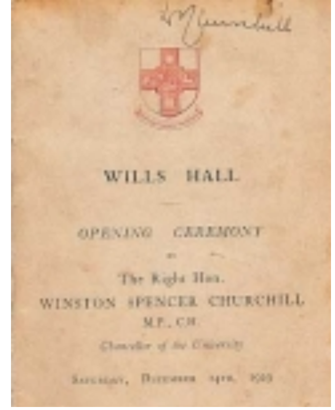
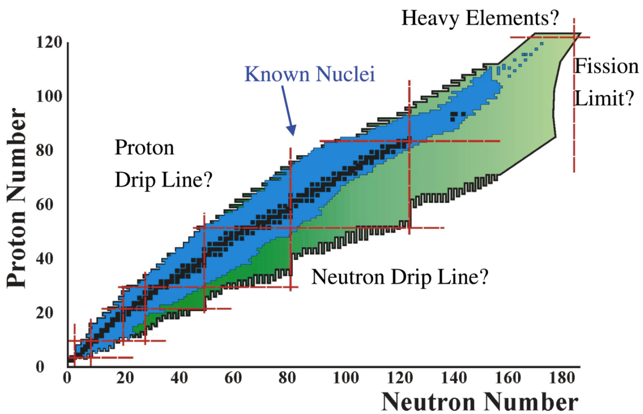
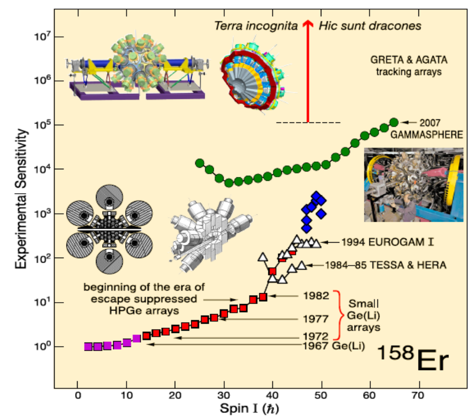
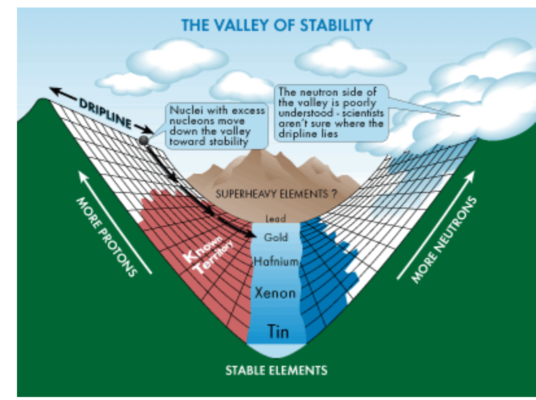
17th UK Nuclear Physics
Postgraduate Summer School
University of Bristol
27th August and 6th September 2013



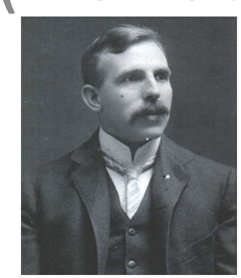
Episode 1. Gamma-Ray Spectroscopy: An Introduction

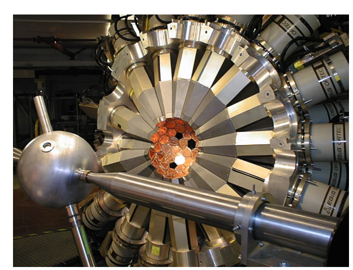


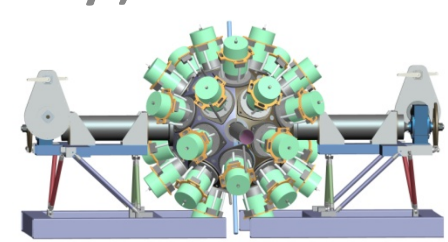




Mark Riley (Florida State University)



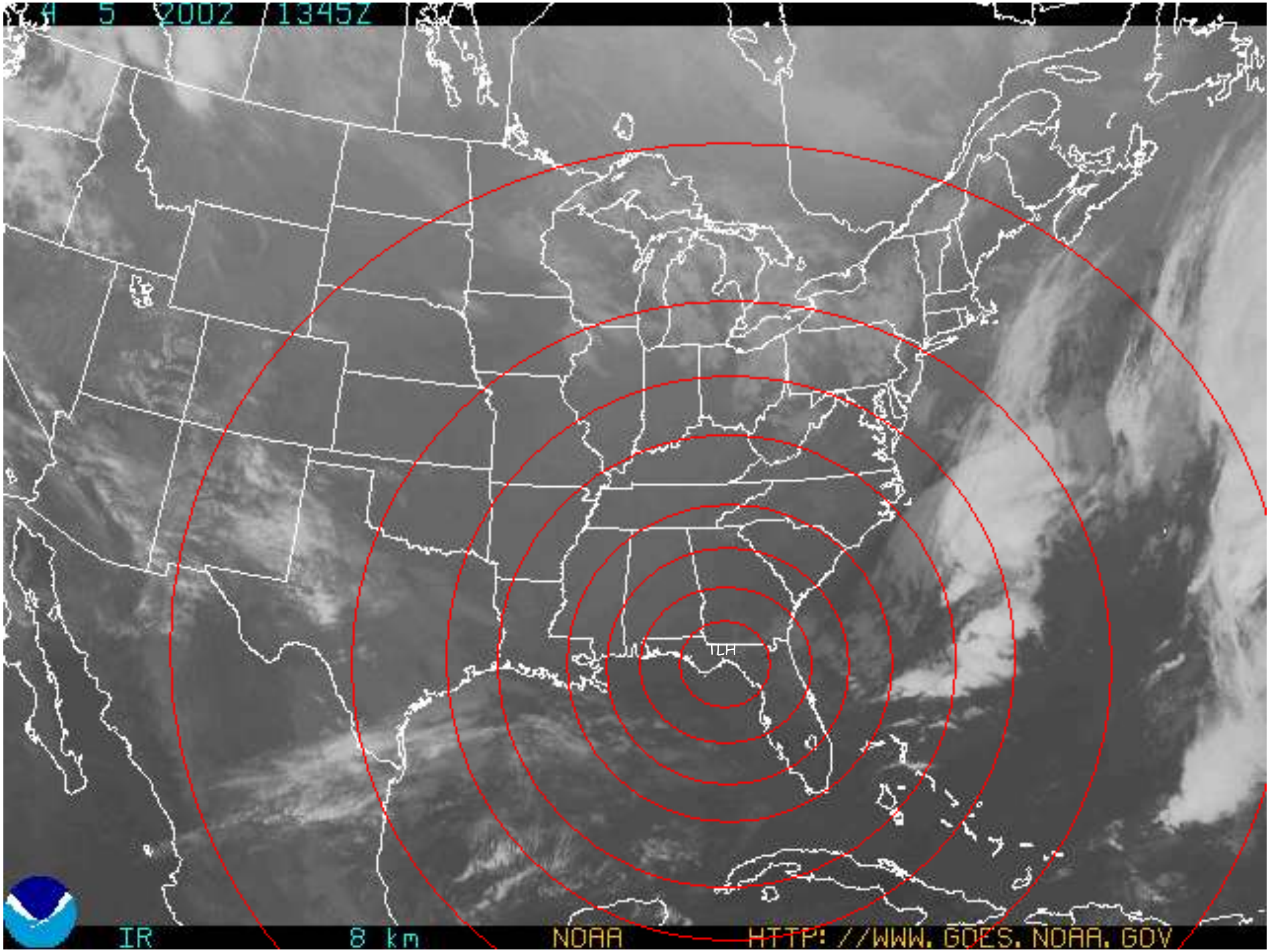




M.A. Riley: Brief history

- 1981: BSc, Physics, University of Liverpool, UK.
- 1985: Ph.D., Nuclear Structure Physics, University of Liverpool, UK.
- 1985-87: Research Associate, Niels Bohr Institute, Denmark.
- 1987-88: Research Associate, Oak Ridge National Laboratory and University of Tennessee.
- 1988-90: Advanced Fellow, University of Liverpool.
- 1991-present: Professor, Florida State University.
- Email: mriley@physics.fsu.edu

Tallahassee, FL



College “Football” at FSU!

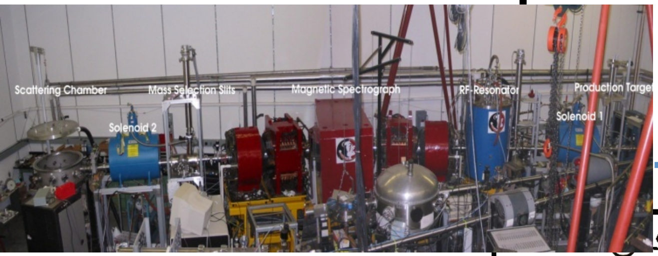
- Stadium seats 85,000…. Used 6 times a year!

College “Football” at FSU!

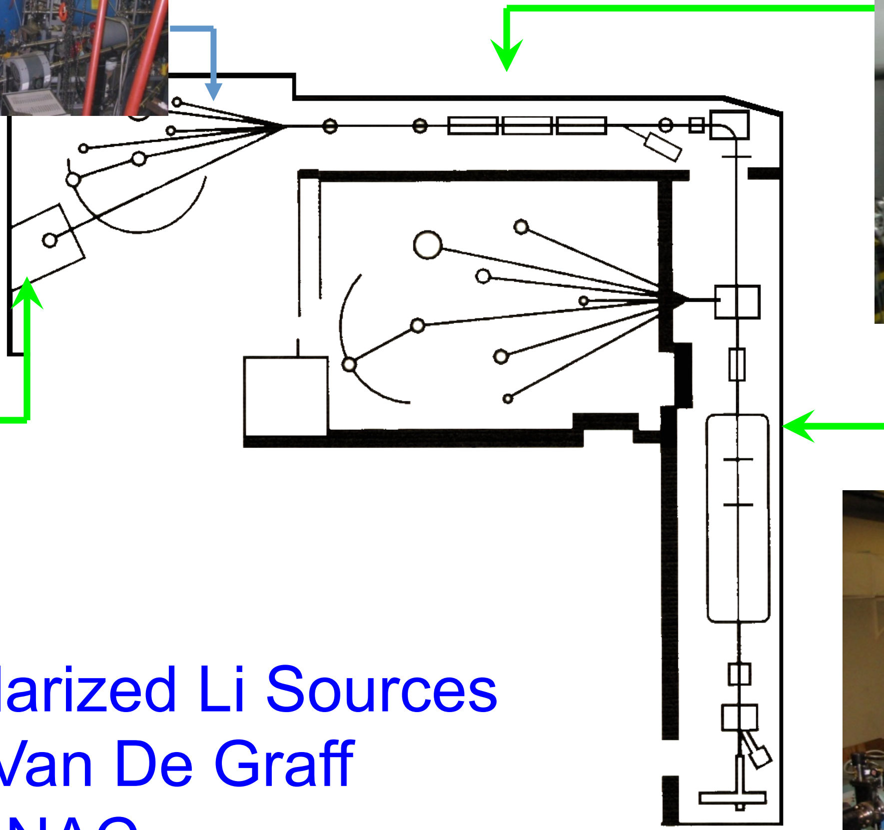
- Stadium seats 85,000…. Used 6 times a year!

Experimental Nuclear Facilities

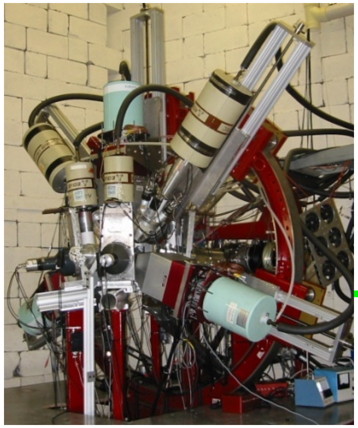
John D Fox Superconducting Accelerator Laboratory



Resolut



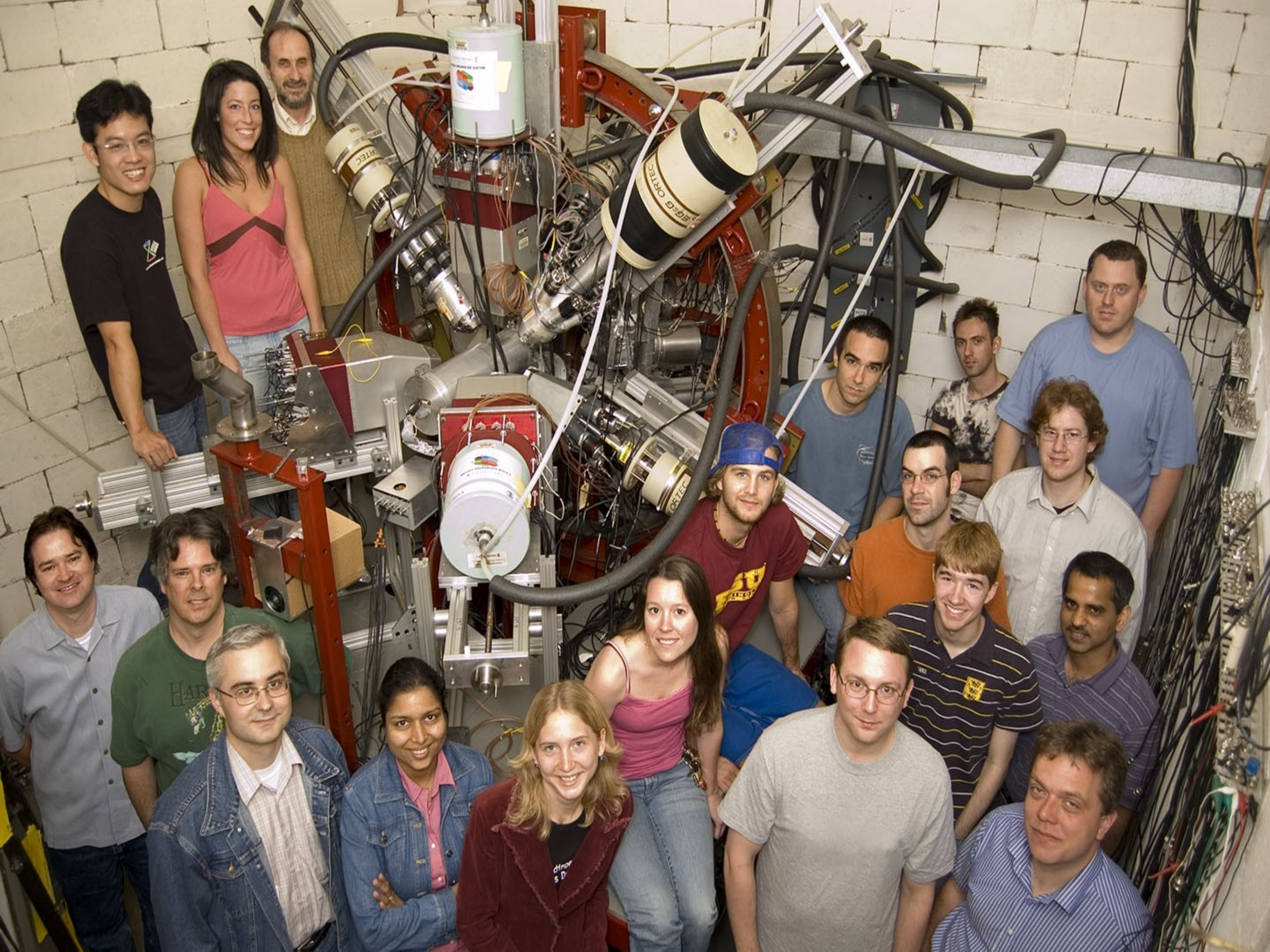
LINAC



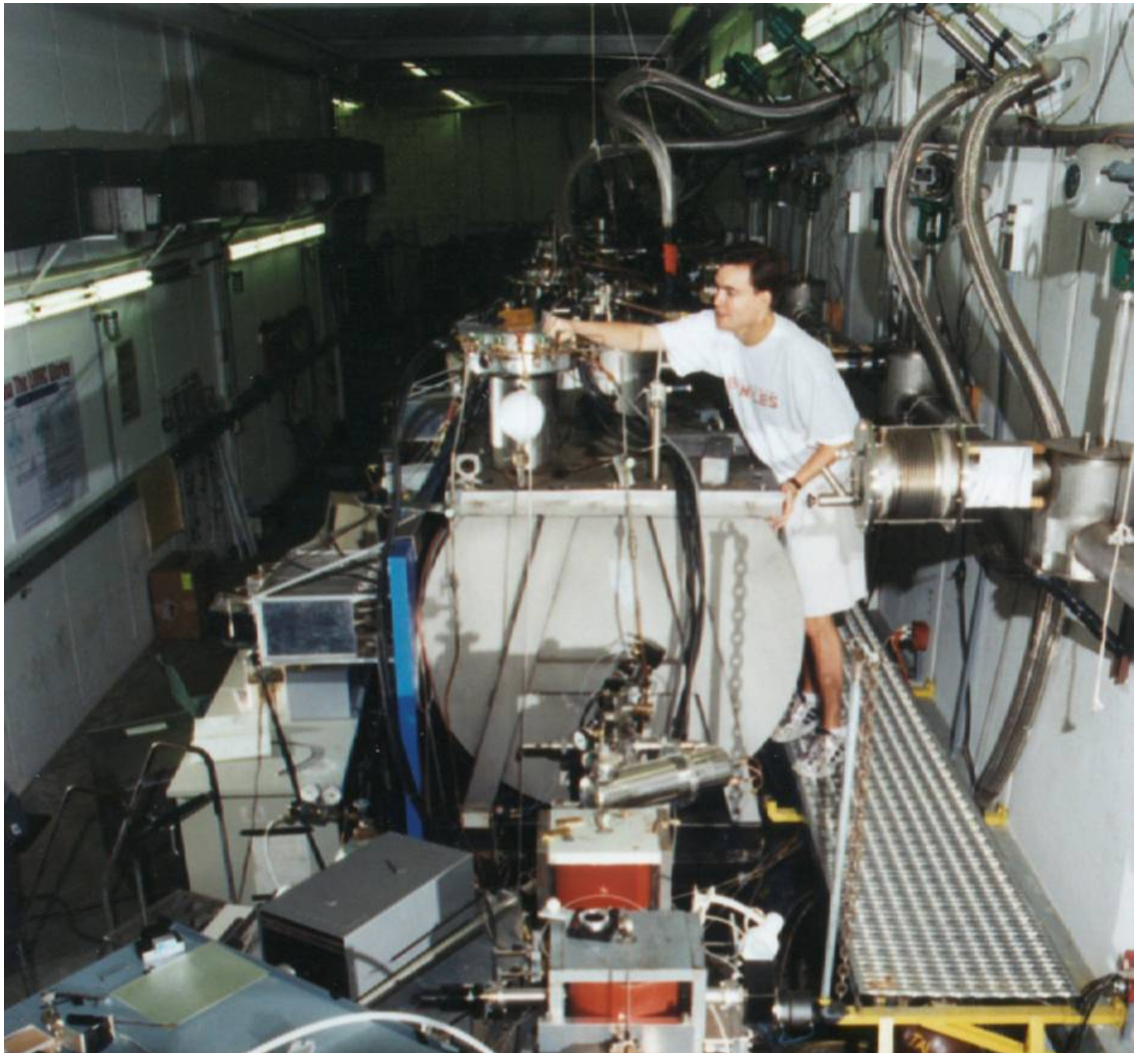
γ ray Array

Tandem

- SNICS and Polarized Li Sources
- 9 MV Tandem Van De Graff
- 12 resonator LINAC
- RESOLUT Radioactive Beam Upgrade!
- 20 Element HPGe γ Ray Detector Array


EG&G ORTEC
ORTEC

Rob Laird at the start



Rob upon graduation!

Job Opening at FSU

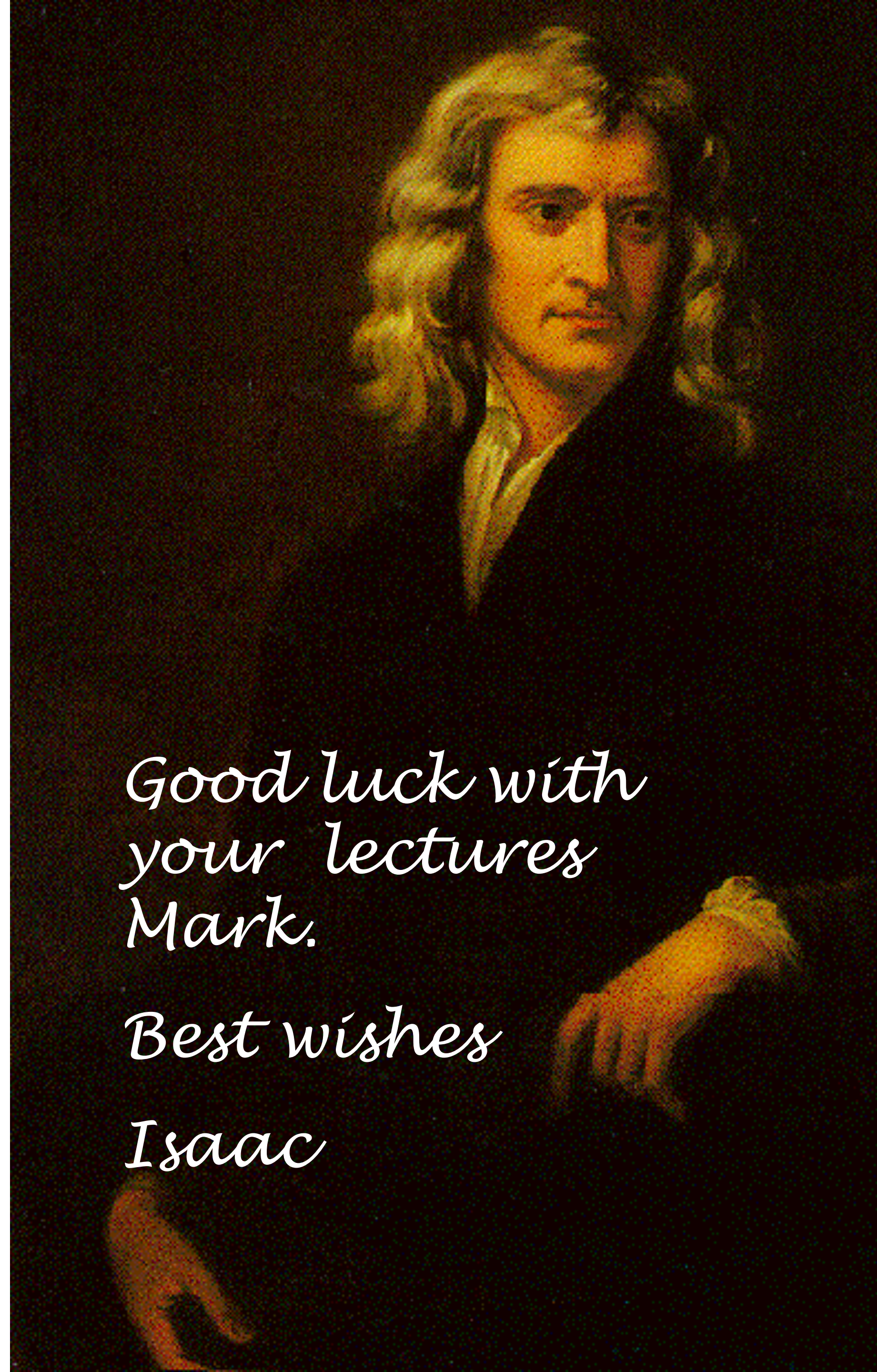
FACULTY POSITION
Experimental Nuclear Physics
Nuclear Astrophysics and/or Physics of Exotic Nuclei
Department of Physics
Florida State University

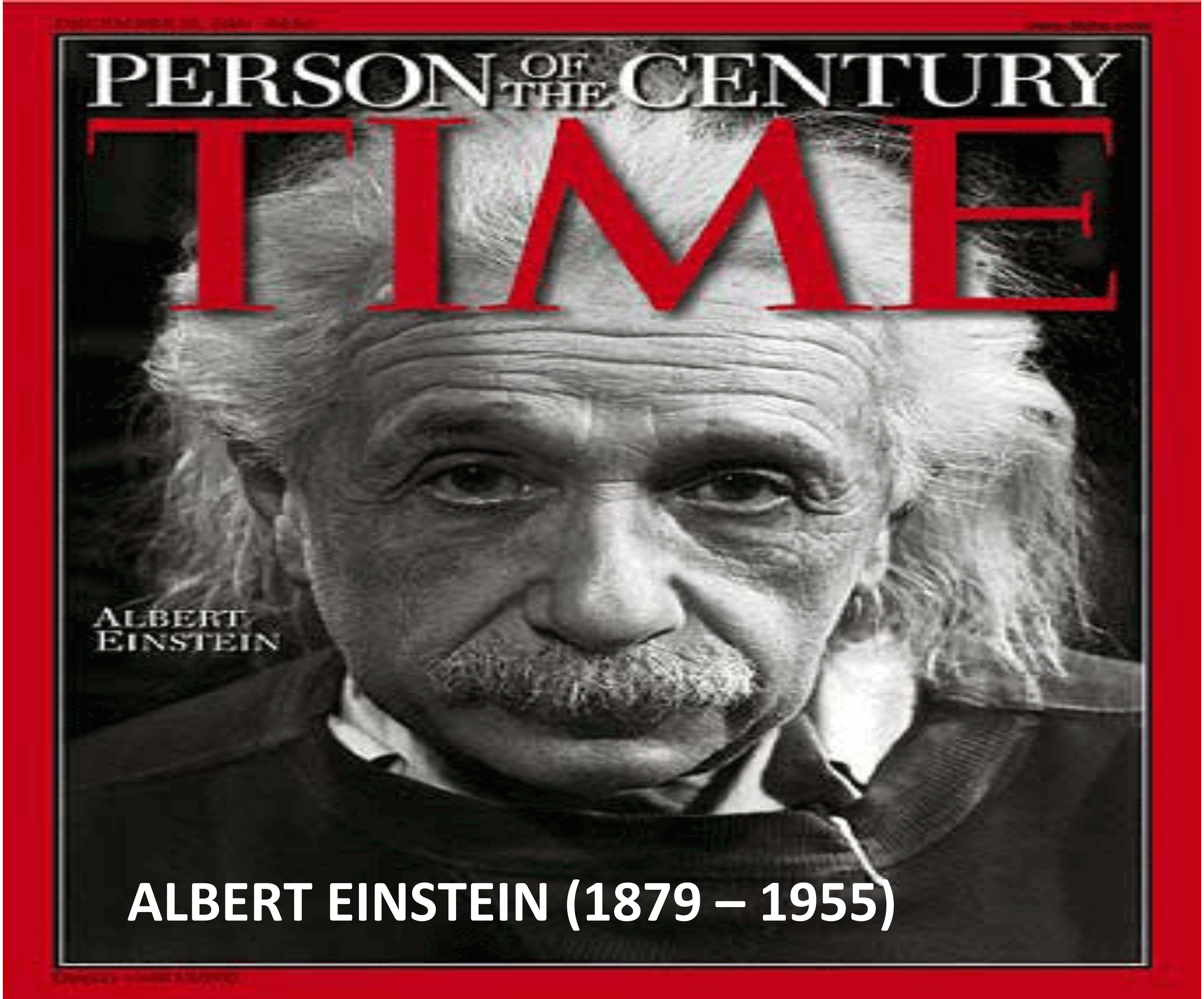
The Florida State University Physics Department invites applications for a faculty position in experimental nuclear physics, with a focus of nuclear astrophysics and/or the physics of exotic nuclei. Compensation and rank will depend on the qualifications of the applicant. The position provides excellent opportunities to pursue original research at the John D. Fox accelerator laboratory and national facilities, leading up to the FRIB laboratory. The experimental nuclear physics group is operating an accelerator laboratory with a 9 MV tandem van-de-Graaff and a 9 MV superconducting LINAC booster. The focus of the scientific program is the RESOLUT in-flight exotic beam facility, which supports research in nuclear astrophysics and the physics of exotic nuclei. The ANASEN active-target detector and the RESONEUT detector array provide world-class scientific opportunities. Additional instrumentation includes a gamma detector array with digital electronics, scattering chambers, neutron TOF detectors, and the flexibility to bring other detection apparatus. Applicants are expected to develop an original research program centered at the local facility, with a perspective for research at national facilities and the planned FRIB laboratory. Applicants should send a letter of interest, a curriculum vitae with a list of publications, a research plan, and arrange for at least three letters of recommendation to be sent to: **Prof. Samuel L. Tabor, Physics Department, Florida State University, Tallahassee, Florida 32306-4350.** Review of applications will begin **August 31, 2013** and continue until the position is filled. *Florida State University is an Equal Opportunity/Affirmative Action Employer and it especially encourages applications from women and members of minority groups.*

PhD Research!

Heroes

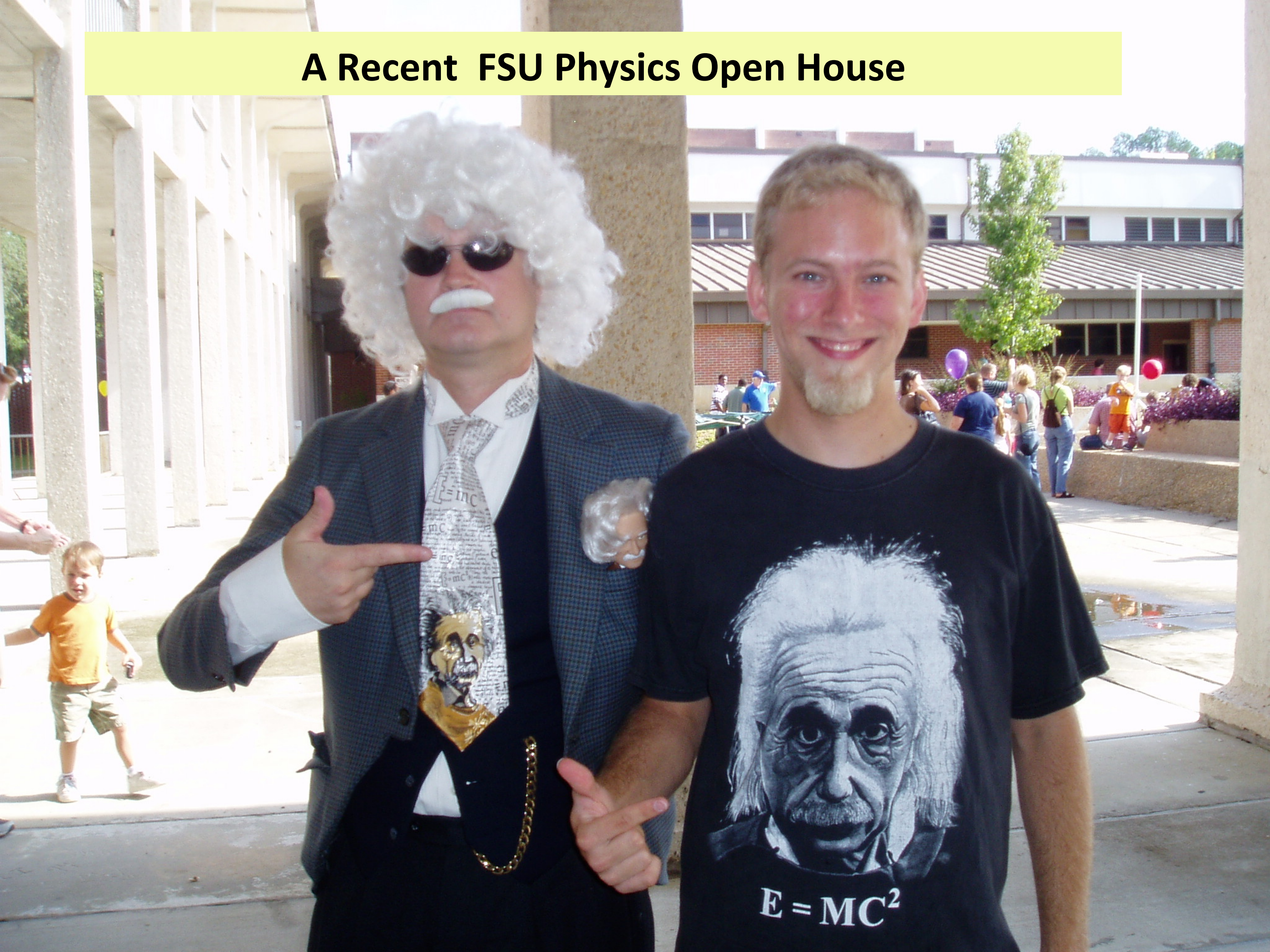
Isaac Newton
(1642 – 1727)





ALBERT EINSTEIN (1879 – 1955)

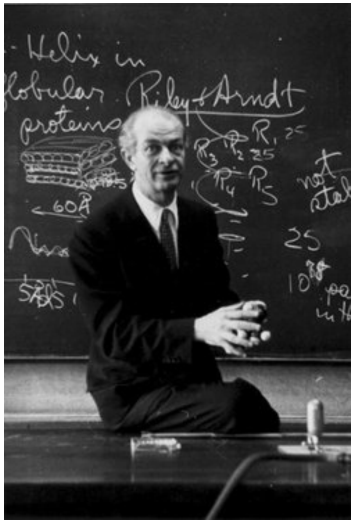
A Recent FSU Physics Open House



Einstein in his 20’s …. YOUR AGE! When he did all his best work! And had his best haircut.

Linus Pauling: (He is one of only two people to have been awarded a Nobel Prize in two different fields (the Chemistry and Peace prizes), the other being Marie Curie (the Chemistry and Physics prizes))

The world progresses, year by year, century by century, as the members of the younger generation find out what was wrong among the things their elders said. So you must always remain skeptical – always think for yourself.

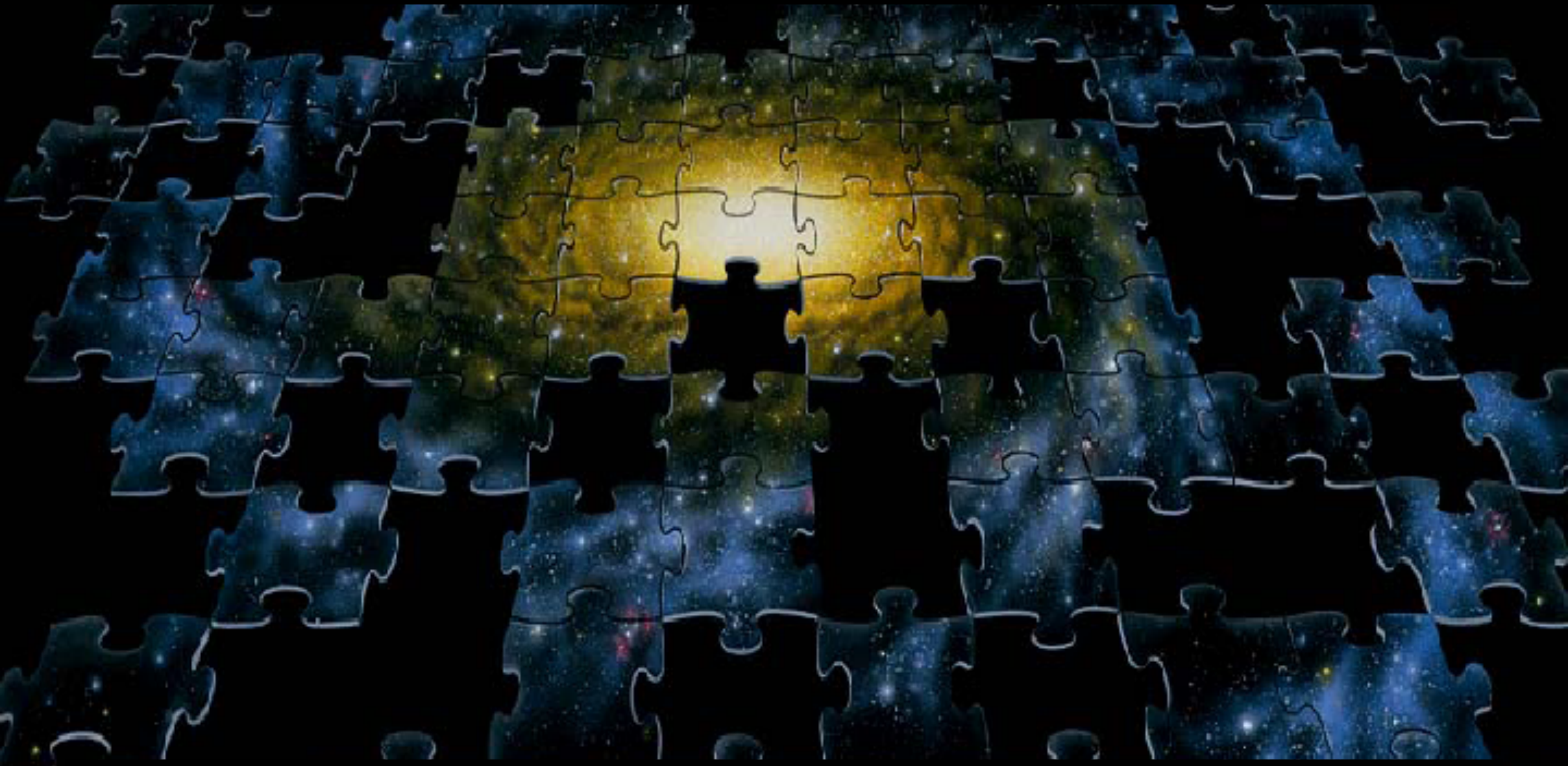


And now for something completely different …….

My third hero at your age …. and any age!

Monty Python!

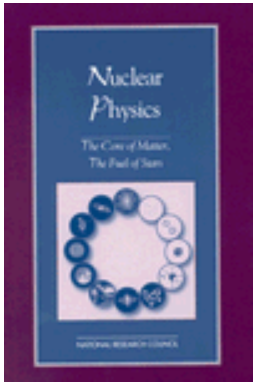
Understanding our Universe?

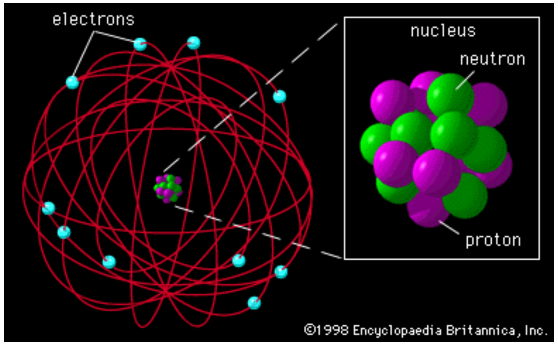


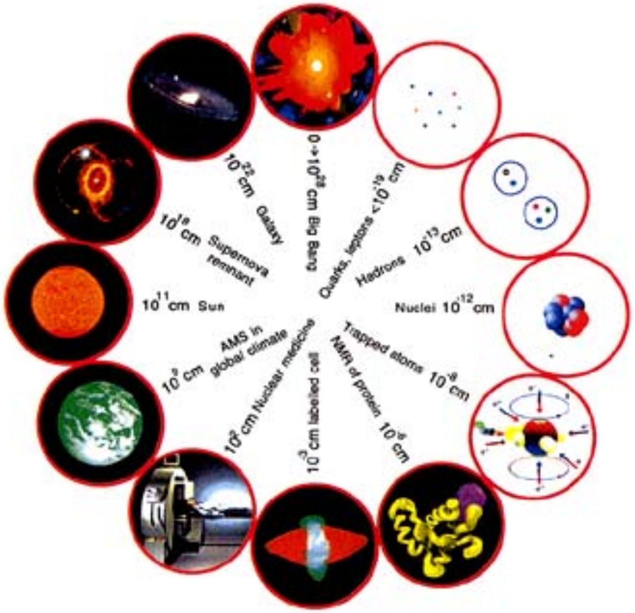
What pieces of the puzzle are we missing?

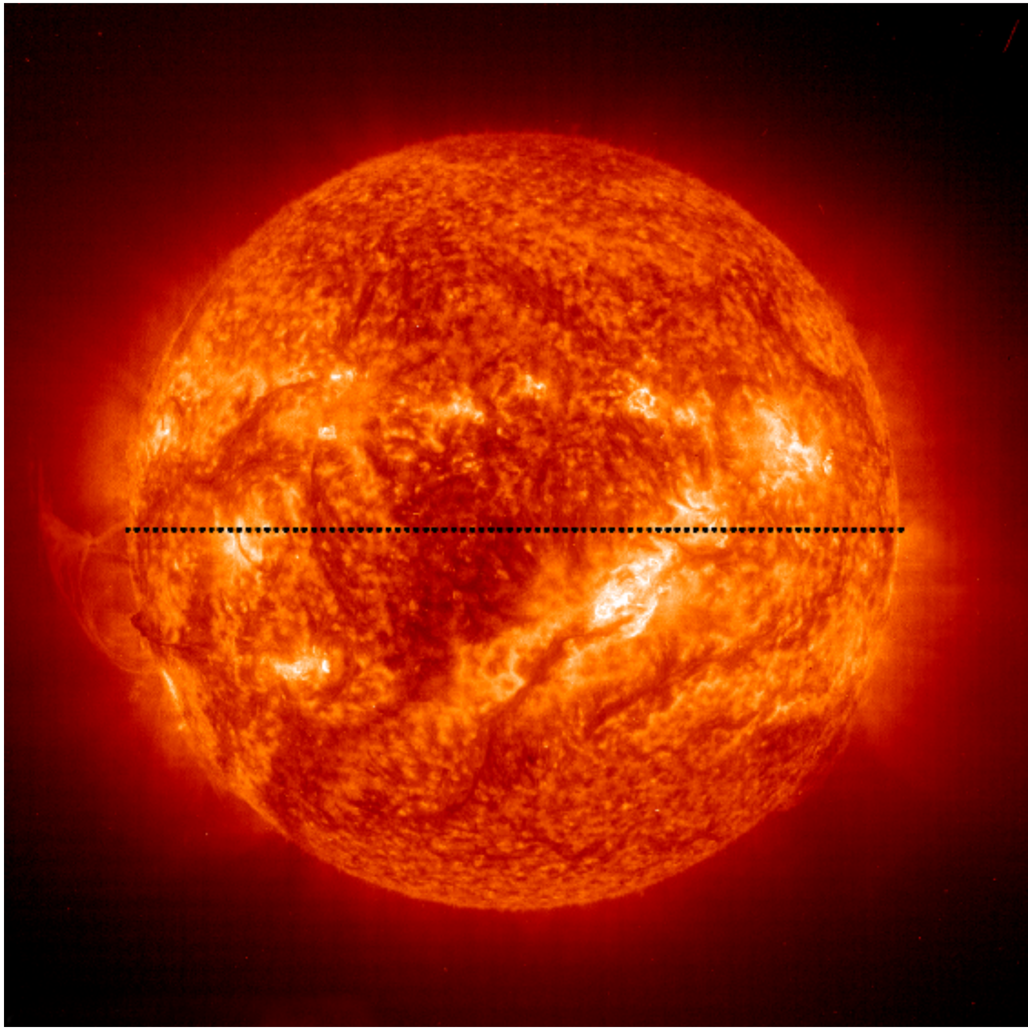
These are very exciting times indeed!

Nuclear Physics: The Core of Matter, The Fuel of Stars. (NRC "Schiffer" Report)









NATIONAL ACADEMY OF SCIENCES
NATIONAL ACADEMY OF ENGINEERING
INSTITUTE OF MEDICINE
NATIONAL RESEARCH COUNCIL

REPORT

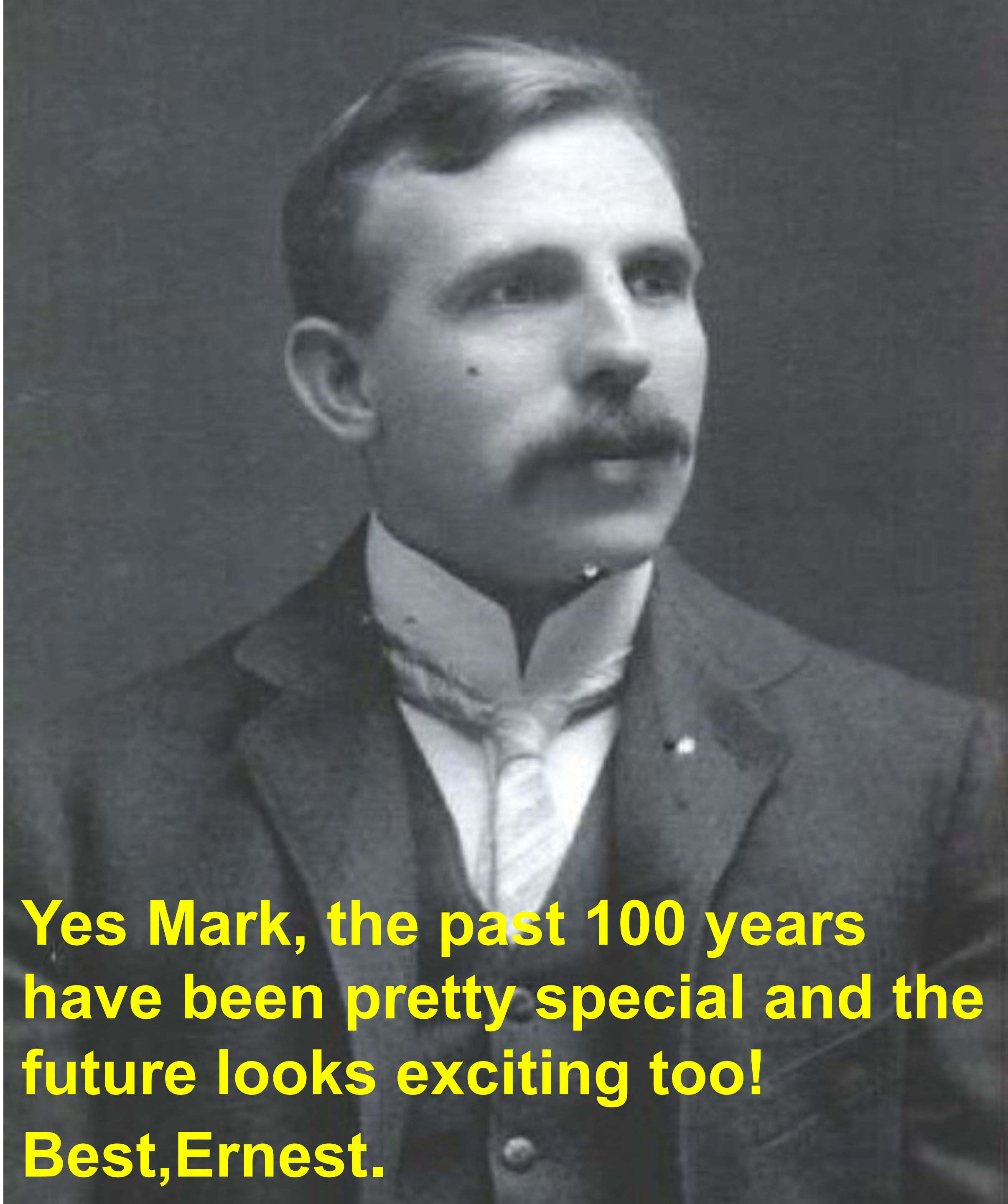
Nuclear Physics: Exploring the Heart of Matter
June 2012

- Nuclear physics today is a diverse field, encompassing research that spans dimensions from a tiny fraction of the volume of neutrons and protons to the enormous scales of astrophysical objects in the cosmos. As described in this decadal survey from the National Research Council (NRC) of the National Academies, **nuclear science is a thriving enterprise; its accomplishments and major discoveries since the last decadal survey are causing a revision of our view of the cosmos, its beginnings, and the structure of matter within it**. Further, the report describes how its **techniques and instruments are being used to address major societal issues in a number of areas, including medicine, national security, energy technology, and climate research**. The survey concludes by presenting a global context for the field and proposing a framework **for progress though 2020 and beyond**.

http://www.nap.edu/catalog.php?record_id=13438

The Scattering of α and β Particles by Matter and the Structure of the Atom
E. Rutherford, F.R.S.*
Philosophical Magazine
Series 6, vol. 21
May 1911, p. 669-688

"It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter…. the atom must be a seat of an intense electric field.."



Rutherford’s Lab in Manchester ~1910

Rutherford's Lab in Manchester ~1911

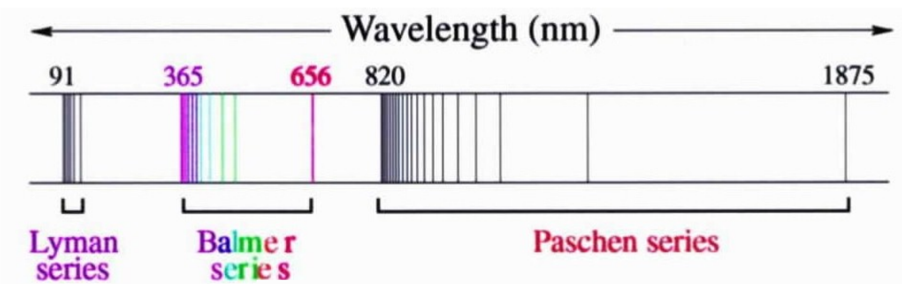
Niels Bohr at Manchester

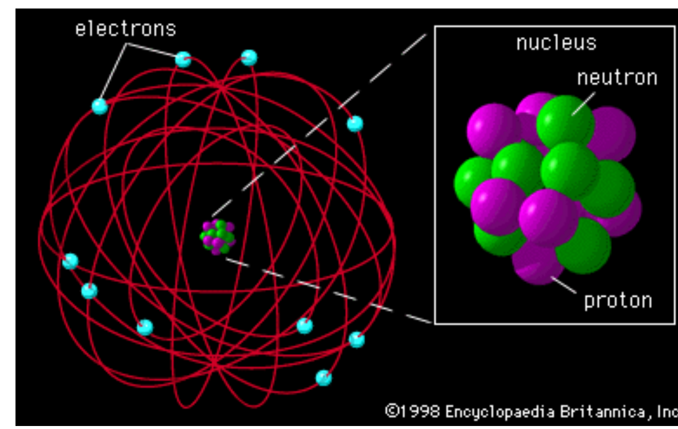
“While at Manchester University, Bohr adapted Rutherford's nuclear structure to Max Planck's quantum theory and so obtained a model of atomic structure (1913).”

•In 1937 Bohr and Kalckar proposed that we could learn about the structure of nuclei by detecting their gamma-ray emissions.

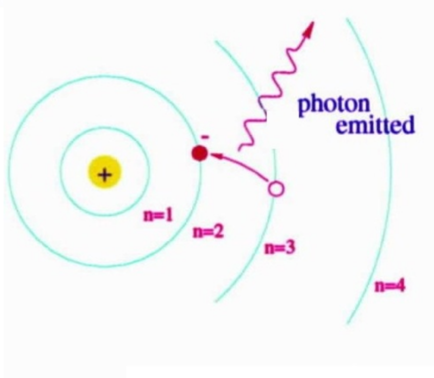
•The picture of the atomic nucleus that has emerged since this pioneering suggestion is extremely rich, displaying a wealth of static and dynamical facets. It continues to amaze and fascinate!

•The number of nucleons is sufficient in this strongly interacting multi-fermion system (<300) to allow correlations but yet finite.

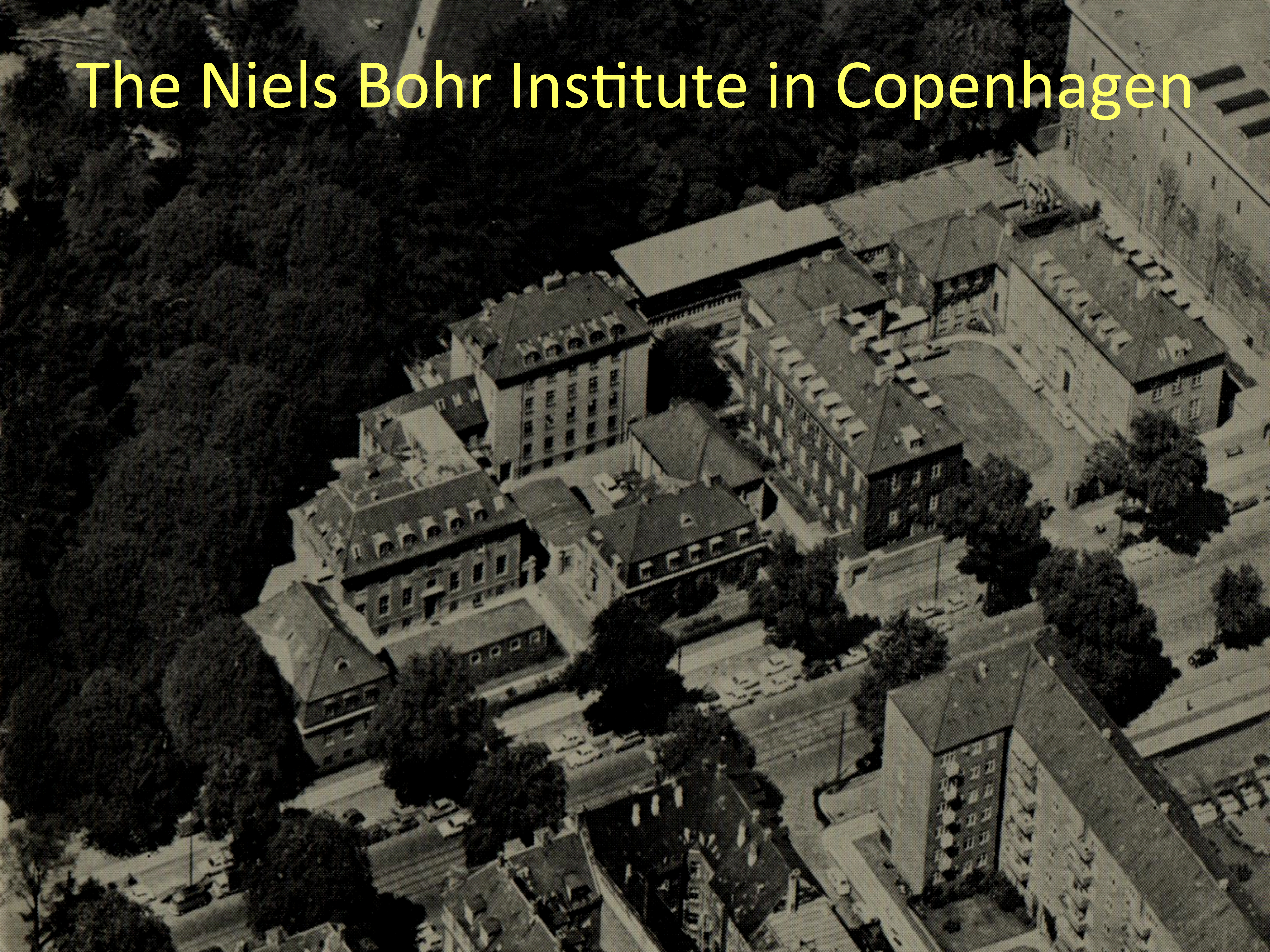




Bohr Atom

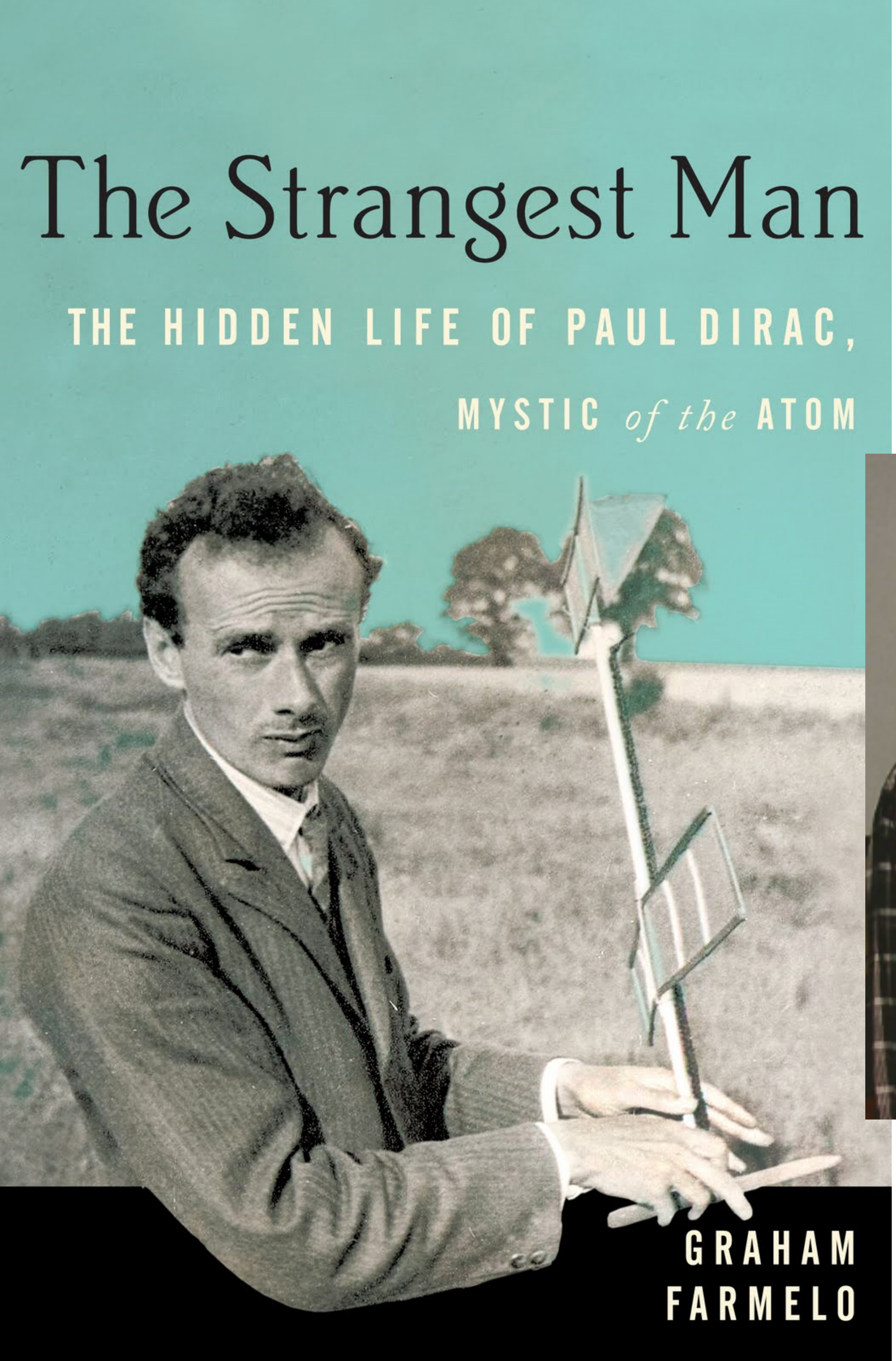


The Niels Bohr Institute in Copenhagen

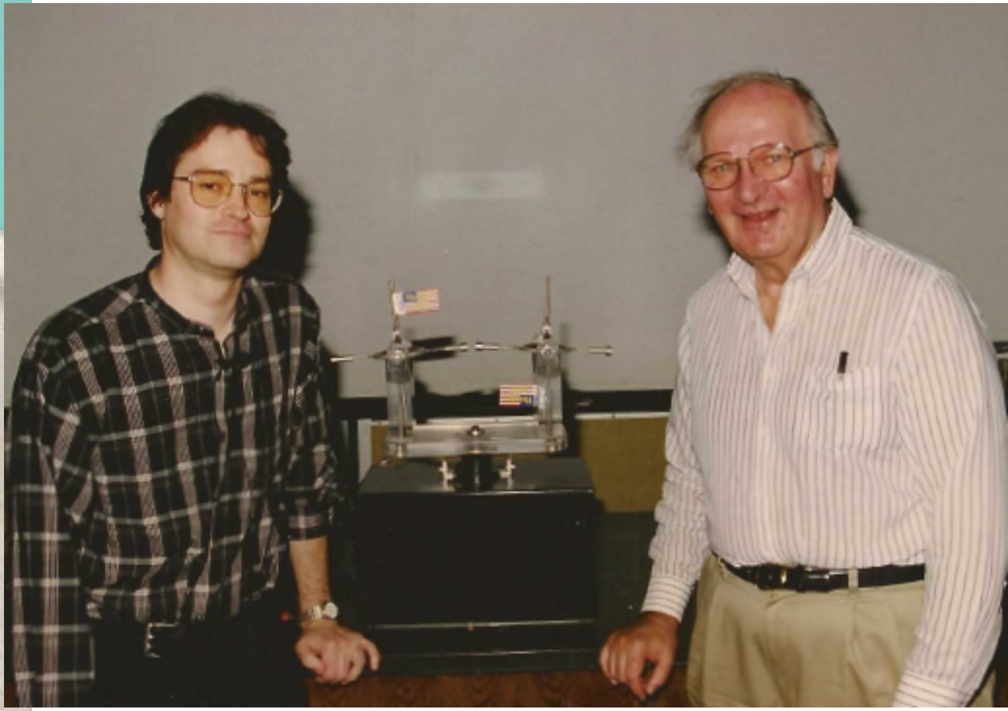


The Niels Bohr Institute in Copenhagen

Bob Schrieffer (BCS) plus “The Backbender”! … more of this later



Nobel Professors at FSU.

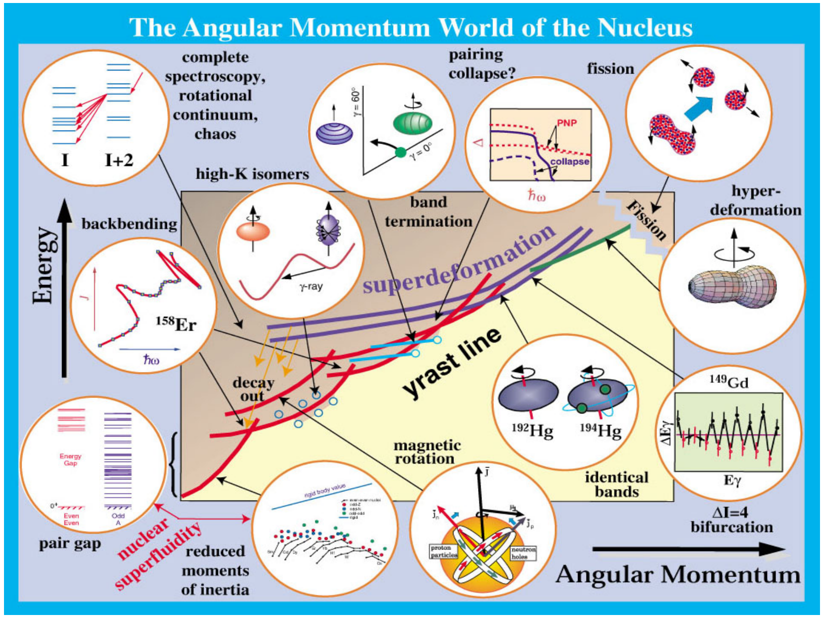


Dirac: Born and grew up in Bristol. He spent the last 14 years of his life at FSU.

•Thus it is sufficiently complex to exhibit a variety of collective properties yet it is simple enough to display both single-particle properties and a single-particle basis of the collective properties.

•Nuclei may exist in a variety of shapes: (prolate, oblate, triaxial, octupole etc.) Also neighbouring nuclei may exhibit quite different shapes. Indeed several shapes may co-exist in the same nucleus.

•Thus structure and shape changes may occur as functions of Z, N, spin, excitation energy, temperature, configuration etc.



•The recent past has seen a colossal advance in our knowledge and understanding of nuclear structure and nuclear shapes.

•Much of the driving force from the experimental side has been through the development of sophisticated multi-detector gamma-ray arrays coupled with heavy-ion accelerators.

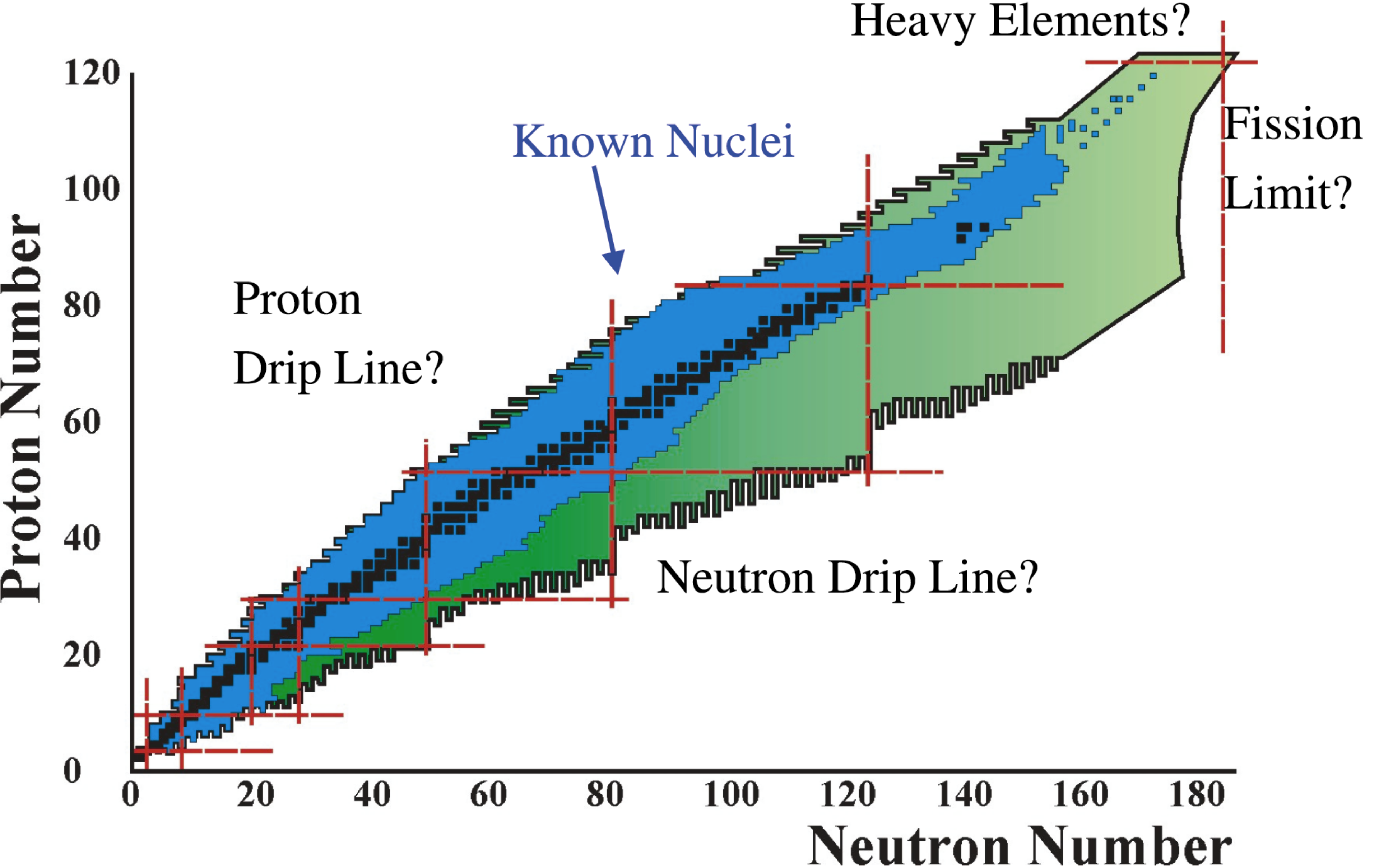
•There has been an intensive interplay between theory and experiment.

•But there have been many unexpected discoveries many of which are not understood.

•We are also finding that old paradigms, universal ideas, are not correct.

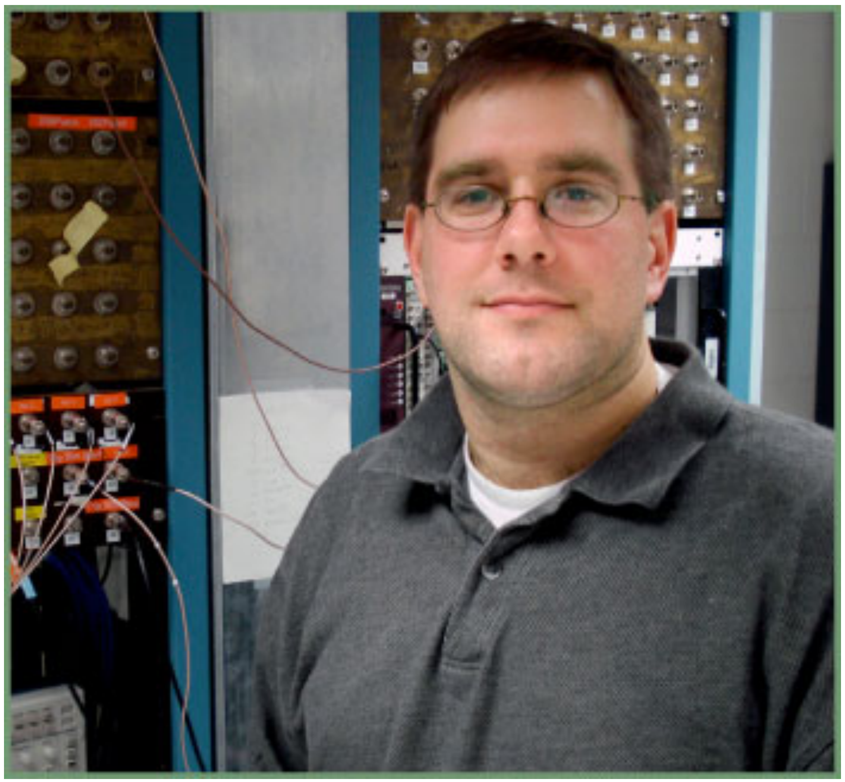
•In these talks I would like to tell you about some of this excitement.

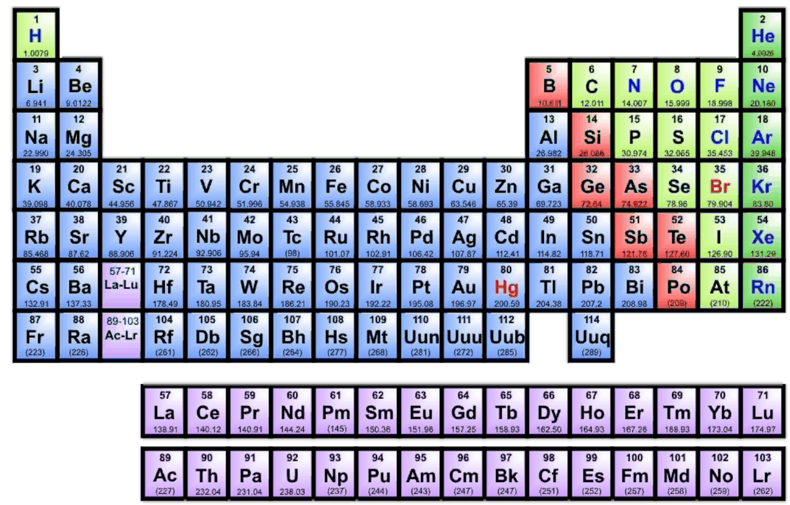
The Chart of the Nuclides



Periodic Table to Nuclear Chart in 1 min

Sean Liddick (MSU)

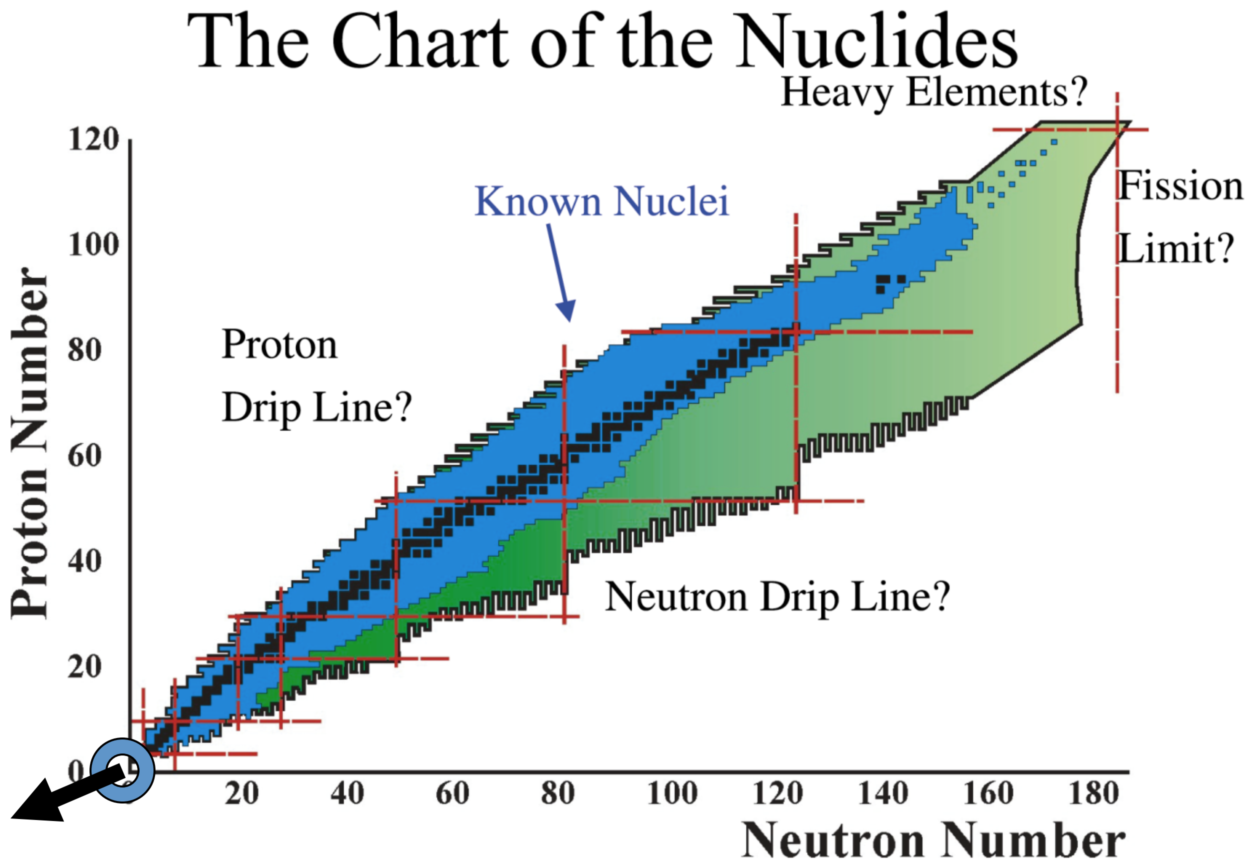




1 H 1.0079																	2 He 4.0026
3 Li 6.941	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.065	17 Cl 35.453	18 Ar 39.948
19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57-71 La-Lu	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89-103 Ac-Lr	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Uun (281)	111 Uuu (272)	112 Uub (285)		114 Uuq (289)				

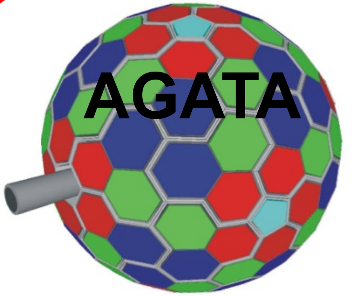
57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

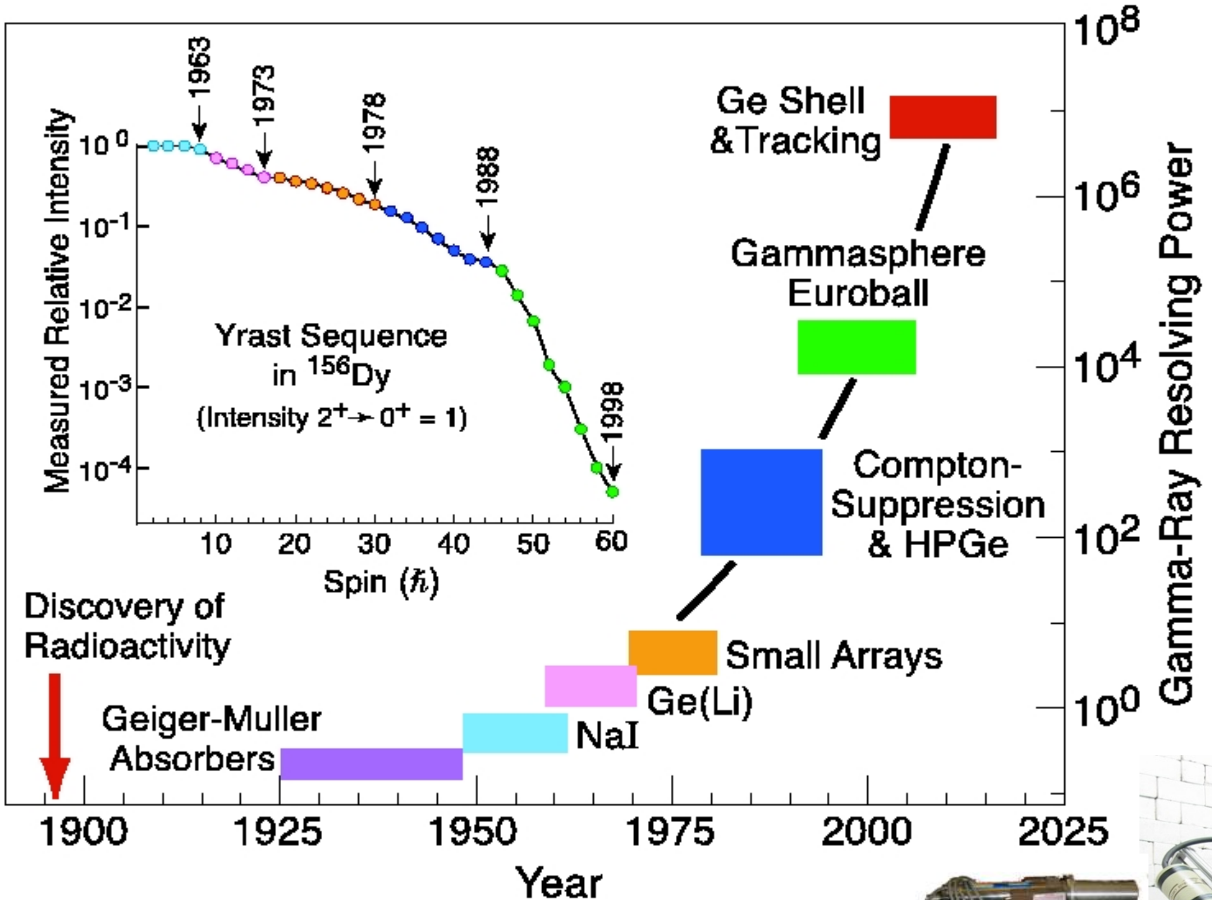
We are Extremists! We want to know where are the limits and what happens on the way?

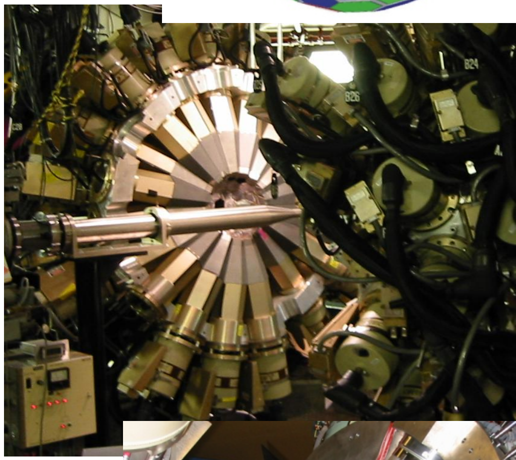


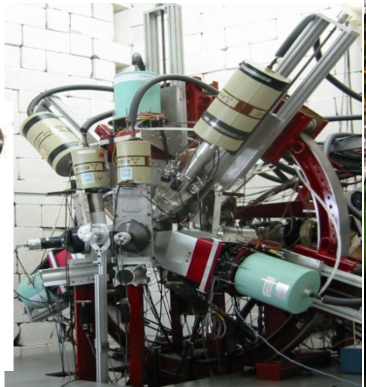
Increasing Angular Momentum and Excitation Energy: An excellent way to investigate nuclear structure, especially to see what the intruder orbitals are doing. More on this later.

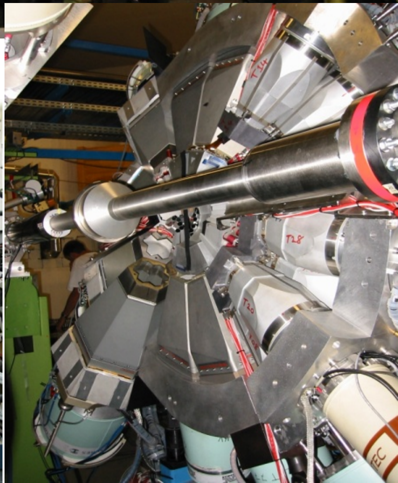
Gamma-Ray Detection Evolution



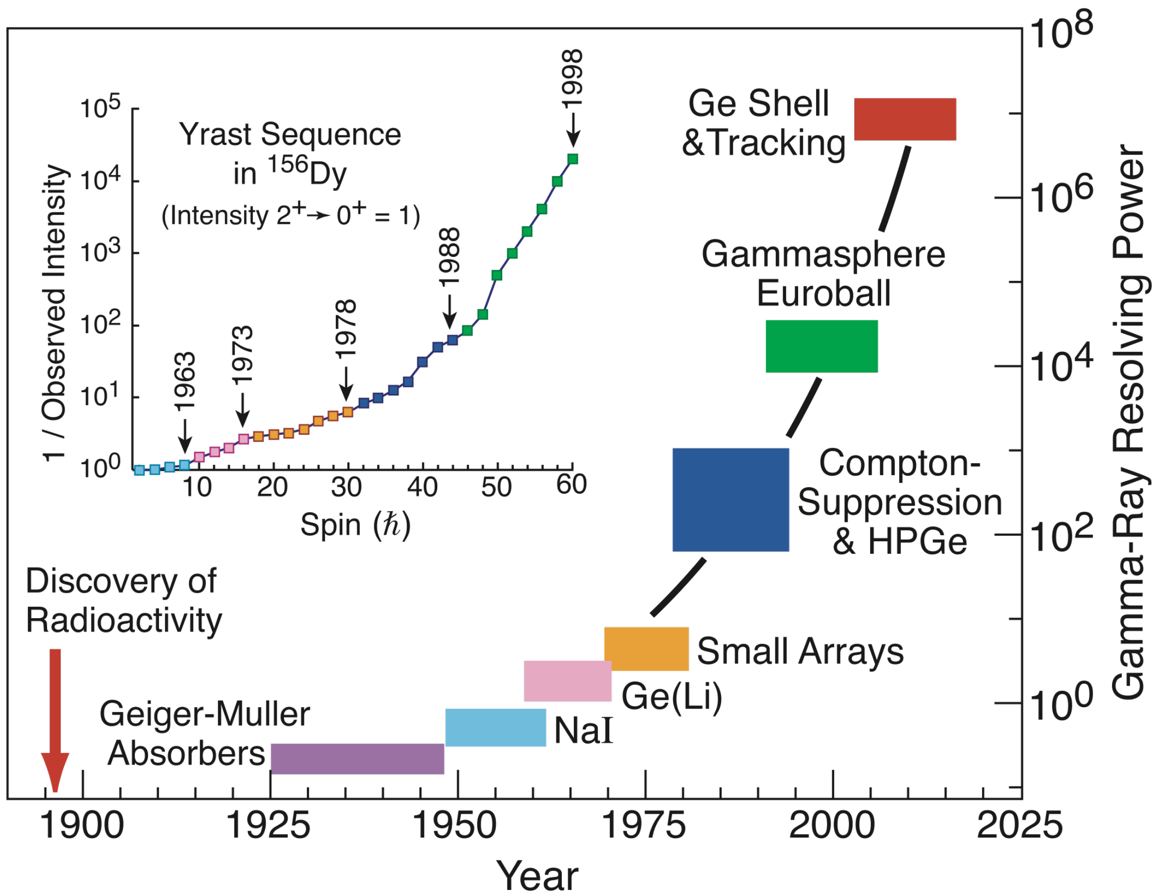






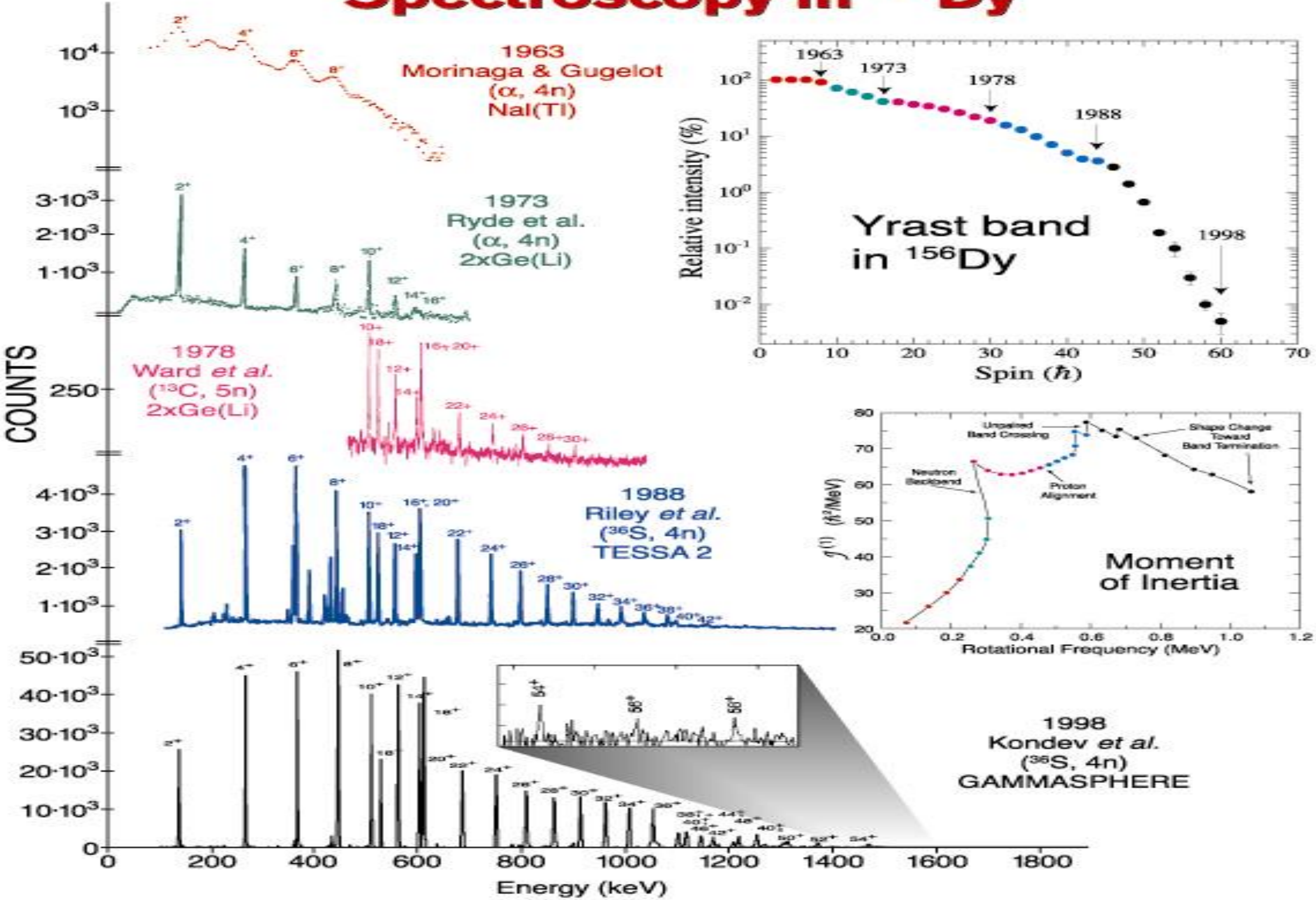


γ-ray array development



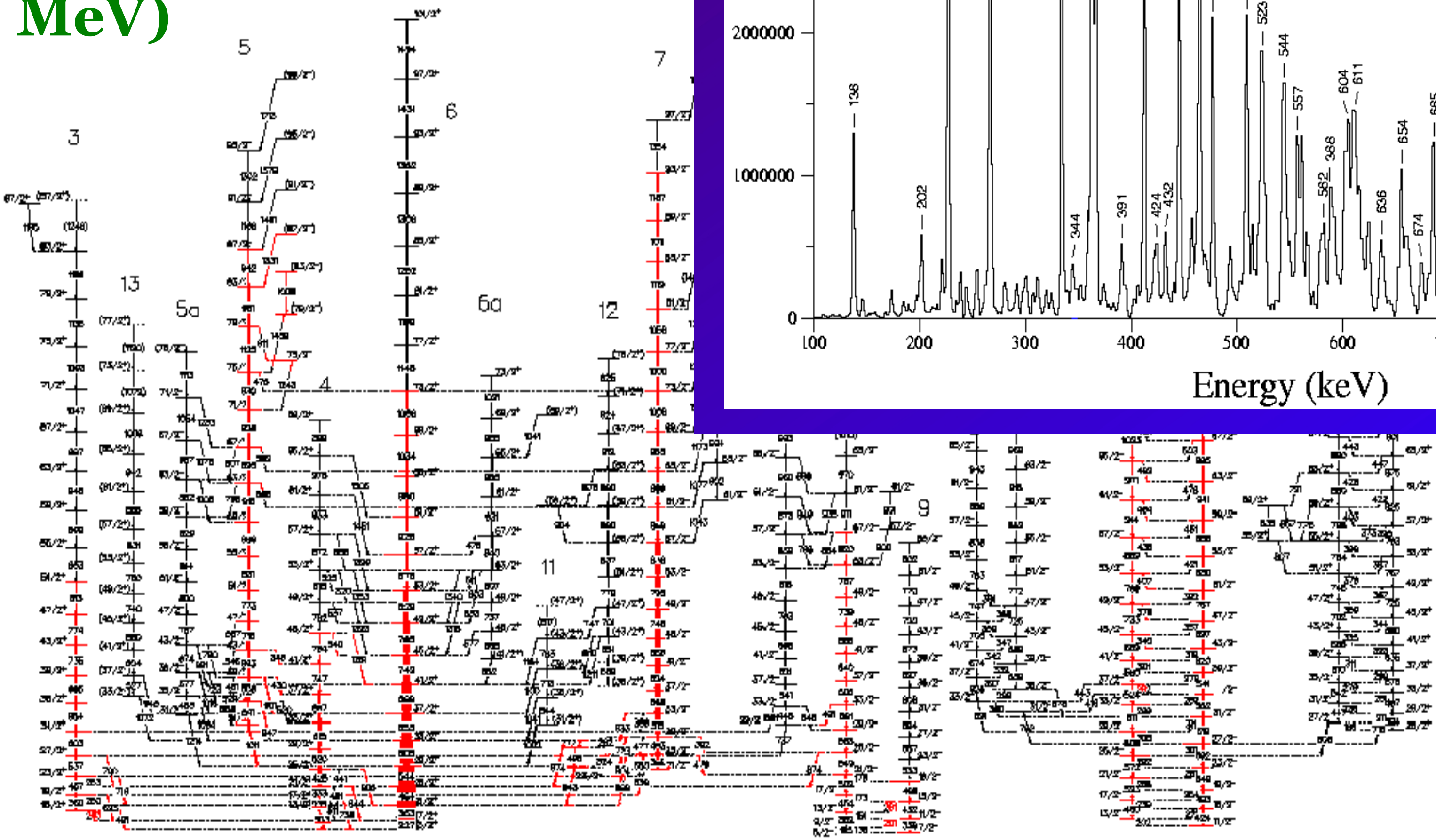
- **The resolving power is a measure of the ability to observe faint emissions from rare and exotic nuclear states.**

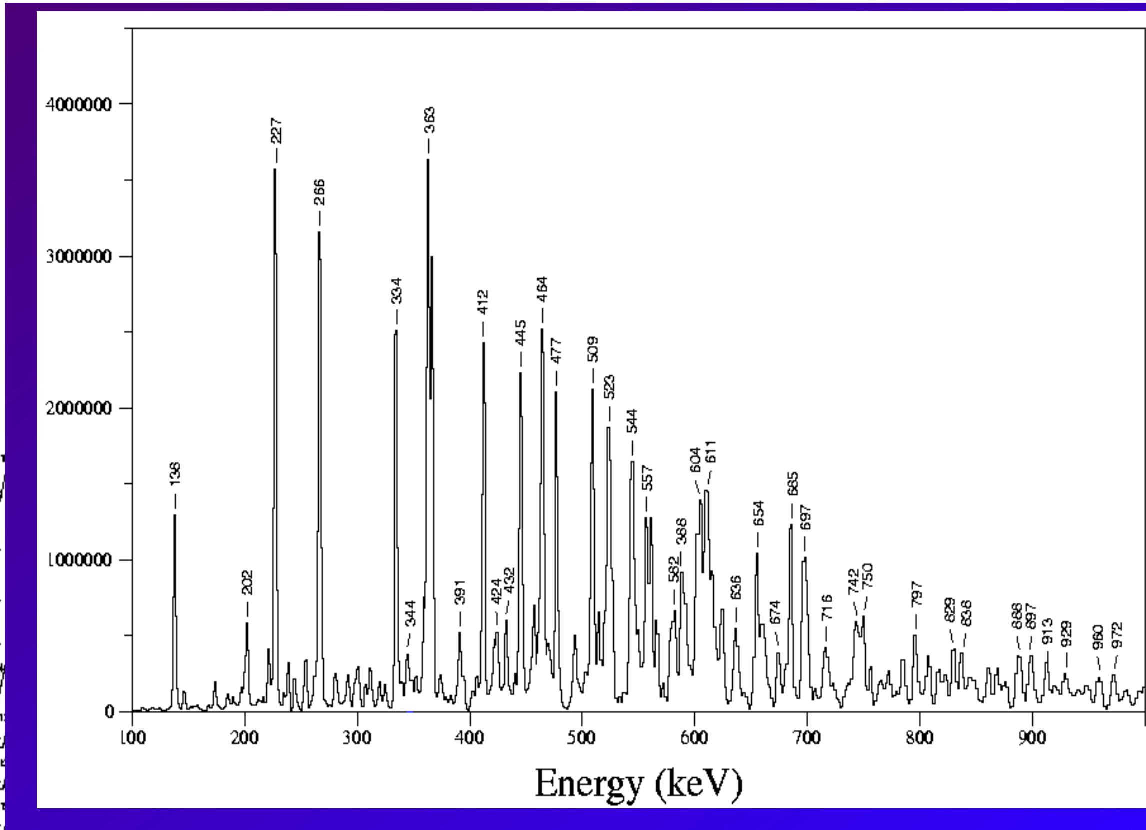
Evolution of High-Spin γ-ray Spectroscopy in ^{156}Dy



Real Energy Level Schemes and the Total γ-Ray Spectrum

100's & 100's of γ 's
Many open channels
High Spins (60 h)
High Excitations (30 MeV)





Nuclear properties from gamma ray studies

< **Coincidence relation**

→ **energy level structure**

< **Angular distribution/correlation**

→ **spin, multipolarity**

< **Doppler shift**

→ **lifetimes, quadrupole moments**

< **Linear polarization**

→ **parity**

Scintillators and semiconductors; pros and cons for γ detection

Scintillators usually have

- Poorer resolution (e.g. ~ 6% for NaI at 1.3 MeV)
- Higher density
- Higher Z
- And therefore better efficiency

Ge detectors have

- The best resolution (~ 0.15% at 1.3 MeV)
- Generally poorer efficiency and peak-to-total (depends on the size of the crystal)
- Require cryogenic operation

Some other semiconductors (e.g. CZT) have

- Have high Z, but cannot be made in big crystals
- Poorer resolution than Ge
- Do not require cryogenics

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Progress in Particle and Nuclear Physics 60 (2008) 283–337

Progress in Particle and Nuclear Physics

www.elsevier.com/locate/ppnp

Review

From Ge(Li) detectors to gamma-ray tracking arrays – 50 years of gamma spectroscopy with germanium detectors

J. Eberth[a,*], J. Simpson[b]

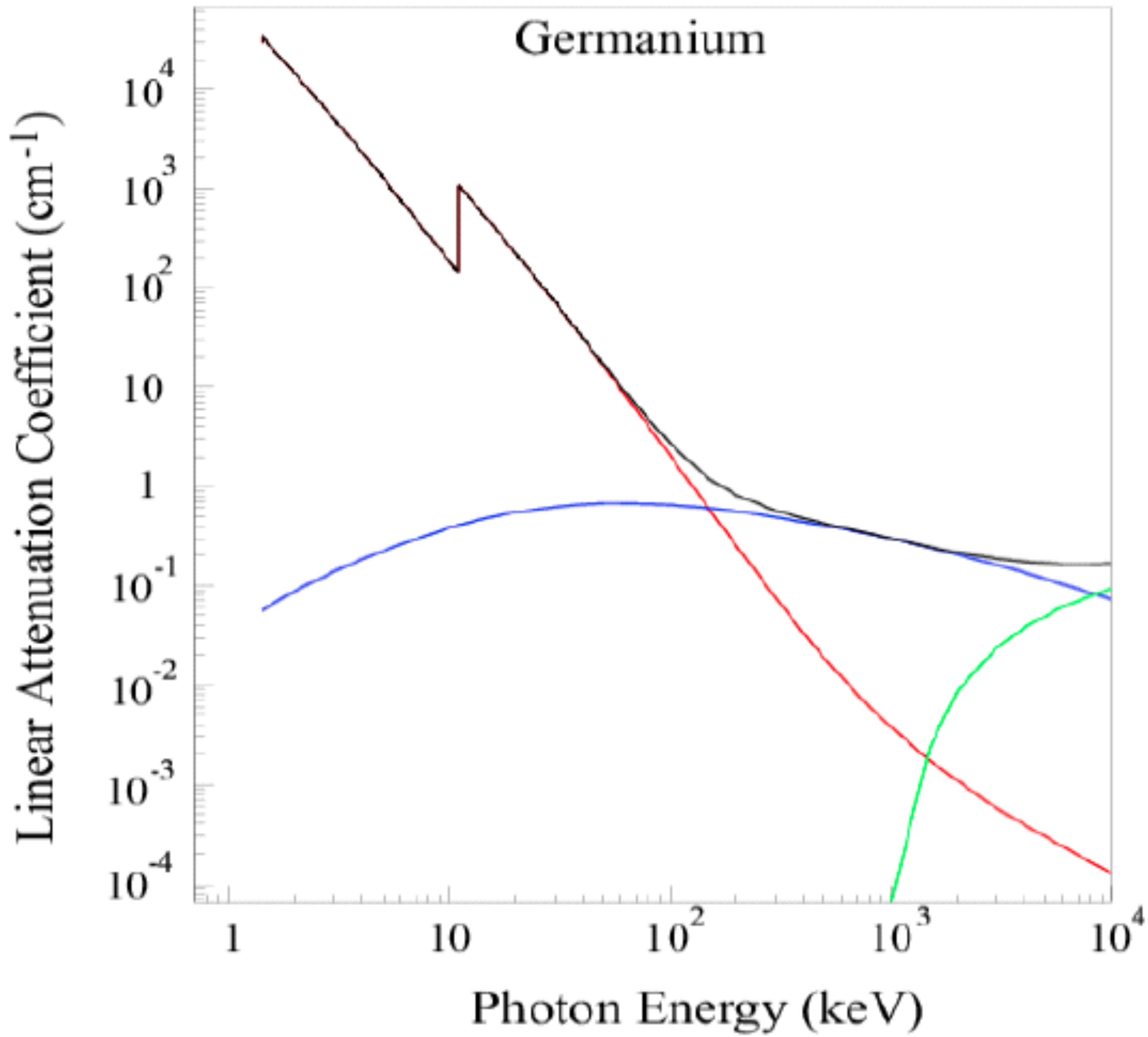
[a] *Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[b] *STFC, Daresbury Laboratory, Daresbury, Warrington WA4 4AD, UK*

Contents

Energy dependence

HOMEWORK
Explain this diagram!

HOMEWORK
How do gamma-rays interact with matter? By which mechanisms?



Compton scattering

- Is important for gamma detection

  - The probability for photoelectric events is relatively low for E_γ > ~ 500 keV
  - Higher-energy gammas generally Compton-scatter inside the detector, losing energy until they are low enough for a photoelectric event
  - So full-energy events at E ~ 2 MeV are usually the result of around four interactions

- But also leads to background in gamma-ray spectra

  - Gammas that enter a detector and Compton-scatter out without being fully absorbed contribute background at energies below the photopeak

Radford

Compton background

- Is a serious problem for high-fold coincidence data

  The peak-to-total ratio for a bare Ge detector at 1.0 -1.5 MeV is typically ~ 0.2, so
  - only 20% of single-γ events are full energy
  - for γ-γ coincidences, only 4% of the events are full energy
  - for γ-γ-γ-γ coincidences, only 0.16% are full energy

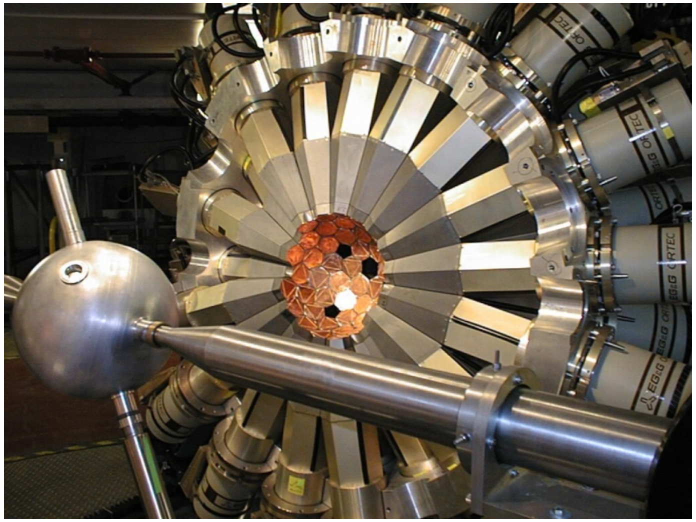
  So if you don't want to collect almost all background events, you need to do something about Compton scattering out of your detectors

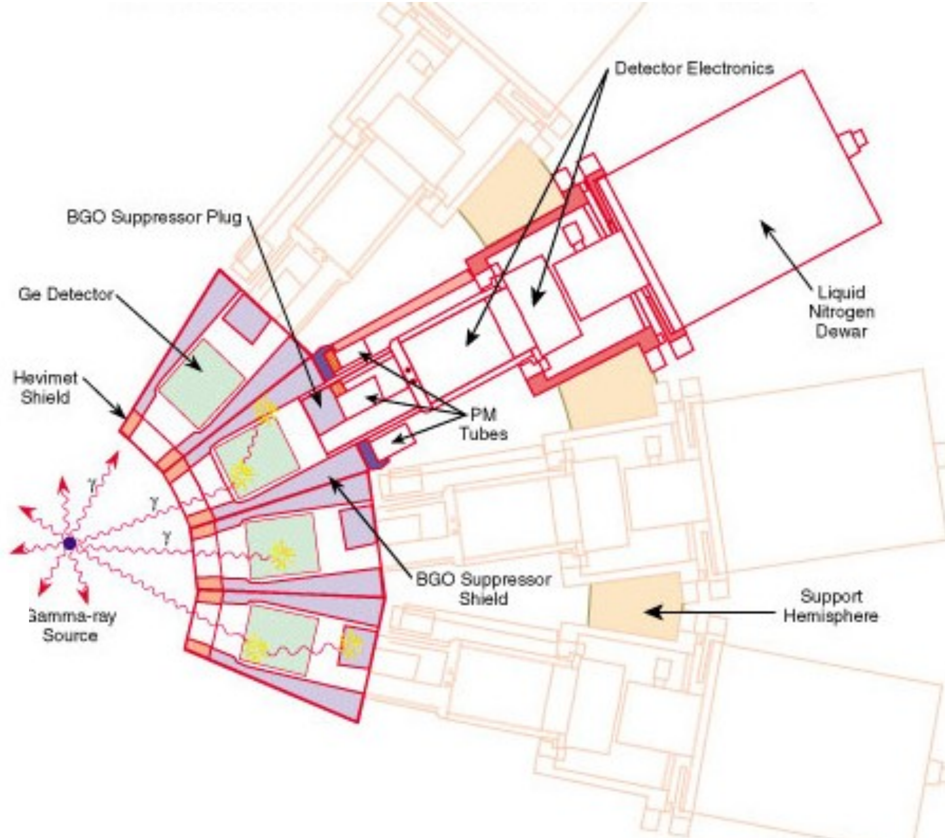
- Compton suppression

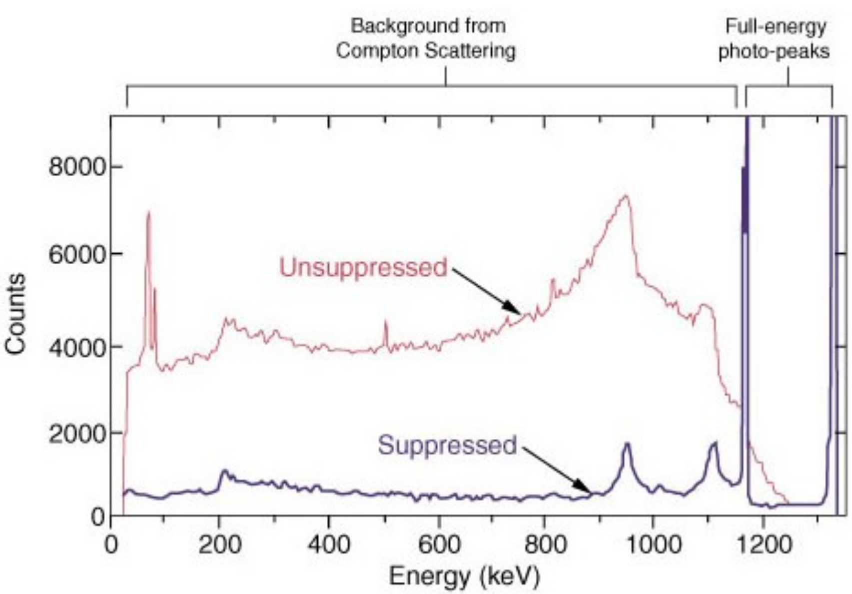
  - Use a scintillator material around the Ge to detect scattered gammas and veto the bad events
  - Typically raises peak-to-total to ~ 0.6

Radford

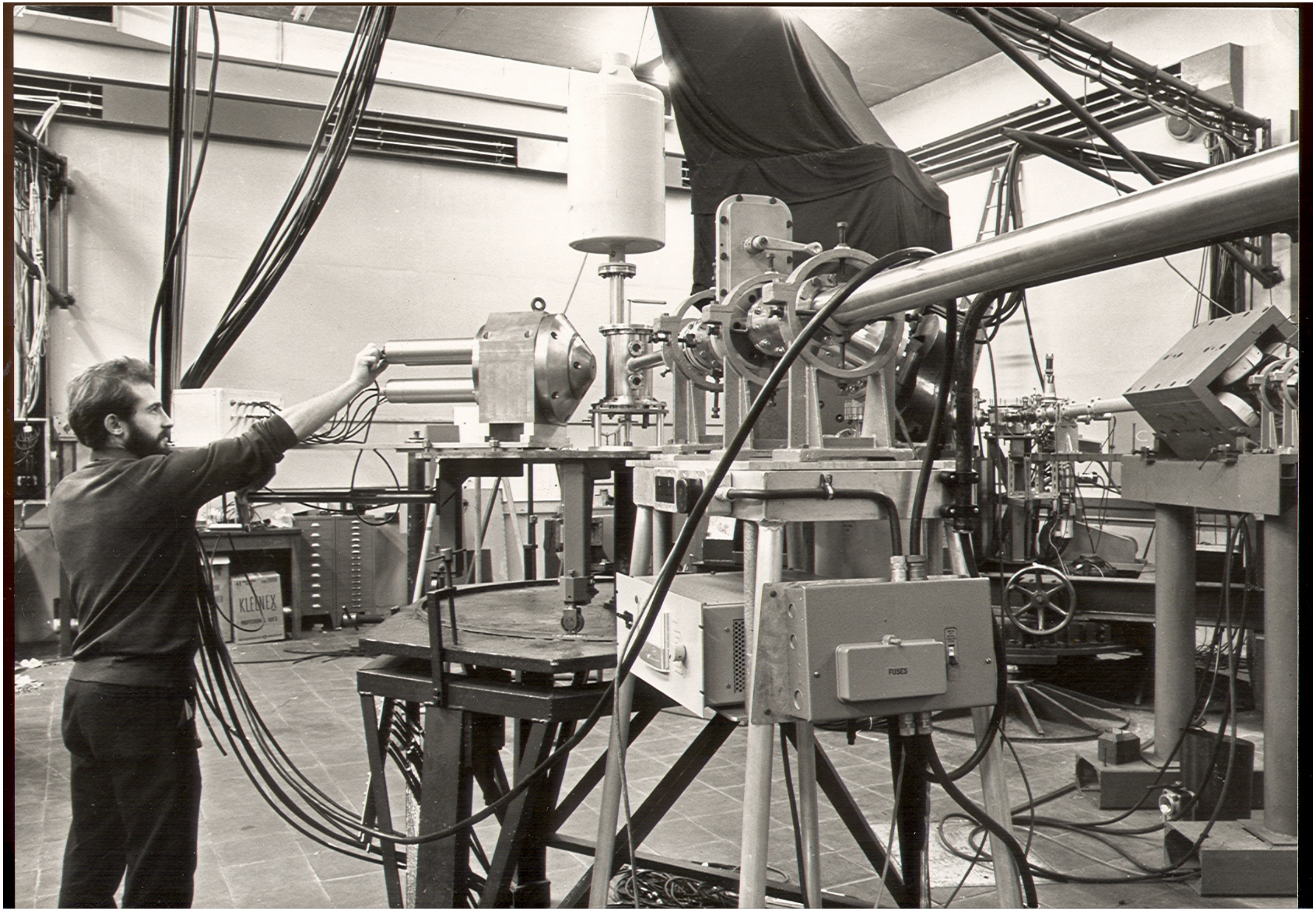
Compton Suppression – improving the peak to background ratio







The First Escape Suppressed Spectrometer at Liverpool



John Francis Sharpey-Schafer 1968

We must show you the Open University video from 1979 at Liverpool!

Arrays of Escape Suppressed Spectrometers

TESSA0 The Escape Suppressed Spectrometer Array

The first one TESSA

Daresbury Study Weekend 1979
Nuclei Far from Stability

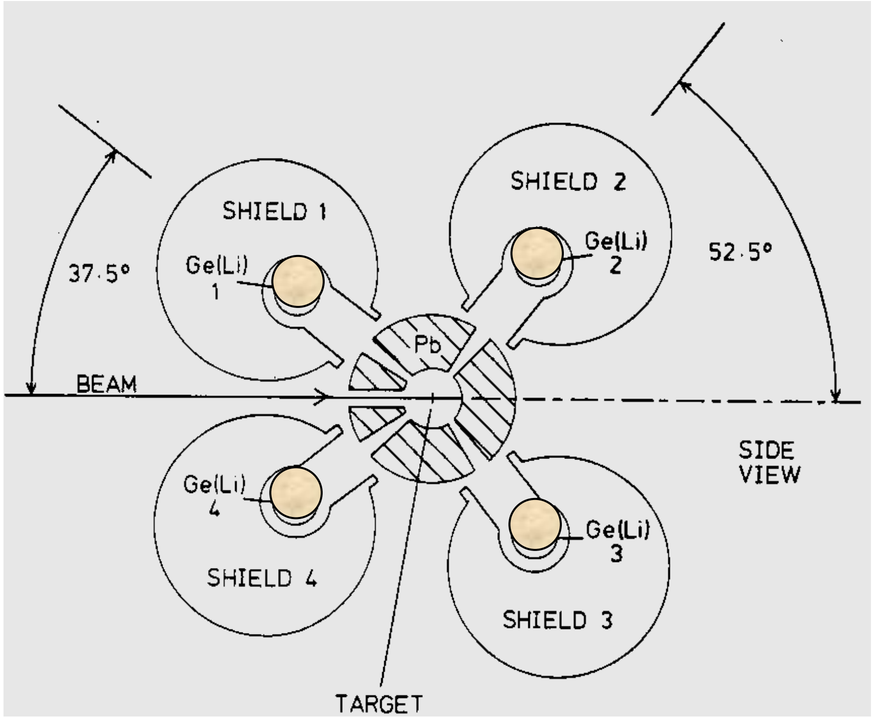
UK Denmark collaboration
Niels Bohr Institute 1980-1982
FN tandem

5 Ge(Li), 5 NaI(Tl) suppression shields

γ^2 Factor of 8 improvement in ph. ph. Coincidences

No channel selection

γ^2 Factor of 8 improvement in ph. ph. Coincidences



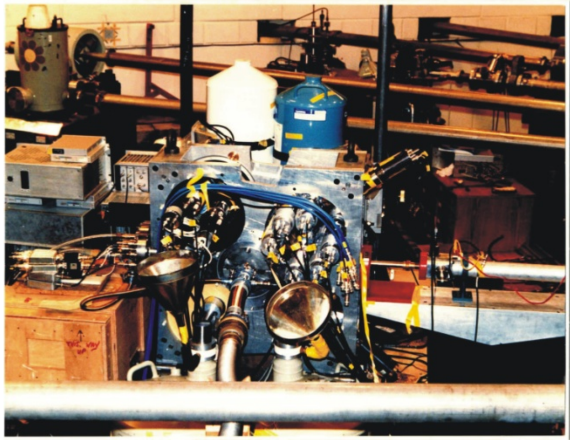
TESSA1
14 element multiplicity filter

From here on …
Lots of slides from John Simpson

TESSA0 The Escape Suppressed Spectrometer Array

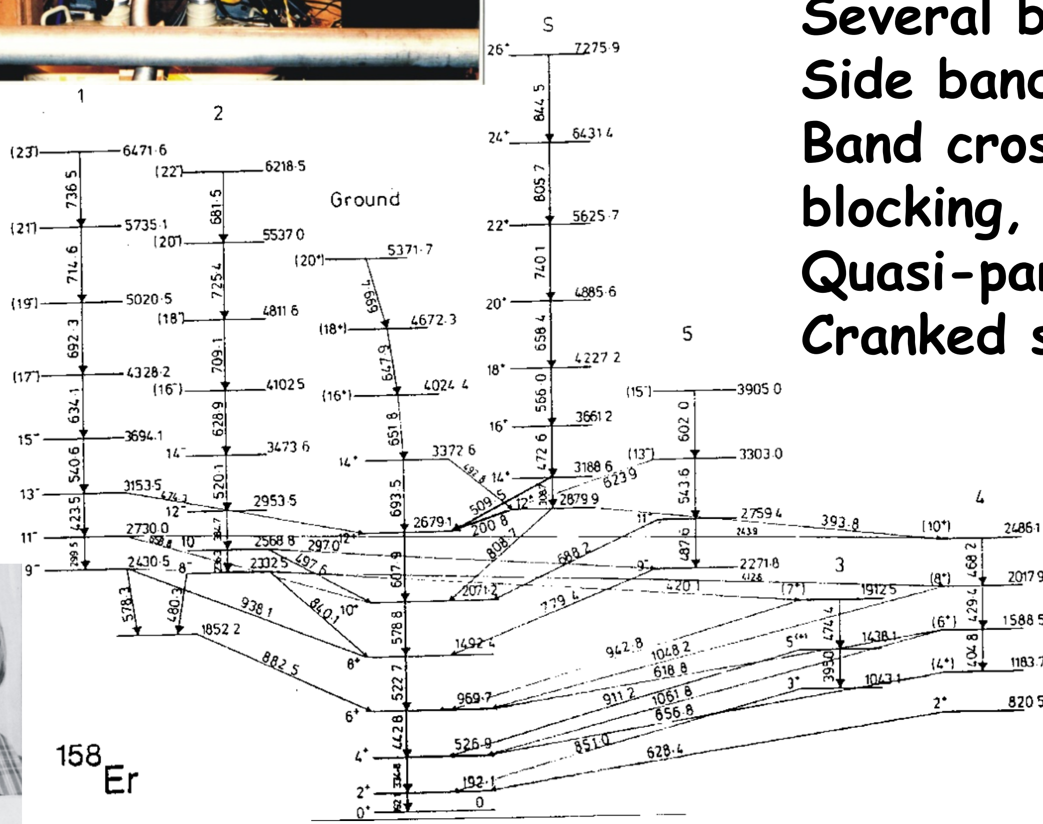
Spectroscopy of nuclei near ^{158}Er (since 1980)

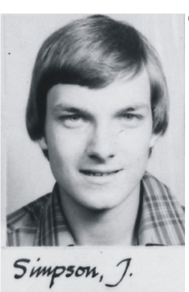
~1980 yrast states to spin ~30, naked Ge arrays



~1980-1982 TESSA

Escape suppressed array at NBI

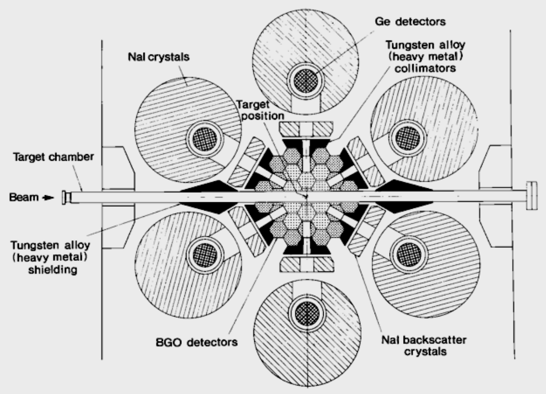




Several bands
Side bands to spins in mid 20's
Band crossing systematics, blocking, pairing reduction
Quasi-particle configurations
Cranked shell model

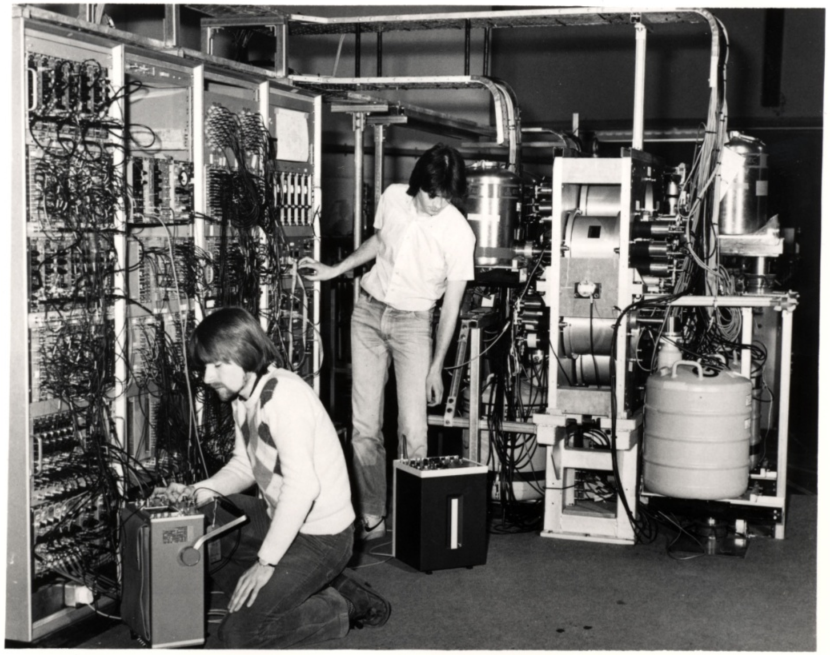
J.Simpson et al., J.Phys. G10 (1984) 383

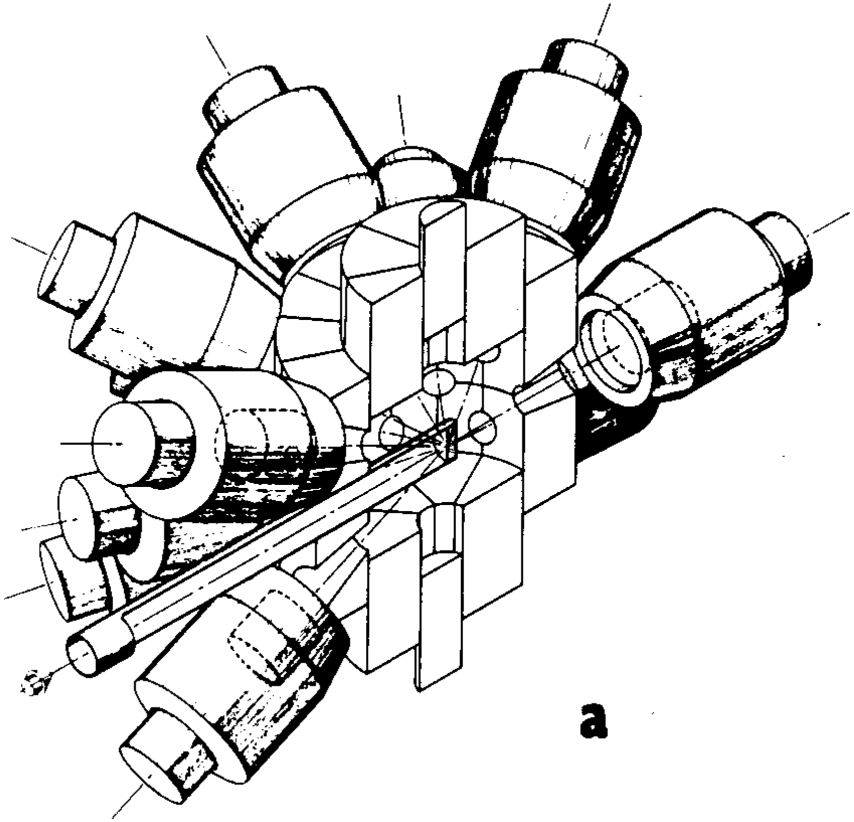
1983 TESSA to Daresbury
Heavier Ion beams
6 ESS, 50 element inner BGO ball



Multiple bands to spin I~40
Prolate to oblate transition
Systematics of second ($\pi h_{11/2}$) alignments
Evidence for superdeformation in ^{152}Dy, $E_{\gamma1}$ vs. $E_{\gamma2}$ plots

TESSA2





~1987

BGO replaces NaI(Tl)

1cm ≅ 1 inch

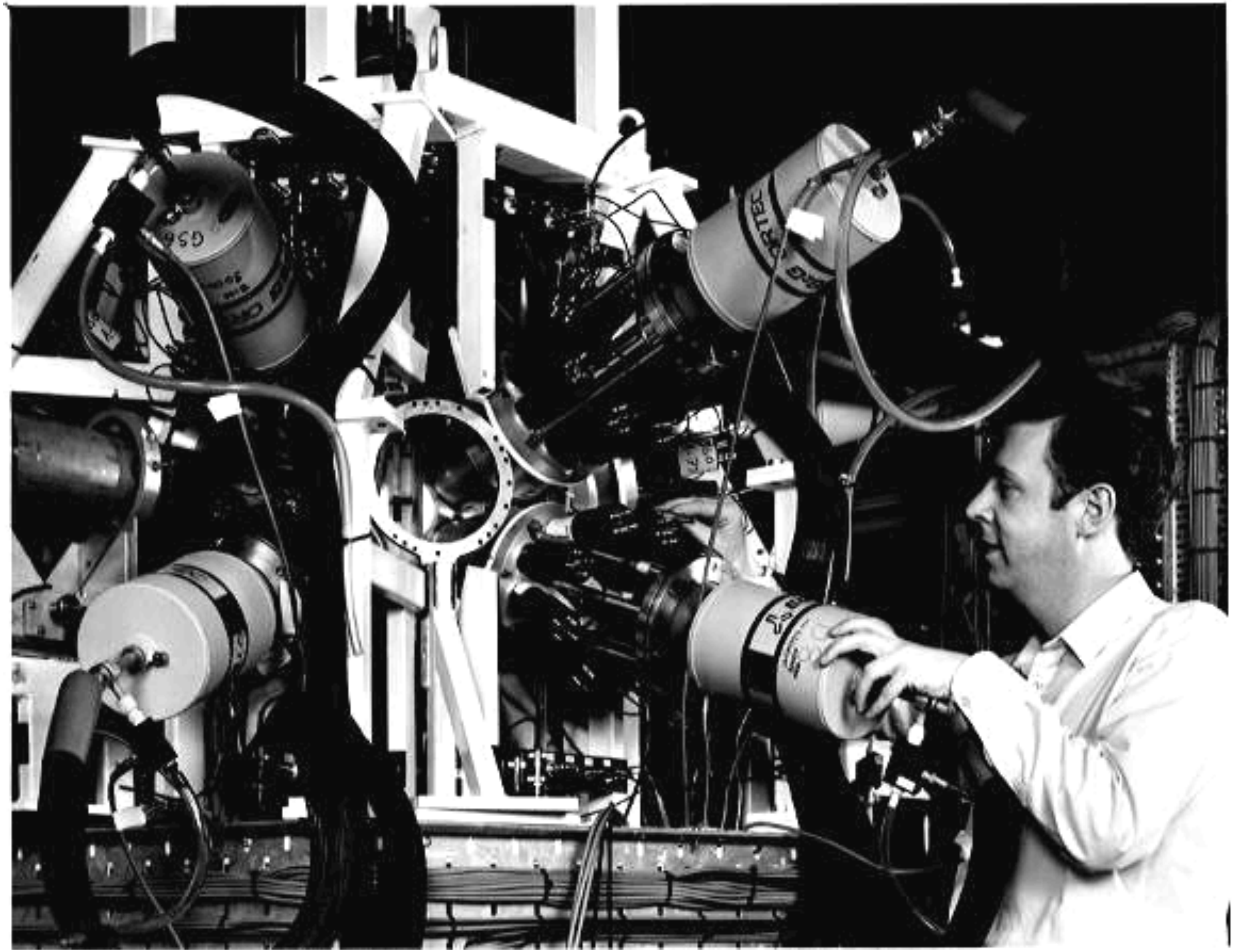
HERA (LBNL)

21 ESS + BGO ball

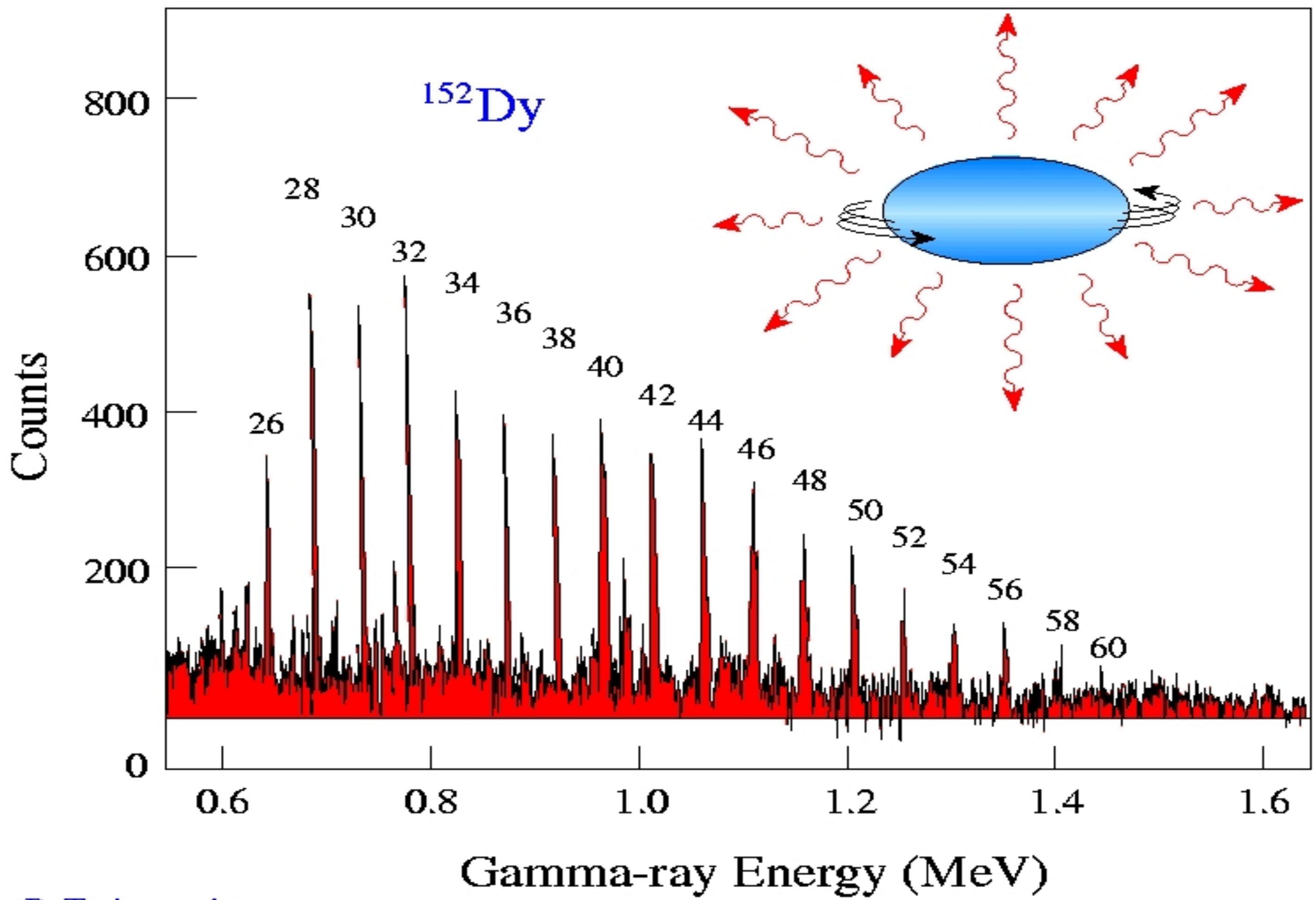
γ-γ-γ

HOMEWORK – WHY BGO?

TESSA3

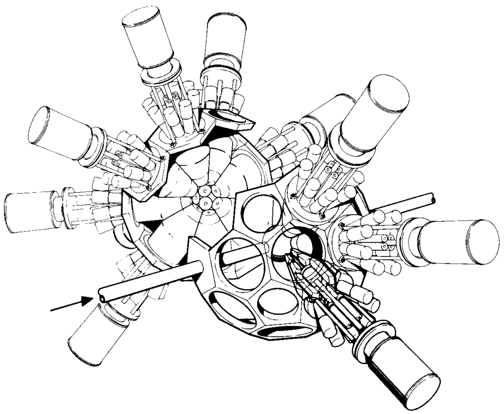


The first case of a high spin superdeformed band



P. Twin et. al
Phys. Rev. Lett. 57 (1986)

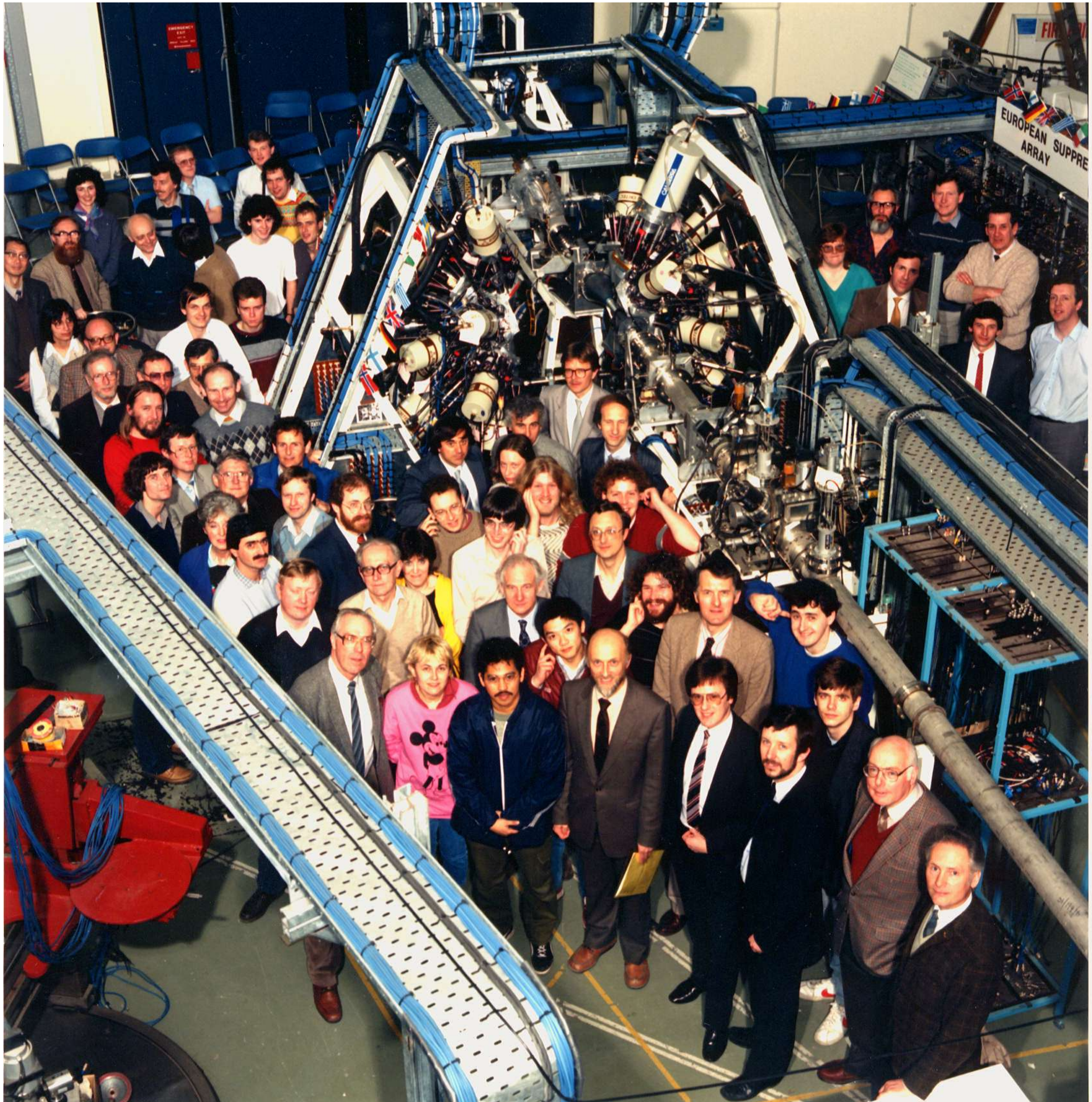
ESSA30



European collaboration
UK, Denmark, Germany, Italy, Greece

30 ESS (British, German, Italian, Scandinavian)
Daresbury
April 1987 for 8 months

Spokespersons:
Ryde, Lisle, Lieder, Sletten, Butler, Nolan, Sharpey-Schafer,
Kirwan, Wadsworth, Hubel, Durell, Lieb, Jones


EUROPEAN SUPPRE
ARRAY
EMERGENCY EXIT

Large array of escape-suppressed spectrometers led to a revolution in gamma-ray spectroscopy

~1990

Many array world wide
10-20 ESS
TESSA, Nordball, Chateau de Cristal, HERA, ORIRIS, MIPAD, 8π, ANL,….

Efficiency ~ 0.5% - 1.5%

Structure features ~1% of total nuclear intensity

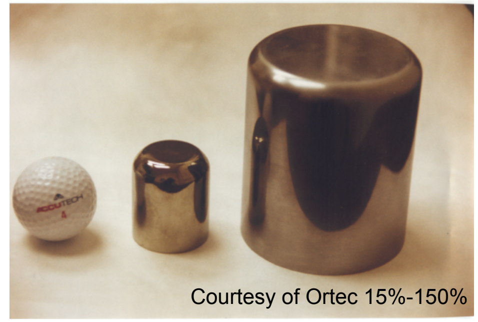
- Superdeformation
- Shape Changes
- Alignments
- N=Z nuclei to Mo
- Damping
- Fission fragment spectroscopy
- Pairing collapse
- Octupole shapes

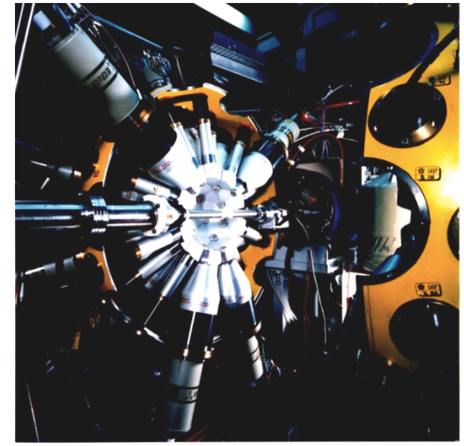
Physics programme required a much more efficiency array with high resolving power to lower the intensity limit by orders of magnitude

Increase the detection efficiency

Use more Ge detectors

Use large Ge detectors 70% - 80%

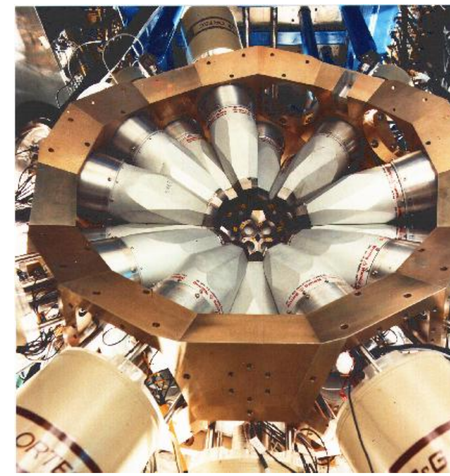

Courtesy of Ortec 15%-150%



Composite Ge detectors (Clovers, Clusters)

GaSp, Legnaro, Italy 40 detectors

Eurogam 1 Daresbury UK/France 45 detectors



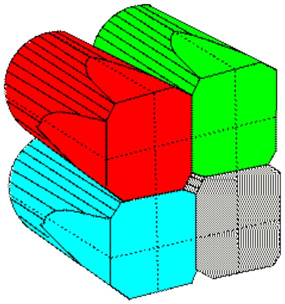
Euroball Strasbourg, Legnaro

Gammasphere E.I. 30-100 detectors. LBNL ANL

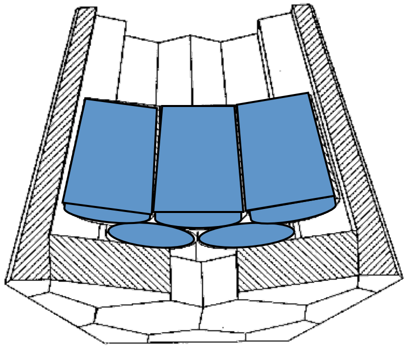
DETECTOR DEVELOPMENTS

Increase photopeak efficiency from 5% to ~10%
Increase granularity, increase resolving power
Use composite Ge detectors
Detector with more than 1 Ge crystal in the same cryostat

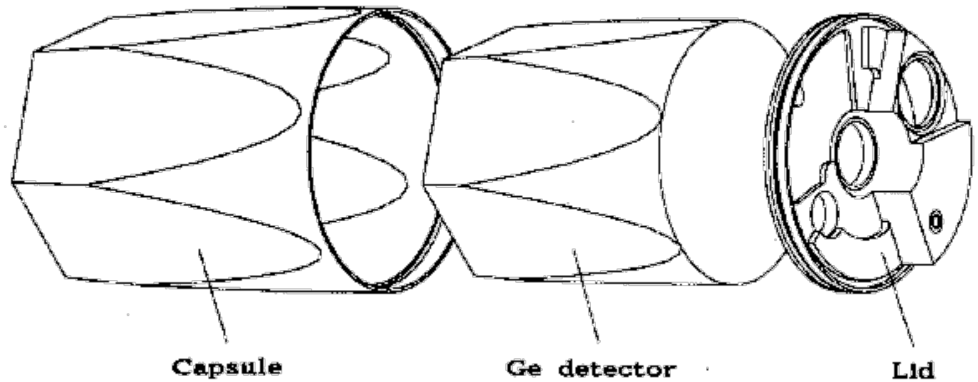
Clover detector
4 crystals per detector
Eurogam II, Euroball



Cluster detector
7 crystals per detector
encapsulated detectors



Cluster detector



Encapsulated Ge detector

Hexagonal tapered crystals ~60 mm dia, ~ 70mm length

Crystal sealed in an Al capsule

Vacuum of crystal and cryostat decoupled

Close packing

Crystal never exposed

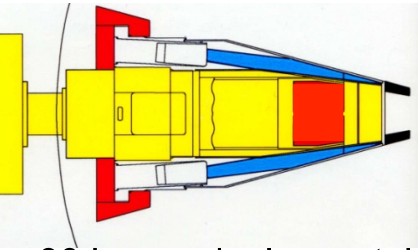
Easy handling and repairs, annealing

Intertechnique (EM), Univ Koln, KFA Julich

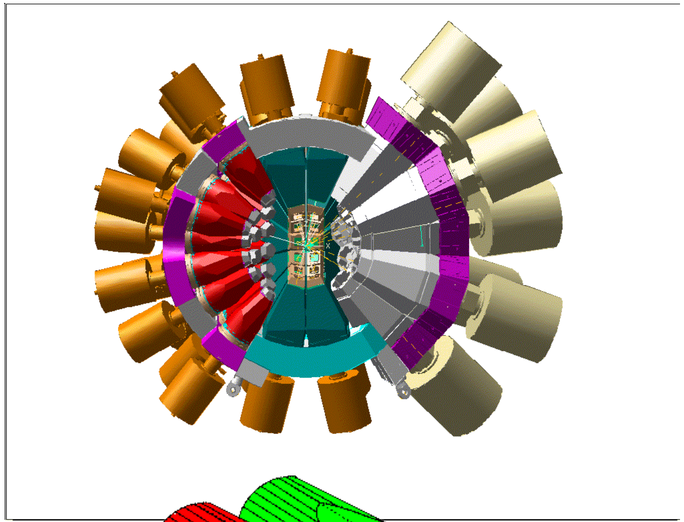
J.Eberth et al., Prog. Part. Nucl. Phys 28 (1992) 49

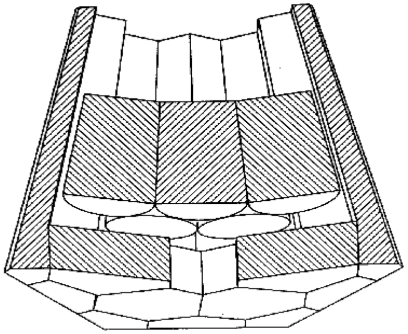
Euroball

European collaboration
France, Denmark, Germany, Italy, Sweden and the UK

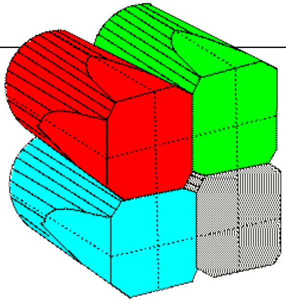


30 Large single crystal
Ge detectors





15 Cluster Ge detectors
7 encapsulated Ge crystals per cluster



26 Clover Ge detectors
4 crystals per cryostat

239 Ge crystals
Suppression shields
Total peak efficiency calculated to be 9.4%
Intensity limit ~ 10^{-5}

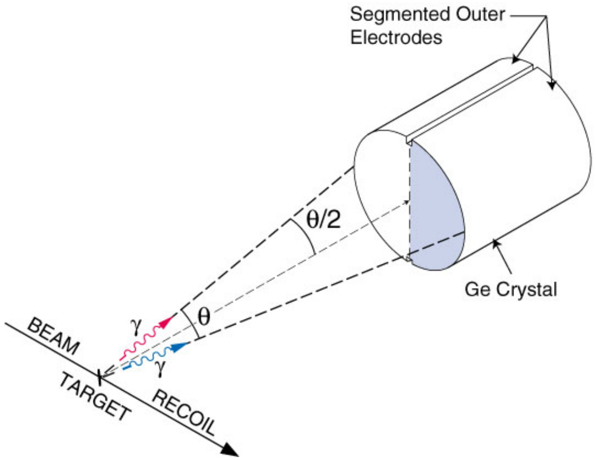
INFN Legnaro Euroball III
IReS Strasbourg Euroball IV
Inner ball

Euroball III at Legnaro

Segmentation of detectors

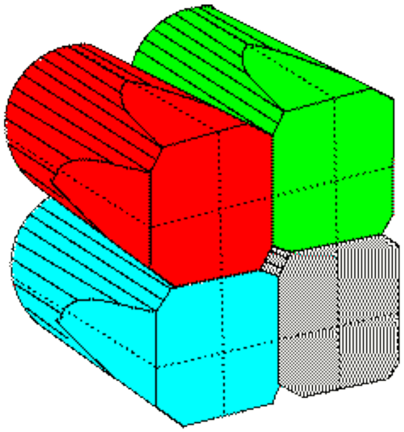
Improve granularity (reduce Doppler broadening)

Gammasphere



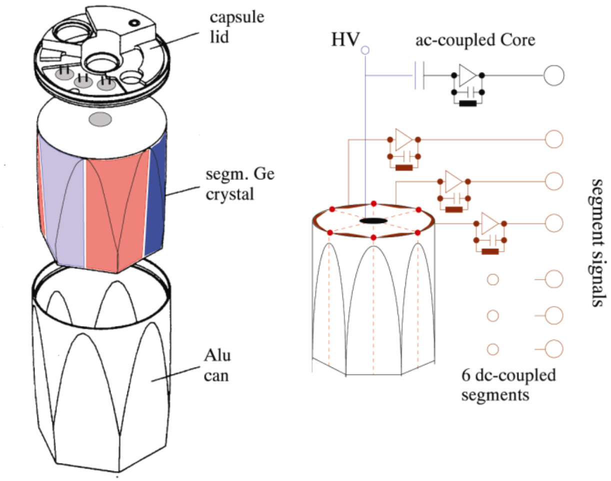
2-fold segmentation
Single crystal Ge detector

Exogam



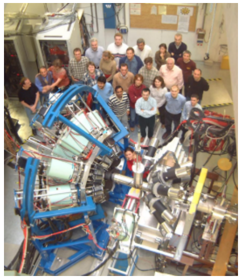
4-fold segmentation
Clover Ge detector

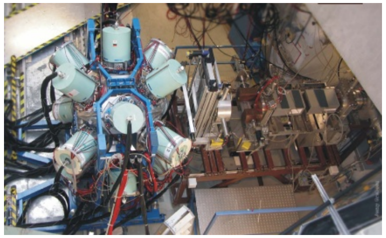
Miniball

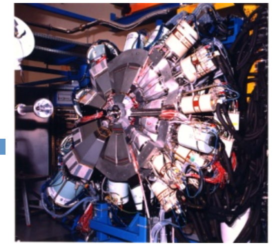


6-fold segmentation
Encapsulated Ge detector

Instrumentation in Europe

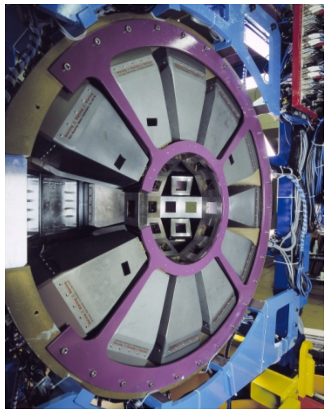




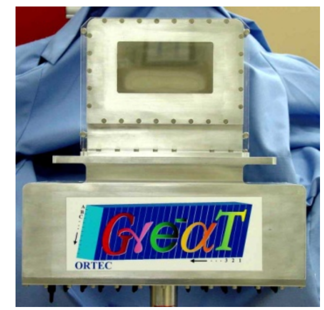


Euroball

RISING, GSI



JUROGAM, GREAT, SaGe, LISA, MARA, JYFL

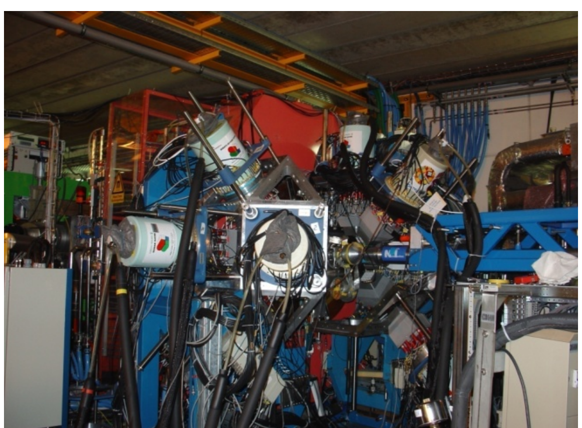


CLARA, LNL

Radioactive beam spectroscopy

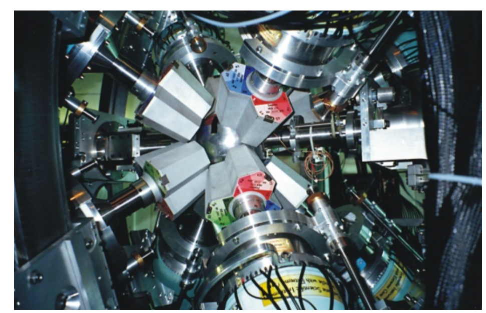
EXOGAM, SPIRAL, Ganil

MINIBALL, RexIsolde, HIE-ISOLDE



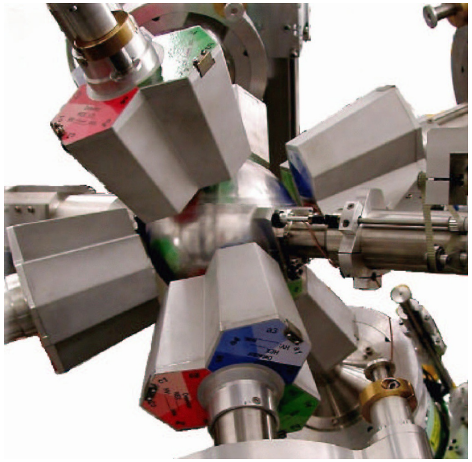
Segmentation
Encapsulation
Position determination from pulse shape analysis

EGAN
GAMMAPOOL
Loan Pool IN2P3/STFC

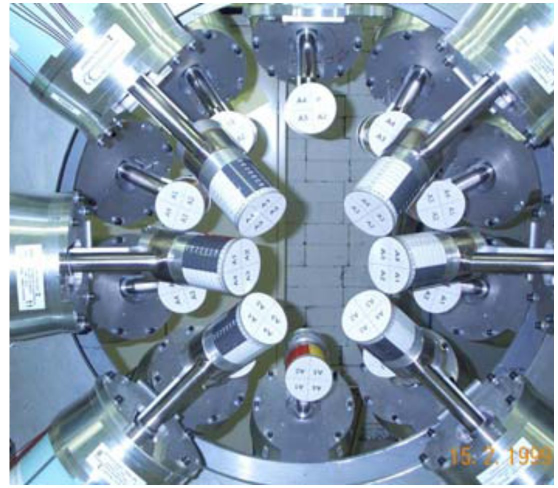


Gamma-ray tracking projects
MARS
TMR EU collaboration

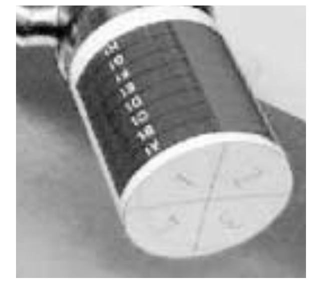
Arrays for the present generation of RIBs

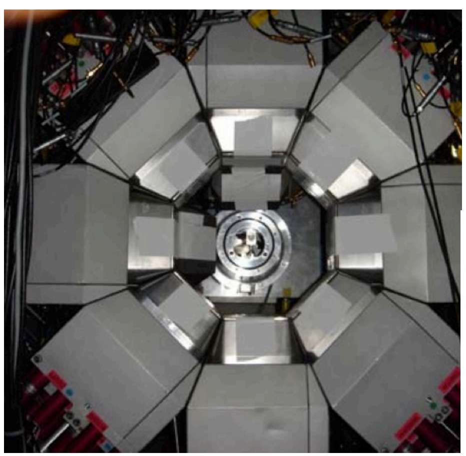
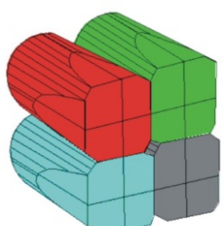



MINIBALL triple-clusters
with 6 and 12 fold segmentation

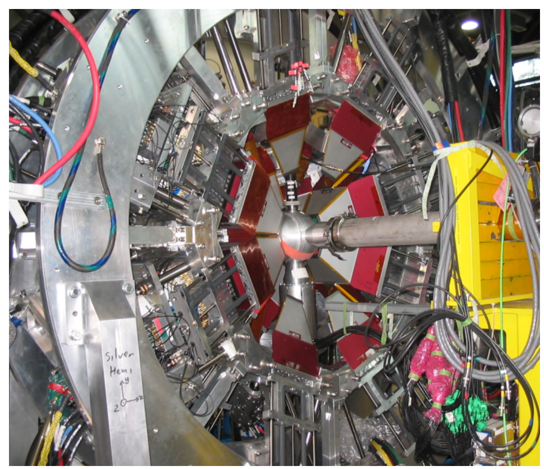


SeGA (Segmented Germanium Array at NSCL) with 32-fold segmentation

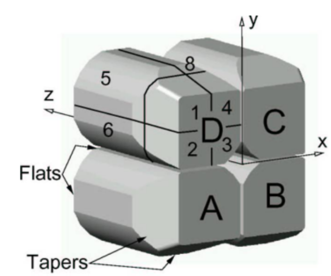


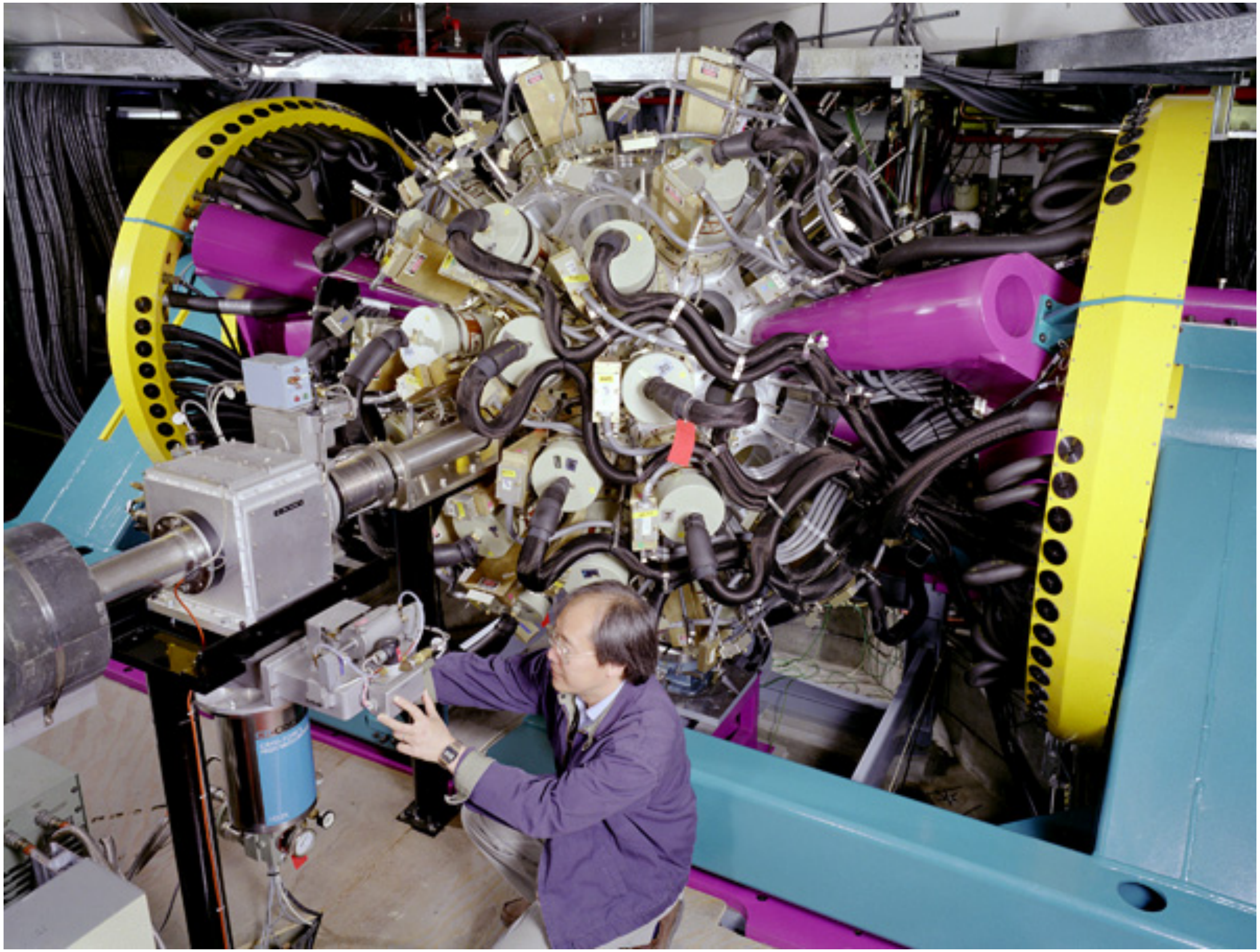
EXOGAM at GANIL
with 4-fold segmented clovers



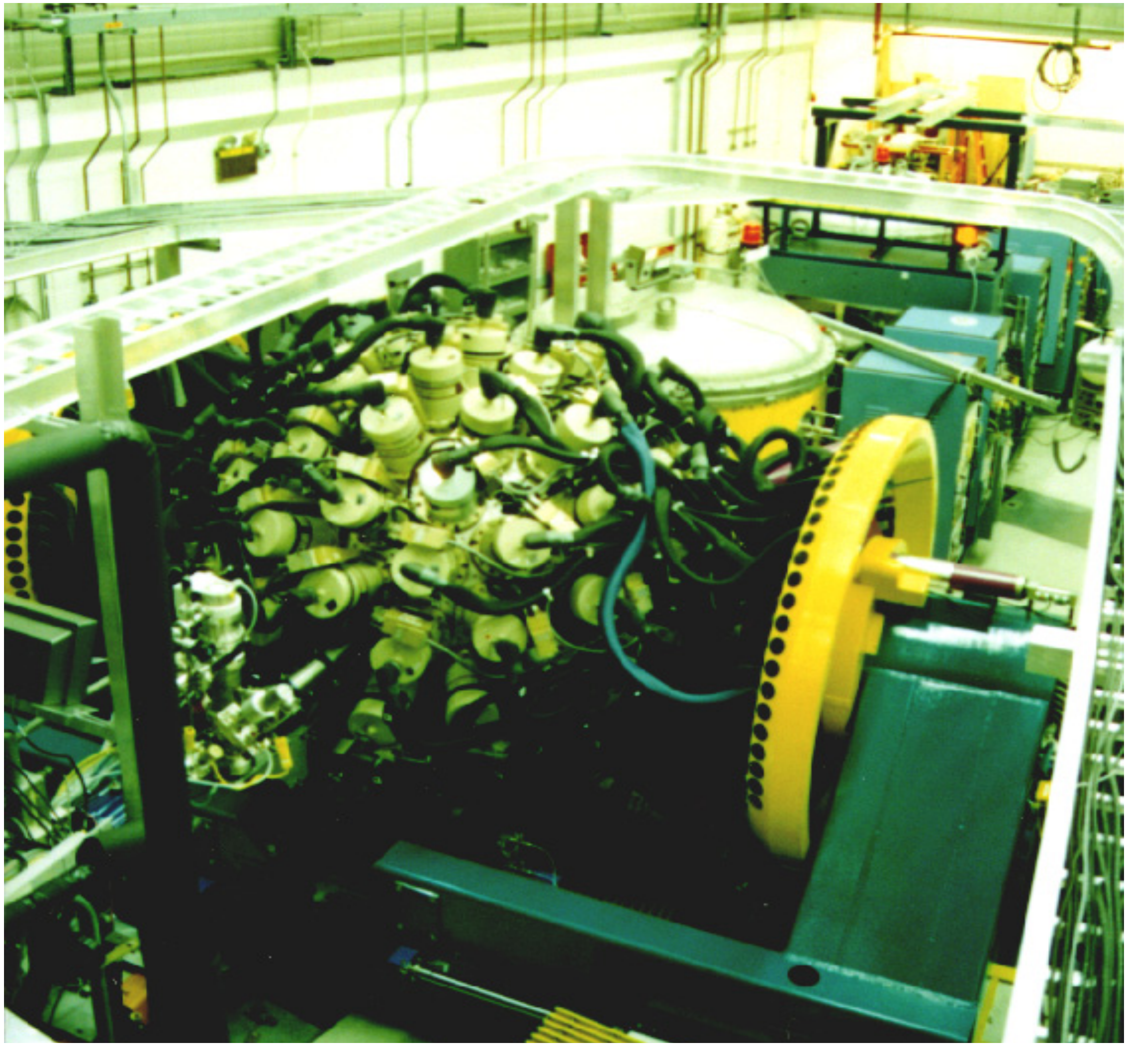
TIGRESS (TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer) with 32 fold segmentation (8-fold segmented clovers)



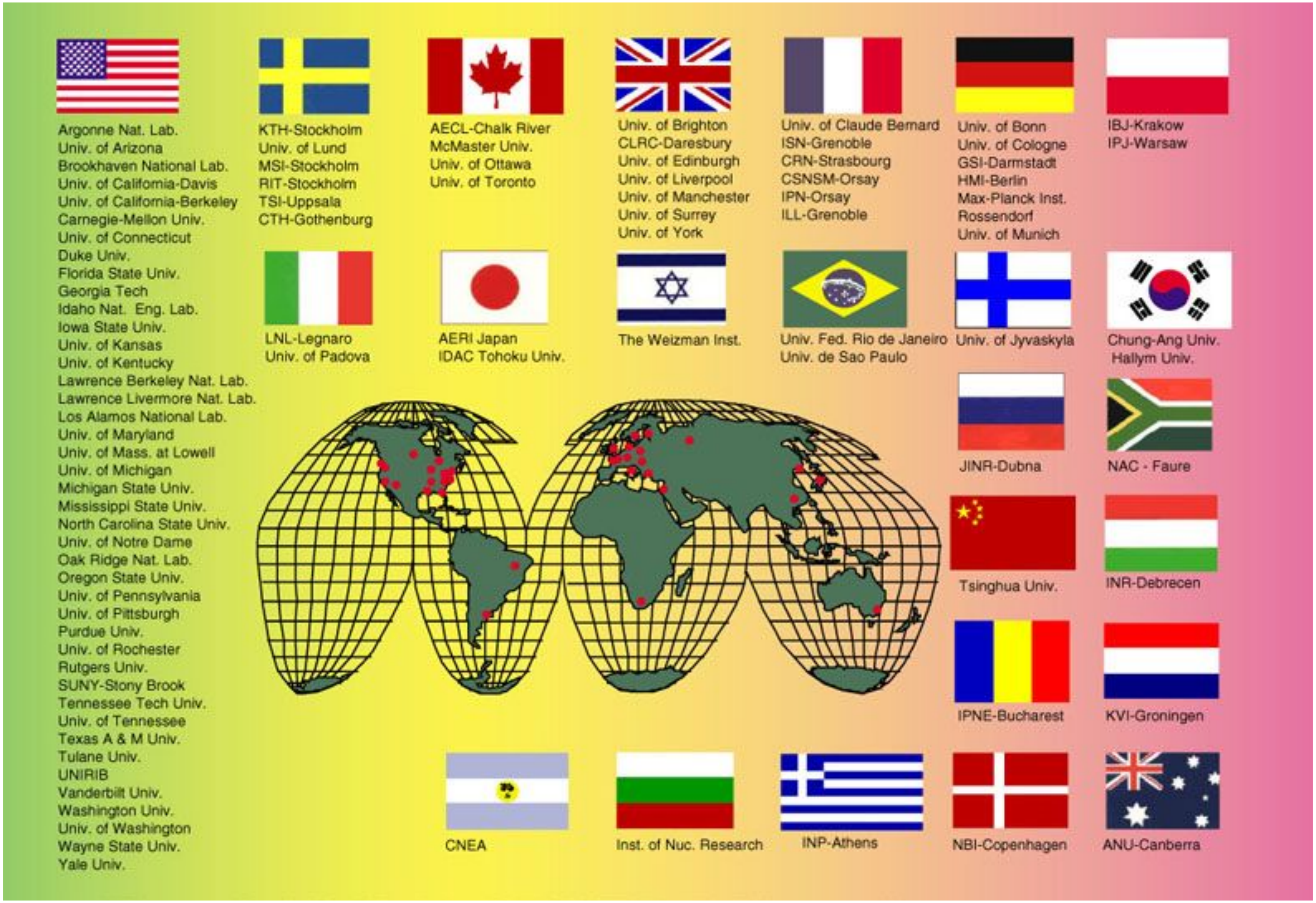
The GAMMASPHERE Spectrometer at Berkeley National Laboratory



GAMMASPHERE + Fragment Mass Analyzer at Argonne National Laboratory



The GAMMASPHERE Collaboration



~100 institutions, ~25 nations, >110 PhD's!

MORE ABOUT Gammasphere

Welcome to the Special Celebration:

“Ten Years of Gammasphere and Beyond”

http://www.physics.fsu.edu/GS10Yr/introduction.htm

Highlight Booklet available at:

http://nucalf.physics.fsu.edu/~riley/gamma/

Webpages at ANL and LBNL
Videos and photos

HOMEWORK: Gammasphere is going through a major upgrade
What is it?

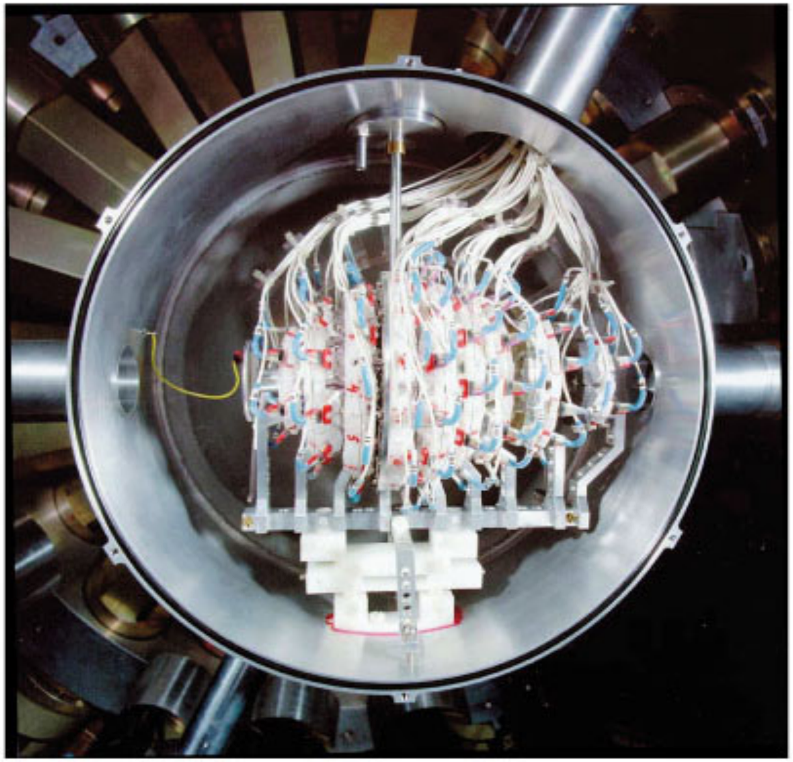
In all of this do not underestimate the importance of auxiliary detectors used in conjunction with the big Ge arrays ….

They have and continue to play a vital and essential role.

The UK is known for its genius in these developments too!

Auxiliary Detectors for GAMMASPHERE

One of the greatest assets of GAMMASPHERE is its ability to be used in conjunction with a wide range of auxiliary detector devices. These systems, as described below, enable new levels of sensitivity to be reached and also enormously increase the range of physics phenomena available for investigation.

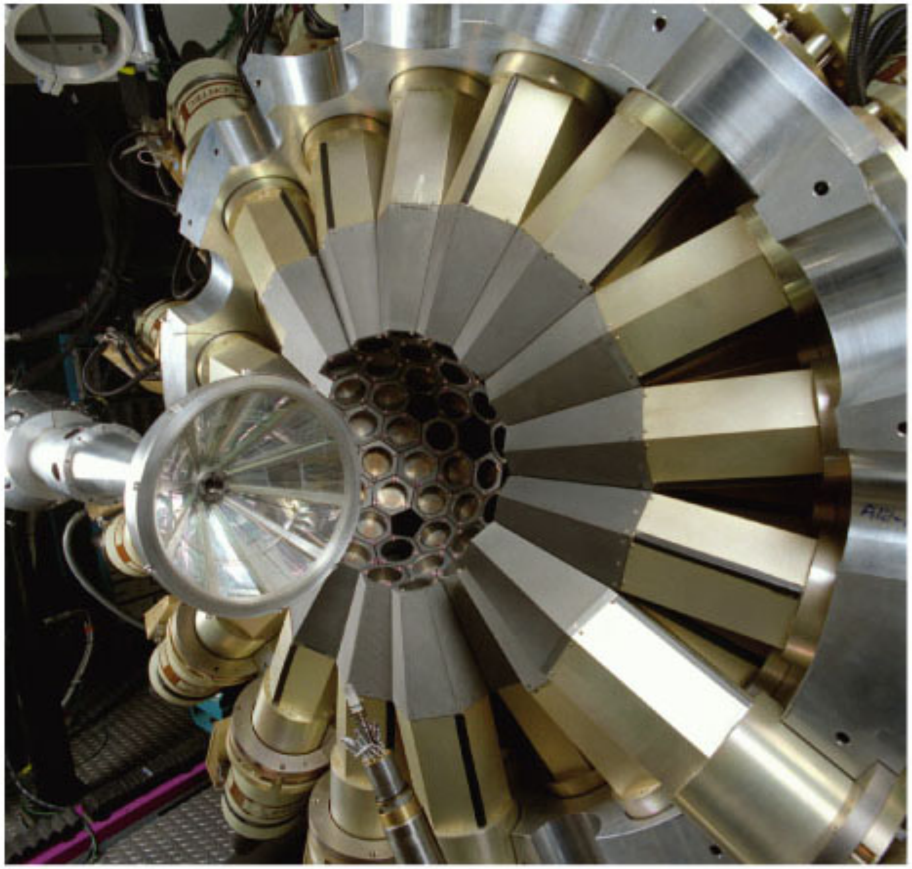


Microball

The Washington University Microball detects light charged particles (^{1,2,3}H, and ^{3,4}He) emitted in the reaction process. It consists of 95 CsI(Tl) scintillators closely packed to cover 97% of 4π and fits neatly inside GAMMASPHERE. Its small mass minimizes scattering of γ-rays, which degrades the performance of the GAMMASPHERE Ge detectors. The resolving power of GAMMASPHERE is enormously improved by the capability of the Microball to select specific charged-particle channels among a large number of reaction products and to determine the direction of the recoiling product nuclei using the measured momenta of all the emitted charged particles. This allows precise Doppler shift corrections to be made that improve the energy resolution of the γ-rays by factors of up to 3 for certain channels.

CHICO

The Rochester University Compact Heavy Ion Counter system (CHICO) was developed specifically to exploit the many advantages of detecting associated heavy-ion reaction products in coincidence with de-excitation gamma rays using GAMMASPHERE. For example, in binary reactions, detection of correlated reaction products allows the measurement of scattering angle, mass and Q-value, and allows correction for the Doppler shift of the gamma rays emitted and identification of the de-exciting recoiling reaction products. It comprises two identical 35.6 cm hemispherical target chambers, one at forward angles and the other at backward angles, each containing 10 position-sensitive parallel-plate avalanche detector panels.



Encyclopedia of Nuclear Physics and its Applications, First Edition. Edited by Reinhard Stock.

Nuclear Gamma Spectroscopy and the Gamma-Spheres

Mark Riley and John Simpson

Abstract

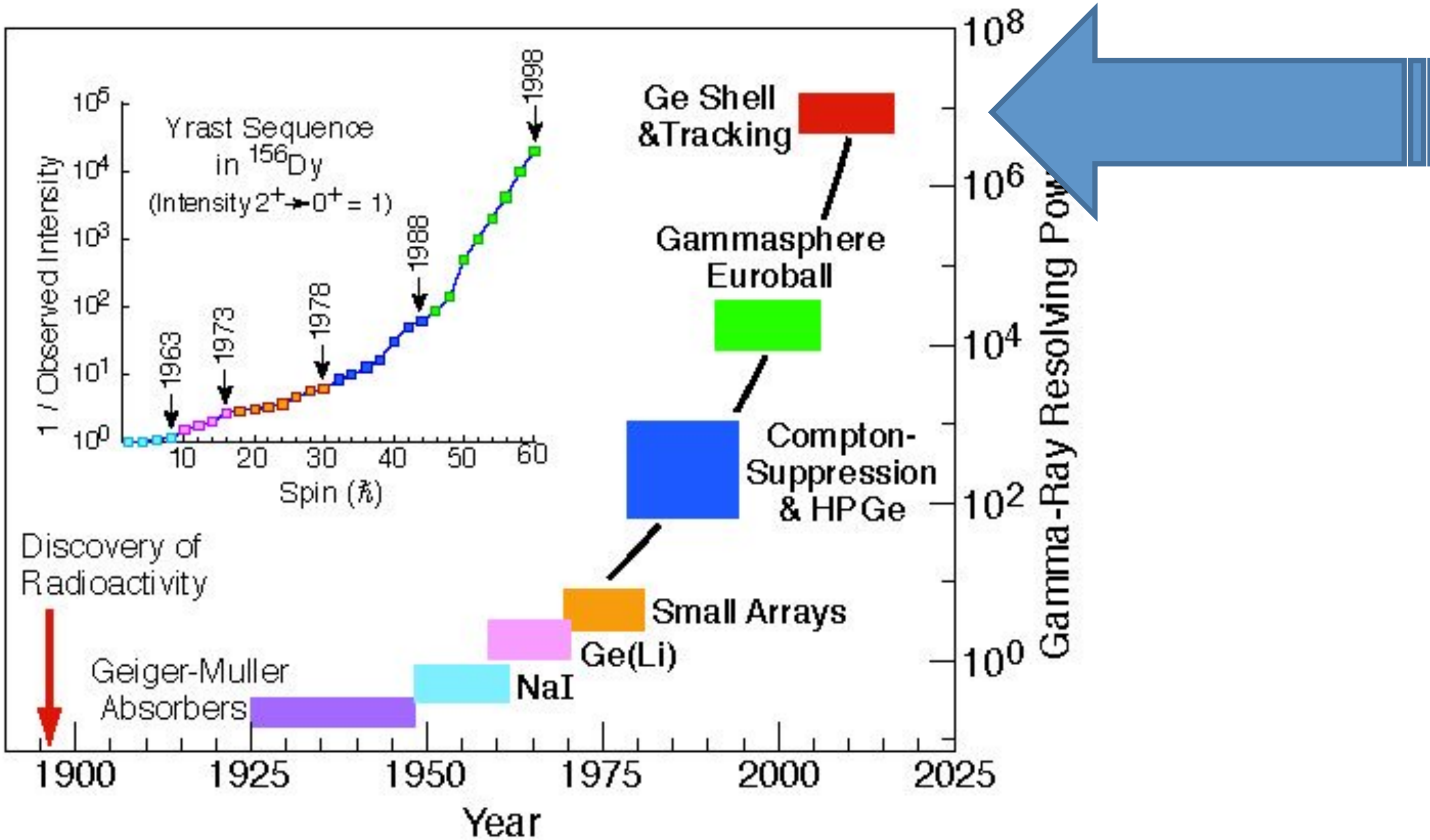
High resolution gamma-ray spectroscopy is one of the most powerful tools to study the structure of atomic nuclei. Significant advances in the development of increasingly sensitive instrumentation have taken place in recent decades. The latest 4π gamma-ray arrays, or "Gamma-Spheres", continue to reveal fascinating new scientific phenomena at the limits of isospin, excitation energy, angular momentum, temperature, and charge. Another huge leap forward in the resolving power of Ge based detection systems is now taking place via the development of gamma-ray tracking arrays which when combined with new accelerator developments, assures a most exciting future to this field. These technical advances also have a wide range of application spin-offs.

1. Introduction

Gamma-ray spectroscopic techniques play a vital role in our investigations into the properties and behavior of the unique strongly interacting aggregation of fermions that we call the atomic nucleus. These studies of the gamma-ray emissions from excited nuclei reveal an extremely rich system that displays a wealth of static and dynamical facets. The number of nucleons is sufficient (< 300) to allow correlations but it is still finite. Thus nuclei exhibit a variety of collective properties yet are simple enough to display both single-particle properties and a single-particle basis of these collective effects. The remarkable diversity of phenomena and symmetries exhibited by nuclei continues to surprise and fascinate scientists as unexpected properties are continually revealed by new experimental investigations arising from the development of increasingly sensitive instrumentation and new accelerator developments.

Every major advance in gamma-ray detector technology has resulted in the discovery of new phenomena bringing significant fresh insight into the structure of nuclei. The different time periods or era's associated with different detector technical advances are presented in Fig. 1. At the present time we find ourselves at the transition from the "Gamma-Sphere's" or large 4π arrays of escape-suppressed spectrometers, such as Gammasphere and Euroball, to the beginning of the development of 4π Ge shell arrays, such as GRETA (Gamma Ray Energy Tracking Array) in the USA and AGATA (Advanced Gamma Tracking Array) in Europe, see Ref. [1] and references therein. These latter systems will abandon physical suppression shields and instead employ the technique of gamma-ray tracking in electrically segmented Ge crystals. As a first step towards the implementation of these 4π Ge arrays the ~1π systems GRETINA (Gamma Ray Energy Tracking In beam Nuclear Array) in the US and the

Evolution of γ-ray detector technology

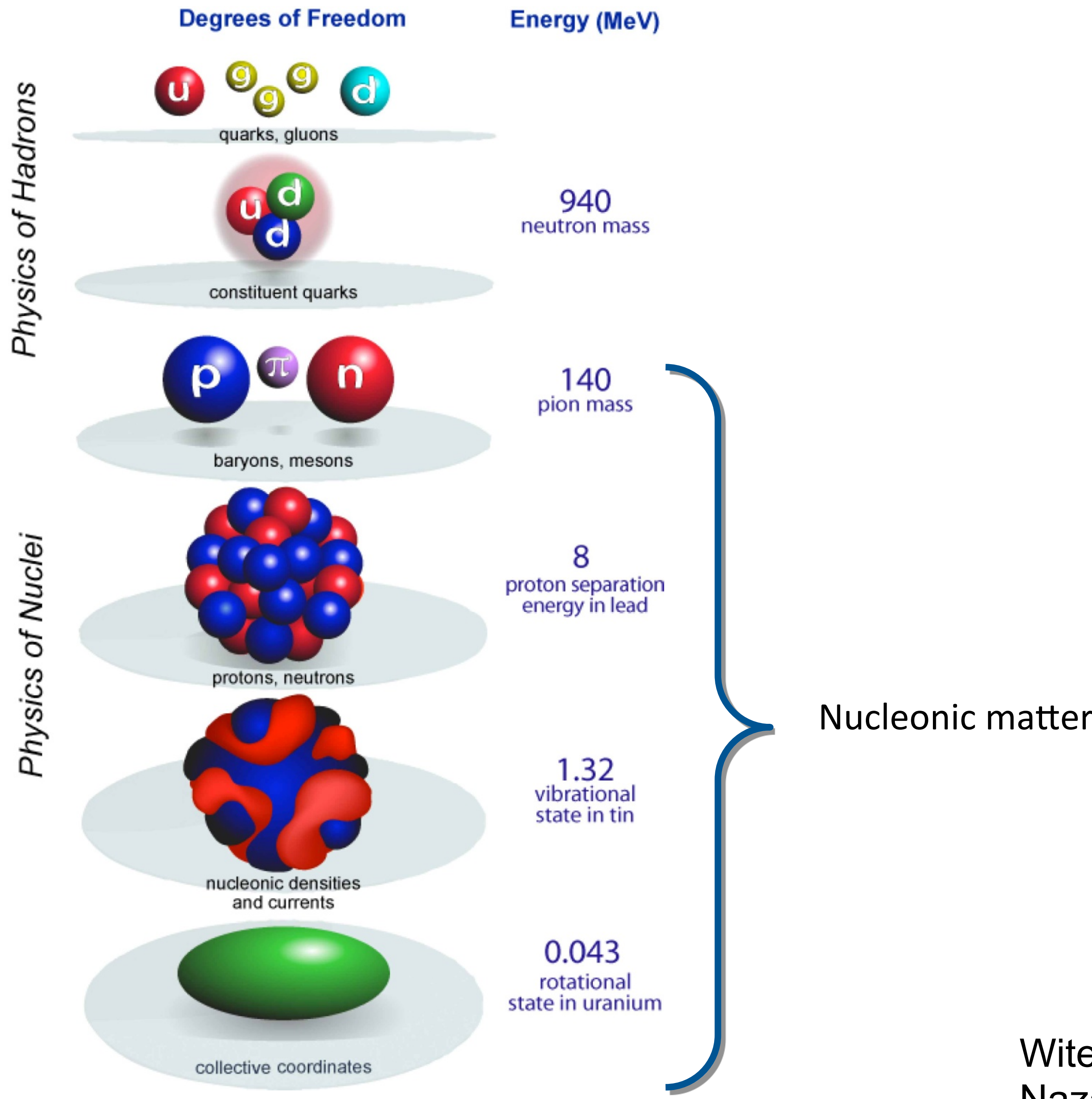


The calculated resolving power is a measure of the ability to observe faint emissions from rare and exotic nuclear states.

Universal Pictures presents The Hulk, directed by Ang Lee, opening June 20, 2003.

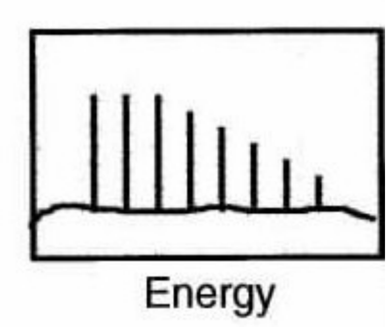
Credit: ILM/Universal

End Episode 1:



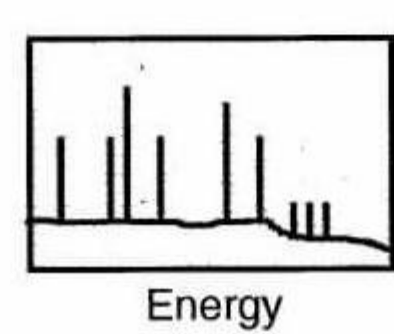
Witek
Nazarewicz

What can we infer from the γ-ray spectra?



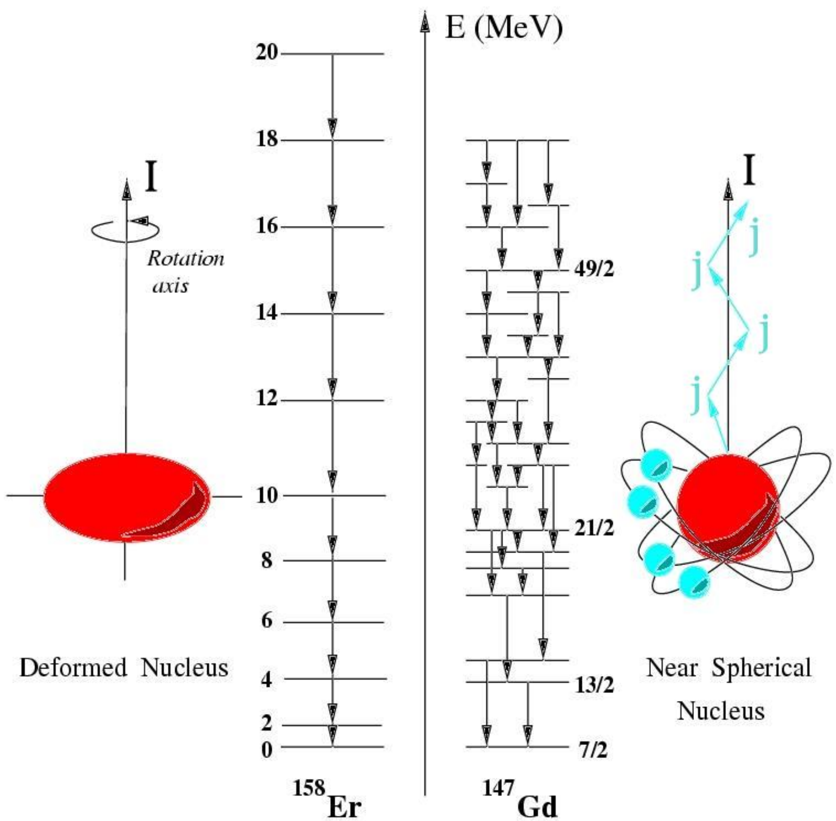
Collective Rotation

Single Particle Alignment



Level Schemes Contain Structural Information

Deformed nucleus rotating about an axis perpendicular to the symmetry axis.



Excitation energy and angular momentum are generated by single particle excitations and continually changing configurations.