Investigating Quasi-Continuum Decay to Discrete Levels

Mathis Wiedeking

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Outline

i. Motivation.

ii. Review of experimental approach to study the region of high-level density.

iii. ^{95}Mo results and conclusions.

iv. ^{74}Ge campaign and preliminary results.

v. Spectrometer + Clovers at iTL.

vi. Summary.

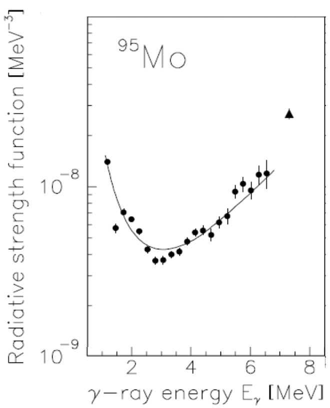
Low-Energy Enhancement

Volume 93, Number 14 PHYSICAL REVIEW LETTERS week ending 1 OCTOBER 2004

Large Enhancement of Radiative Strength for Soft Transitions in the Quasicontinuum

A. Voinov,[1,2,*] E. Algin,[3,4,5,6] U. Agvaanluvsan,[3,4] T. Belgya,[7] R. Chankova,[8] M. Guttormsen,[8] G. E. Mitchell,[4,5] J. Rekstad,[8] A. Schiller,[3,†] and S. Siem[8]

First report of enhancement E. Tavukcu, Ph.D. thesis, North Carolina State University, 2002.



PHYSICAL REVIEW C 71, 044307 (2005)

Radiative strength functions in $^{93-98}$Mo

M. Guttormsen,[1,*] R. Chankova,[1] U. Agvaanluvsan,[2] E. Algin,[2,3,4,5] L. A. Bernstein,[2] F. Ingebretsen,[1] T. Lönnroth,[6] S. Messelt,[1] G. E. Mitchell,[3,4] J. Rekstad,[1] A. Schiller,[2] S. Siem,[1] A. C. Sunde,[1] A. Voinov,[7,8] and S. Ødegård[1]
[1]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*
[2]*Lawrence Livermore National Laboratory, L-414, 7000 East Avenue, Livermore, California 94551*

Continued observations of low-energy enhancement for light- and medium-mass nuclei. Much debate over the last decade if the enhancement is real or an artifact.

Needs clarification

PHYSICAL REVIEW C 79, 024301 (2009)

Test of the statistical model in ^{96}Mo with the BaF_2 γ calorimeter DANCE array

S. A. Sheets,[1] U. Agvaanluvsan,[2] J. A. Becker,[2] F. Bečvář,[3] T. A. Bredeweg,[4] R. C. Haight,[4] M. Jandel,[4] M. Krtička,[3] G. E. Mitchell,[1] J. M. O'Donnell,[4] W. Parker,[2] R. Reifarth,[4] R. S. Rundberg,[4] E. I. Sharapov,[5] J. L. Ullmann,[4] D. J. Vieira,[4] J. B. Wilhelmy,[4] J. M. Wouters,[4] and C. Y. Wu[2]

Some experiments do not provide conclusive evidence.

PHYSICAL REVIEW C 77, 054319 (2008)

Two-step γ cascades following thermal neutron capture in ^{95}Mo

M. Krtička[*] and F. Bečvář
Faculty of Mathematics and Physics, Charles University in Prague, V Holešovičkách 2, CZ-180 00 Prague 8, Czech Republic

Others show that the low-energy enhancement does not exist.

Impact of PDR and LE-Enhancement

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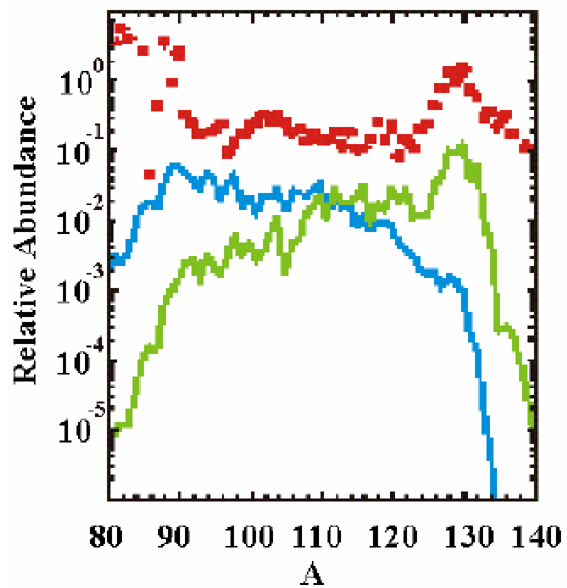
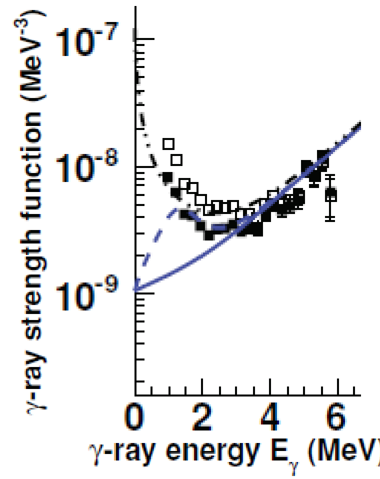
The low-energy part is particularly important for understanding nuclear reactions in astrophysical environments.



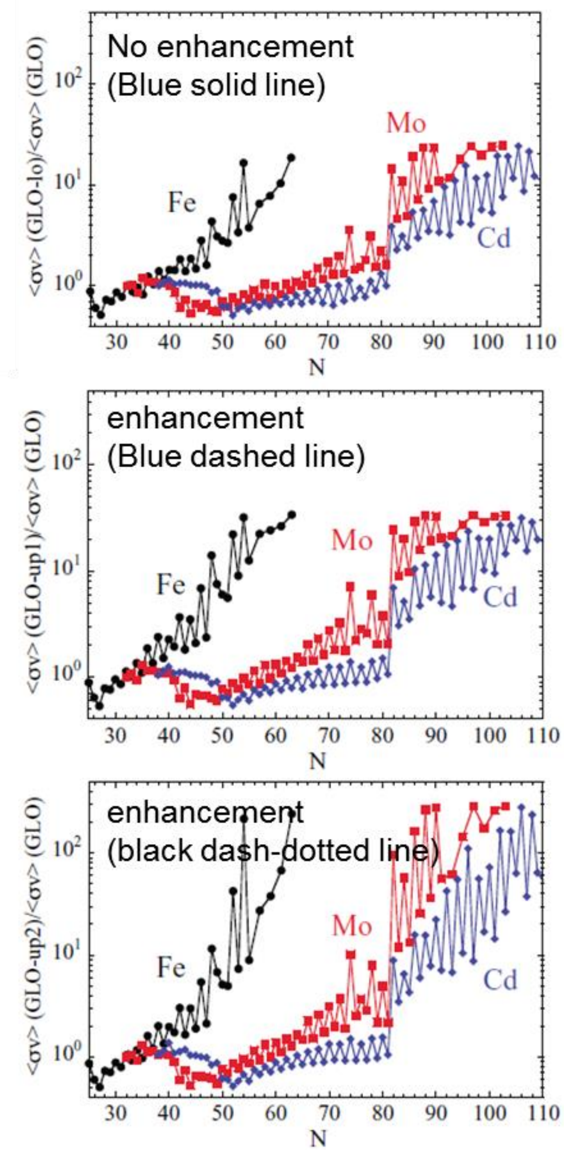
Impact of PR on the r-abundance distribution with T=10^9K and neutron density 10^{20} cm^{-3}. Abundance calculations with standard GDR component and the GDR+PR strength compared to the solar system. Use of GDR produces A~90-110, PR accelerates production of A~130



Predictions compared to GLO estimates for T=10^9K typical of r-process synthesis.

Influence of the enhancement on (n,g) reaction rates becomes more important with increase in neutron number.

Effect is significant and can increase reaction rates by order of magnitude



S. Goriely, Phys. Lett. B 436, 10 (1998).

A.C. Larsen and S. Goriely, Phys. Rev. C 82, 014318 (2010).

Motivation and Experiment

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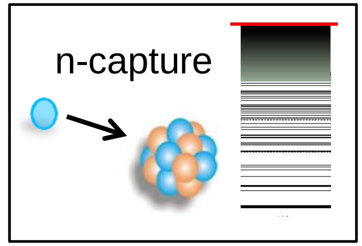
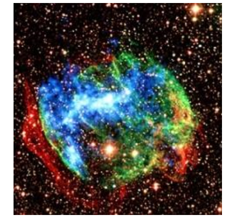
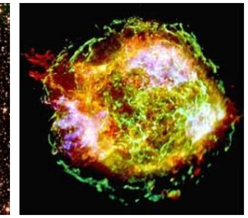
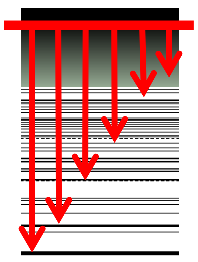
Application: Impact of astrophysical environments on reaction rates?

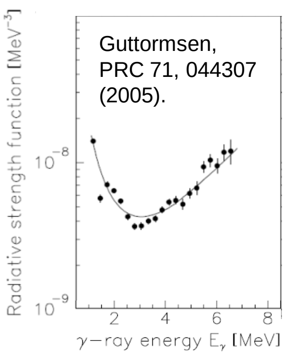






http://rst.gsfc.nasa.gov/Sect20/A6.html

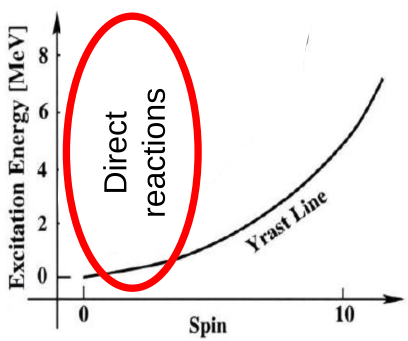




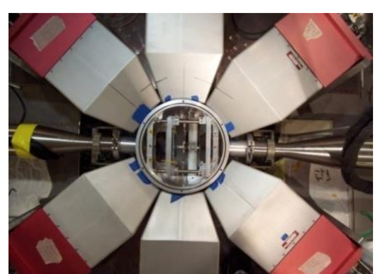
Physics: Does the low-energy enhancement exist?
What is its origin?
Do we all measure the same thing?
Reaction dependence?
Validity of the Axel-Brink Hypothesis?

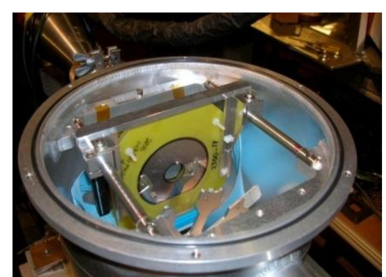
Needed: New experimental approach

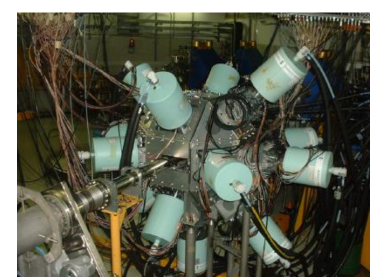
Use direct or scattering reactions $^{94}Mo(d,p)^{95}Mo$.



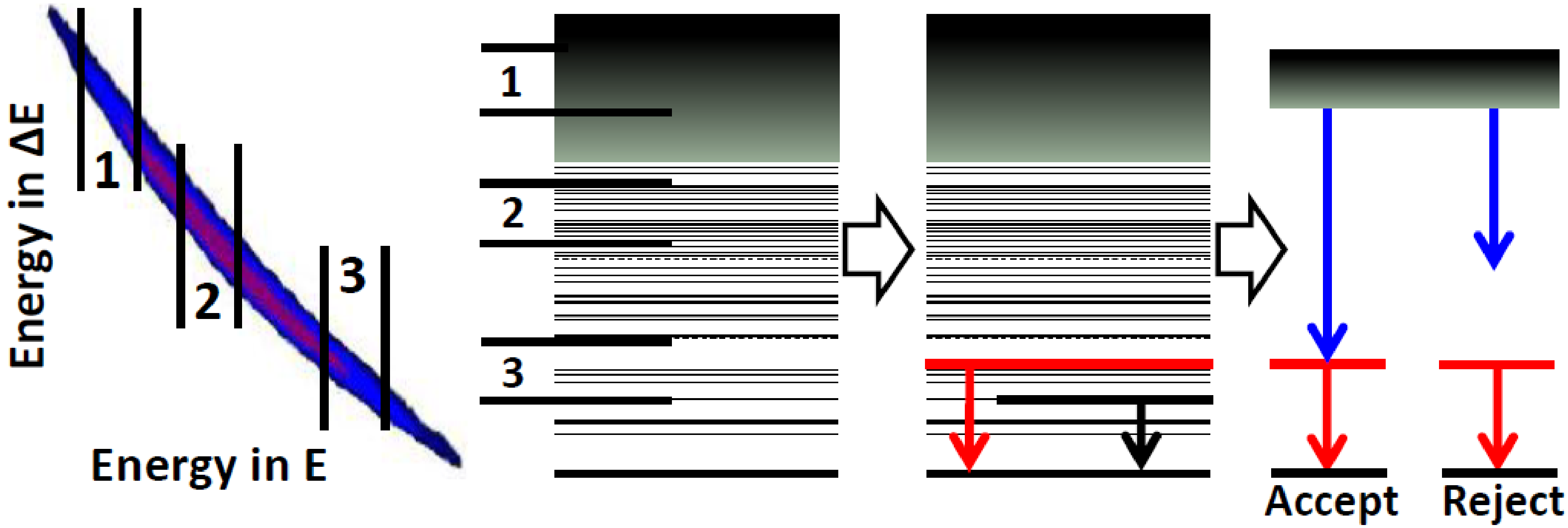
Clover and Silicon detectors
STARS-LIBERACE at LBNL
AFRODITE + Silicon at iTL

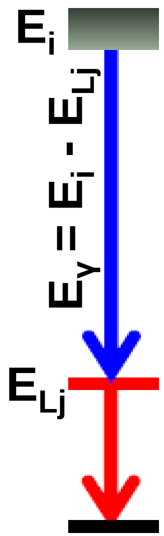






Review: Extracting information





$$f(E_\gamma) \equiv f_{J^\pi}(E_\gamma) = \frac{\overline{\Gamma}_{J^\pi}(E_i, E_\gamma)\rho_{J^\pi}(E_i)}{E_\gamma^{2\lambda+1}}$$

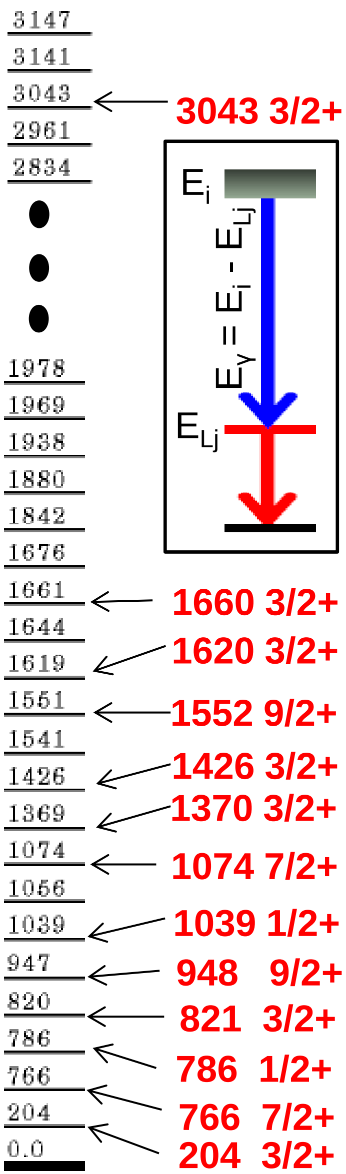
Exploiting this equation and assuming dipole transitions dominate:

$$N_{L_j}(E_i) \propto \sum_{J^\pi} \sigma_{J^\pi}(E_i)\overline{\Gamma}_{J^\pi}(E_i, E_i - E_{L_j})\rho_{J^\pi}(E_i)$$

$$= f_{J^\pi}(E_i - E_{L_j})E_\gamma^3 \sum_{J^\pi} \sigma_{J^\pi}(E_i)$$

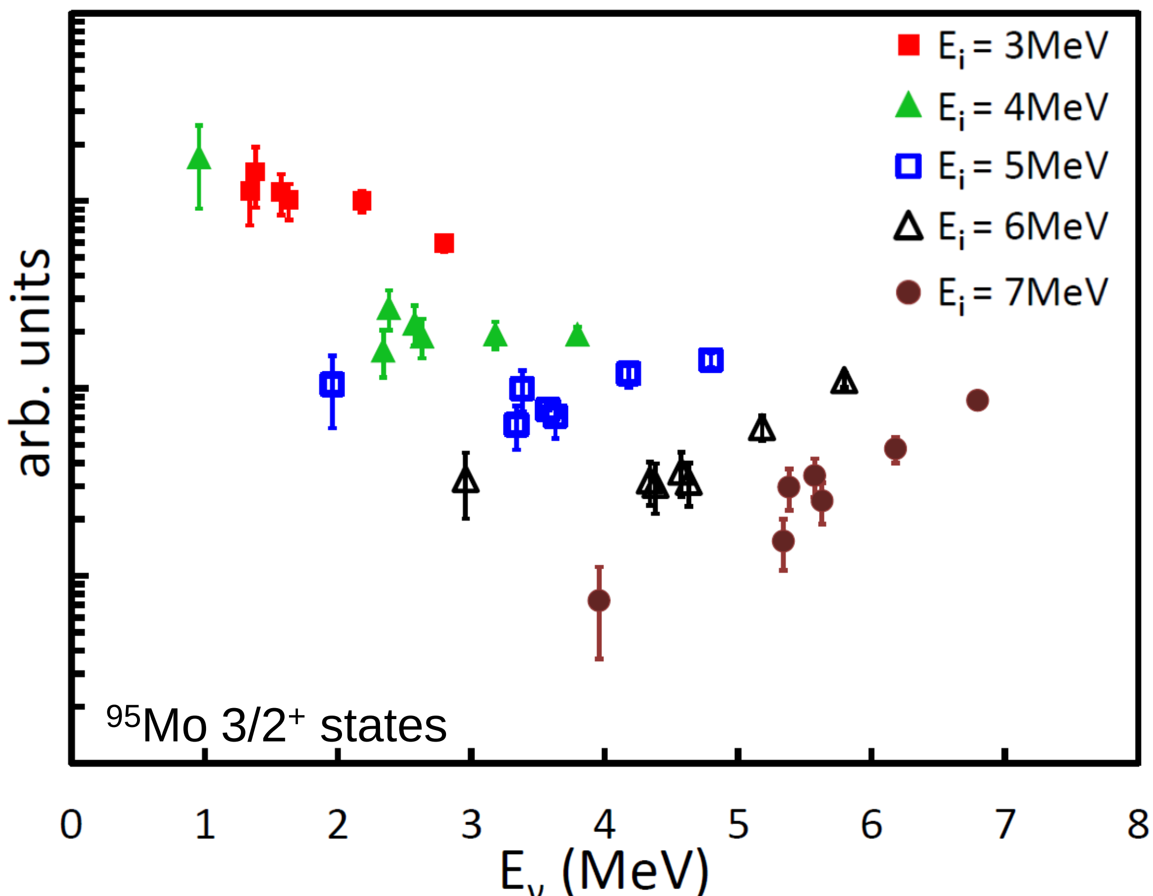
$N_{Lj}(E_i)$ corrected for efficiencies (event-by-event) and branching ratios.

^{95}Mo data

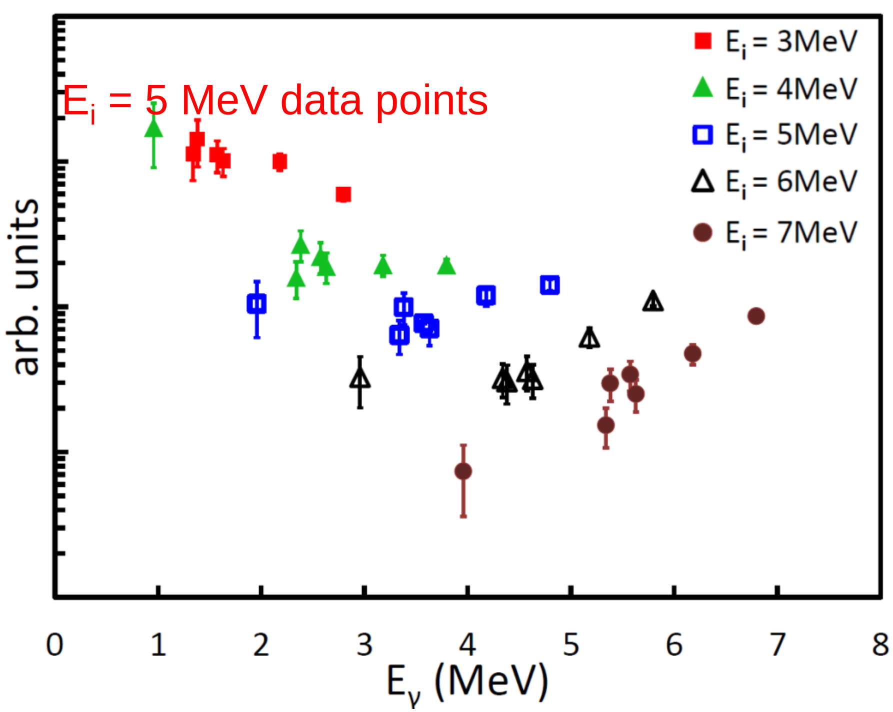


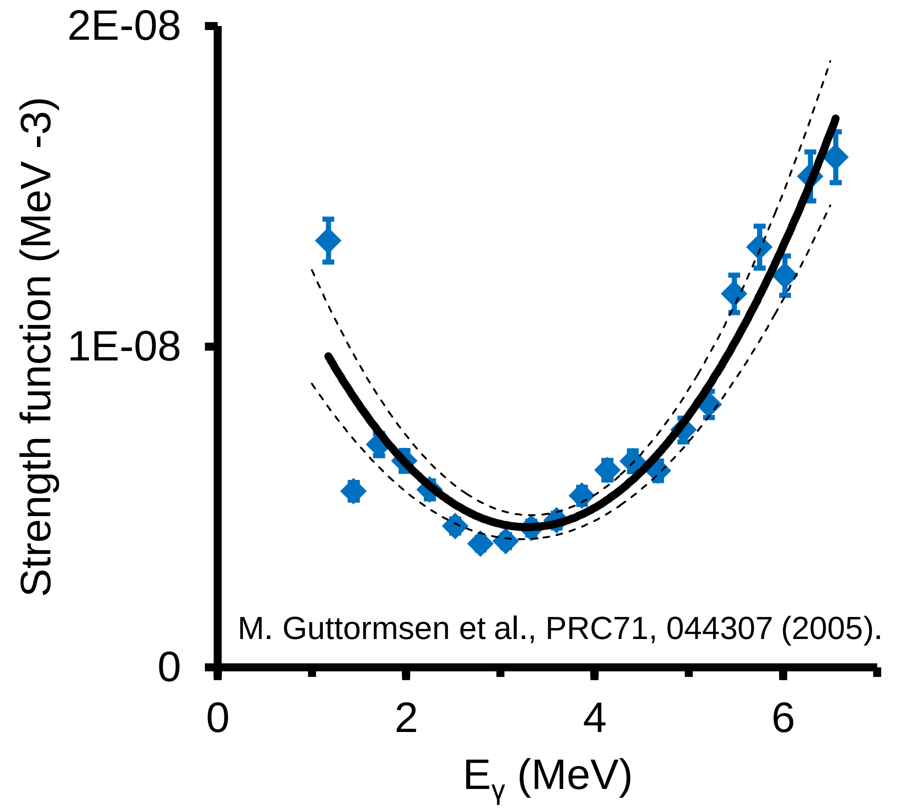
13 states with enough statistics:
- 7 states of $3/2^+$
- 2 states of $1/2^+$
- 2 states of $7/2^+$
- 2 states of $9/2^+$

Two ways to present the results:
- i) χ^2 method
- ii) Ratio method



^{95}Mo 3/2^{+} states comparison



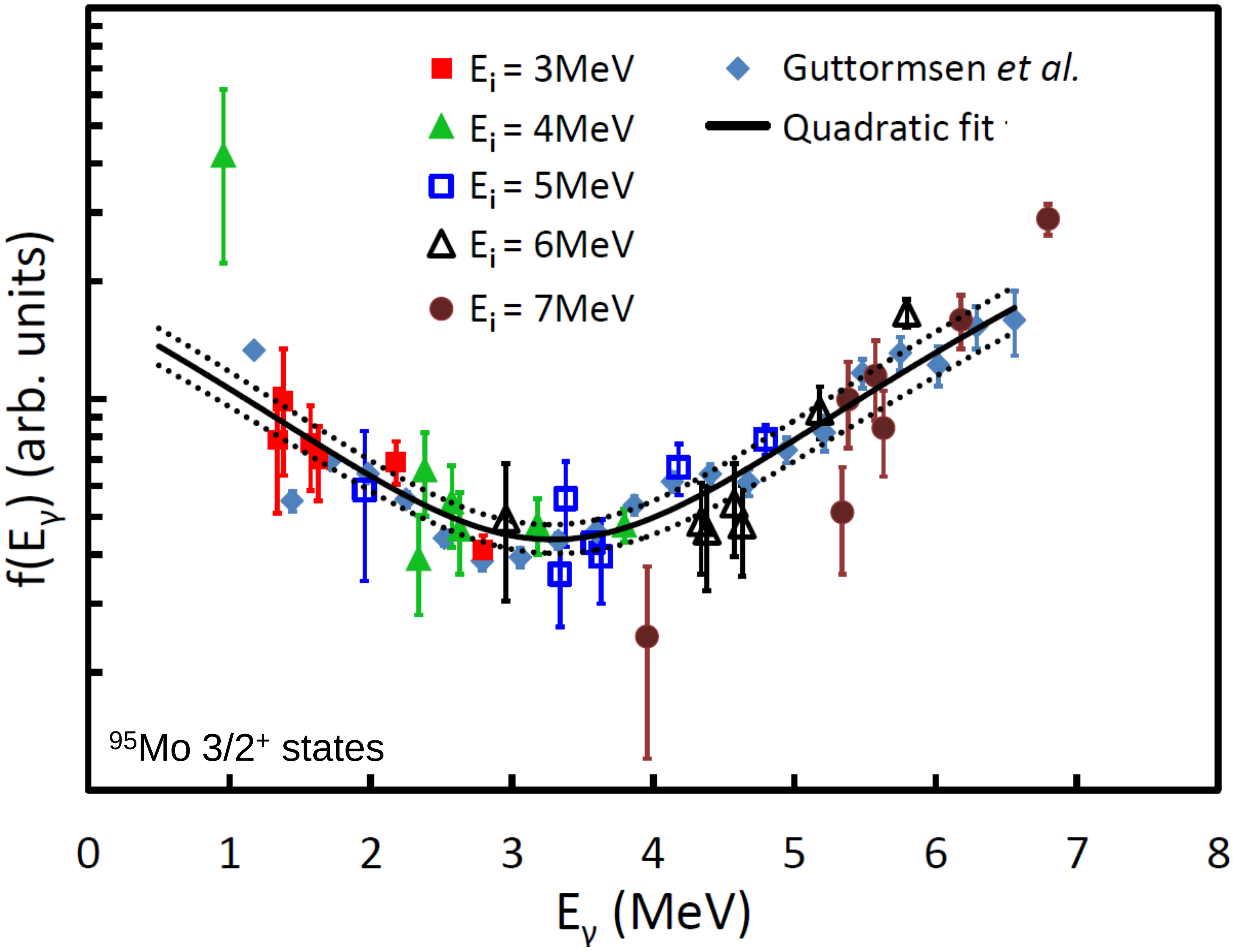


Each set of intensities, for a given E_i, feeding states of same spin and parity originates from:

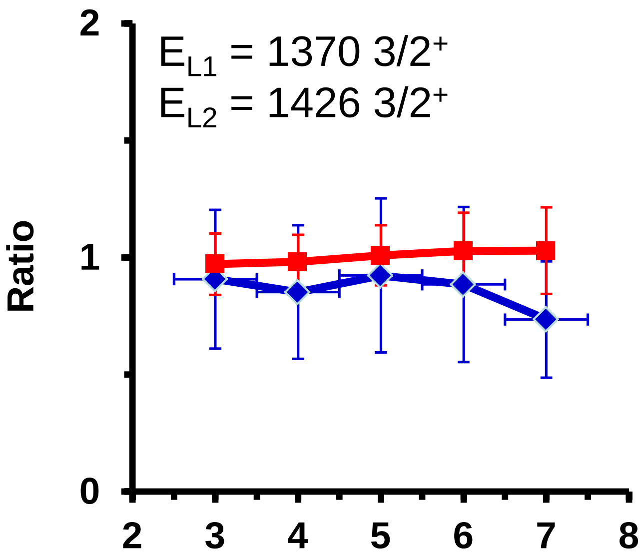
1) same level density.
2) Same spin and energy dependence of (d,p) cross section.

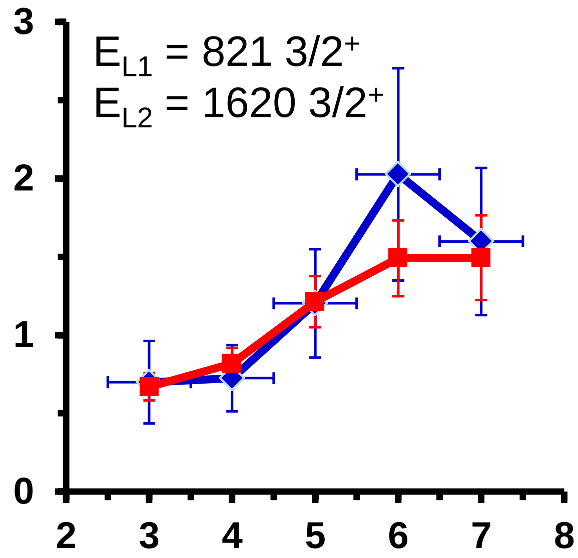
→ χ^2 minimization for each set of points at E_i.

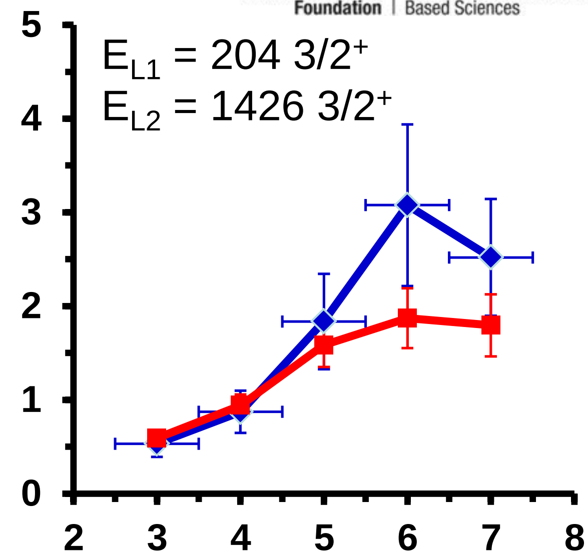
^{95}Mo: χ^2 minimization

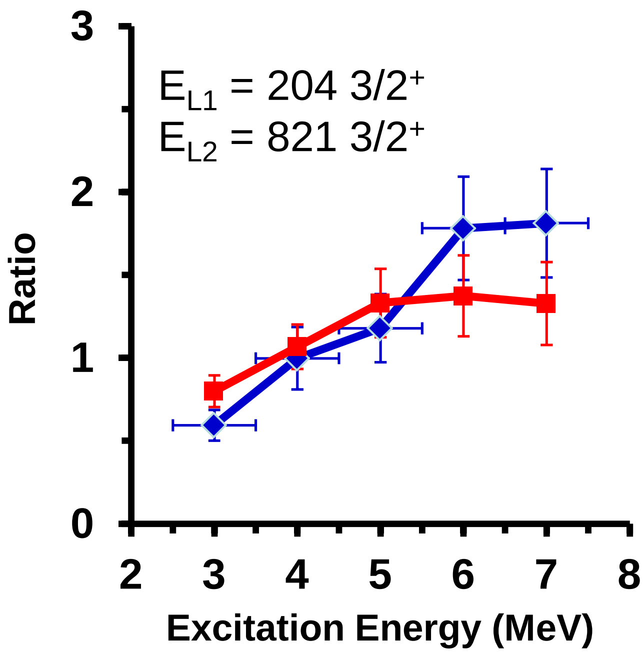


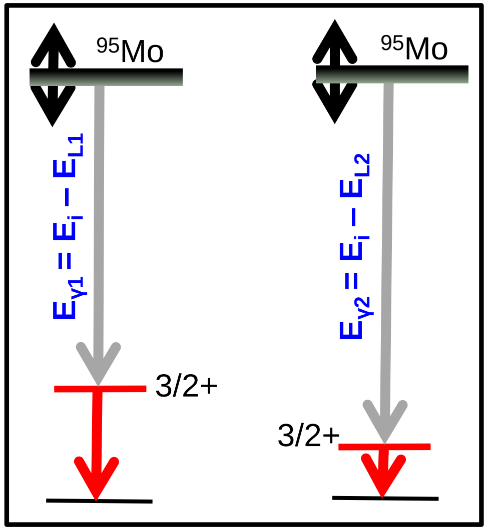
Experiment, Guttormsen









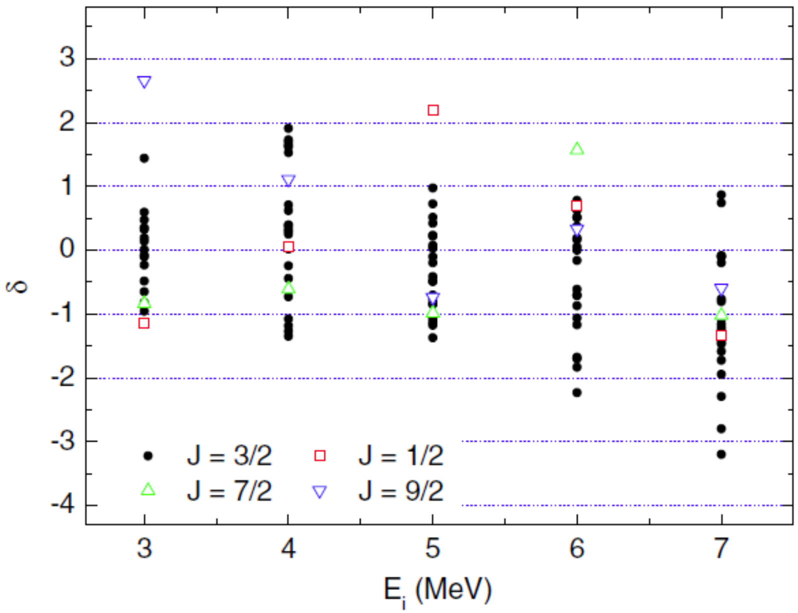


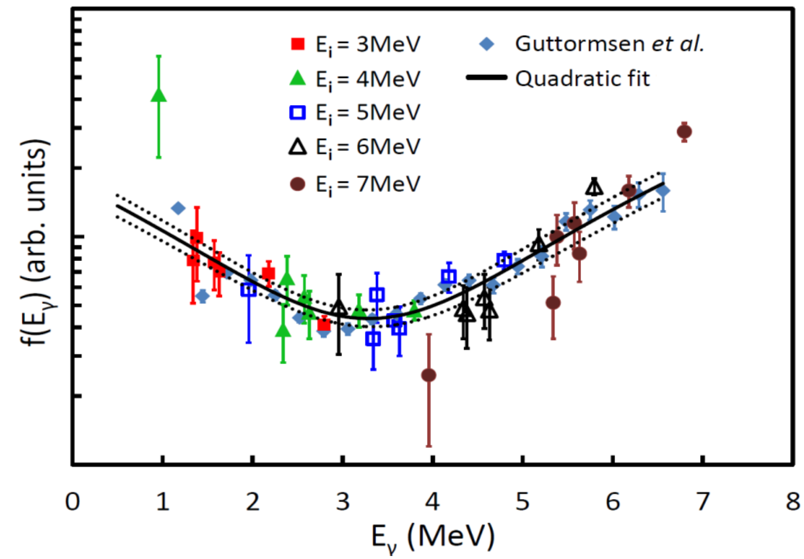
$$N_{L_j}(E_i) \propto \sum_{J^\pi} \sigma_{J^\pi}(E_i)\overline{\Gamma}_{J^\pi}(E_i, E_i - E_{L_j})\rho_{J^\pi}(E_i)$$
$$= f_{J^\pi}(E_i - E_{L_j})E_\gamma^3 \sum_{J^\pi}\sigma_{J^\pi}(E_i)$$

$$R = \frac{f(E_i - E_{L1})}{f(E_i - E_{L2})} = \frac{N_{L1}(E_i)(E_i - E_{L2})^3}{N_{L2}(E_i)(E_i - E_{L1})^3}$$

24 ratios in total:
Independent of level density,
(d,p) cross-section,
systematic uncertainties

Photon strength in ^{95}Mo





- (d,p) reactions to populate ^{95}Mo.
- New experimental approach studying statistical decay to individual discrete levels.
- proton-gamma-gamma coincidences to extract primary transitions.
- Strength extracted without any model dependencies or assumptions (eg level density).
- For the first time independent confirmation of the shape of photon strength.
- Now focus can shift to understanding the underlying mechanism.

PRL **108,** 162503 (2012) PHYSICAL REVIEW LETTERS week ending 20 APRIL 2012

Low-Energy Enhancement in the Photon Strength of ^{95}Mo

M. Wiedeking,[1,2] L. A. Bernstein,[1] M. Krtička,[3] D. L. Bleuel,[1] J. M. Allmond,[4] M. S. Basunia,[5] J. T. Burke,[1] P. Fallon,[5] R. B. Firestone,[5] B. L. Goldblum,[5,6,7] R. Hatarik,[5] P. T. Lake,[5] I-Y. Lee,[5] S. R. Lesher,[1] S. Paschalis,[5] M. Petri,[5] L. Phair,[5] and N. D. Scielzo[1]

[1]*Physical and Life Sciences Directorate, Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
[2]*iThemba LABS, P.O. Box 722, Somerset West 7129, South Africa*

Collaboration Goals

Many open questions need to be answered:

- Statistical gamma-ray spectra for application purposes (NIF).
- Is the shape of statistical spectra for a given nucleus reaction dependent?
- Do different experimental methods yield the same result?
- What is the origin of the low-energy enhancement?
- Is the Brink Hypothesis valid?

To tackle these (and more) questions a collaboration was established in 2010:

Collaboration White Paper (2010):

Statistical γ-ray studies in support of s-process (n,γ) measurements at NIF

L.A. Bernstein, D. Bleuel, J.A. Caggiano, R. Hatarik, D.H.G. Schneider, W. Stoeffl-LLNL, USA
R.B. Firestone, M.S. Basunia, A. Hurst – LBNL, USA
M. Wiedeking – iThemba LABS, South Africa
M. Krticka, F. Becvar – Charles University, Prague, Czech Republic
S. Siem, A. Görgen, M. Guttormsen, A.C. Larsen, A. Bürger – University of Oslo, Norway

The Germanium (Z=34) isotopic chain is of interest for a variety of applied nuclear science purposes due to its presence in high-resolution solid state and scintillation detectors and its use as a density-matching diagnostic constituent in plastic ignition capsules at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory. Germanium nuclei are also an ideal laboratory for studying nuclear structure at intermediate excitation energies ($2 \leq E_x$ *(MeV)* $\leq S_n$) due to the wide range of particle separation energies ($S_n \leq 10.75$ MeV) and a readily studied low-lying level discrete

^{74}Ge

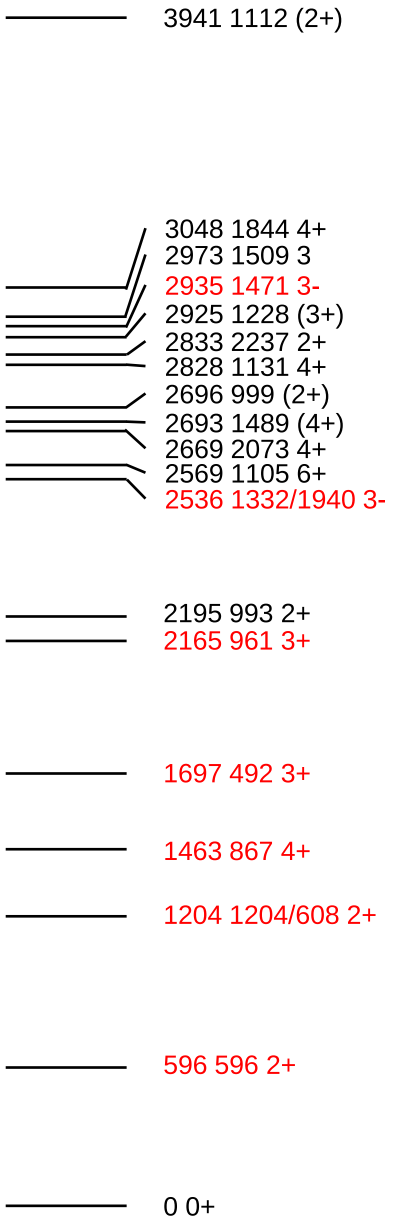
- ^{74}Ge to be studied in a series of measurements:
- Use different beams on ^{74}Ge to populate states (p, ^{4}He, ^{3}He, gamma, n)
- questions to be answered: is the statistical spectrum independent on incident beam?
- PSF to individual discrete states in two different reactions using p and ^{4}He beams

- July 2011 (total of 112 hours)
- 4 Silicon annular particle detectors with a total of 128 channels and 6 high-purity Germanium detectors with a total of 24 channels.
- populated in the reaction ^{74}Ge(p,p') with 18 MeV.
- Analysis by B.V. Kheswa (Ph.D. student) at iThemba LABS in South Africa.

- Beam time in November 2012 (218 hours)
- 2 Silicon W1 particle detectors with 64 channels and 9 Clover detectors.
- populate ^{74}Ge nuclei in the reaction ^{74}Ge(^{4}He,^{4}He') 47 MeV
- Analysis by D. Negi (post-doc) at iThemba LABS in South Africa

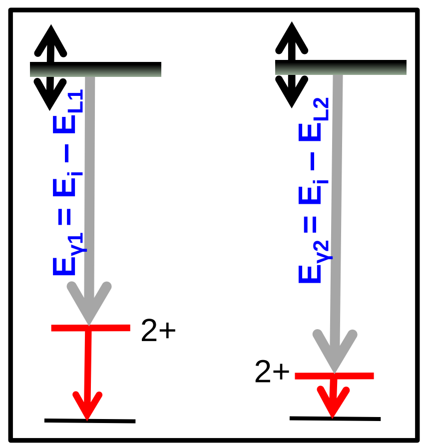
Combining these results following individual analyses will be very interesting and educational.

^{74}Ge: Ratio Method



Extracted quasi-continuum feeding to 7 states (red). Other good candidates are shown in black.
Total of five 2+ , three 3+, two 3-, five 4+, one 6+
χ^2 minimization for 2+ and 4+ levels and Ratio Method: 10 for 2+ and 4+, three for 3+, one for 3-

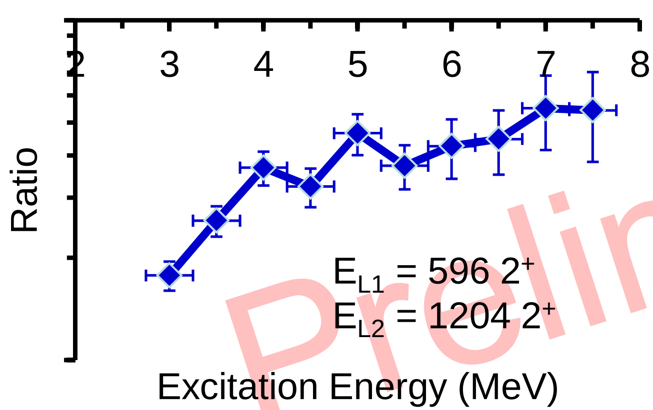
These ratios are independent of level density, cross-section, systematic errors.

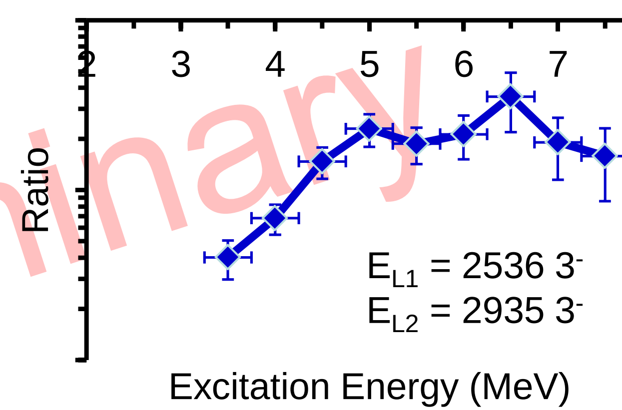


$$N_{L_j}(E_i) \propto \sum_{J^\pi} \sigma_{J^\pi}(E_i) \overline{\Gamma}_{J^\pi}(E_i, E_i - E_{L_j}) \rho_{J^\pi}(E_i)$$
$$= f_{J^\pi}(E_i - E_{L_j}) E_\gamma^3 \sum_{J^\pi} \sigma_{J^\pi}(E_i)$$

$$R = \frac{f(E_i - E_{L1})}{f(E_i - E_{L2})} = \frac{N_{L1}(E_i)(E_i - E_{L2})^3}{N_{L2}(E_i)(E_i - E_{L1})^3}$$

Thanks to B.V. Kheswa





iThemba LABS

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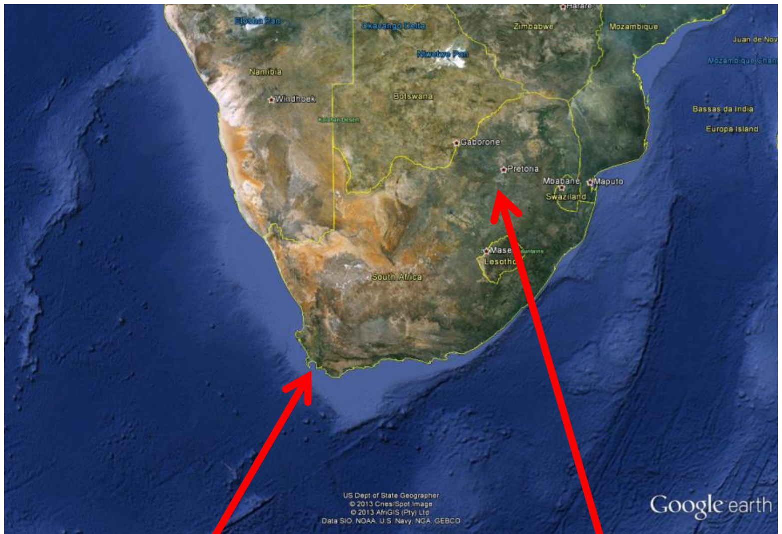
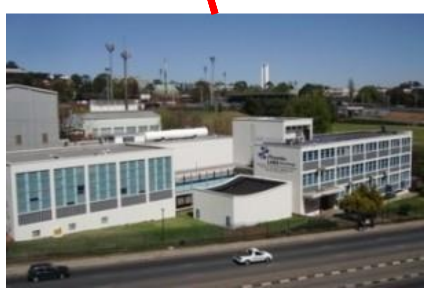
The iThemba Laboratory for Accelerator-Based Sciences is a group of multi-disciplinary research laboratories administered by the National Research Foundation of South Africa.

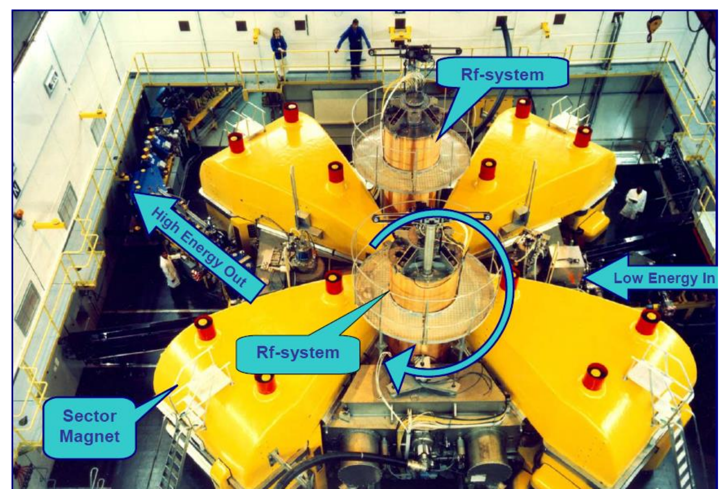


Isotope Production, Medical Irradiation, Research. 3 accelerators (K200 cyclotron, 11 MeV cyclotron and 3MV Van de Graaff (Materials Research).
K200 Separated Sector Cyclotron

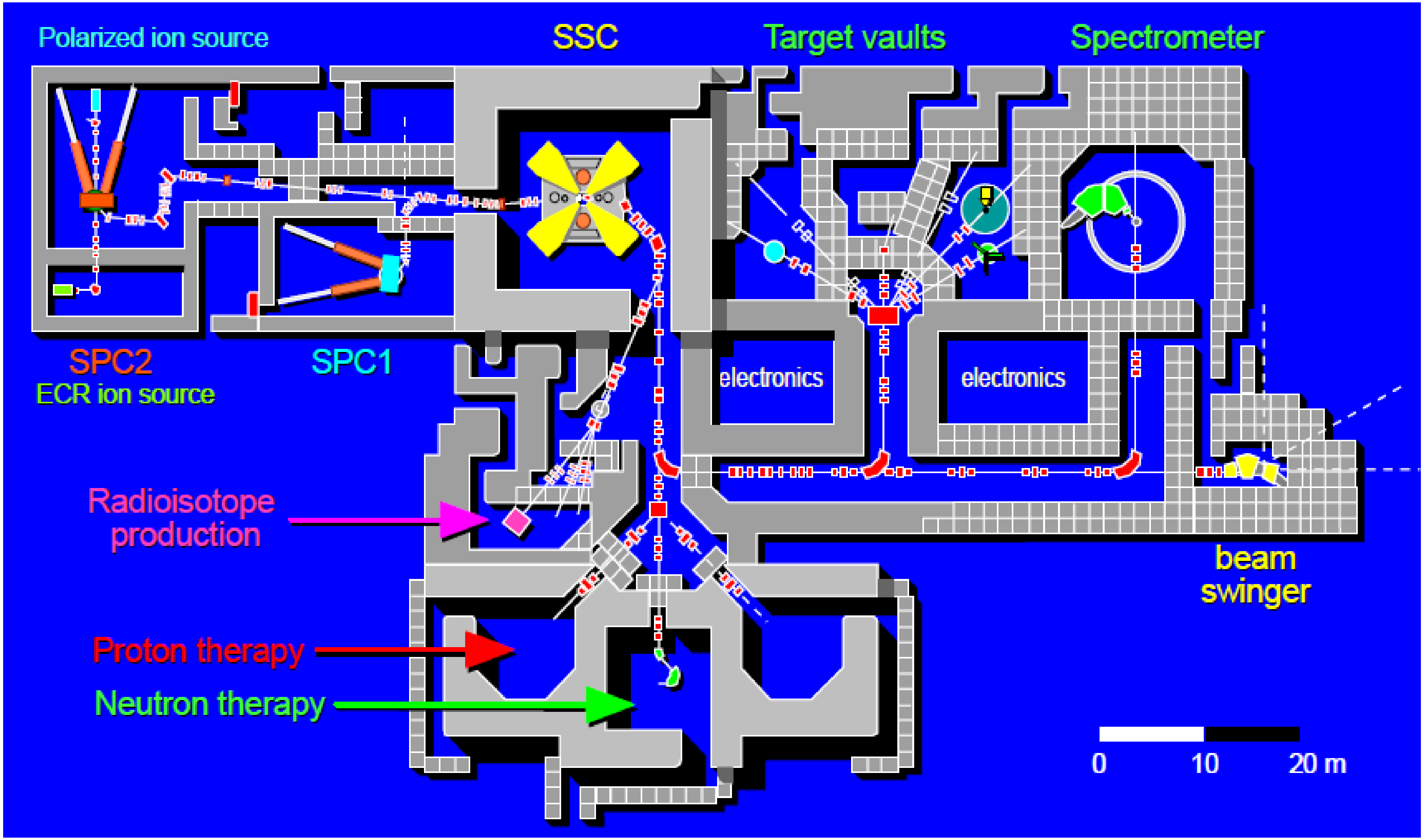
iThemba LABS Cape Town



iThemba LABS Gauteng
Accelerator Mass Spectrometry



Separated-Sector Cyclotron Facility



Beam time is shared…

Nuclear Physics

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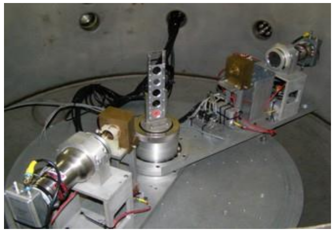
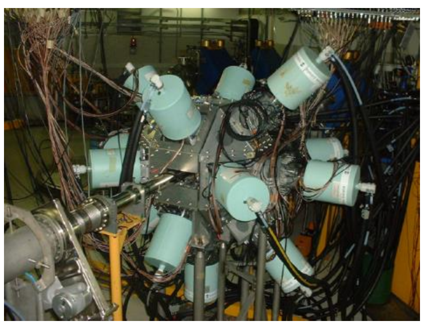
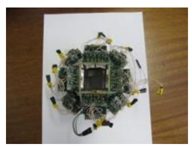
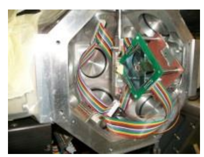


Scattering Chamber: reaction mechanism studied with light and heavy ions. Two movable arms makes it useful in measuring angular distribution in different nuclear reactions.

Quasi-monoenergetic neutrons of energy 10-200 MeV produced in the ^{7}Li(p,n)^{7}Be or ^{9}Be(p,n)^{9}B reactions. Facility used for physics studies and applications eg. Metrology, Environmental Radiation Laboratory





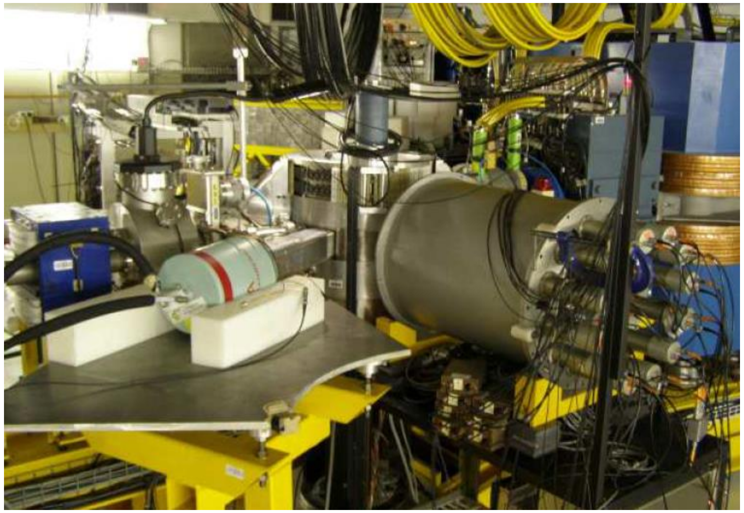


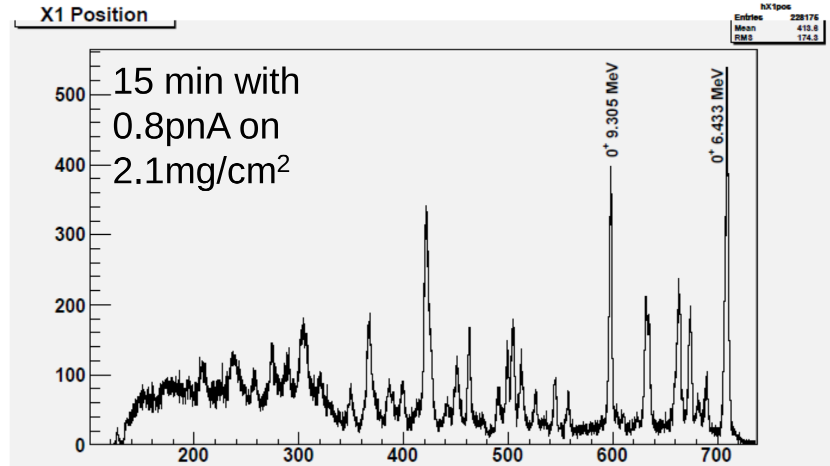
9 Compton suppressed Clover detectors and 8 LEPS detectors can be coupled to CSI (DIAMANT), recoil detector, annular and square silicon detectors, solar cells, Cologne plunger.
Digital electronics (XIA) as of July 2012.

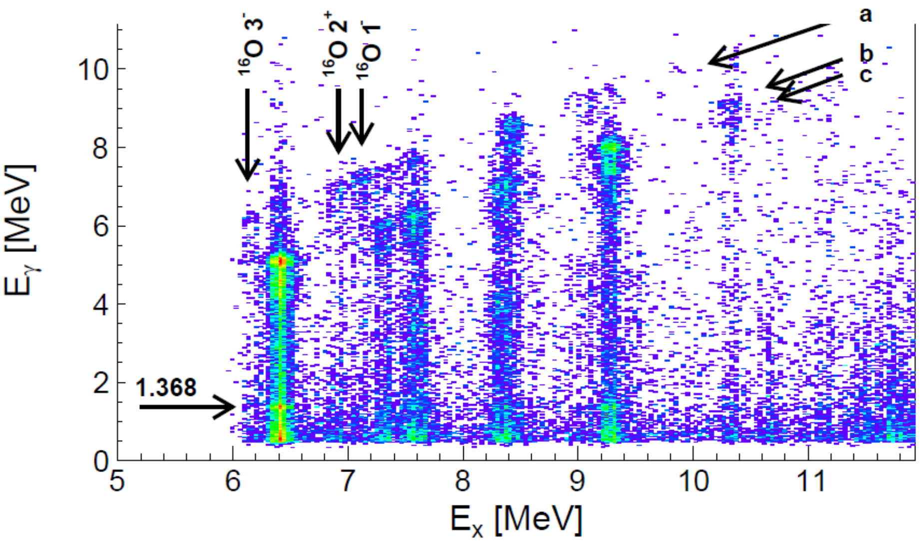
K600 used for high resolution (25 keV) measurements in the p energy region to 200 MeV.
Zero degree mode available.
Flight path for a particle from target to focal plane ~8m.
Focal plane consists of multi-wire drift chambers and a pair of plastic scintillation detectors.
Dec 2012: coupled AFRODITE to K600 for the first time.

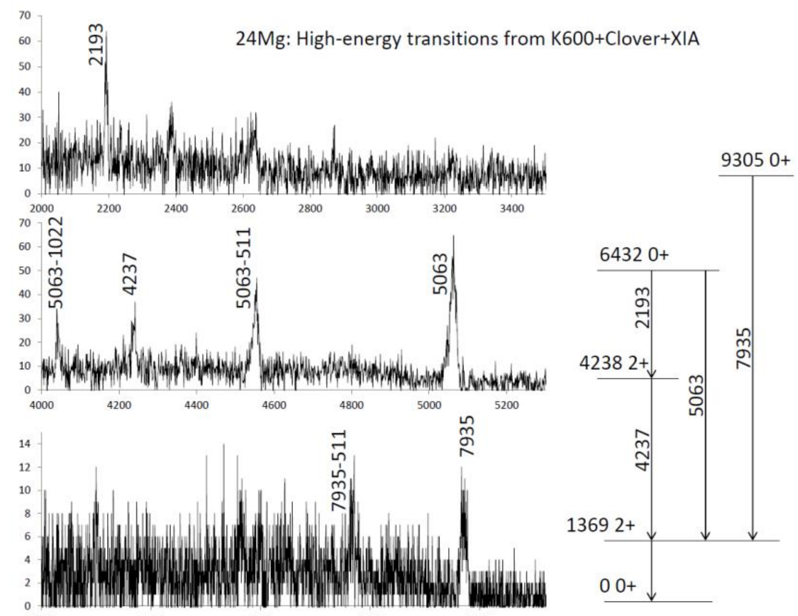
K600+AFRODITE

^{24}Mg(α,α') at 160 MeV









Conclusion

i. Method to characterize feeding from the quasi-continuum to discrete states.

ii. ^{95}Mo data and comparison to Oslo data.

iii. Confirmation of the low-energy enhancement.

iv. First theoretical interpretation (talk by E Litvinova).

v. Investigating reaction dependence of PSF to states of different spin/parity in ^{74}Ge.

vi. Coupling Spectrometer, silicon, and γ-ray detectors at iThemba LABS South Africa.

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