Gamma-Rays: The Key to Unlocking the Mysteries of the Atomic Nucleus

Mark Riley (Florida State University)
Understanding our Universe?

What pieces of the puzzle are we missing?

These are very exciting times indeed!
Yes Mark, the past 100 years have been pretty special and the future looks exciting too! Good luck with your talk. Best, Ernest.

"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
“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).”
Heroes
Isaac Newton
(1642 – 1727)

Good luck with your talk too, Mark.
Best wishes
Isaac
ALBERT EINSTEIN (1879 – 1955)
Einstein in his 20’s .... YOUR AGE!
When he did all his best work!
And had his best haircut.
Linus Pauling:
Two Times Nobel Prize Winner
(Chemistry and Peace)

• 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 college
Monty Python!
Music heroes too!
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 through 2020 and beyond.

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

- Degrees of Freedom
  - Quarks, gluons
  - Constituent quarks

- Energy (MeV)
  - Neutron mass: 940 MeV
  - Pion mass: 140 MeV
  - Proton separation energy in lead: 8 MeV
  - Vibrational state in tin: 1.32 MeV
  - Rotational state in uranium: 0.043 MeV

Physics of Nuclei

- Nucleonic densities and currents
- Collective coordinates

Nucleonic matter
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.
The Niels Bohr Institute in Copenhagen
The Niels Bohr Institute in Copenhagen
Paul Dirac was a British theoretical physicist. Dirac made fundamental contributions to the early development of both quantum mechanics and quantum electrodynamics. He held the Lucasian Chair of Mathematics at the University of Cambridge.

Paul Adrien Maurice Dirac (August 8, 1902 – October 20, 1984)
Among his many contributions, Dirac formulated the Dirac equation, which describes the behavior of fermions and which led to the prediction of the existence of antimatter. Dirac shared the Nobel Prize in physics for 1933 with Erwin Schrödinger, “for the discovery of new productive forms of atomic theory.” Paul Dirac spent the last fourteen years of his life at Florida State University.
Bob Schrieffer and yours truly plus “The Backbender”!
... more of this later
The Chart of the Nuclides

- Proton Number
- Neutron Number

- Known Nuclei
- Heavy Elements?
- Fission Limit?
- Proton Drip Line?
- Neutron Drip Line?
Periodic Table to Nuclear Chart in 1 min
Sean Liddick (MSU)
Atom:
- electron shells

Krypton Atom

noble gases (closed shells)

Atom:
- electron shells

Nucleus:
- proton/neutron shells

Krypton Atom

magic nuclei (closed shells)

Shell Model of Atoms

Shell Model of Nuclei
We still have a long way to go before we can say we understand the nucleus. It is a wild and mysterious place!
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.
Deformation Systematics

*Moller Chart of Nuclides 2000*

*Quadrupole Deformation*

Doubly Magic: **Spherical**

Midshell: **Deformed**

Oblate (Door knob)

Prolate (US football)
Rotation can reveal information about the internal structure!

- Hard boiled and soft boiled egg experiment.
Spinning things is fun!
Rotations in the Universe

Typical size (cm)

Revolutions/sec

Nazarewicz
- Need to catch as many of the $\gamma$ rays in each cascade as possible.

- Need efficient detector systems!
- In nuclear reactions, eg, fusion evaporation, when we create our hot, excited, rapidly rotating nuclei we need to catch as many of the γ rays emitted in each cascade or flash as possible.

- Need efficient detector systems!
Gamma-Ray Detection Evolution

- **Yrast Sequence in $^{156}$Dy** (Intensity $2^+ \rightarrow 0^+ = 1$)
- **Ge Shell & Tracking**
- **Gammasphere Euroball**
- **Compton-Suppression & HPGe**
- **Small Arrays**
- **NaI**
- **Ge(Li)**

**Discovery of Radioactivity**

- **1900**
- **1925**
- **1950**
- **1975**
- **2000**
- **2025**

**Gamma-Ray Resolving Power**

- $10^0$
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$
- $10^6$
- $10^7$
- $10^8$
Gammasphere: 
The most powerful Gamma-Ray Spectrometer for nuclear structure studies in the world!
Universal Pictures presents The Hulk, directed by Ang Lee, opening June 20, 2003.
Credit: ILM/Universal
The GAMMASPHERE Collaboration

~100 institutions, ~25 nations
SNICS and Polarized Li Sources
9 MV Tandem Van De Graaff
12 resonator LINAC
RESOLUT Radioactive Beam Upgrade!
20 Element HPGe $\gamma$ Ray Detector Array
Rob Laird at the start
Rob upon graduation!
Skills learnt at FSU in high demand.
Many go into careers at Nat. Labs
Daniel Archer, R&D 100 Winner in 2005, seen here with the Secretary of Homeland Security, Tom Ridge, and the National Press describing the ARAM radiation detector system which he developed and is now in production and in use at airports, seaports and border crossings.

In Fall 2010 I invited Dan back to speak to the new crop of students. Here he is back in the Gamma Cave encouraging the students to work hard and finish their PhD studies because the country needs their expertise and there are jobs out there!
Backbending
Nuclear Superfluidity and Rotation

The unique laboratory of the nucleus is found to display superfluid properties.

The superfluid condensate arises from nucleons teaming up in time-reversed "Cooper" pairs and scattering coherently.

But collective rotation of the nucleus tries to break these correlated fermions apart (The Mottelson-Valatin Effect).
Dear Arne and Hans,

Thank you for the photographs which I received, a very exciting story. It is extremely nice to have rather conclusive evidence for the occurrence of matching isospin resonances for angular momentum values in the region $I \geq 16$; these are exhibited, perhaps, even more dramatically in the profile of inertia as a function of the rotational frequency (the enclosed figure). The frequency is defined as the derivative of the appropriate for an axial symmetric

$$\omega = \sqrt{\frac{\mathcal{O}(I^2)}{I(I+1)}}$$

or

$$\omega^2 = 4 \mathcal{O}(I^2)(I^2+1)/I(I+1)$$

In the last expression, the energy derivatives taken from the observed transition energies

$$\left(\frac{dE}{d(I+1)}\right)_{I(I+1)} = \frac{\mathcal{O}(I^2)}{I(I+1)}$$

The moment of inertia is also defined in terms of the derivative of the observed energy

$$\frac{dE}{d(I+1)} = \left(\frac{dE}{d(I+1)}\right)_{I(I+1)}$$

Another interesting feature of your data concerns the value of $\mathcal{O}$ at the singularity point. If the pairing correction were to completely disappear, one would expect $\mathcal{O} = \mathcal{O}_{\text{sym}}$. However, since the transition frequency for neutrons and protons is quite

$$\mathcal{O}_{\text{sym}} = \frac{1}{2}\mathcal{O}(I^2+I+1)$$

As can be seen, the $\mathcal{O}_{\text{sym}}$ is likely to be somewhat below $\mathcal{O}_{\text{sym}}$ after first ionization.

I am sending my compliments and best wishes for continued successful hunting in this exciting field.

A. M. A. Rohr
B. M. Mottelson

Built by Ray Willis
Nuclear Research Workshop, FSU, 1997
\[
\overline{I} = \overline{R} + \sum \overline{j}
\]

Total Spin = Collective Rotation + Aligned Spin

"Backbending" Demonstration Schematic
Show video
Evolution of Gamma-Ray Spectroscopy and $^{158}$Er
(Nat. Acad. Sci. Decadal Report June 2012, p 49)
Nuclear Physics: The Heart of Matter)

- New Detector Systems = New Physics
“The Fascinating Nuclear Structure
World of Erbium-158”
Wang, Riley, Simpson and Paul

“If the theoretical spin assignments turn out to be correct, the experimental band 1 in 158Er would be the highest spin structure ever observed.”
Afanasjev, Shi, Nazarewicz, PRC 86, 031304® (2012)
The Future
The calculated resolving power is a measure of the ability to observe faint emissions from rare and exotic nuclear states.
Compare GRETA with Gammasphere

<table>
<thead>
<tr>
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<th>Gammasphere</th>
<th>GRETA</th>
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<tbody>
<tr>
<td>Efficiency (1 MeV)</td>
<td>8%</td>
<td>55%</td>
</tr>
<tr>
<td>Efficiency (15 MeV)</td>
<td>0.5%</td>
<td>12%</td>
</tr>
<tr>
<td>Peak/Total (1 MeV)</td>
<td>55%</td>
<td>85%</td>
</tr>
<tr>
<td>Position resolution</td>
<td>1 mm</td>
<td>20mm</td>
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GREITIA-GRETA
The Future of Gamma-Ray Spectroscopy Workshop
August 17 & 18, 2006
Florida State University, Tallahassee, Florida

Grigory Ragochev Alfredo Galindo-Uribarri Krzysztof Starosta Witek Nazarewicz Dirk Weisshaar Sam Tabor Karin Glasmacher Thomas Lagergren David Radford
Anatoli Afanasjev Alexander Volya Warren Cluff I-Yang Lee Doug Cline Kim Lister Rod Clark Paul Fallon Mark Riley Demetrios Sarantites
2007 Long Range plan

Gamma-Ray Tracking

.......the construction of GRETA should begin upon successful completion of GRETINA. This gamma-ray energy tracking array will enable full exploitation of compelling science opportunities in nuclear structure, nuclear astrophysics, and weak interactions.
The First Detector for GRETINA ($1M!)
**GRETA to GRETA for FRIB**

It has been called “A jewel in the crown of FRIB”
Tim Hallman, Aug 2011: “The importance of GRETA in the out years is understood and is part of DOE planning.”
FRIB + GRETA
The Revolution in Nuclear Physics Continues!
The Future: A New Accelerator in the USA. It will be the Best in the World for Nuclear Structure Physics!

• And Detectors matter too!
• GREAT: the World’s most powerful Gamma-Ray Detector!
Studying the Origin of the Elements: Facility for Rare Isotope Beams, FRIB

- Funded by DOE Office of Science Office of Nuclear Physics + Michigan State University, $730M.
- T. Glasmacher, Project Director, ex-FSU (Dr. Cottle).
- Completion date 2022.
- Key Feature is 400kW beam power ($5 \times 10^{13}^{238}\text{U/s}$)
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped, and reaccelerated beams
The Chart of the Nuclides

Heavy Elements?

Known Nuclei

Fission Limit?

Proton Drip Line?

Neutron Drip Line?
Facility for Rare Isotope Beams, FRIB
Thomas at FSU 20 years ago!
A few final quotes

Linus Pauling

“Satisfaction of one's curiosity is one of the greatest sources of happiness in life.”

Albert Einstein

“The important thing is not to stop questioning.”
A few final quotes

Linus Pauling
“Satisfaction of one's curiosity is one of the greatest sources of happiness in life.”

Albert Einstein
“The important thing is not to stop questioning.”

Monty Python
“Always look on the bright side of life”
Show Michael Turner video
Our best chance to understand our Universe better is you!