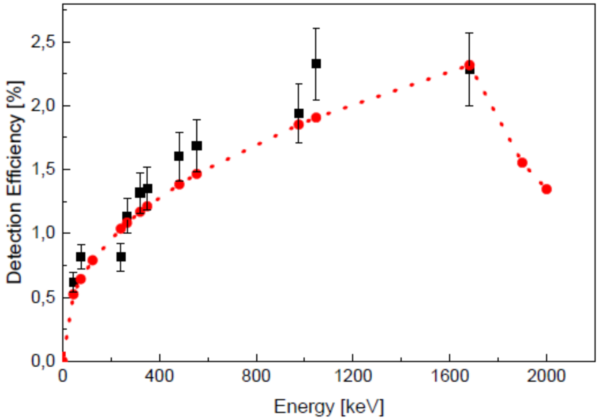
Spectrometer Characterised

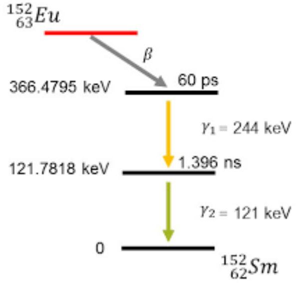




$$B\rho(E) = \frac{0.001074Tm\sqrt{E^2 + 2m_oc^2E}}{m_oc^2}$$







ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 964, 1 June 2020, 163809

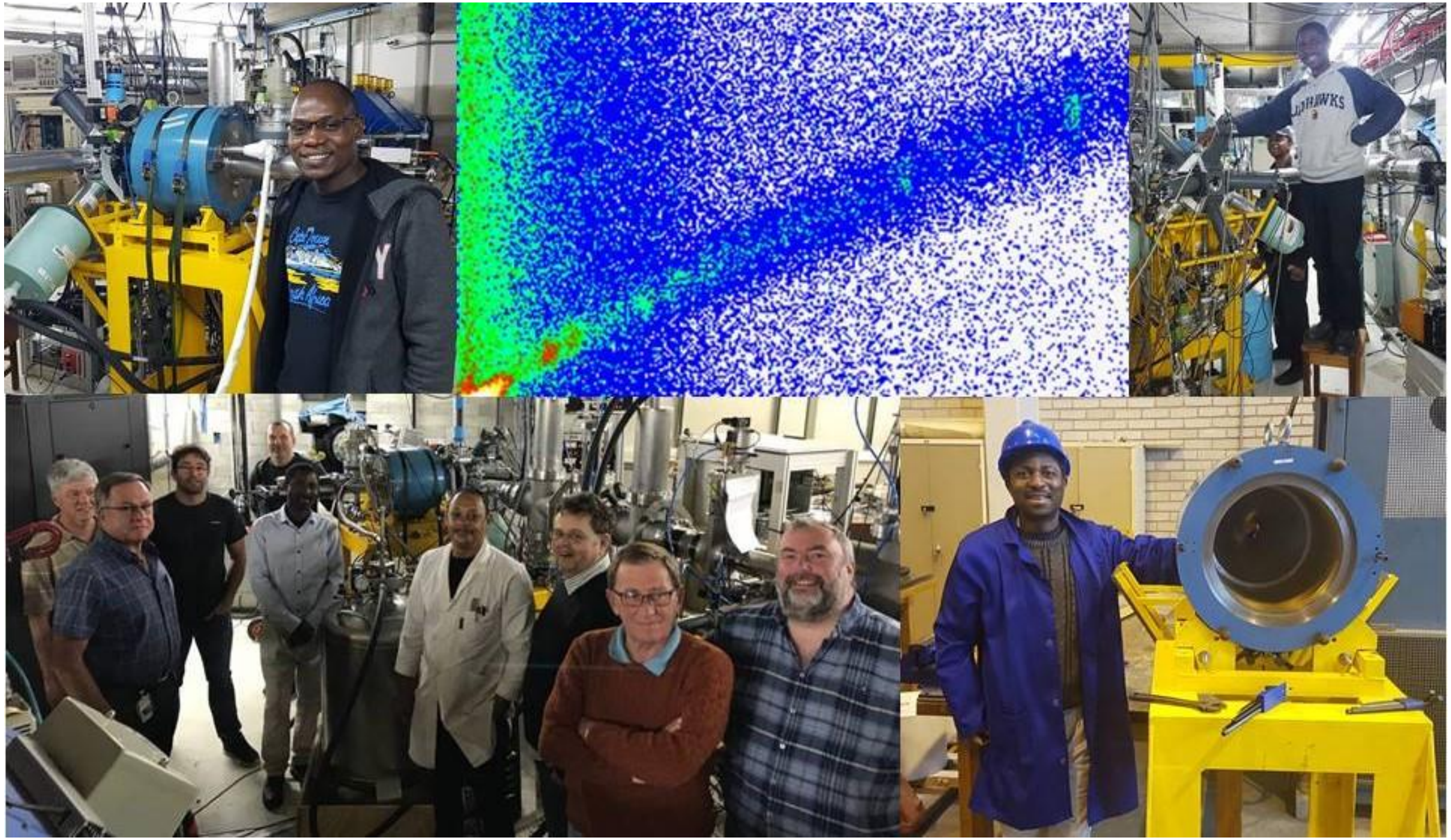
Electron spectrometer for electric monopole ($E0$) transition studies in nuclei

A.A. Avaa [a, b], P. Jones [b], I.T. Usman [a], M.V. Chisapi [b, c], T. Kibédi [d], B.R. Zikhali [b, e], L. Msebi [b, e]

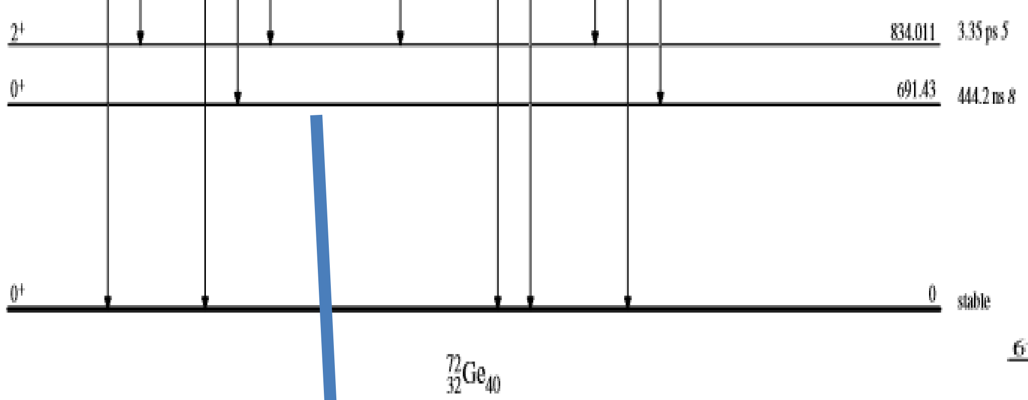
[a] School of Physics, University of the Witwatersrand, Johannesburg, 2000, South Africa
[b] iThemba Laboratory for Accelerator Based Sciences (iThemba LABS), PO Box 722, Somerset West, 7129, South Africa
[c] Department of Physics, Stellenbosch University, P/B XI, Matieland, 7602, South Africa
[d] Department of Nuclear Physics, Australian National University, Canberra, ACT 0200, Australia
[e] Department of Physics, University of the Western Cape, P/B X17, Bellville, 7535, South Africa

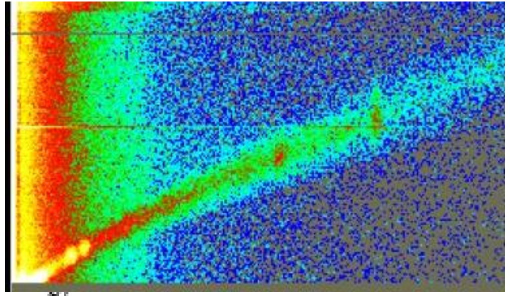
Received 14 November 2019, Revised 15 March 2020, Accepted 17 March 2020, Available online 20 March 2020.

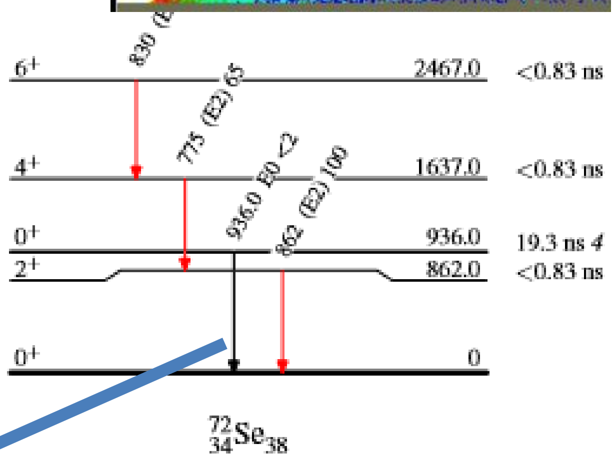
Electric monopole (E0) transitions
^{72}Ge ^{72}As ^{72}Se nuclei - Commissioned October 2018



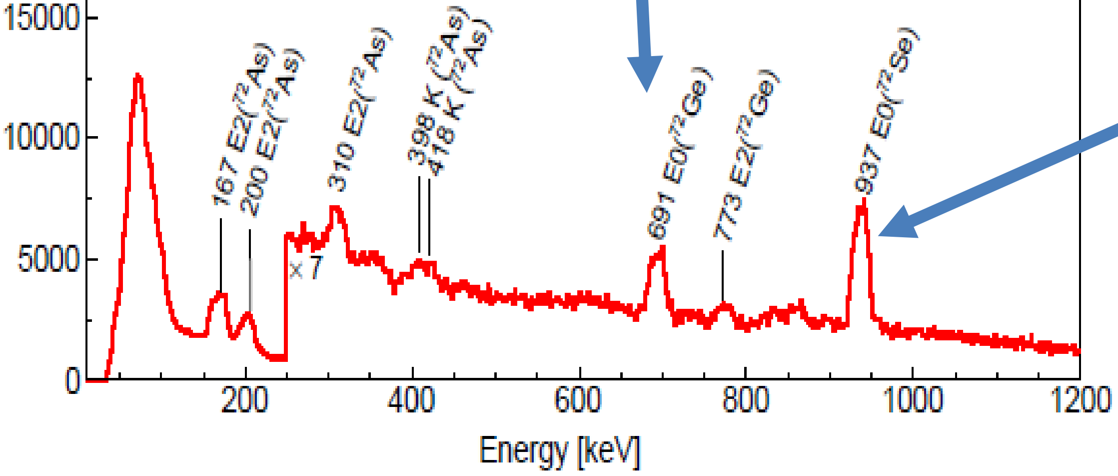
Results







Electrons

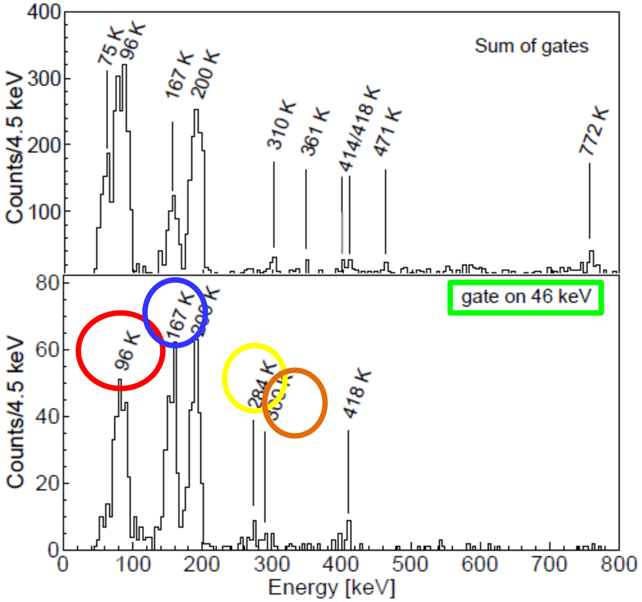


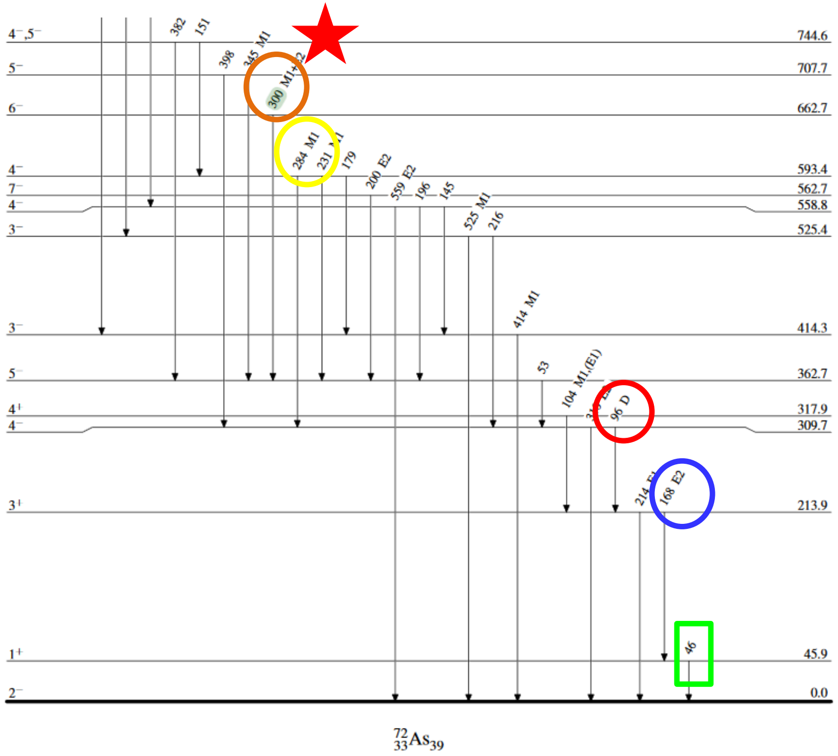
^{70}Ge(α, α') 30 MeV

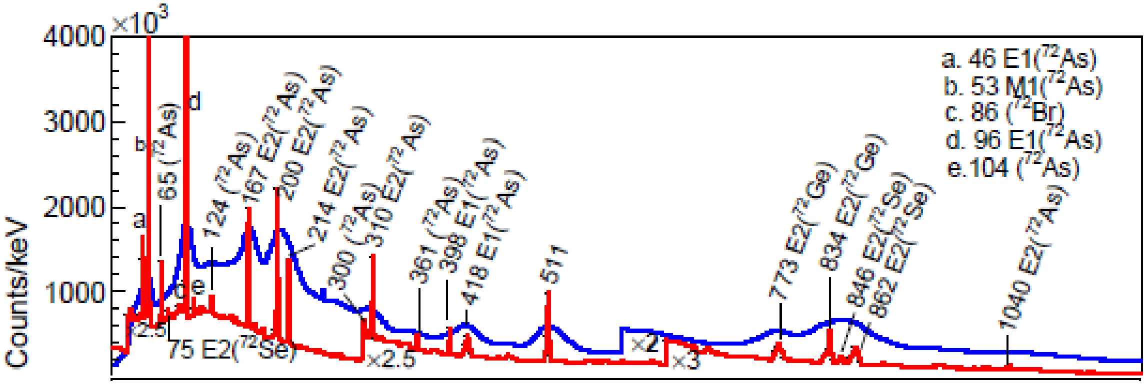
~ 48 hours swept field

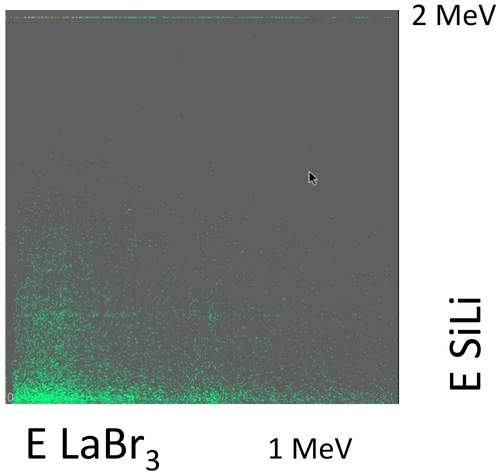
A.A. Avaa, University of the Witwatersrand / iThemba LABS

Electrons, Gamma rays – or the lack of

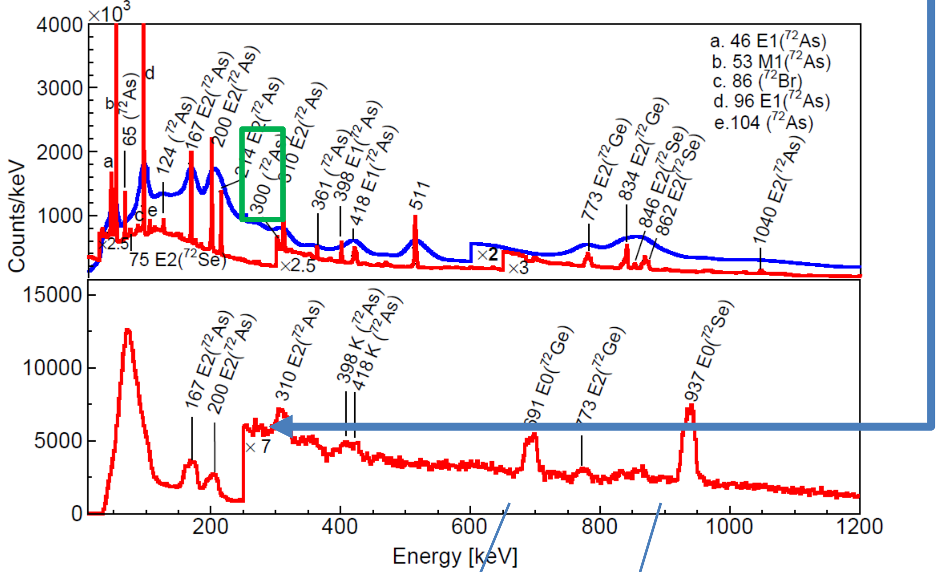


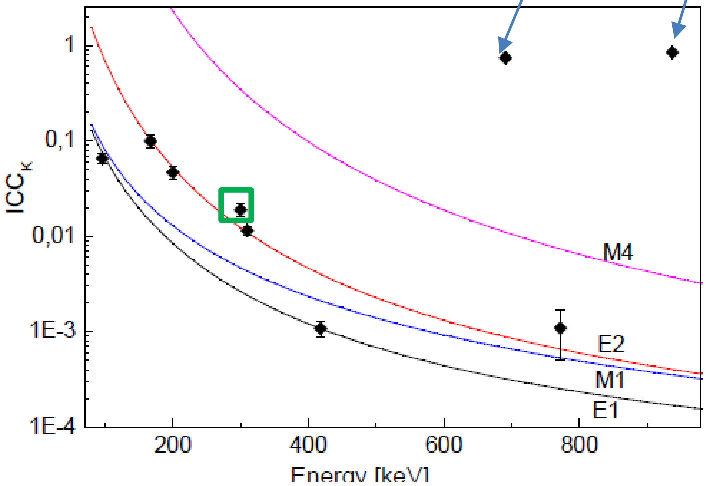


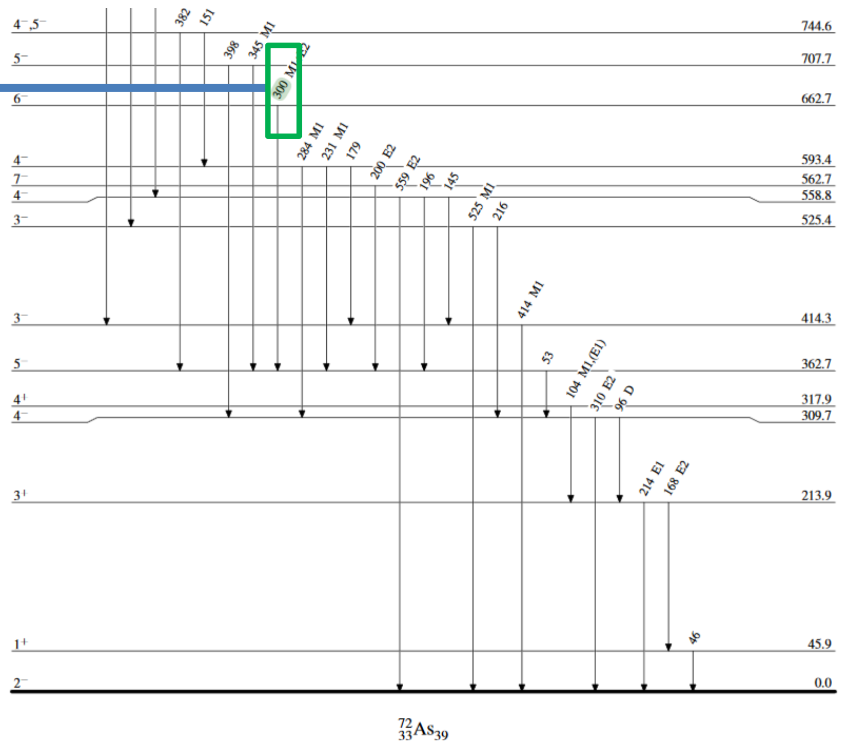




Results







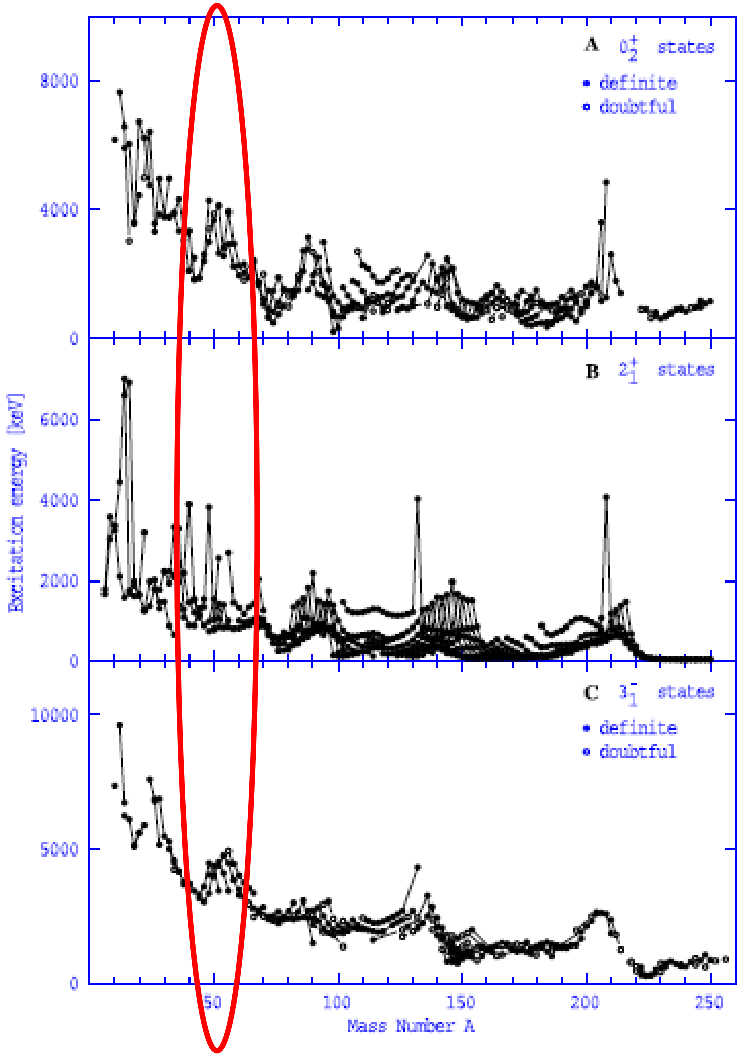
$$\rho^2(E0) = \frac{ln(2)}{\Omega_{tot}(E0) \times (1 + \frac{I_{tot}(E2)}{I_{tot}(E0)}) \times T_{1/2}}$$

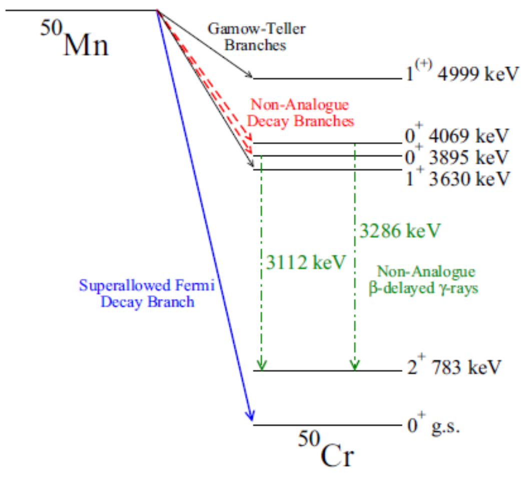
E0(keV)	$q_K^2(E0/E2)$		$\rho^2(E0)\times10^3$		K/L	
$(0_2^+ \rightarrow 0_1^+)$	This work	Ref	This work	Ref	This work	Ref
^{72}Ge 691					9.3(4)	8.4(6)[b]
^{72}Se 937	0.54(17)	0.6(4)[a]	37(1)	29(18)[a]	7.3(6)	8.1(3)[b]

W.T. Chou et al., Nuclear data sheets 73 (1994) 215

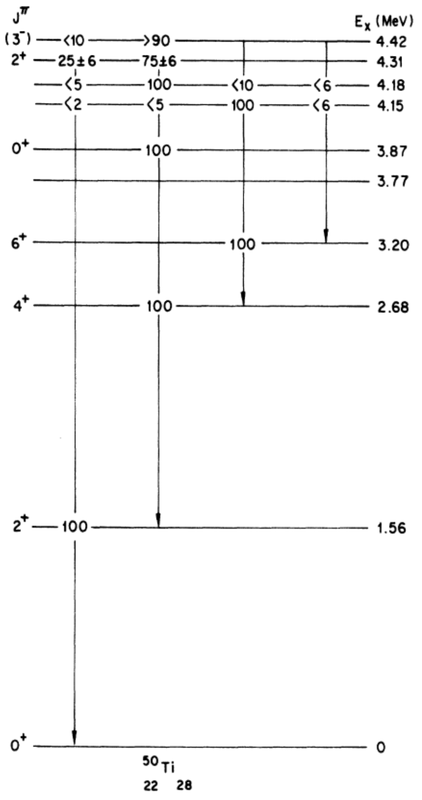
J.E. Draper et al. Phys. Rev. C 9 (1974) 948

Electric Monopole Transitions (*E0*) in the Study of ^{50}Ti and ^{50}Cr Nuclei





K.G. Leach et al., Phys. Rev. **C. 94**, 011304(R) (2016)



J. G. Pronko et al., Phys. Rev. **C 10**, 1345 (1974).

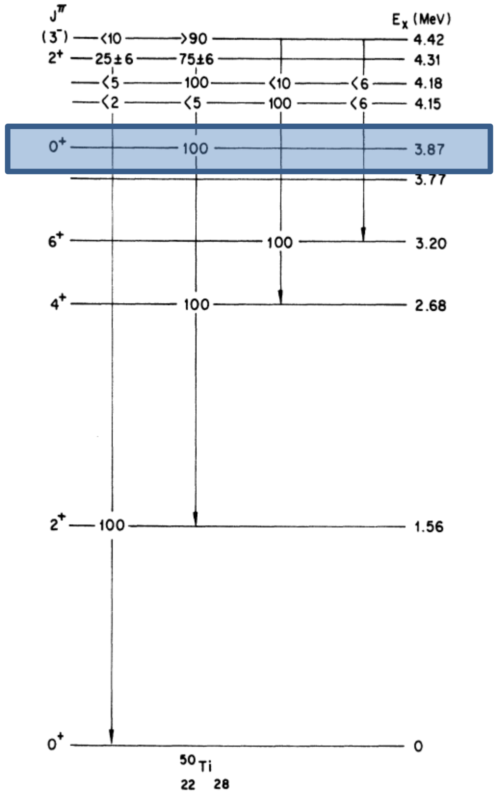
PhD M.V. Chisapi

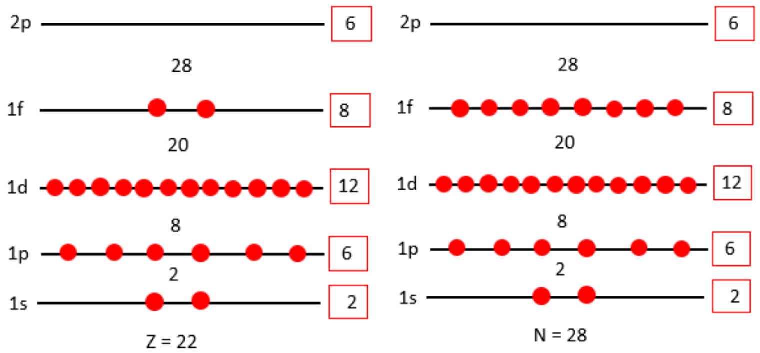
Motivation ^{50}Ti

According to the shell model the ground state of ^{50}Ti consists of two $1f_{7/2}$ protons and eight $1f_{7/2}$ neutrons outside the ^{40}Ca doubly magic core.

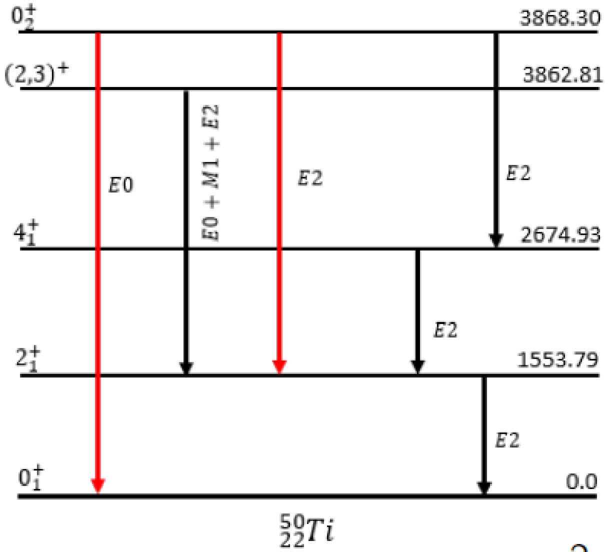
In the ground state, the two $1f_{7/2}$ protons are coupled to zero, giving spin of $J^{\pi} = 0^{+}$, and the lower-lying excited states are expected to result from the coupling of the two $1f_{7/2}$ protons in a level sequence of $J^{\pi} = 2^{+}, 4^{+}$, and 6^{+} (...this indeed has been shown by experiments).

The $E \geq 3.77$ MeV states on the other hand are expected to be dominated by more complicated configurations, e.g. 1p-1h and 2p-2h neutron excitation coupled to the two $f_{7/2}$ proton configuration.





Nuclear electromagnetic transitions



E (keV)	Transition	α_K (E2)	Ω_K (E0)	α_π (E2)	Ω_π (E0)	I_π/I_K
3868.30	E0: $0_2^+ \rightarrow 0_1^+$		1.964×10^8		3.42×10^{10}	174.13
2314.51	E2: $0_2^+ \rightarrow 2_1^+$	1.97×10^5		4.67×10^4		23.71
1553.79	E2: $0_2^+ \rightarrow 4_1^+$	4.14×10^5		1.09×10^4		2.64
1193.37	E2: $2_1^+ \rightarrow 0_1^+$	7.26×10^5		8.24×10^6		0.11

Table: Transition of interest in ^{50}Ti.

$$W(i;\mathrm{E0}) = \Omega_i \rho^2 = \frac{1}{\tau_i} = \frac{\ln 2}{(T_{1/2})_i} = \rho^2 \sum_i \Omega_i(Z,E), \qquad (1)$$

i (the decay channel)= K, L, . . . , or IPF.

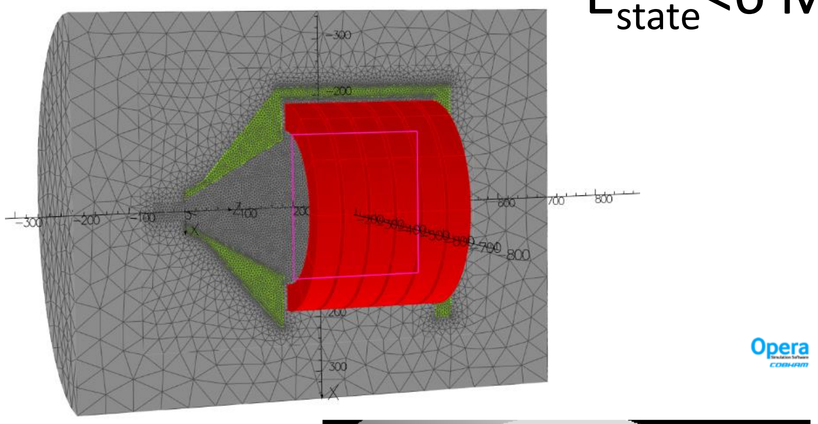
ρ^2: monopole transition strength (carries all nuclear structure information), τ_i is the partial lifetime and

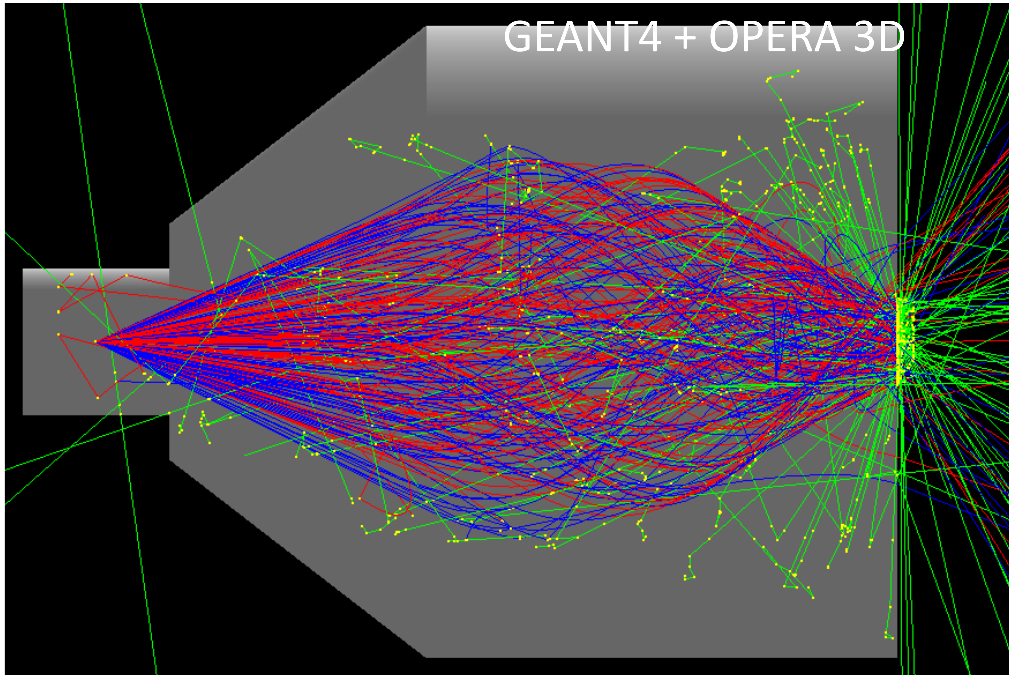
Ω_i: electronic factor (purely a function of atomic quantities).

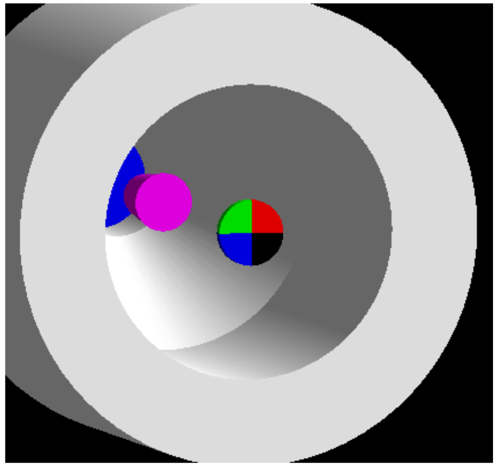
$$\rho(E0) = \langle 0_f^+ | \sum_p \frac{r_p^2}{R^2} | 0_i^+ \rangle = \langle 0_f^+ | \frac{M(E0)}{eR^2} | 0_i^+ \rangle \qquad (2)$$

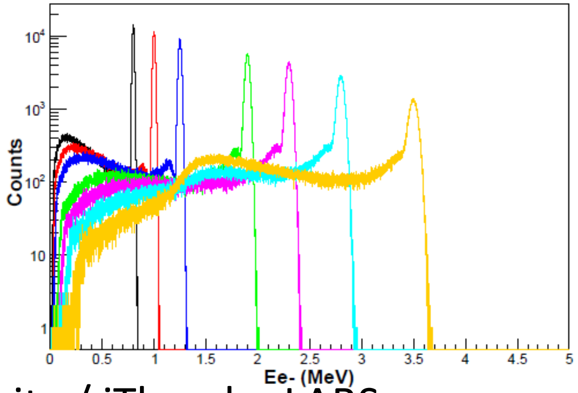
Pair detection, simulation
Low energy E0 – move to higher E

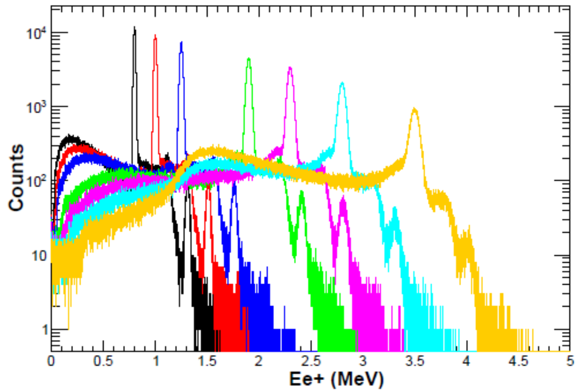
E_{state}<6 MeV





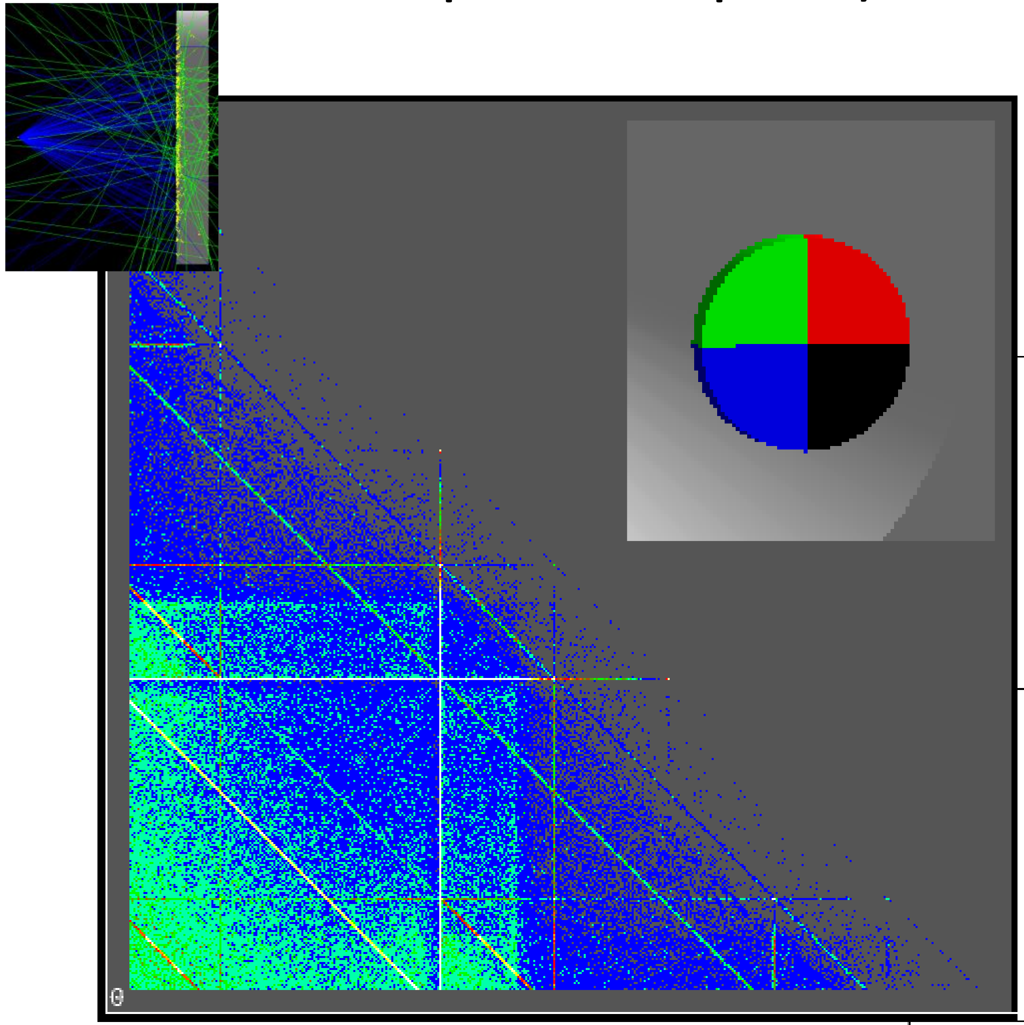


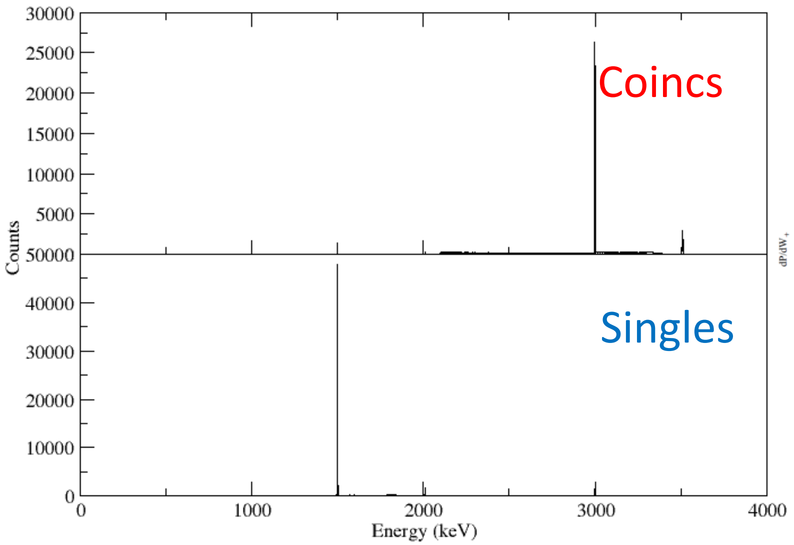


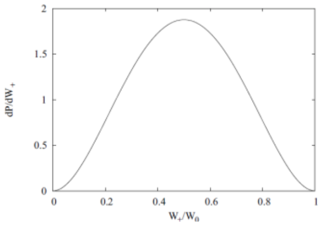


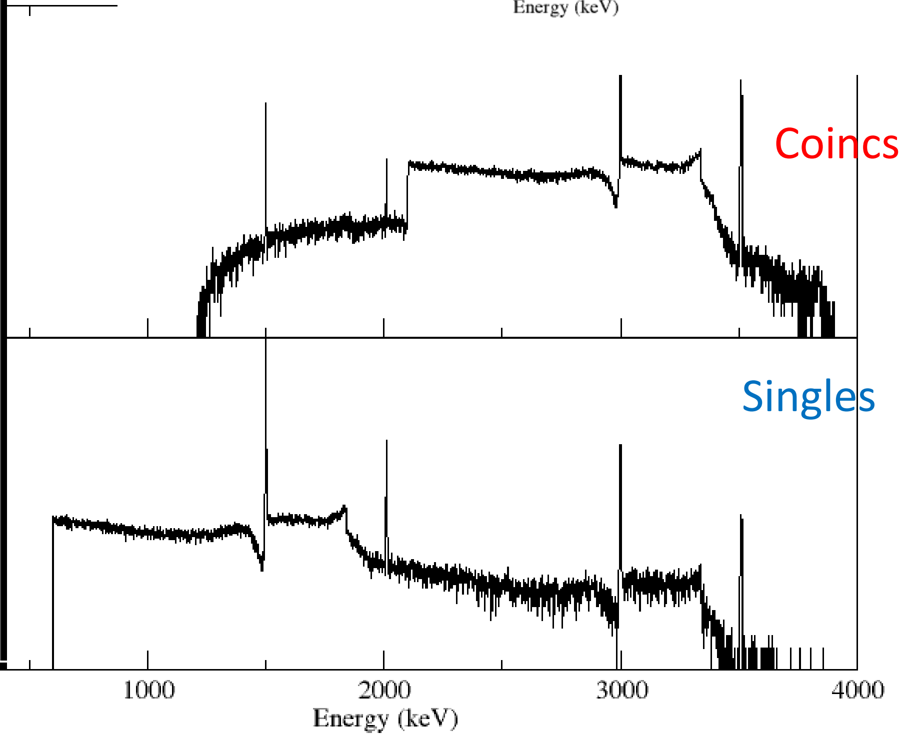
M. V. Chisapi, Stellenbosch University / iThemba LABS

Positron – Electron coincidences: GEANT (3 MeV electron/positron pairs)

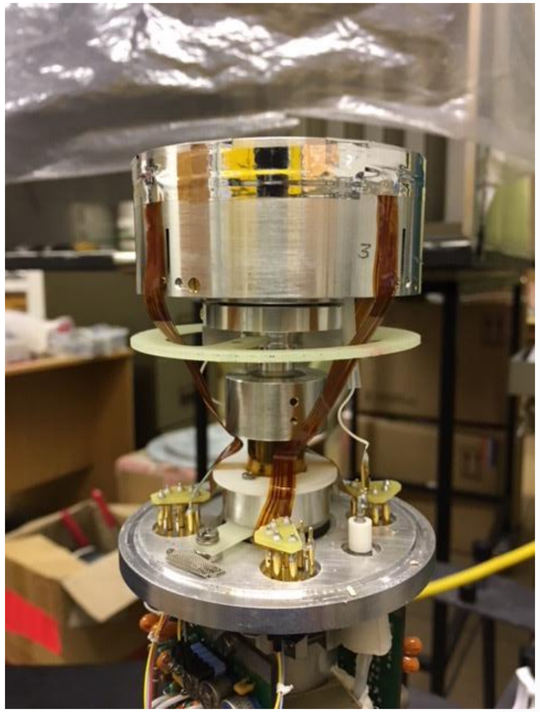


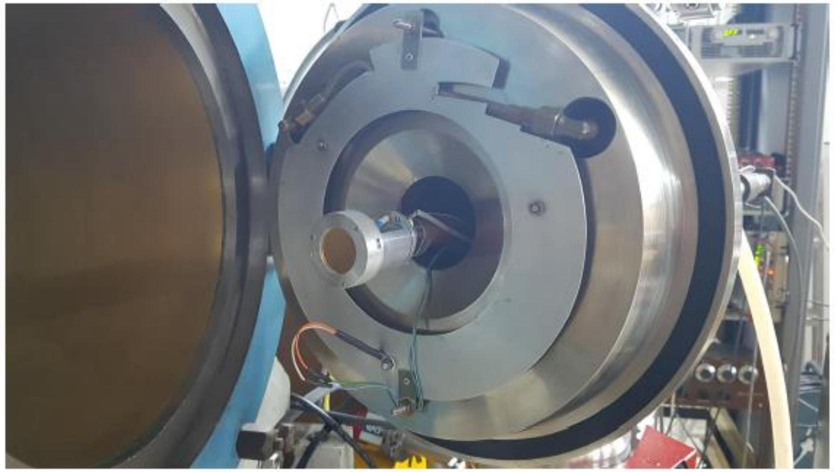




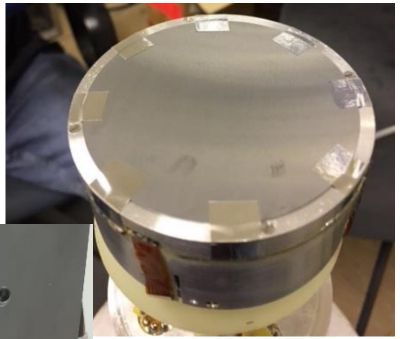


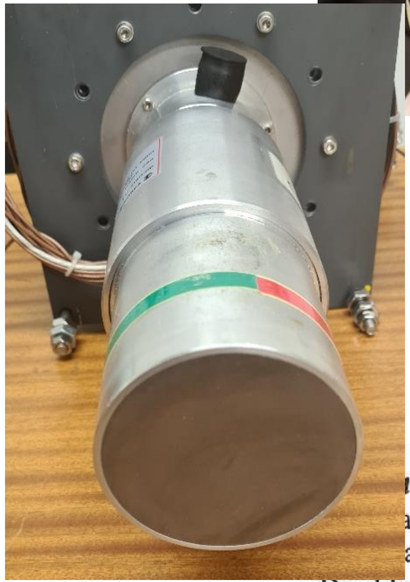
Detector & magnetic lens modifications

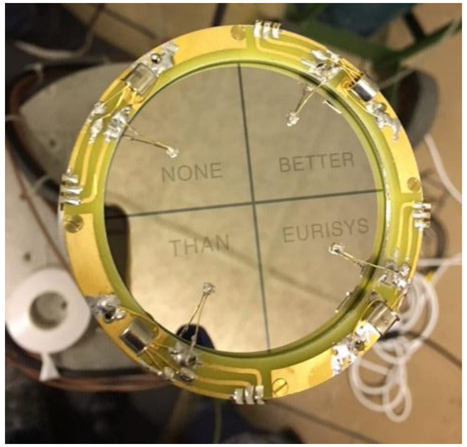


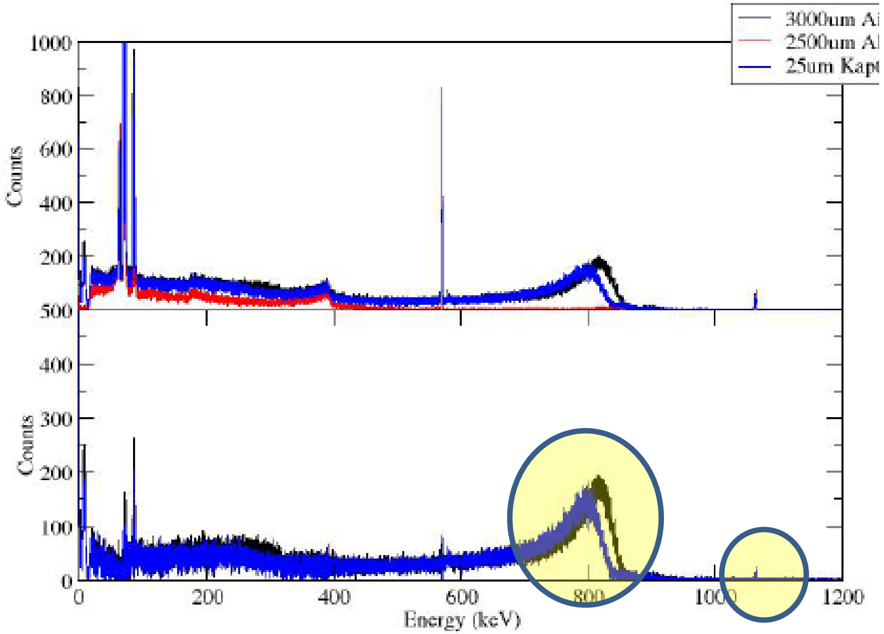


LEPS Detector tests







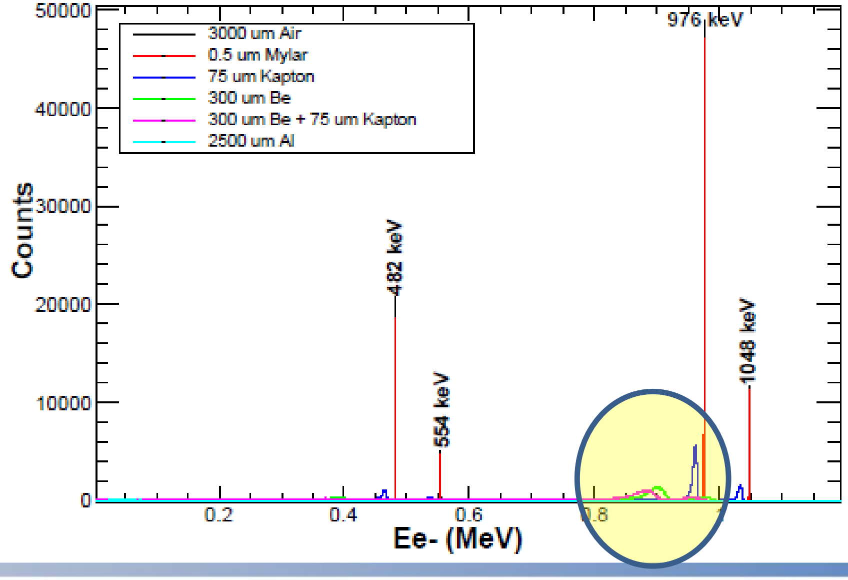


…etrical characteristics of the germanium crystal :

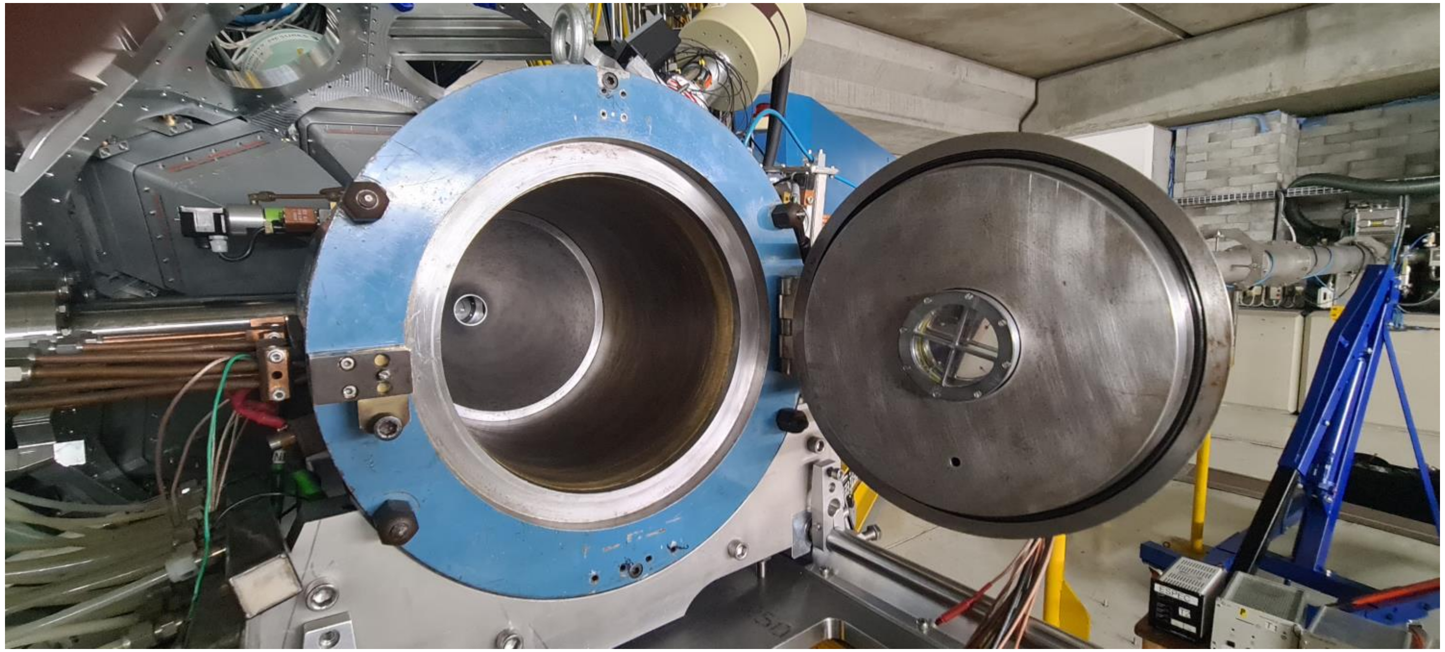
…al diameter :	66 mm	Length :	11 mm
…area :	2800 mm^2	Distance from cap :	15 mm
Dead layer :	≤0.5 µGe	Weight:	202g

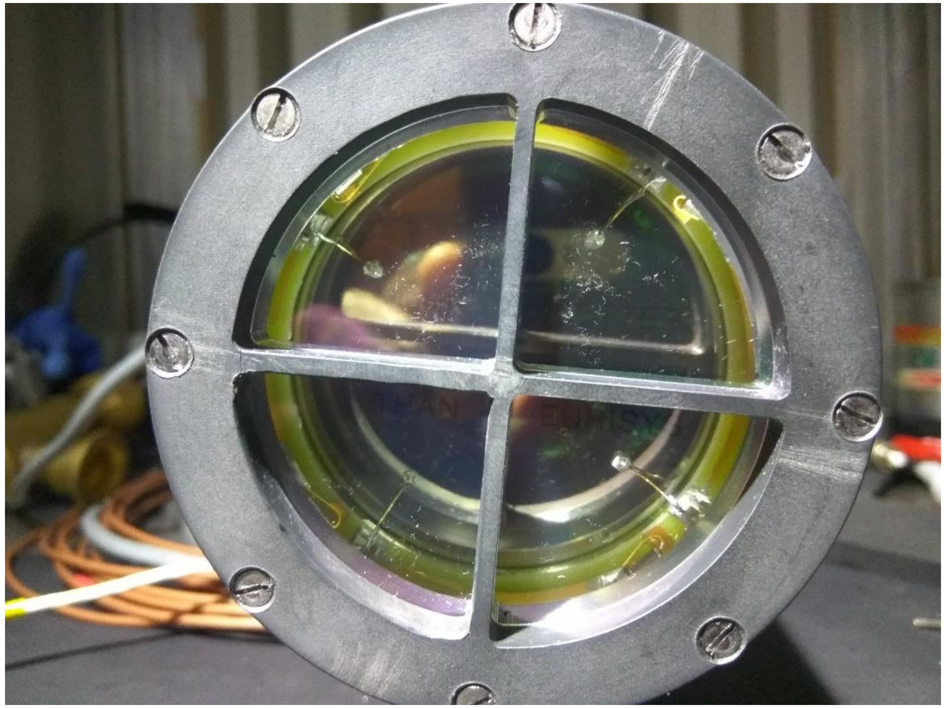
Cryostat : Type :SBF00 PA3 DAR N°660
Holding time : 2 days

End cap : Diameter : 80 mm Length : 90 mm
Entrance window : Be Thickness : 300 µm



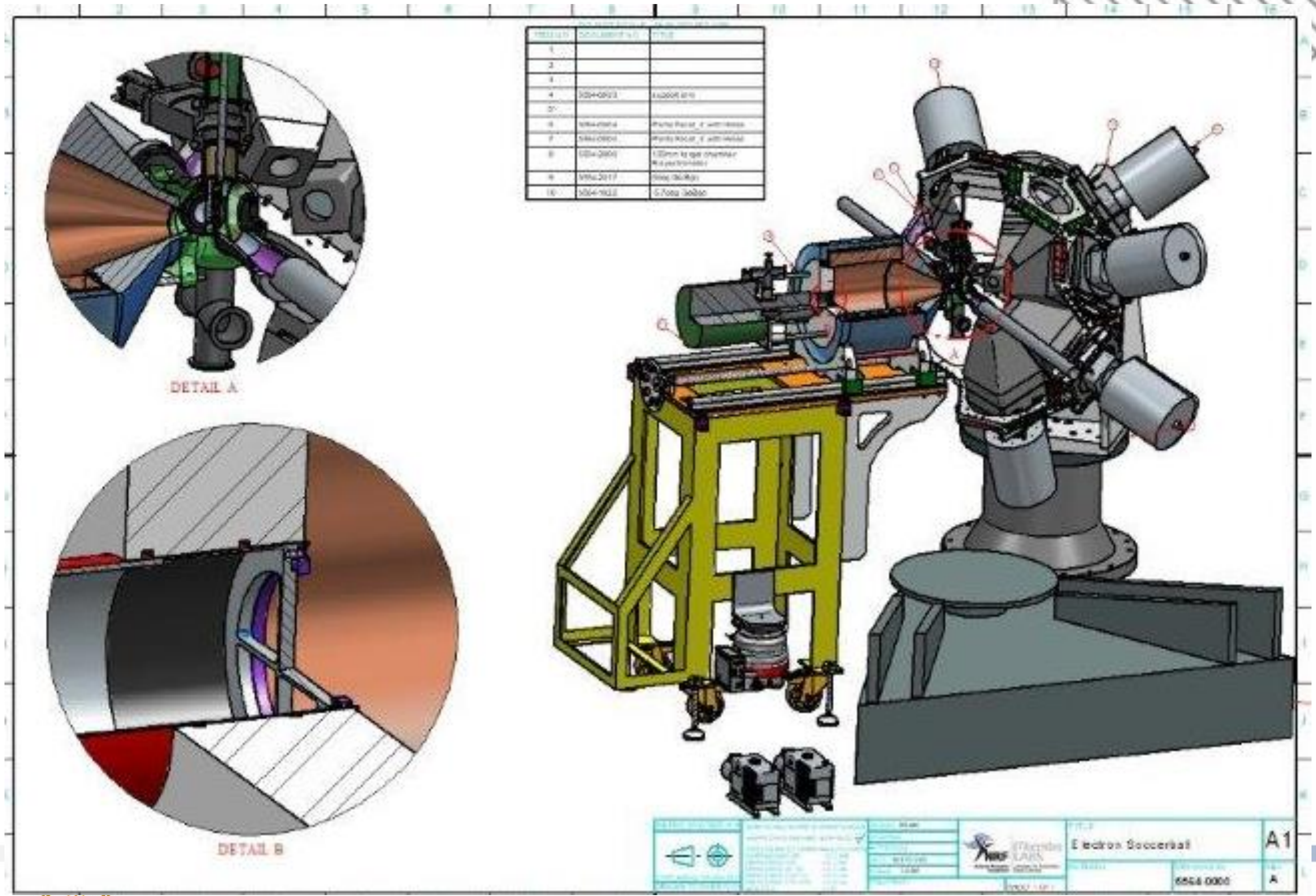
Detector Re-encapsulation

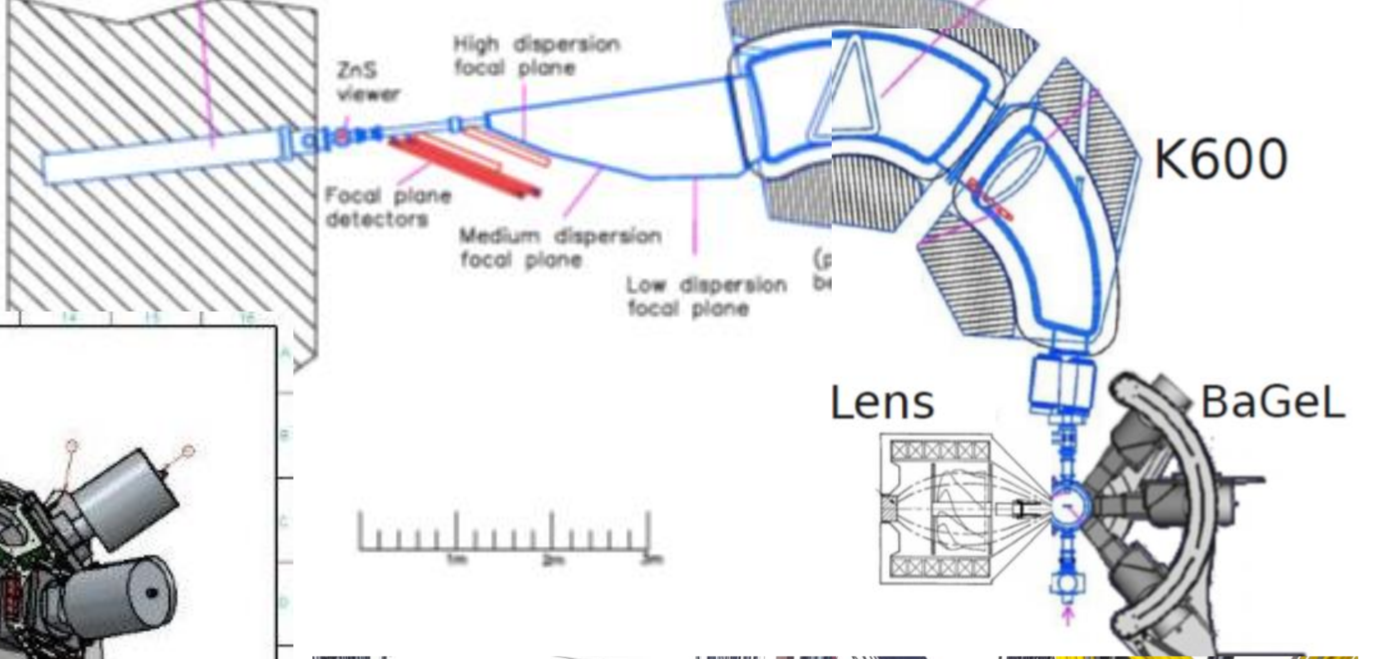


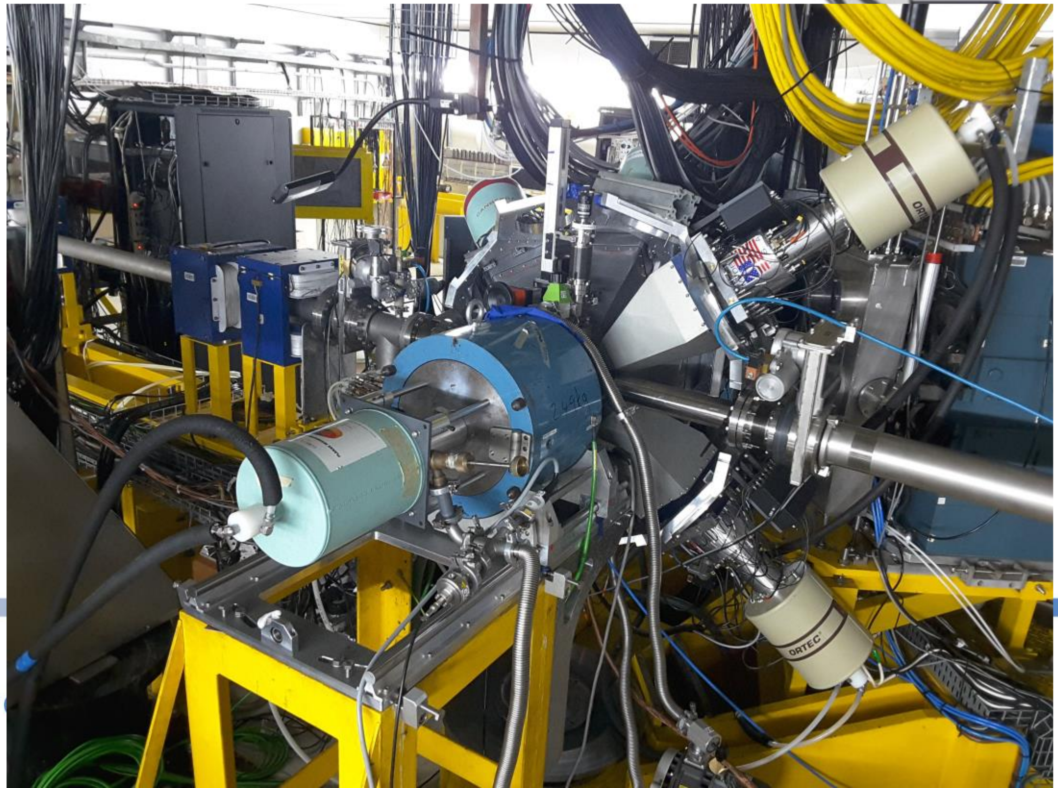


0.5 um mylar window
Differential pumping

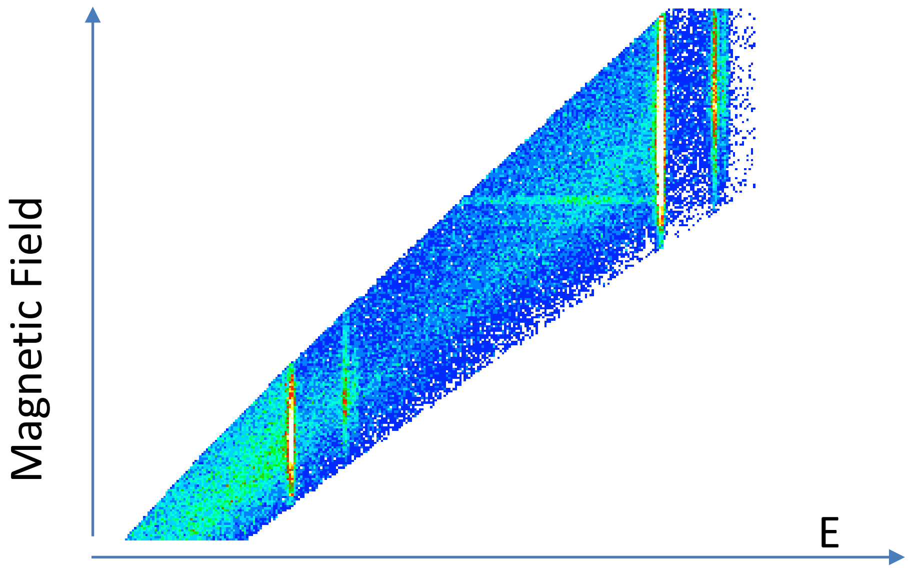
System integration at K600 spectrometer at iThemba LABS

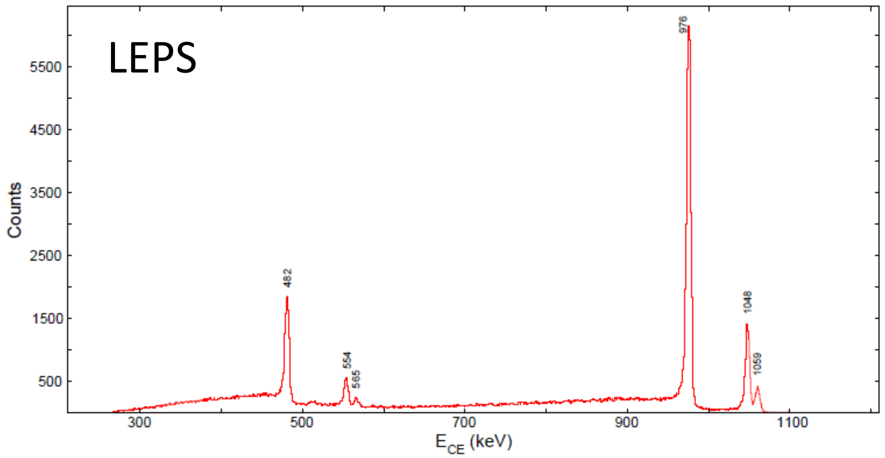


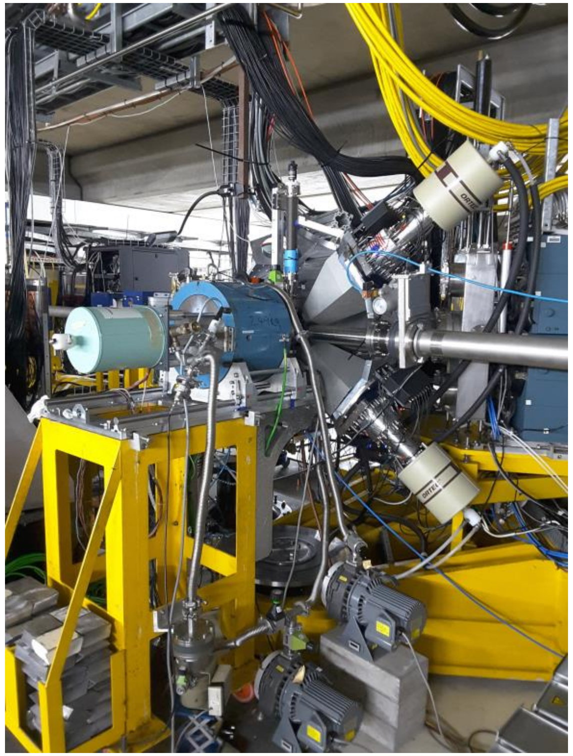


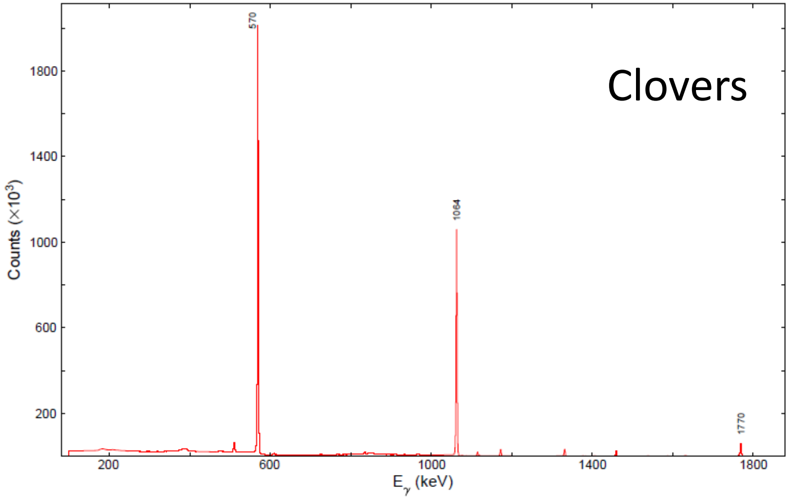


^{207}Bi Source spectra with detectors

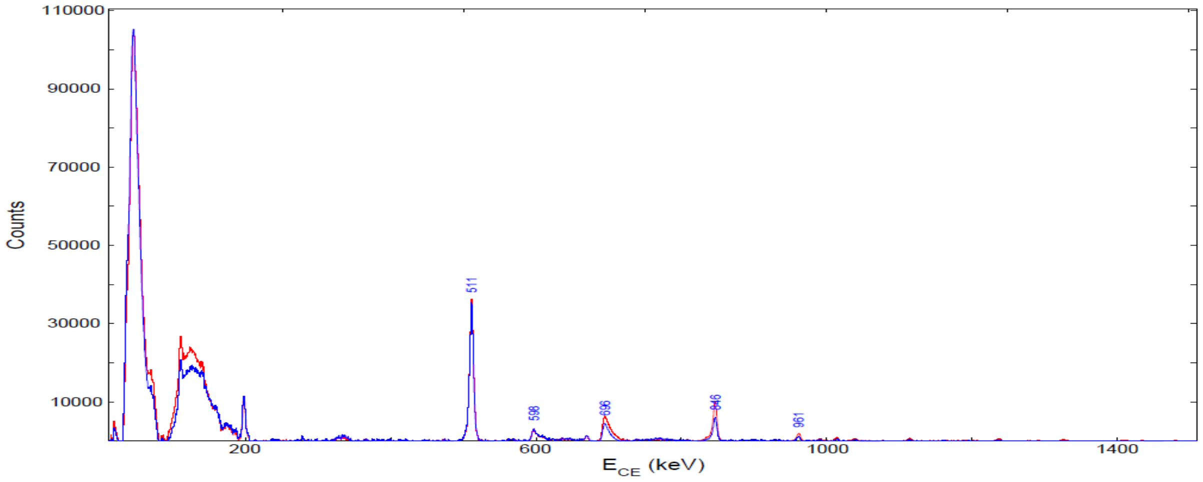


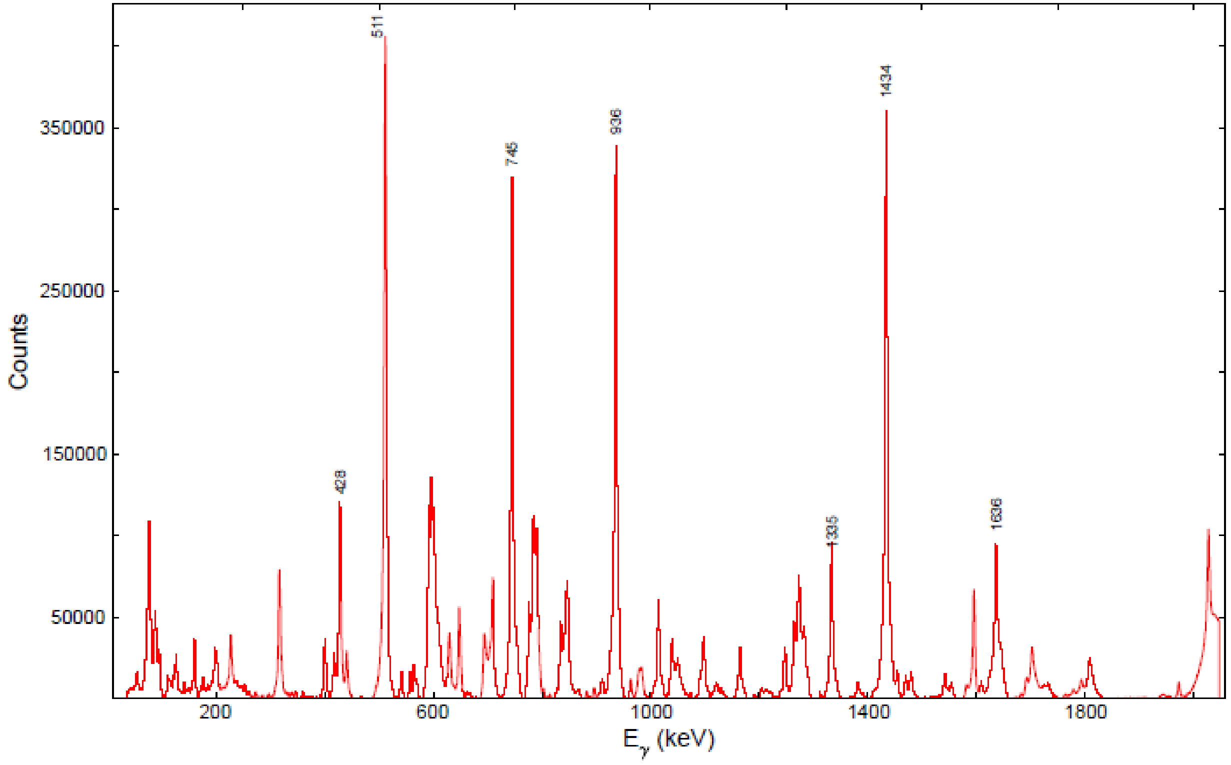






First in-beam data (December 2020)





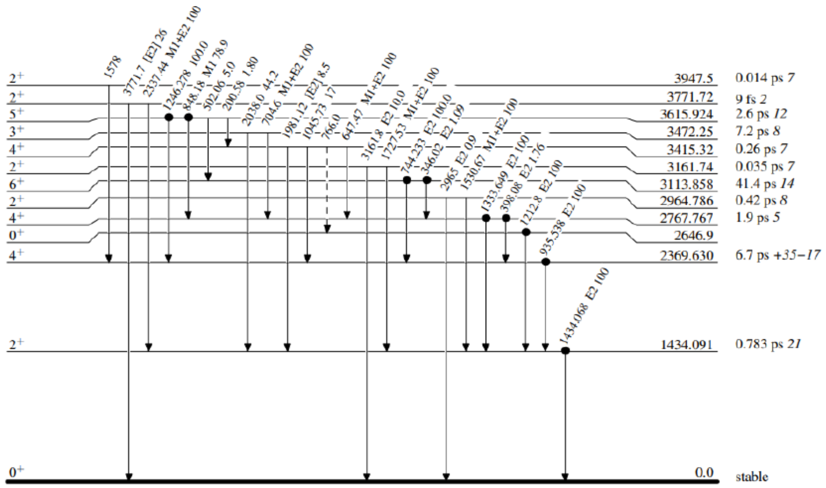
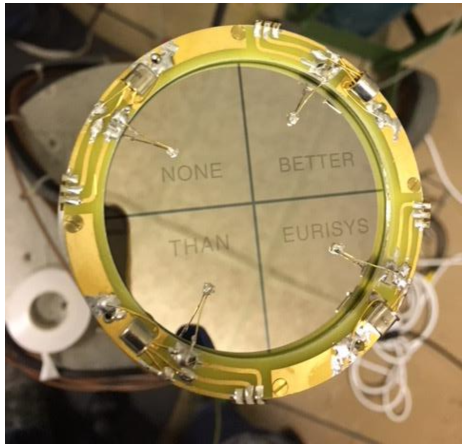


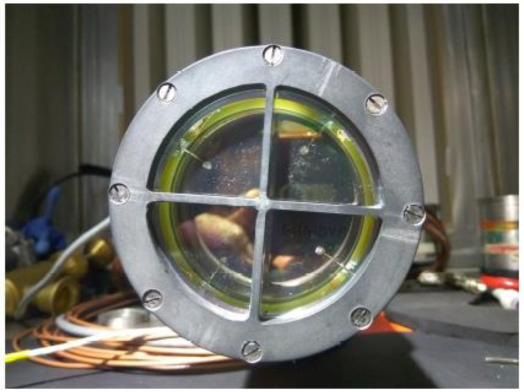
Figure 5.11: Level scheme for ^{52}Cr.

^{50}Cr(α, α’) 30 MeV

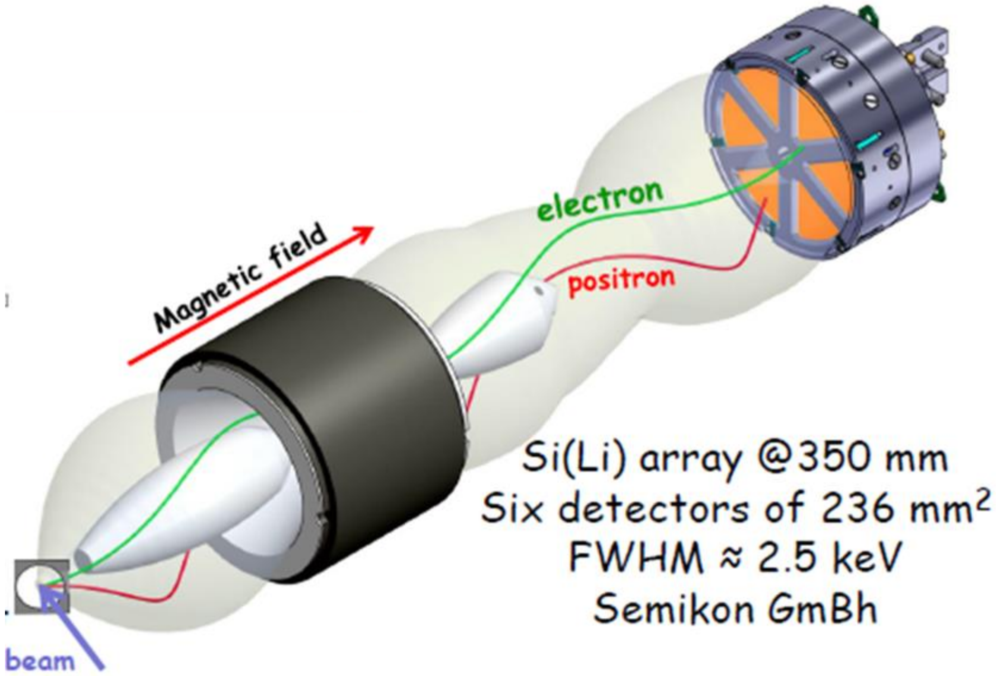
~ 48 hours swept field

Detector Development Plan





Increase granularity
Maintain thickness ~11mm
Investigate instrumentation



Super-E – Australian National University

IRG - South Africa-Joint Institute for Nuclear Research (SA-JINR)-Grants for JINR

NAME OF GRANT-HOLDER:	Dr PM Jones
INSTITUTION:	iThemba Laboratory for Accelerator Based Sciences
REFERENCE NO:	JINR200401510933
UNIQUE GRANT NO:	129599
PERIOD OF SUPPORT:	2021 - 2023

Planar Si(Li) Detectors with a Large Active Volume

Yu. B. Gurov[a,b], S. L. Katulina[a], S. V. Rozov[a], V. G. Sandukovsky[a], and J. Yurkowski[a,c]

[a] *Joint Institute for Nuclear Research, ul. Joliot-Curie 6, Dubna, Moscow oblast, 141980 Russia*

[b] *National Research Nuclear University "MEPhI", Kashirskoe sh. 31, Moscow, 115409 Russia*

[c] *Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, Krakow, 31-342 Poland*

Received July 16, 2009

Ion-Implanted HPGe Detectors for Multilayer Spectrometers of Charged Particles

Yu. B. Gurov*, K. N. Gusev, S. L. Katulina**, M. Mitura-Novak***, B. Raihel***, V. G. Sandukovsky**, and J. Yurkowski*****

* *Moscow Engineering Physics Institute (State University), Kashirskoe sh. 31, Moscow, 115409 Russia*

** *Joint Institute for Nuclear Research, ul. Joliot-Curie 6, Dubna, Moscow oblast, 141980 Russia*

*** *Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*

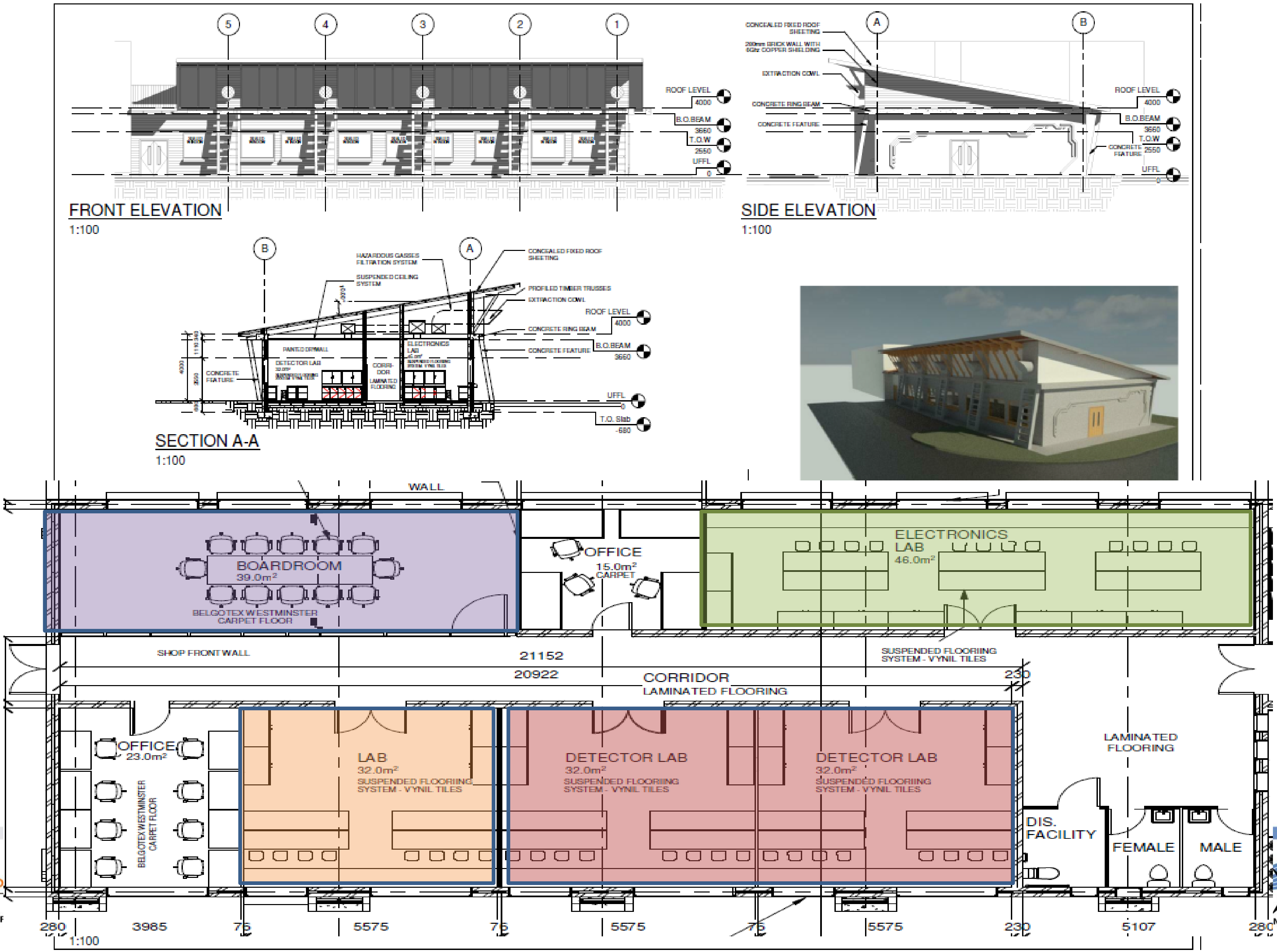
Received March 12, 2004

Plans 2021-2023

- Prototyping detector
- Simulations
- Segmentation
- Technology transfers
- Experiments

TIP : The Technology Innovation Platform 2021-2022

DELTA
built environment consultants



science & inno
Department:
Science and Innovation
REPUBLIC OF SOUTH AFR

NRF
National Research Foundation

iThemba LABS
Laboratory for Accelerator Based Sciences

Ongoing projects

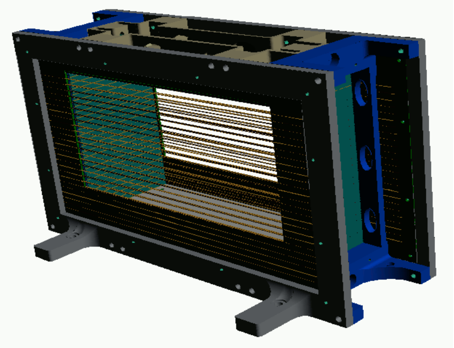


Fig 1. Frame of the FPD

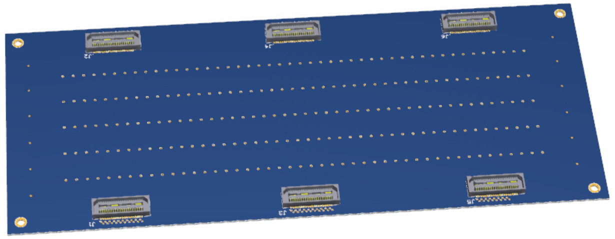
DSP: R. Neveling, P. Adsley *et al.*

Need for low energy particle detection at the K600

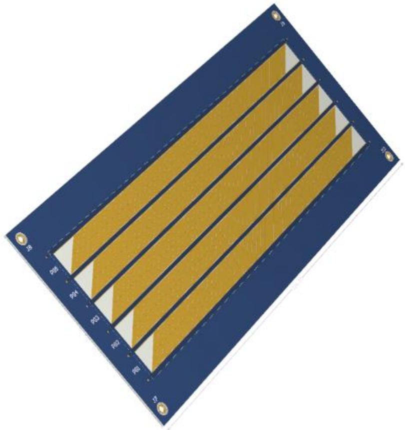
The aim is to build a prototype of a low-pressure focal plane position sensitive detector along the lines of the detector used for MAGNEX (Eur. Phys. J. A (2012) 48: 59). The prototype will be rectangular in shape, with dimensions of the active volume approximately 220mm wide, 100mm high and 100mm deep.
Currently the mechanical design frame is completed (above) for the prototype.

The design process of the 5 PCB's for the FPD is completed and in the procurement process. The PCBS are 5mm thick to give the structure strength and prevent distortion when tungsten wires is installed. The PCB on the right (below) consist of 5x46 =230 anode pads that is routed to 6 high density connectors via 4 layers. Special care is taken to ensure shortest routing between the pad and the high-density connector.

GEM detectors in medical applications

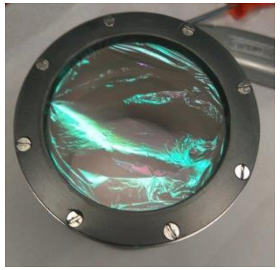


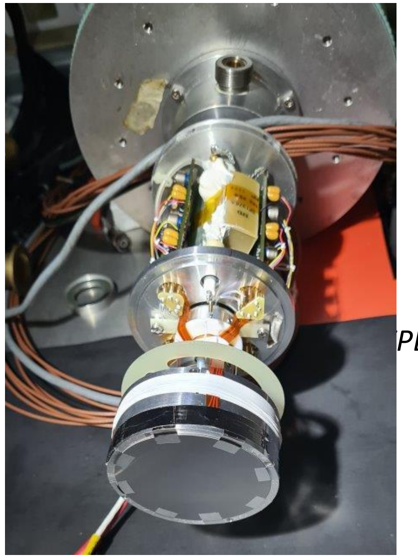
Bottom Layer Anode Plane with connectors



Top Layer of Anode plane PCB

New projects





PD

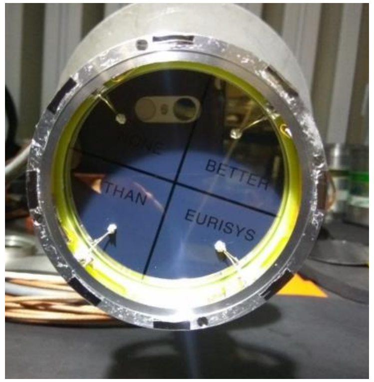
DSP / INIT: MV Chisapi, P. Jones *et al.*

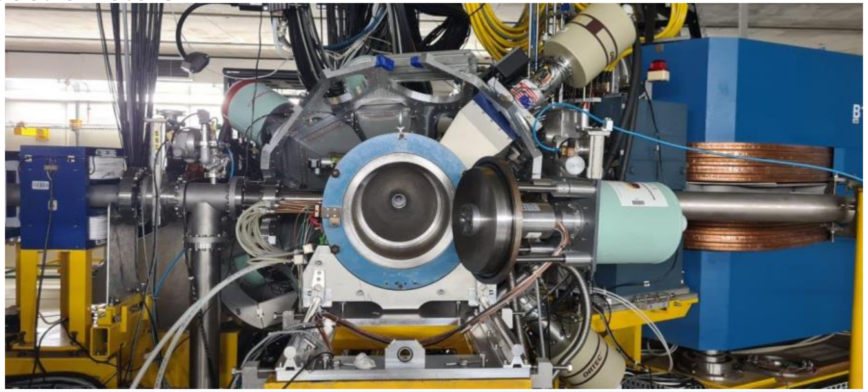
Innovative Detector Development for Nuclear Science

The demands placed on traditional solid-state detectors become ever increasing as the limits of nuclear spectroscopy shrink. Through the development of innovative techniques, starting with solid-state detector fabrication, through the coupling to electronics, cryogenics, and then to instrumentation, new detectors can be researched and developed for nuclear science. The application, or adaptation of these novel detectors into experiments and subsequent instrumentation through modern digitisation techniques can not only extract the basic spectroscopic measurables, but unfolding the detectors signal itself can allow for insight and discrimination into the incident radiation and extraction of further details through the study of the interaction of the radiation with the detector itself.

The production and use of these detectors will be invaluable to the scientific programme both at the Joint Institute for Nuclear Research (JINR) and iThemba LABS (Laboratory for Accelerator Based Sciences) to further fundamental science and to catalyse innovative techniques and methodologies between the two institutes and countries.

Develop new segmented Ge detectors for particle spectroscopy (electron-positron pairs) for measurement of E0 states with magnetic spectrometers.





In summary…

- Need for understanding the nature of modes of nuclear L=0 states; *breathing* or *shape changing / coexistence*
- Electron spectroscopy theme ongoing at iThemba LABS, capacity development, research enhancements, look out !
- Coupling with K600 spectrometer in 0^o mode for L=0 modes
- Study of 0^+ states through internal-pair formation
- South Africa – JINR collaboration for new detectors for spectroscopy and experiments
- Technology innovation platform at iThemba LABS for projects

This work is based on the research supported wholly by National Research Foundation of South Africa (118645, 90741) and iThemba LABS .