Present Status and Challenges of

Using Magnetic Moments to Unveil the Structure of the Atomic Nucleus

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JAGIELLONIAN
UNIVERSITY
IN KRAKOW

Jagiellonian Symposium
on Fundamental and Applied
Subatomic Physics

UNIVERSIDAD
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DE COLOMBIA

Some History

$$\mu_n = \frac{e\hbar}{2m_p}$$

In the beginning (1922) Stern-Gerlach performed their experiment.

- Spin quantization.
- Measurements of atomic magnetic moments.
- Measurements of magnetic moment of proton.

$$\mu_\pi = +2.792847350(9)\,\mu_n$$

The next day (1925) Goudsmit and Unlenbeck discovered the electron' spin.

The third day (30′s) the neutron was discovered, its magnetic moment was measured, and the magnetic moment of the deuteron was predicted …

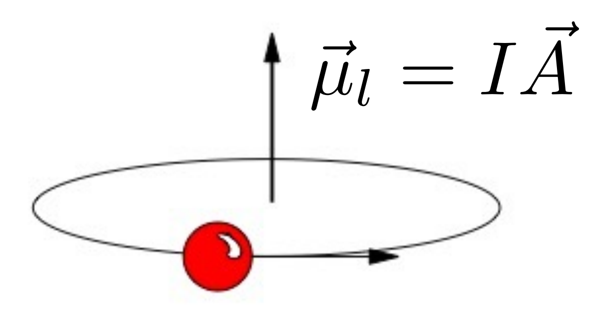
$$\mu_\nu = -1.91304272(45)\,\mu_n$$

What is the magnetic moment in the nucleus

The nucleus is composed by moving protons and neutrons

Current densities create magnetic moments

Orbital



Only protons have an orbital magnetic moment!

Classical Mechanics

$$|\vec{\mu}_l| = \frac{e}{2m}\left|\vec{l}\right|$$

Quantum Mechanics

$$\hat{\mu}_{l_z} = \frac{e\hbar}{2m}\hat{l}_z$$

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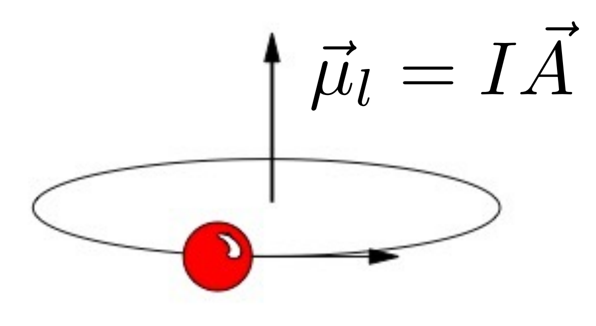

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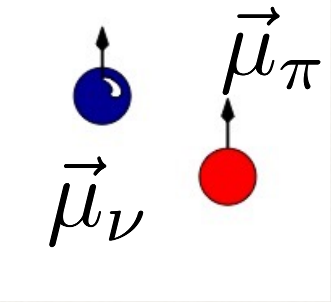
Intrinsic



Only Quantum Mechanic Picture

$$\hat{\mu}_{\pi,\nu} = g_{\pi,\nu}\frac{e\hbar}{2m}s_{\pi,\mu}$$

	π	ν
μ	+2.7928…	-1.9130…
g	+5.5856…	-3.8260…

$$\mu_{deuteron} = \mu_\pi + \mu_\nu = +0.8798\mu_N\ (predicted)$$

$$\mu_{deuteron} = +0.85741(2)\mu_N\ (measured)$$

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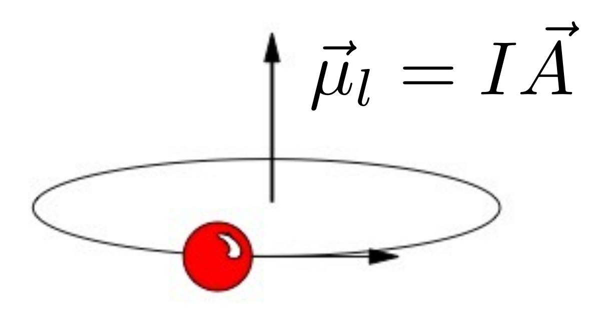
The nucleus is composed by moving protons and neutrons

Current densities create magnetic moments

Orbital



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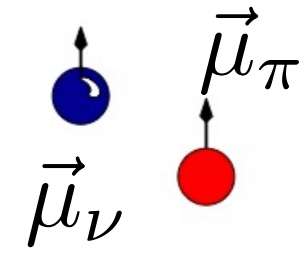
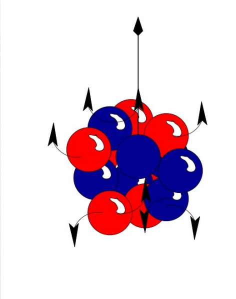


Only Quantum Mechanic Picture

$$\hat{\mu}_{\pi,\nu} = g_{\pi,\nu}\frac{e\hbar}{2m}s_{\pi,\mu}$$

Nuclear Magnetic Moment



$$\hat{I} = \hat{l} + \hat{s}$$

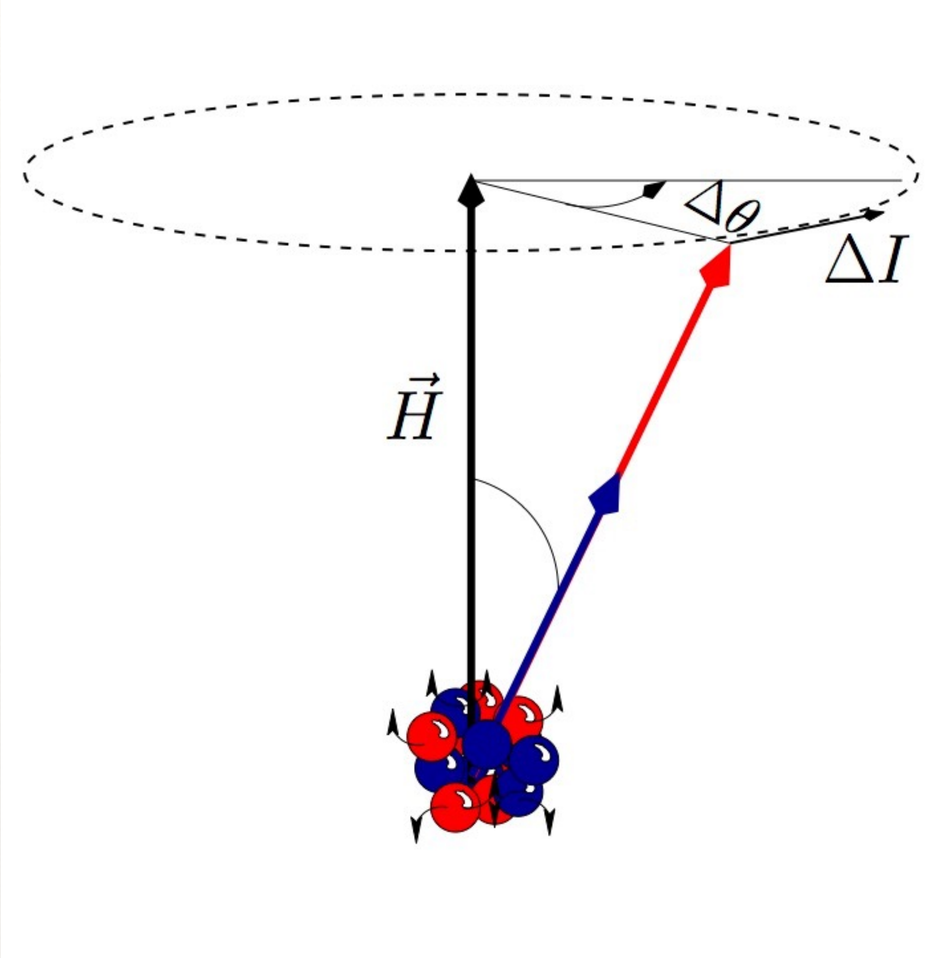
$$\hat{I}_z = \hat{l}_z + \hat{s}_z$$

When $I = I_z$ the state is aligned.

$$\hat{\mu}_{I_z} = \sum_{i=1}^{A} \hat{\mu}_{l_z} + \hat{\mu}_{s_z}$$

We measured $$g = \frac{\mu/\mu_N}{I/\hbar}$$

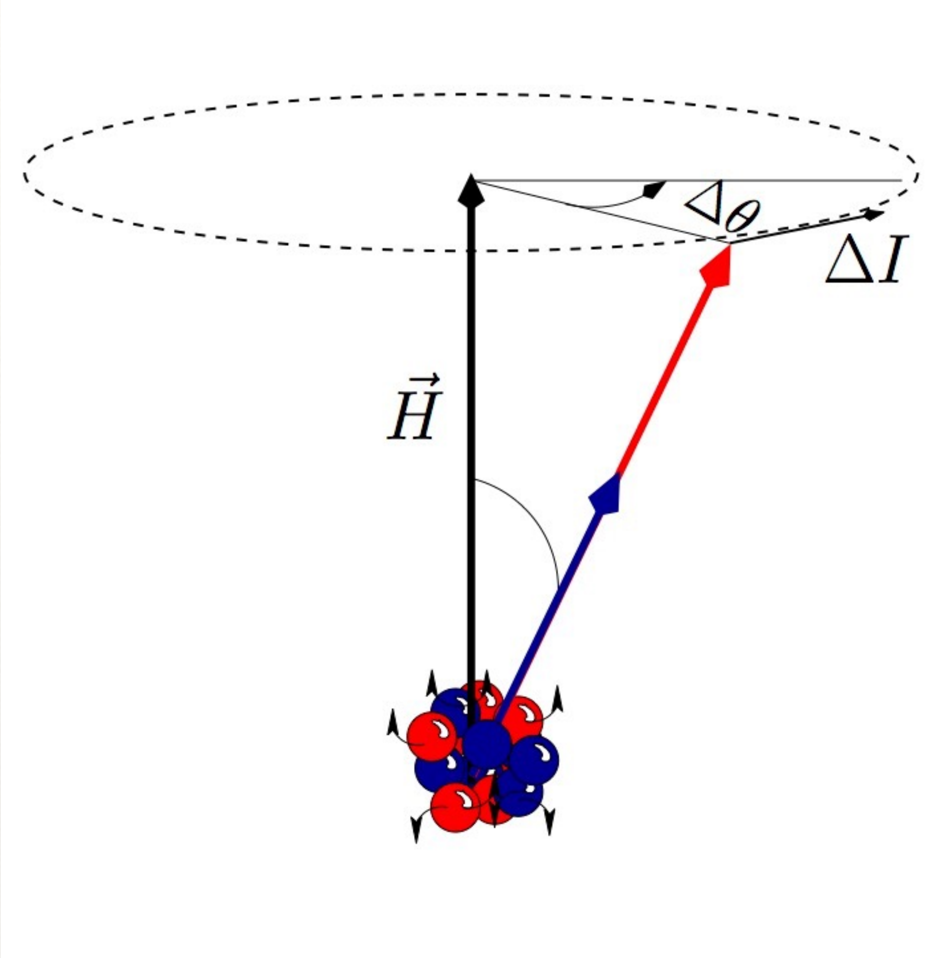
How do we measure a nuclear magnetic moment?



Magnetic Moments are measured by subjecting the excited nucleus to an external magnetic field and observing the Larmor precession of the nuclear spin.

$$\Delta\theta = -\frac{\mu_N}{\hbar} g|\vec{H}|\Delta t$$

How do we measure a nuclear magnetic moment?



Magnetic Moments are measured by subjecting the excited nucleus to an external magnetic field and observing the Larmor precession of the nuclear spin.

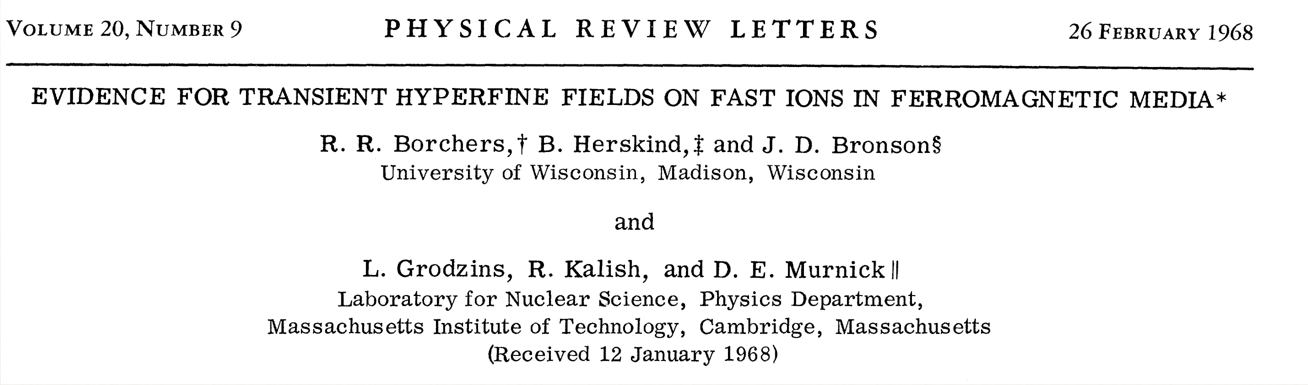
$$\sim\text{mrad} \longleftarrow \Delta\theta = -\overset{\overset{\sim 10^7\ \mathrm{s/T}}{\uparrow}}{\frac{\mu_N}{\hbar}}\, \underset{\underset{\sim 0.5}{\downarrow}}{g}\, |\vec{H}| \Delta t \longrightarrow \sim\text{ps}$$

$$\boxed{|\vec{H}| \sim 10^3\ Tesla!}$$

Earth magnetic field ~ 3.6 x 10^{-5} Tesla.
LHC superconducting magnet is ~ 8 Tesla.
J-PARC ~ 2.5 Tesla (Tuesday by Megumi Naruki)
KLOE array ~0.52 Tesla (Today by Elena Perez del Rio)

How do we obtain a magnetic field of 10^3 Tesla?

The 4th day (1967) magnetic Transient Fields were discovered (by accident).



VOLUME 20, NUMBER 9 PHYSICAL REVIEW LETTERS 26 FEBRUARY 1968

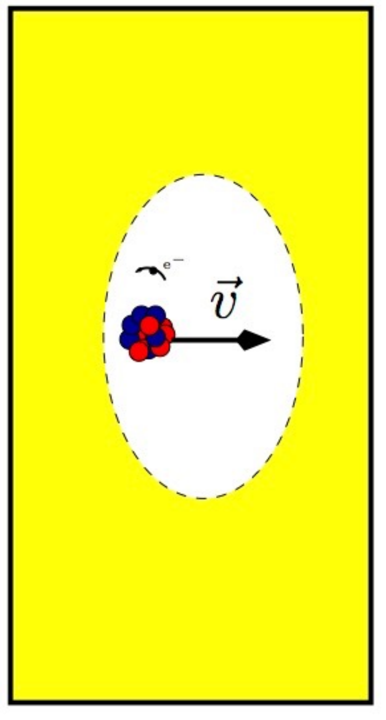
EVIDENCE FOR TRANSIENT HYPERFINE FIELDS ON FAST IONS IN FERROMAGNETIC MEDIA*

R. R. Borchers,† B. Herskind,‡ and J. D. Bronson§
University of Wisconsin, Madison, Wisconsin

and

L. Grodzins, R. Kalish, and D. E. Murnick‖
Laboratory for Nuclear Science, Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 12 January 1968)



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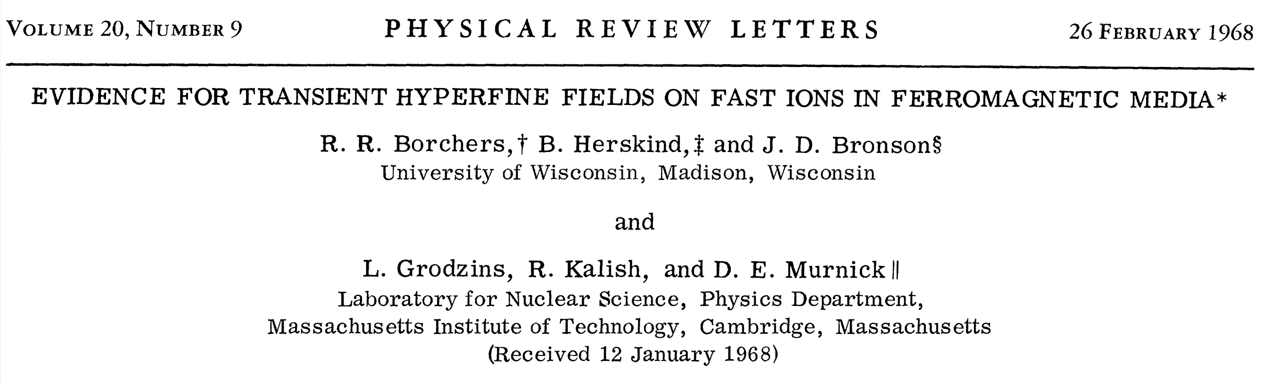

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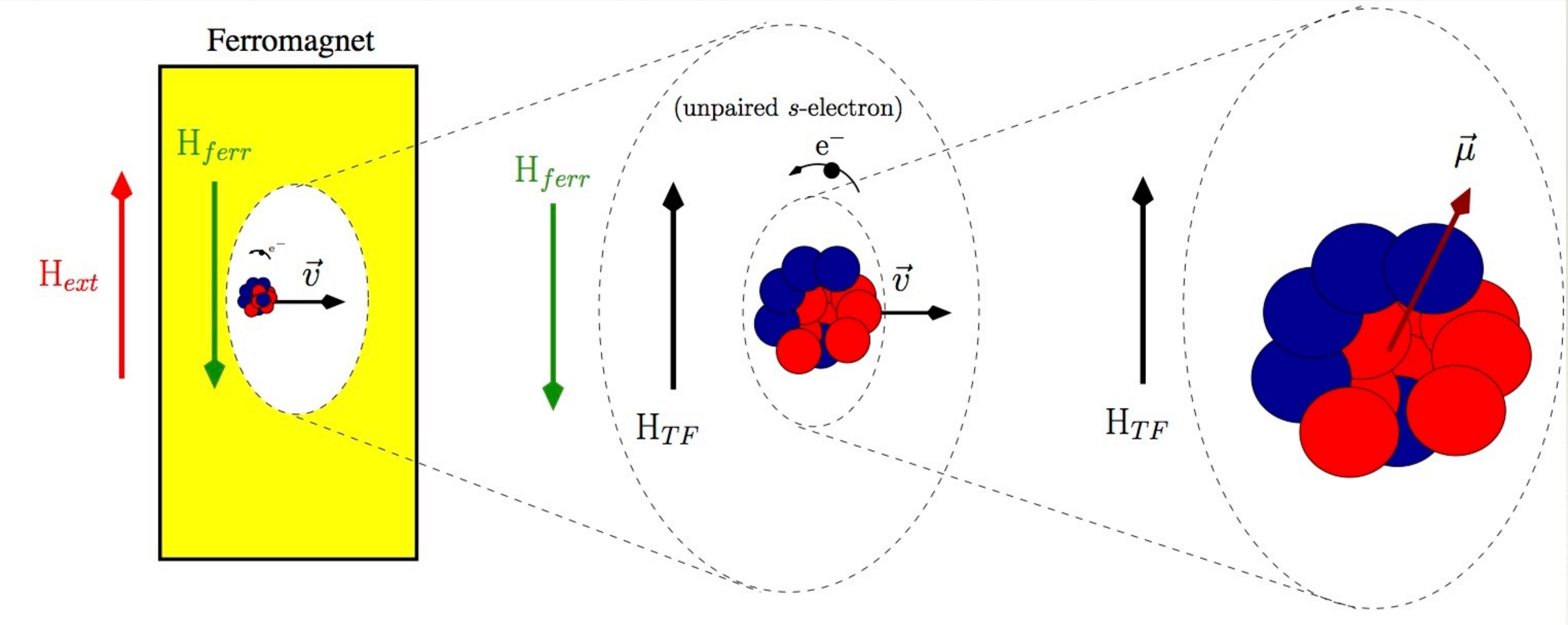
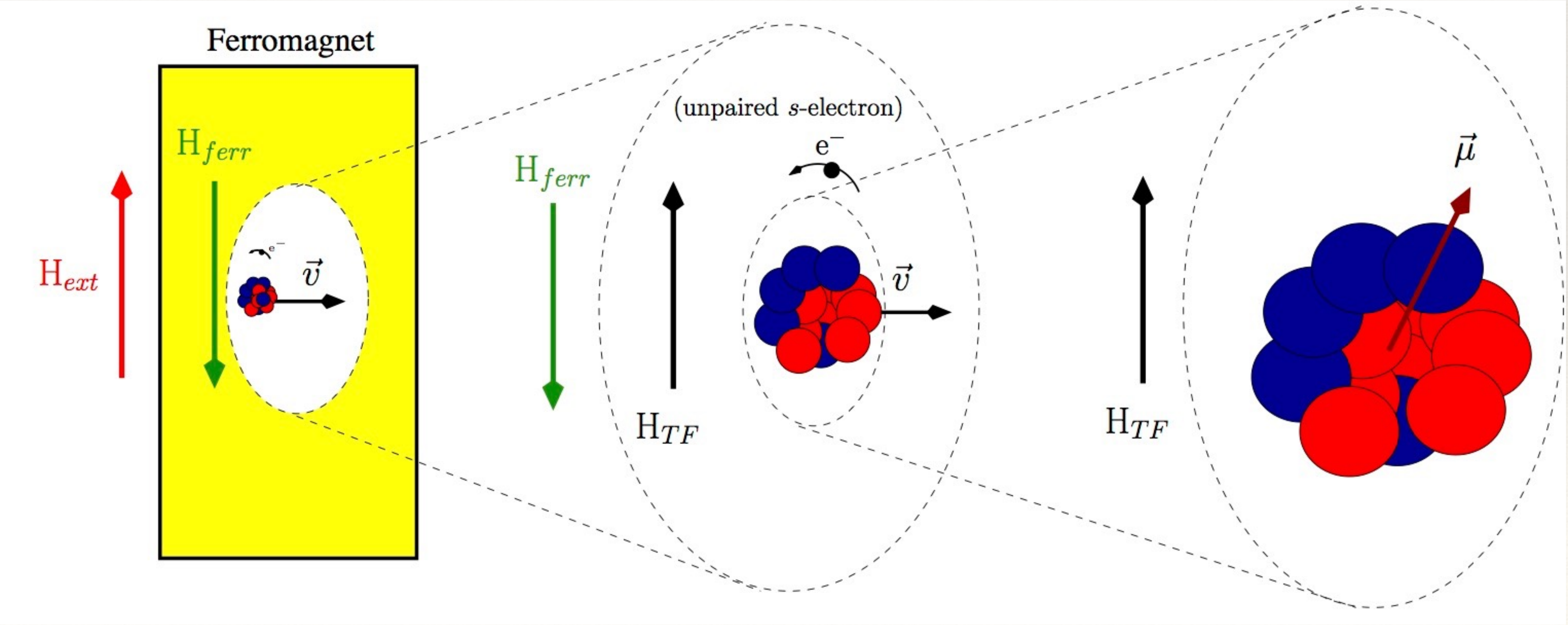


How do we obtain a magnetic field of 10^3 Tesla?

The 4th day (1967) magnetic Transient Fields were discovered (by accident).

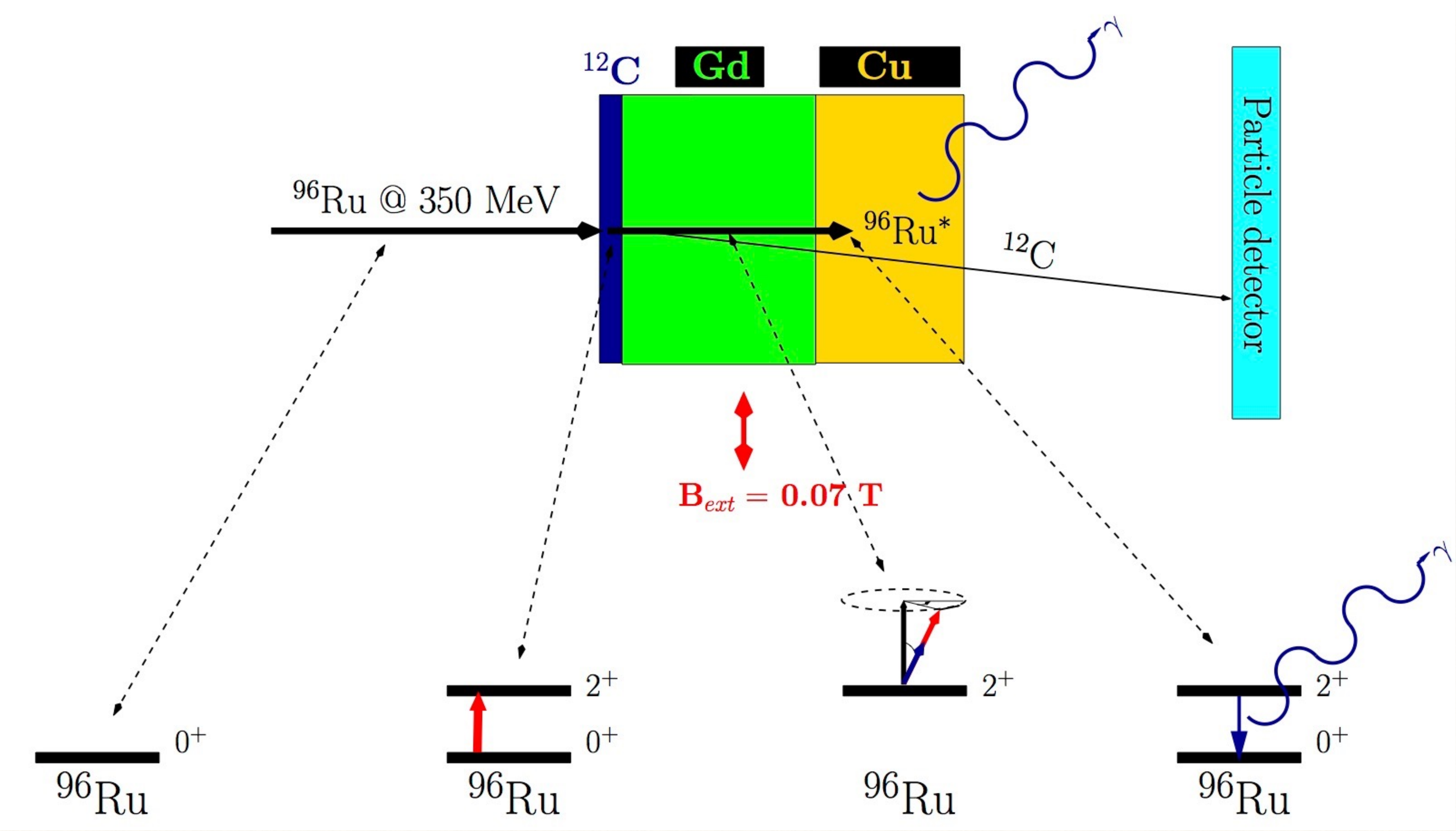
1. The picture of the Magnetic Transient Field is not completed.
2. Parametrization for H_{TF} are utilized.
3. The obtention of H_{TF} from first principles is worth to do.



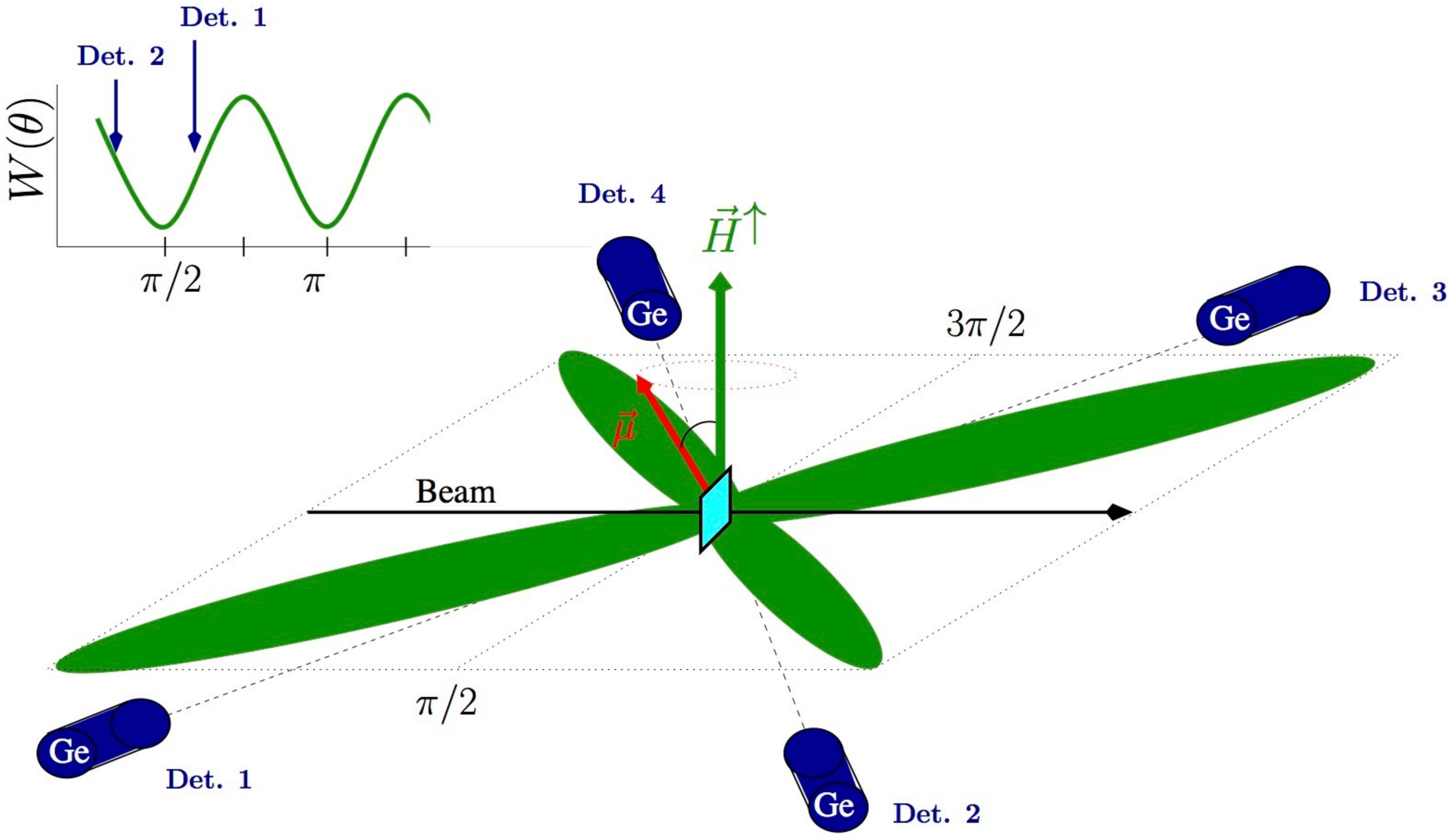
How can we use this in a nuclear reaction?

Coulomb excitation reactions provide a nice way to obtain aligned states.

$^{12}C(^{96}Ru,^{12}C)^{96}Ru^*$



Measurement using a quadrupole 2^+ to 0^+ transition



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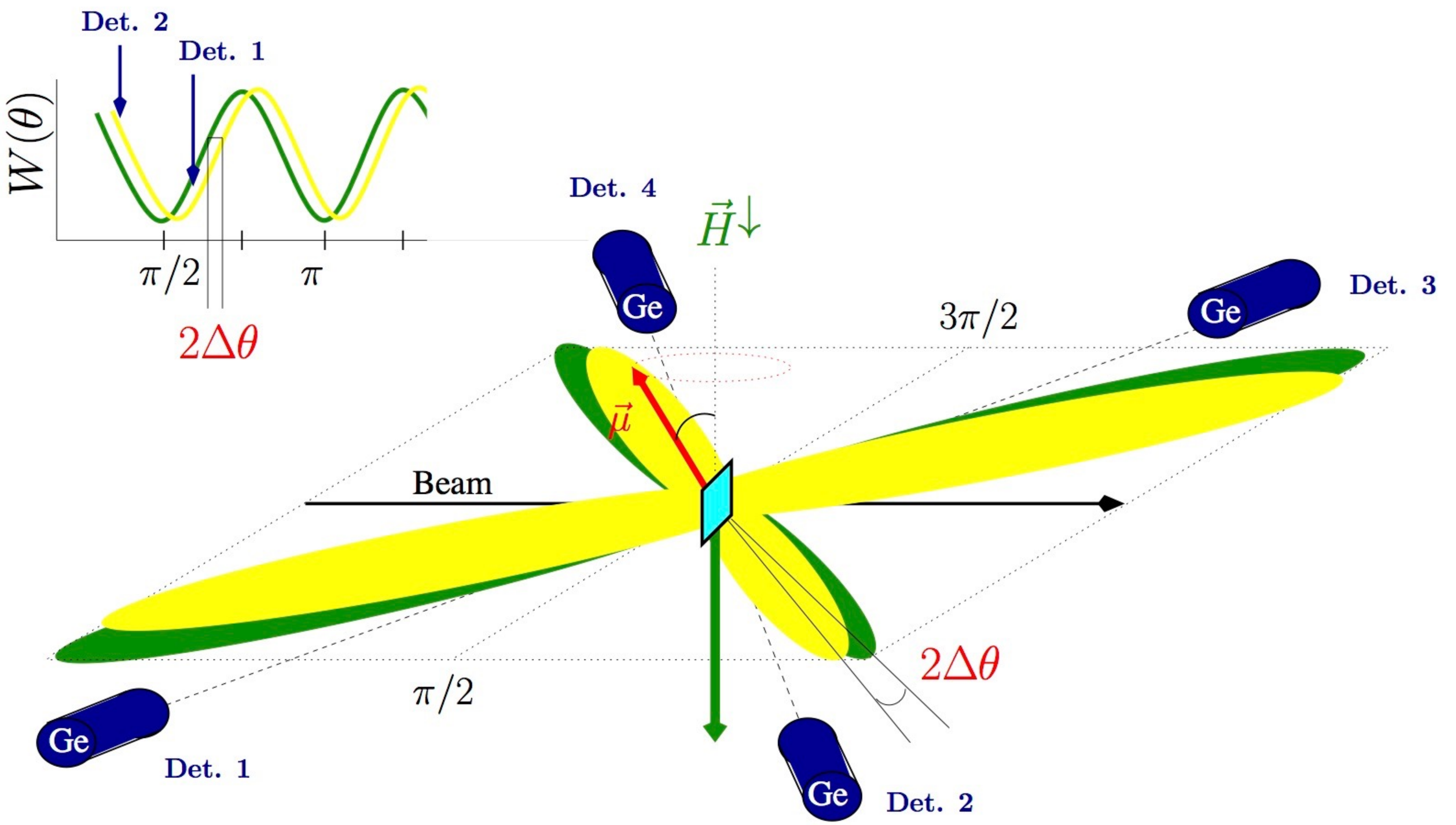

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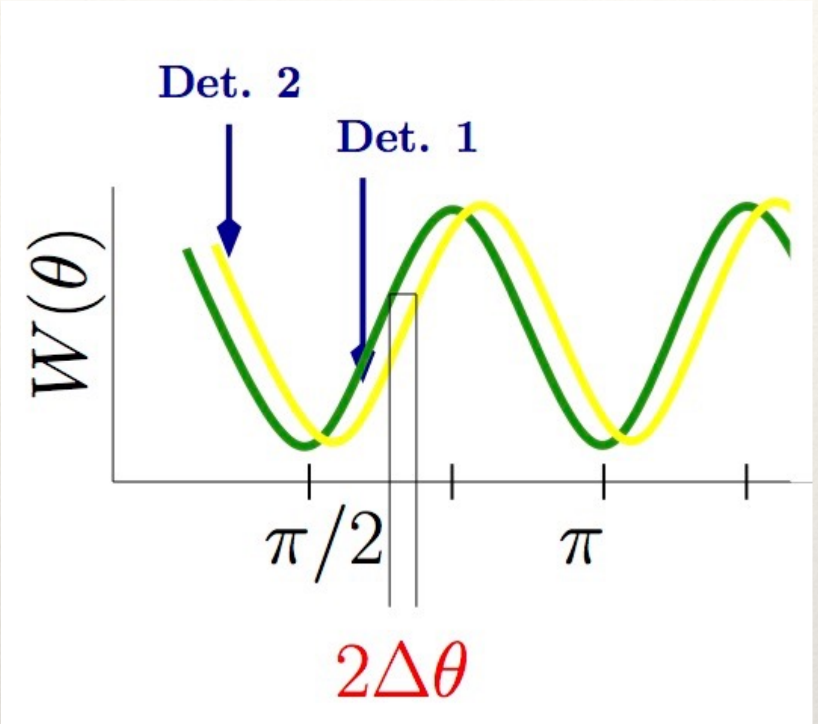


Difference between peak counting ratios

$$\epsilon = \frac{N^{\uparrow}_{\gamma 1} - N^{\downarrow}_{\gamma 1}}{N^{\uparrow}_{\gamma 1} + N^{\downarrow}_{\gamma 1}}$$

$$\Delta\theta = \frac{\epsilon}{S(\theta)}$$

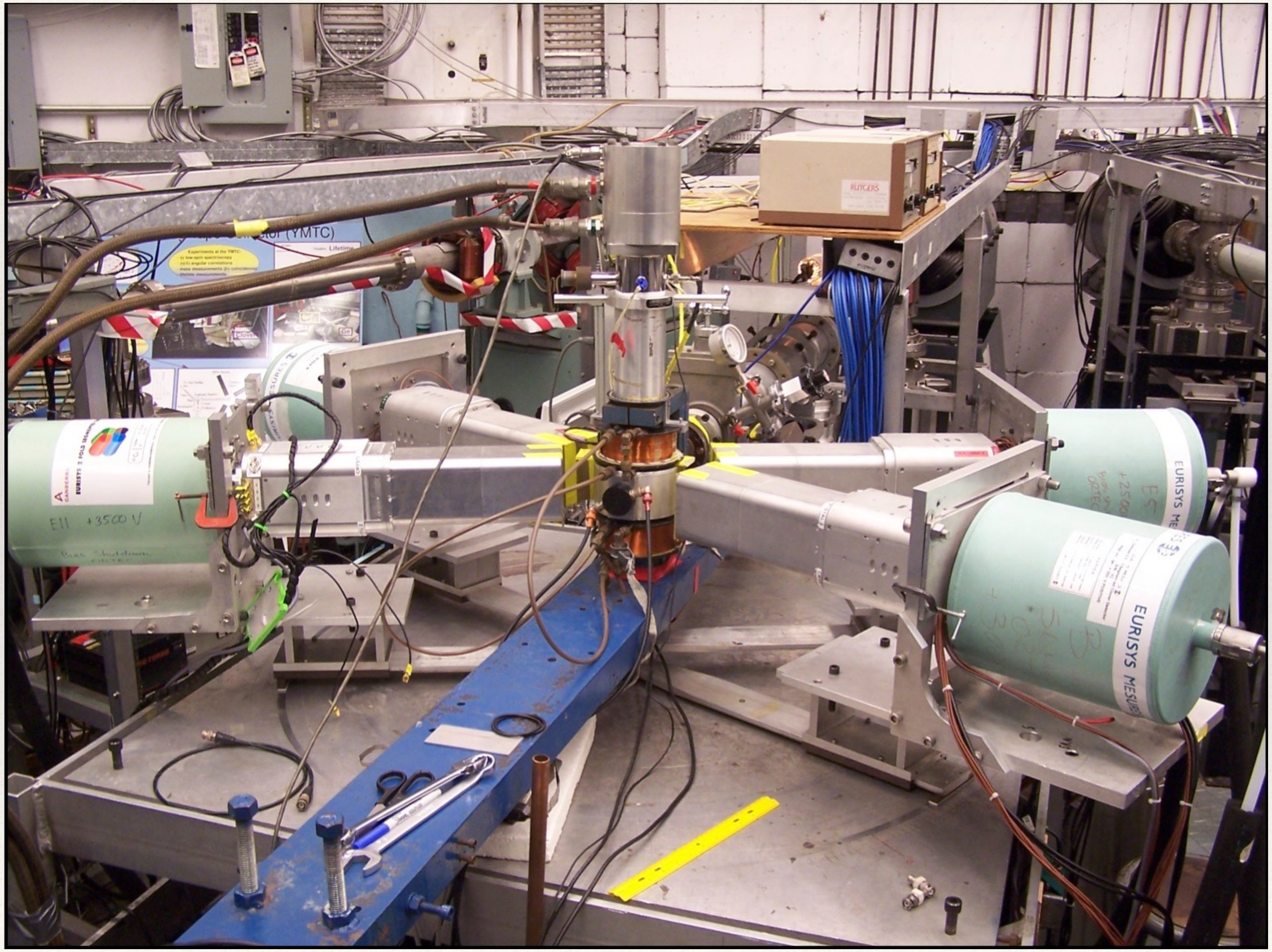
Slope at angle θ

$$\boxed{g = \frac{\Delta\theta}{\frac{\mu}{\hbar}\int_{t_{in}}^{t_{out}} H_{TF}(v(t), Z) \cdot \exp(-t/\tau) \cdot dt}}$$

This is the so called Transient Field (TF) method to measure nuclear magnetic moments.

The Experimental Setup

In the 5th day measurements were performed.



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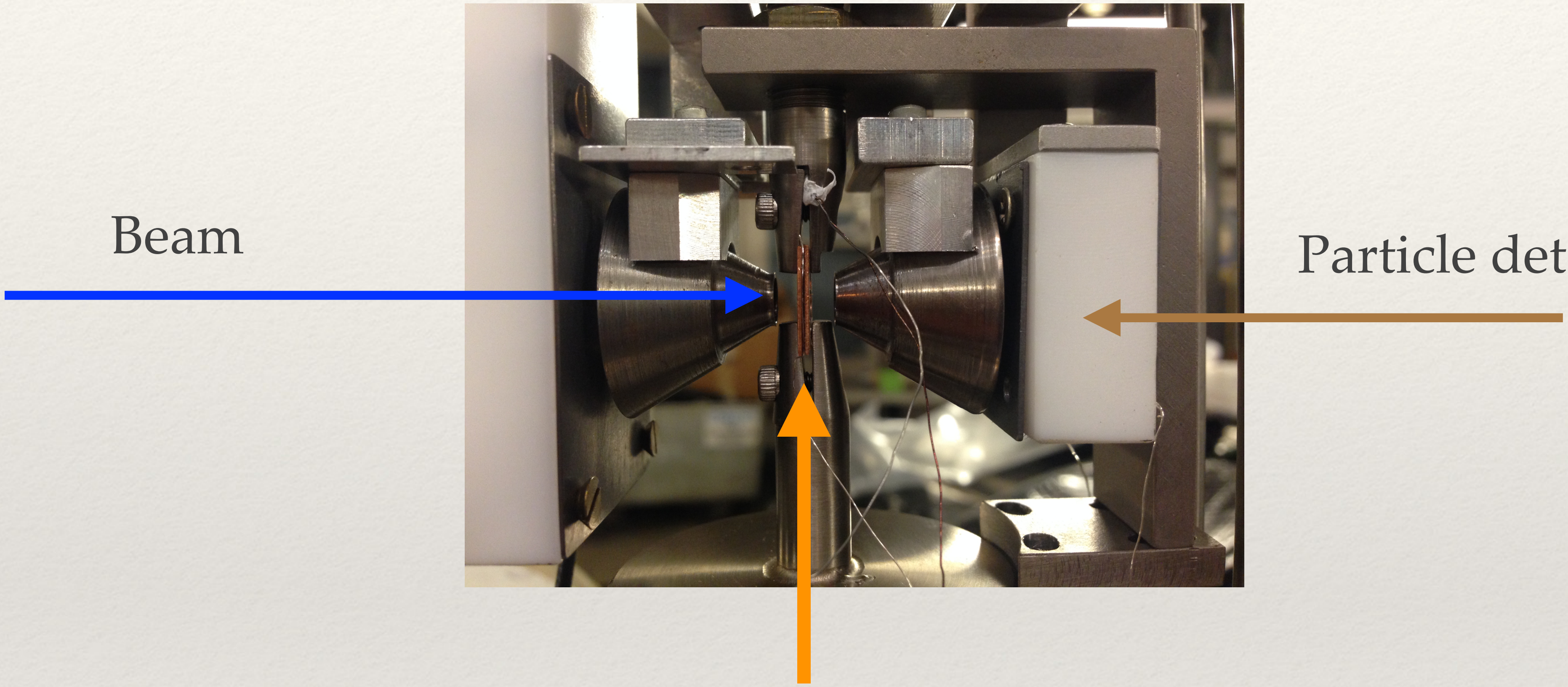


Beam

Particle detector

Target

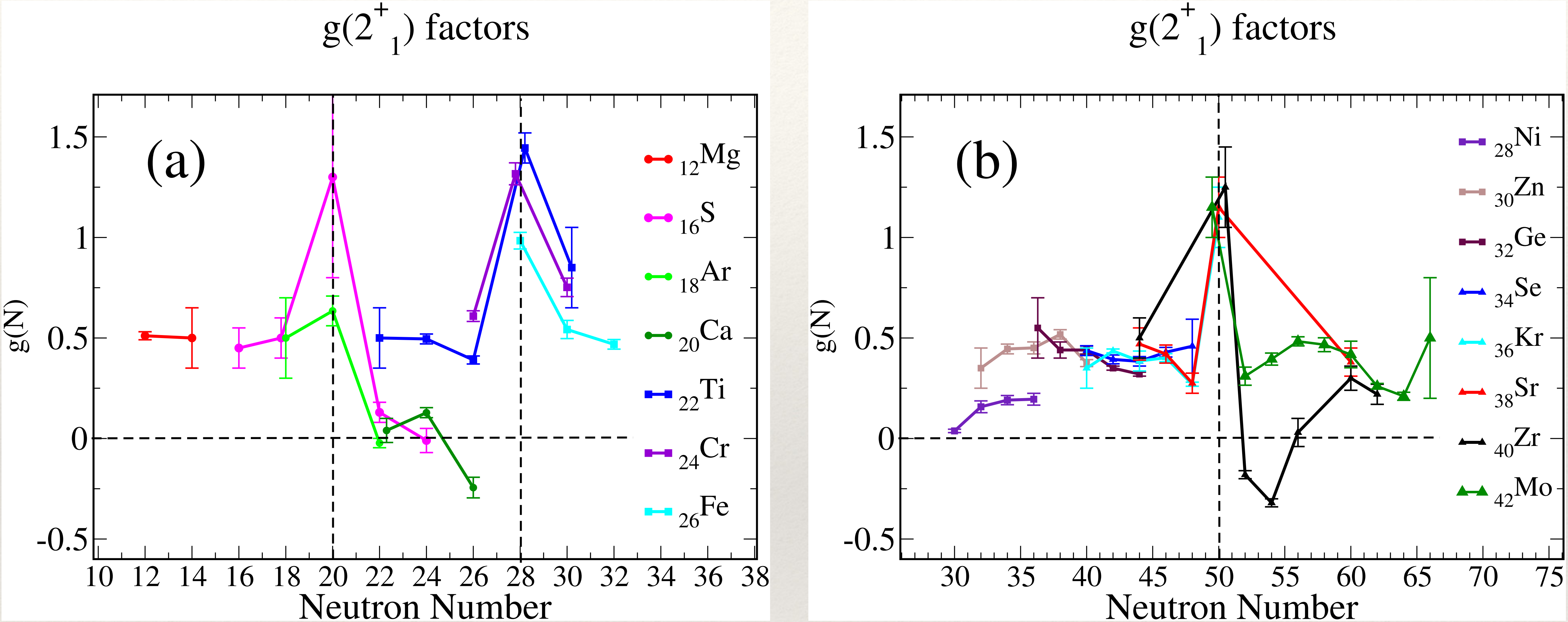
Before

After

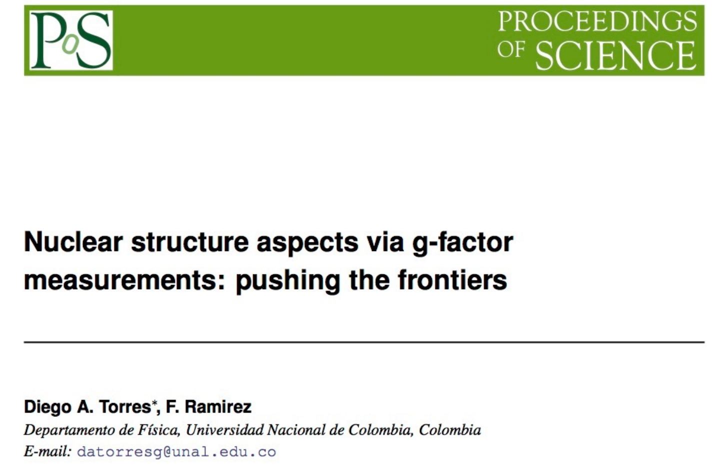
Results

In the 6th day data analysis started!

The regions around N=20, 28 and 50



- At magic numbers g factors are high.
- Negative values are originated by a pure shell model picture, ^{40}Ar, or by core excitations ^{42}Ca.
- Negative g factor values for ^{92,94}Zr are produced by neutron excitations in the $d_{5/2}$ shell.



Nuclear structure aspects via g-factor measurements: pushing the frontiers

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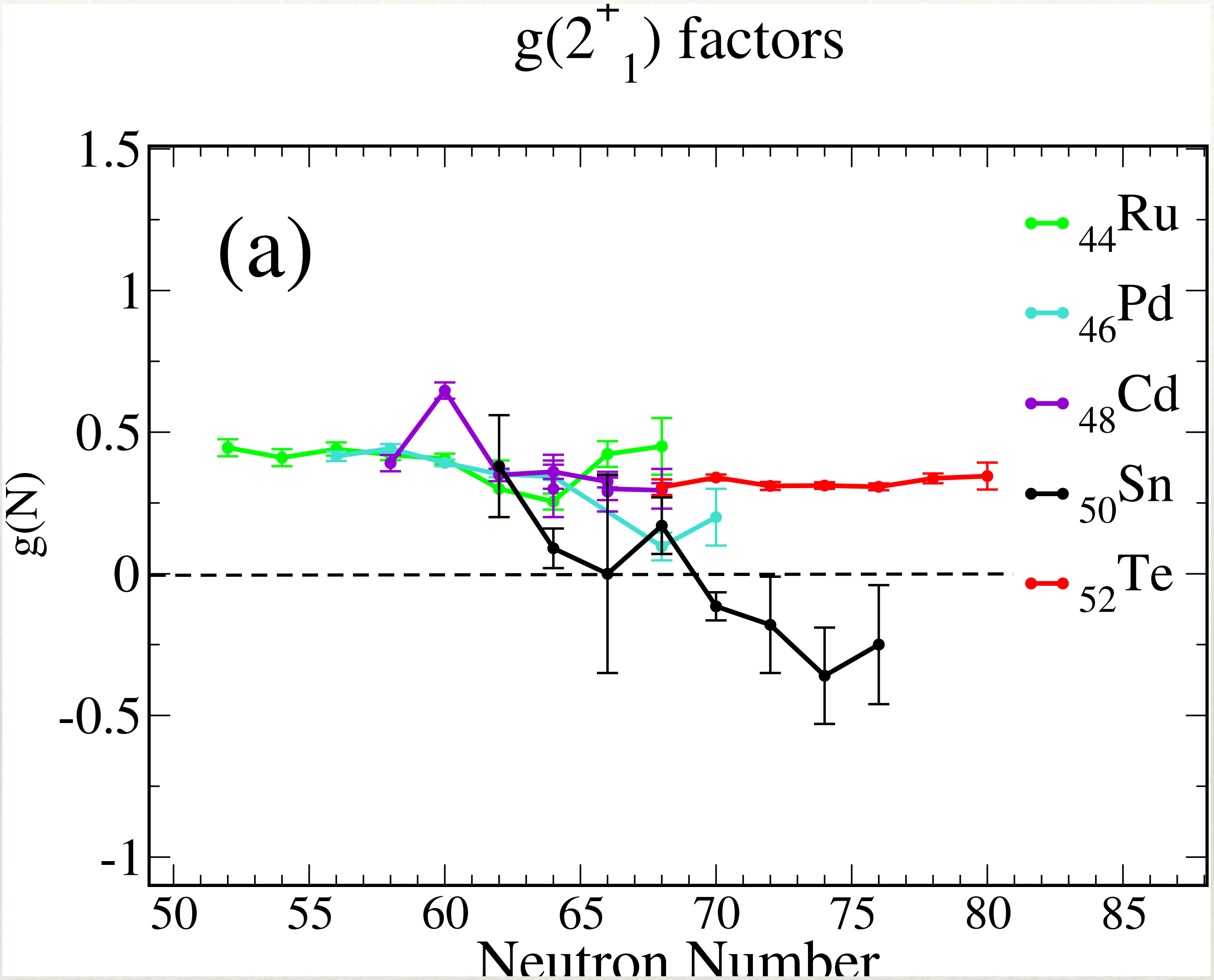
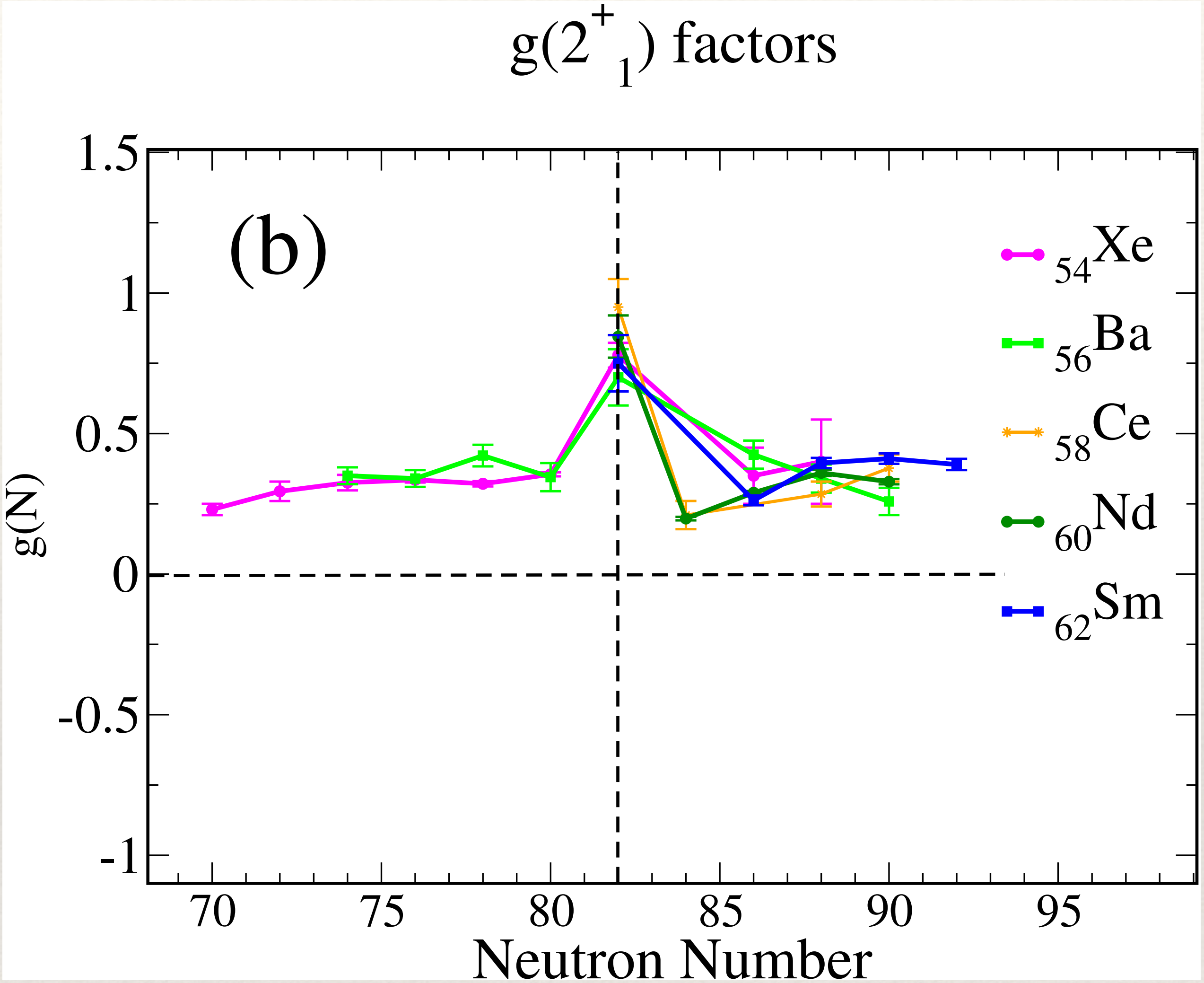
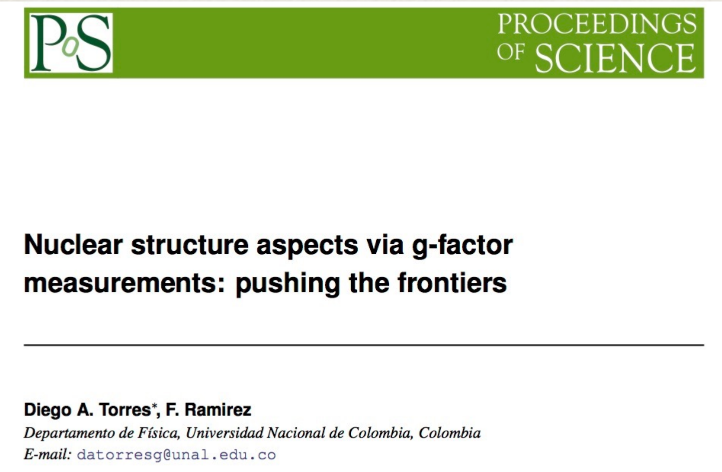
E-mail: datorresg@unal.edu.co

The regions around 50<N<90





For negative g factor values of Sn isotopes, the filling of the $h_{11/2}$ orbital plays a relevant role.



PoS PROCEEDINGS OF SCIENCE

Nuclear structure aspects via g-factor measurements: pushing the frontiers

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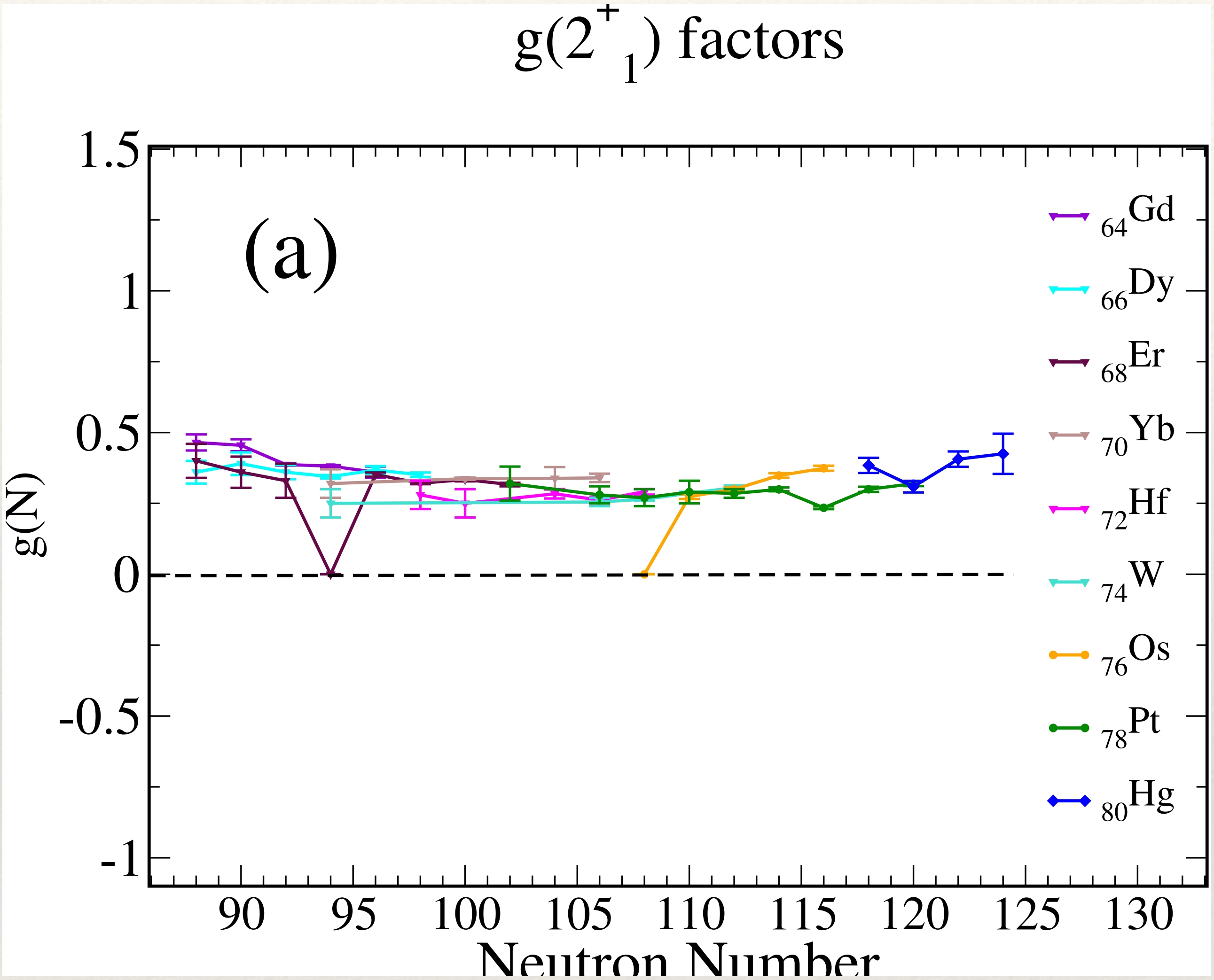
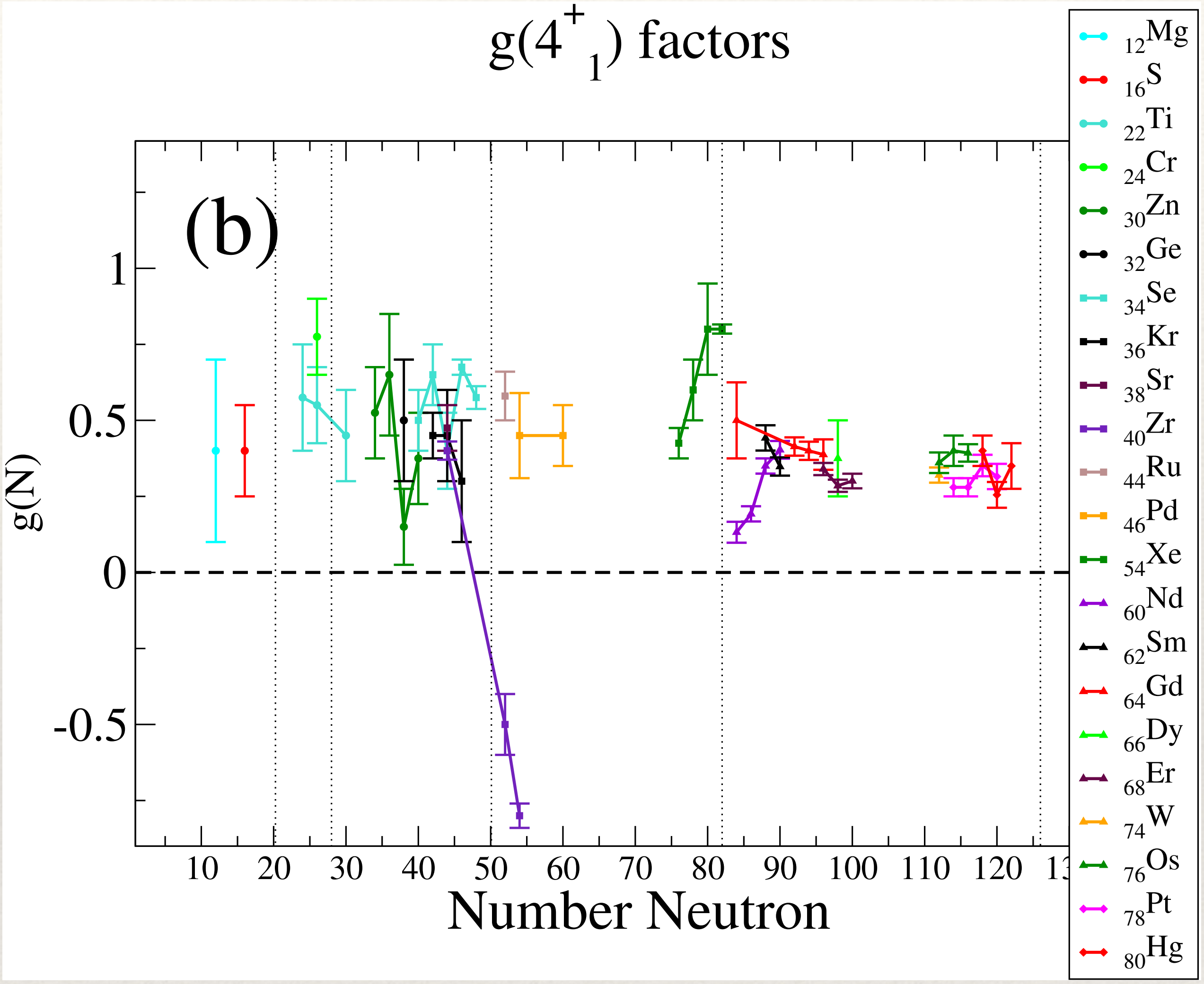
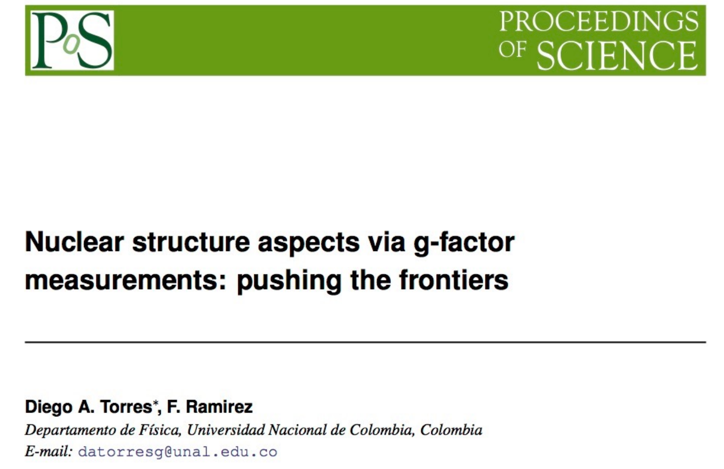
The first frontier: $g(I>2^+)$







PROCEEDINGS OF SCIENCE

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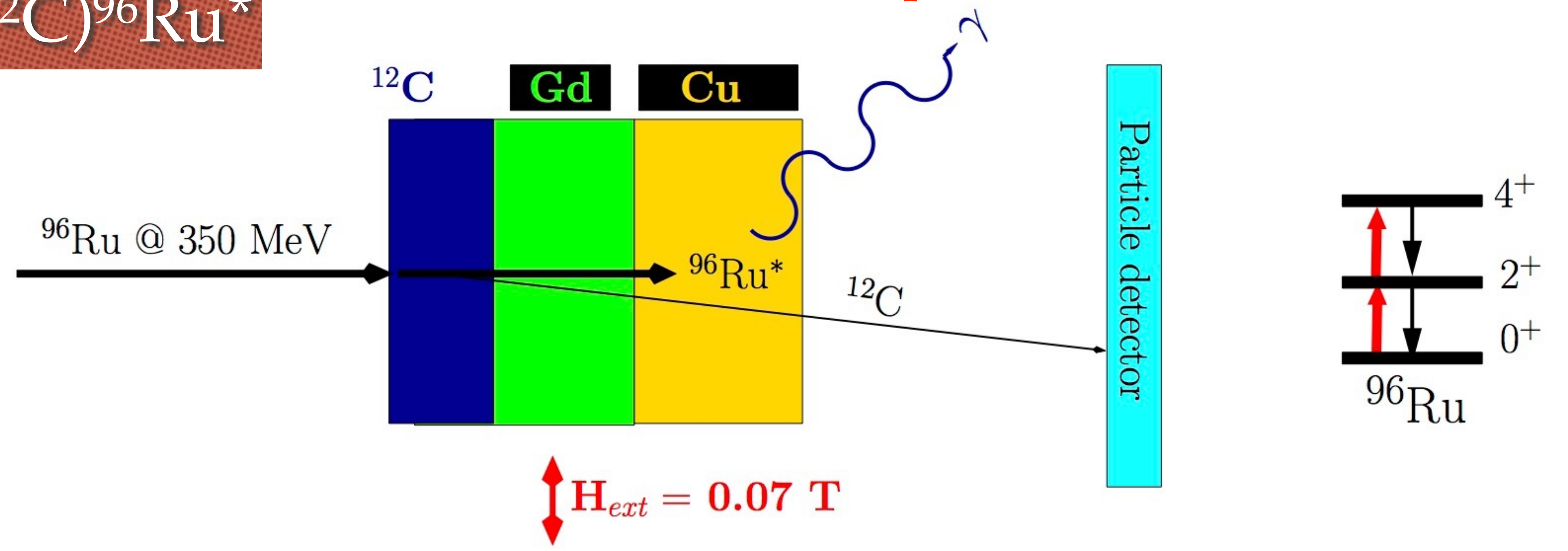
Nuclear structure aspects via g-factor measurements: pushing the frontiers.
PoS Proceedings of Science, 10th Latin American Symposium on Nuclear Physics and Applications (2013)
http://pos.sissa.it/archive/conferences/194/021/X\%20LASNPA_021.pdf

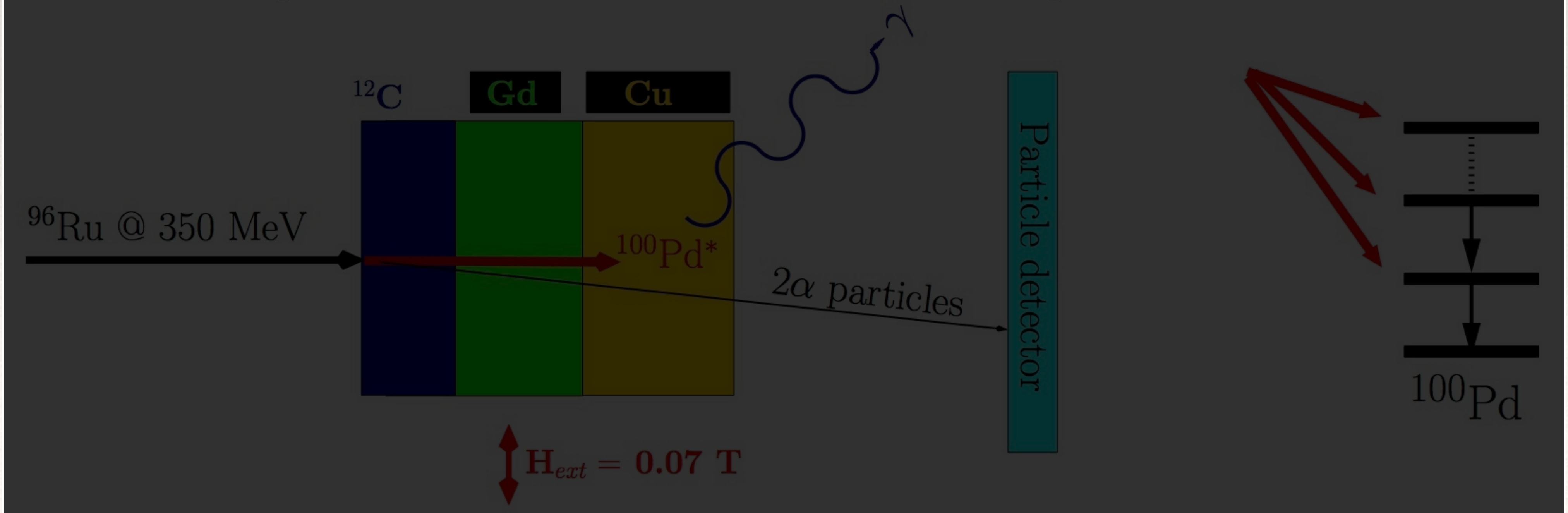
The first frontier: g(I>2^+)

$^{12}C(^{96}Ru,^{12}C)^{96}Ru^*$

Coulomb Excitation Experiment



Alpha-transfer Excitation Reaction Experiment



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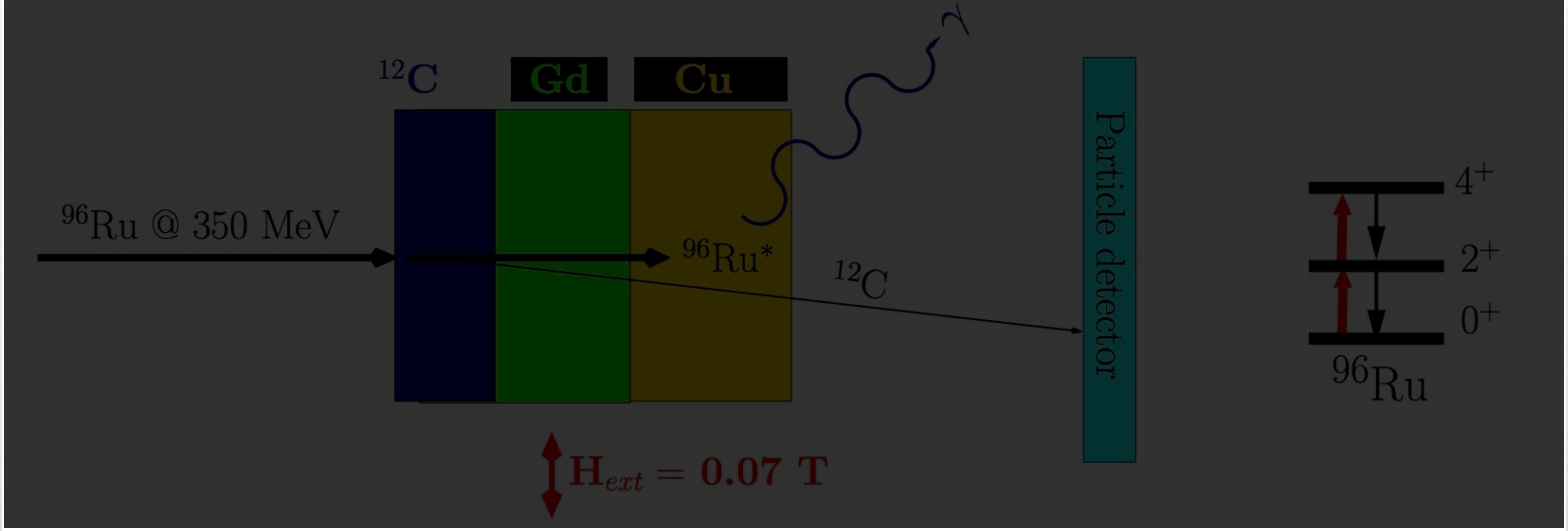

Alpha-transfer Excitation Reaction Experiment

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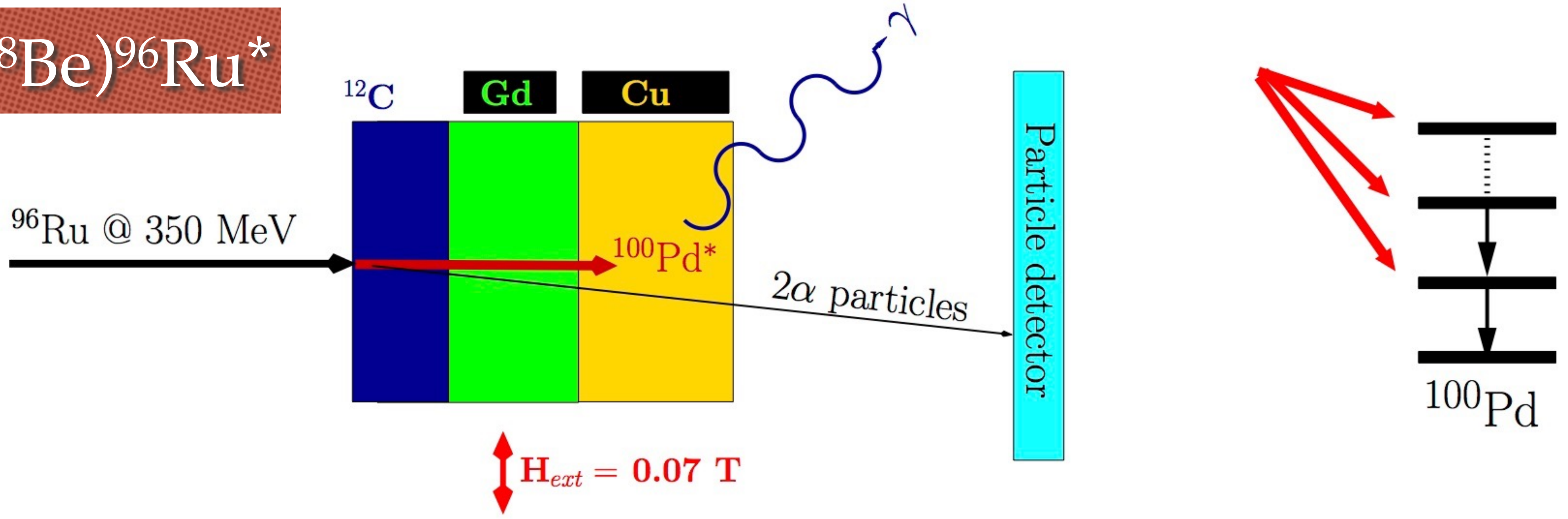
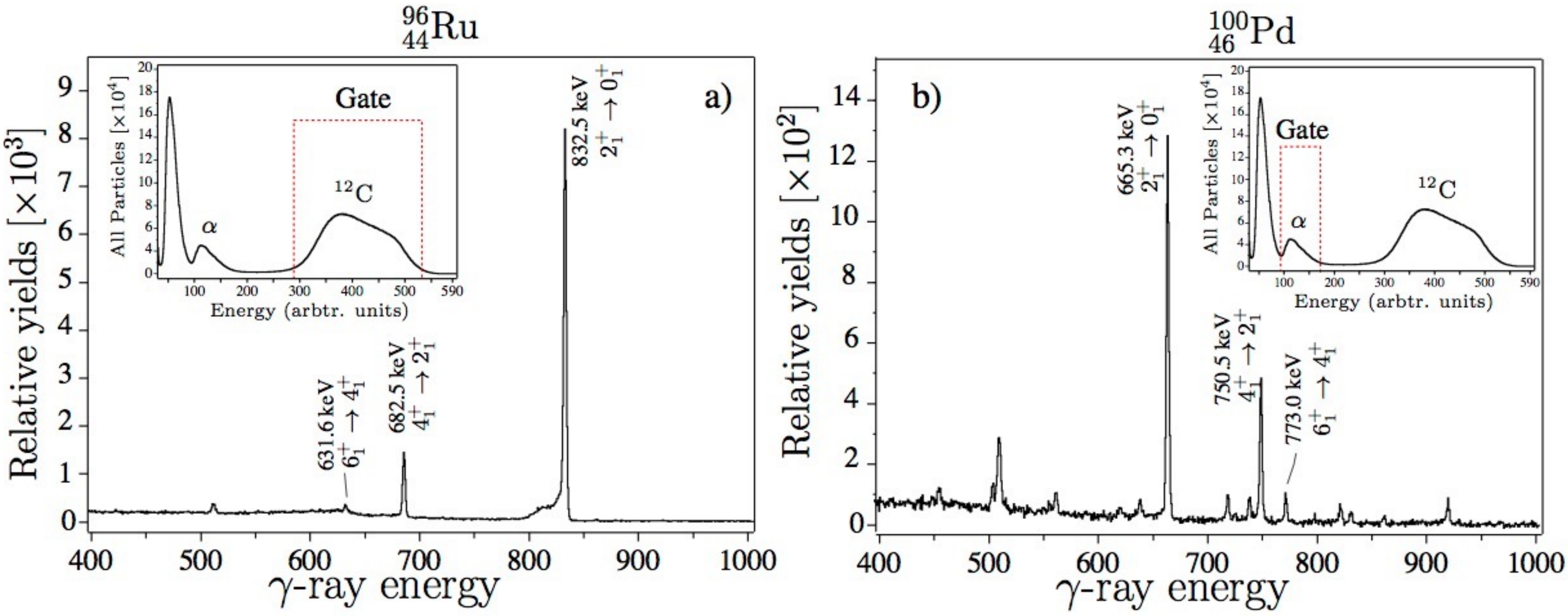


Coulex Vs. Alpha Transfer

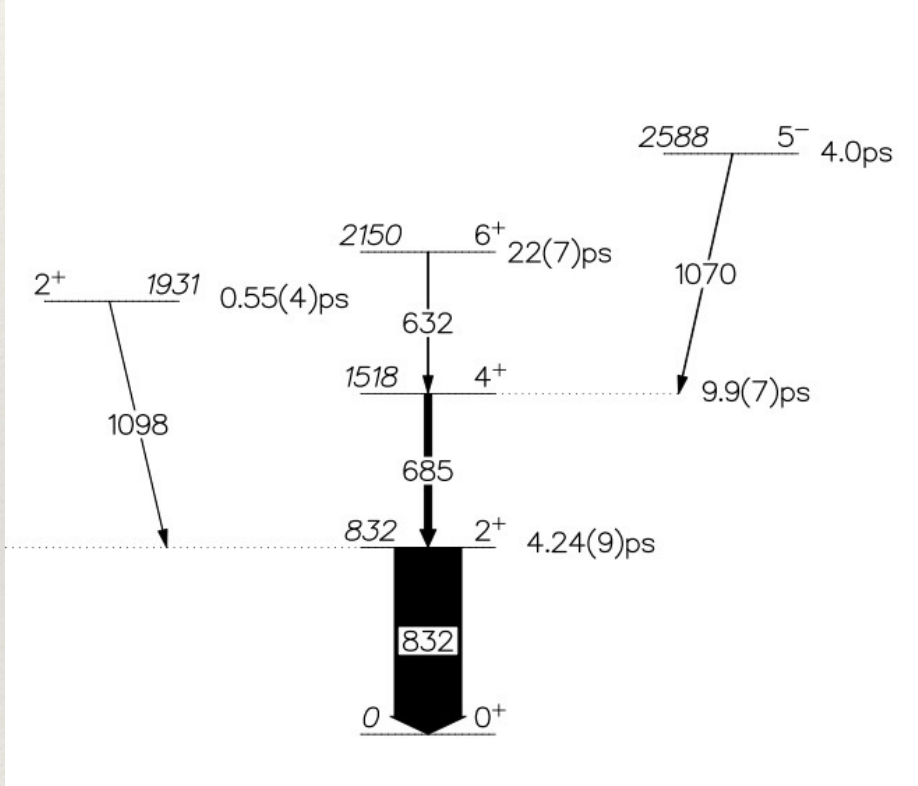
Coulomb Excitation **Alpha Transfer Reaction**



Coulex Vs. Alpha Transfer

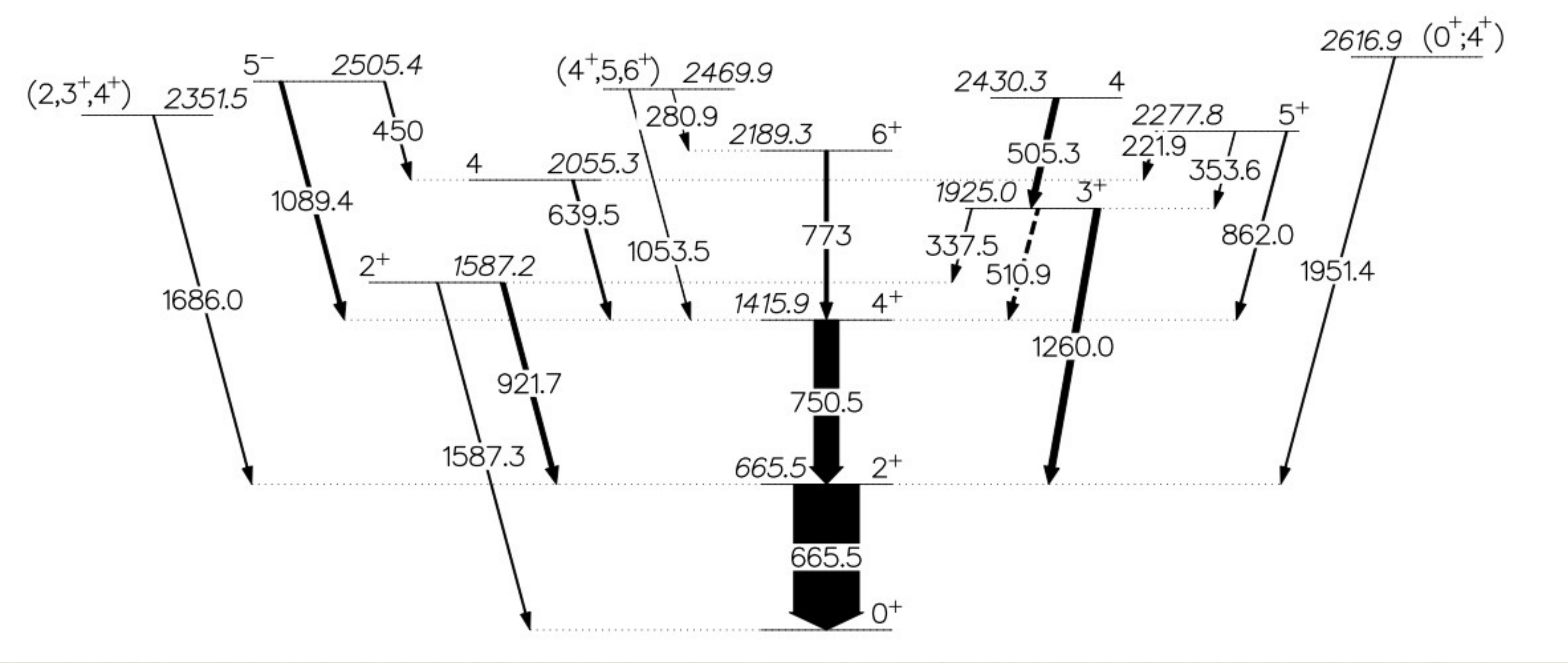
Coulomb Excitation

^{96}Ru



Alpha Transfer Reaction

^{100}Pd



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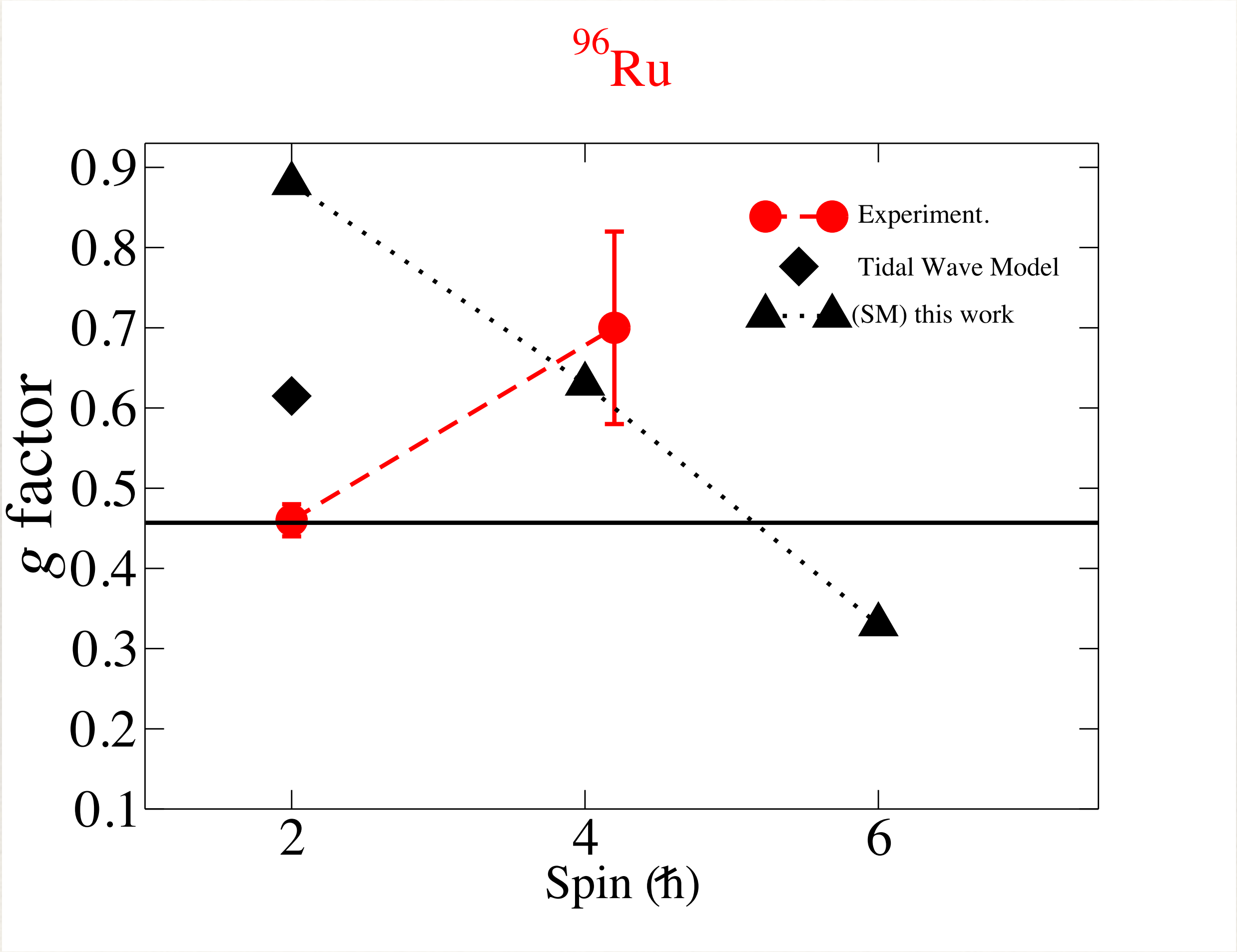
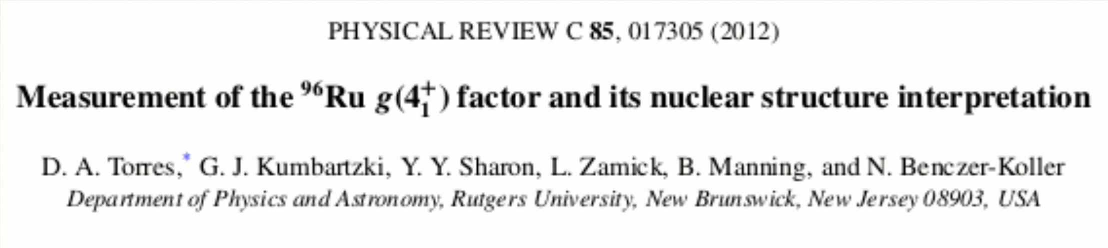




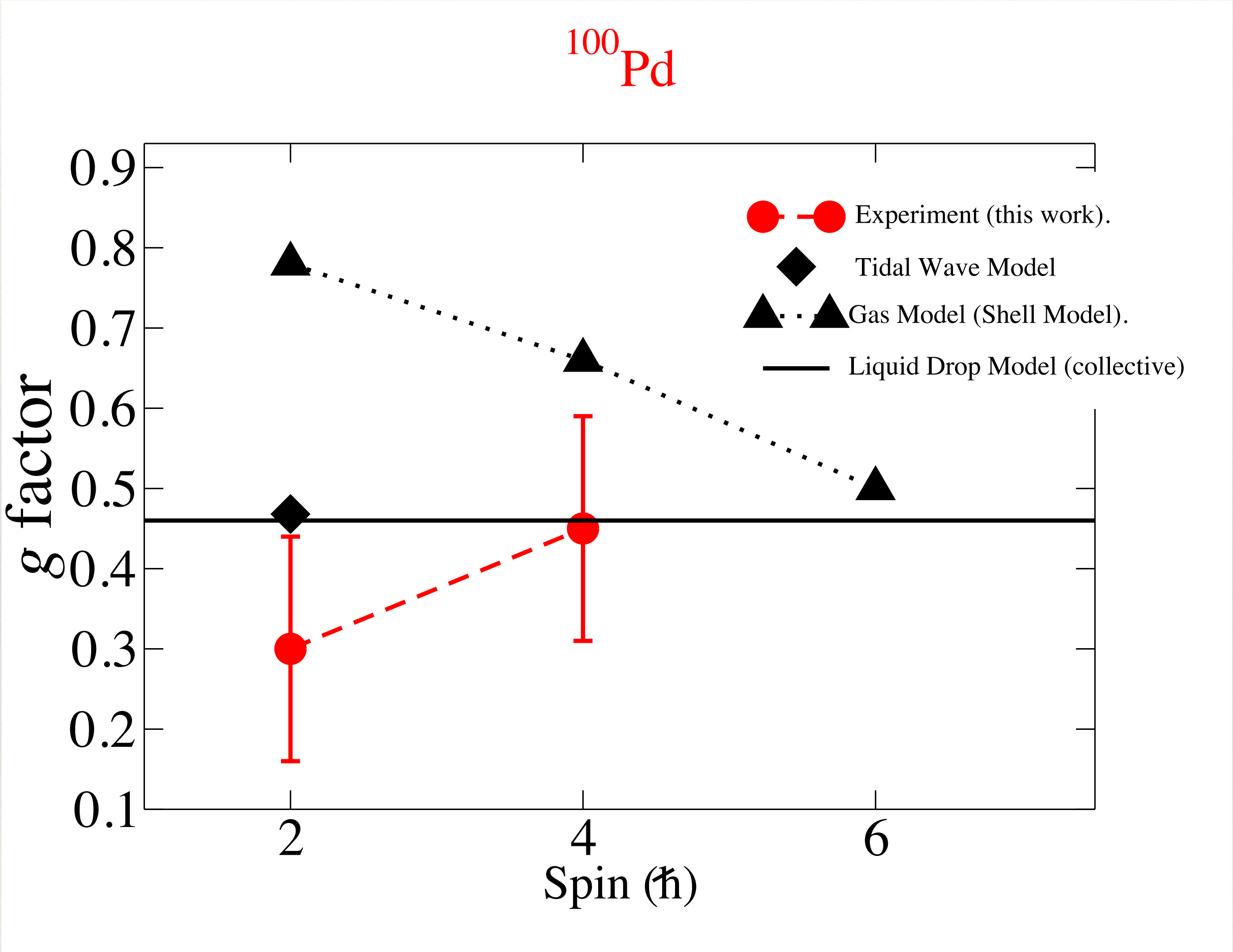
PHYSICAL REVIEW C **85**, 017305 (2012)

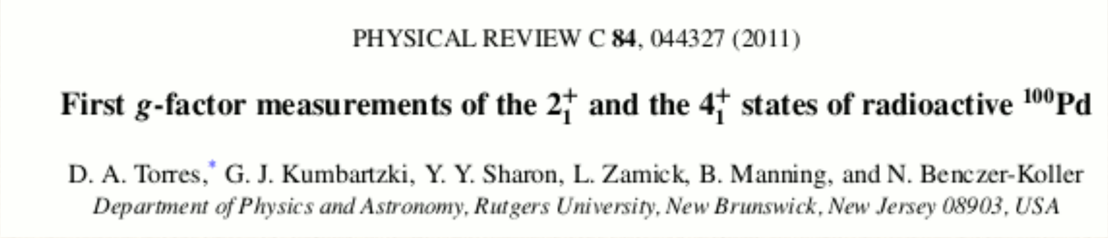
Measurement of the ^{96}Ru $g(4_1^+)$ factor and its nuclear structure interpretation

D. A. Torres,[*] G. J. Kumbartzki, Y. Y. Sharon, L. Zamick, B. Manning, and N. Benczer-Koller
Department of Physics and Astronomy, Rutgers University, New Jersey 08903, USA

Alpha Transfer Reaction

^{100}Pd





PHYSICAL REVIEW C **84**, 044327 (2011)

First g-factor measurements of the 2_1^+ and the 4_1^+ states of radioactive ^{100}Pd

D. A. Torres,[*] G. J. Kumbartzki, Y. Y. Sharon, L. Zamick, B. Manning, and N. Benczer-Koller
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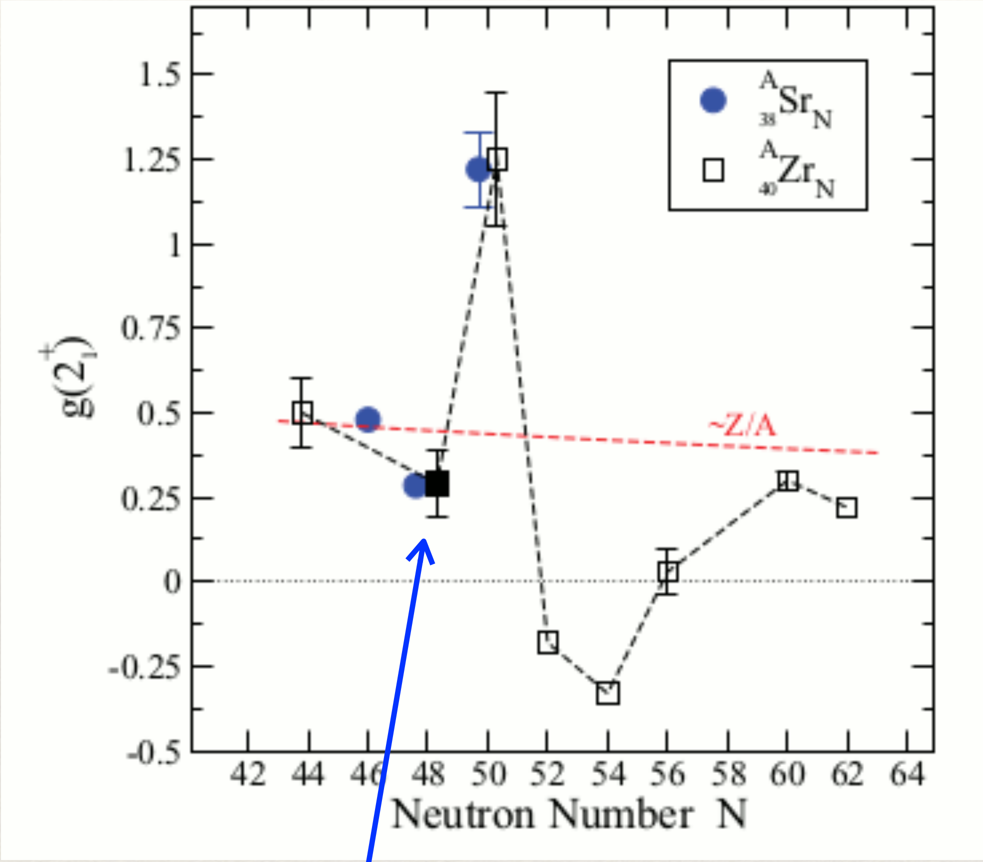
The negative g(4^+) of ^{86}Sr

$$^{86}_{38}\mathrm{Sr} + 2\mathrm{p} = ^{88}_{40}\mathrm{Zr}$$

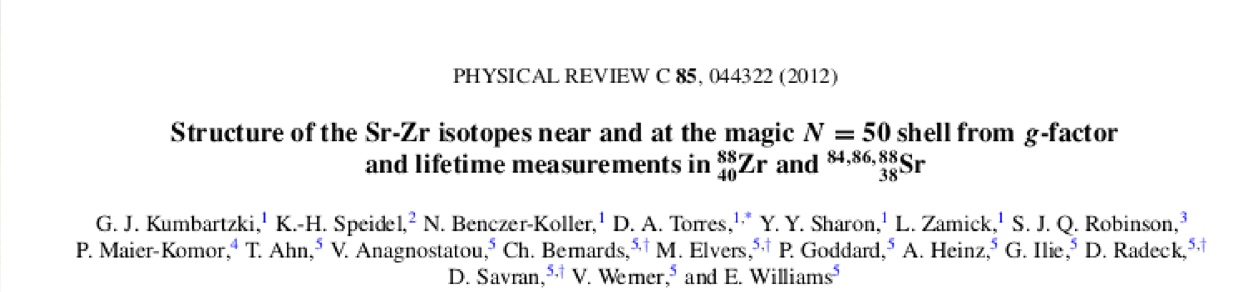
2p in the $p_{1/2}$ shell



		$g(4^+_1)$	
	Exp.	JJ4B	JUN45
^{88}Zr	+0.65(18)	+0.84	+0.49
^{86}Sr	**-0.68(49)**	+0.22	-0.07

$$1p_{3/2}, 0f_{5/2}, 1p_{1/2}, 0g_{9/2} \text{ for p and n.}$$

		$g(2^+_1)$	
	Exp.	JJ4B	JUN45
^{88}Zr	+0.30(11)	+0.77	+0.39
^{86}Sr	+0.29(1)	+0.38	+0.29



PHYSICAL REVIEW C **85**, 044322 (2012)

Structure of the Sr-Zr isotopes near and at the magic $N = 50$ shell from g-factor and lifetime measurements in $^{88}_{40}$Zr and $^{84,86,88}_{38}$Sr

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The negative g(4^+) of ^{86}Sr

$$^{86}_{38}\mathrm{Sr} + 2\mathrm{p} = ^{88}_{40}\mathrm{Zr}$$

2p in the $p_{1/2}$ shell

Some possible configurations to obtain a negative *g*-factor value

$$g(p_{1/2})_\pi = -0.529$$

$$g(g_{9/2})_\nu = -0.425$$

$$g(p_{3/2})_\nu = -1.275$$

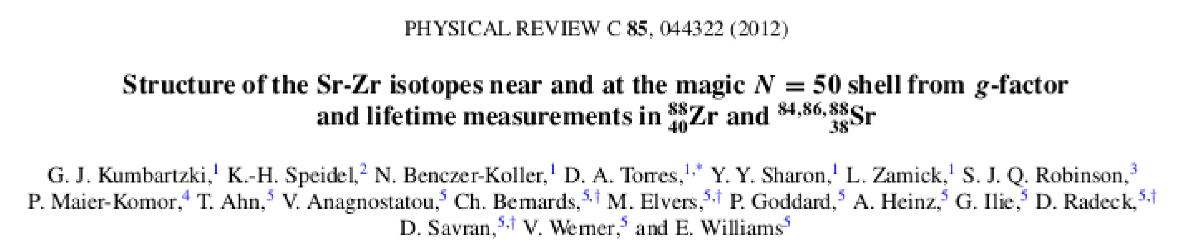
$$g(f_{5/2})_\nu = +0.547$$

……

$$g(g_{9/2})^2_\nu \text{ or } g(p_{3/2}, f_{5/2})_\nu$$

	$g(4_1^+)$		
	Exp.	JJ4B	JUN45
^{88}Zr	+0.65(18)	+0.84	+0.49
^{86}Sr	**-0.68(49)**	+0.22	-0.07

$1p_{3/2}, 0f_{5/2}, 1p_{1/2}, 0g_{9/2}$ for p and n.



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The semi-magic core ^{88}Sr Vs. ^{90}Zr

^{88}Sr and ^{90}Zr have been utilized as closed shell cores for large scale shell model calculations in the 28 < Z < 50 region.

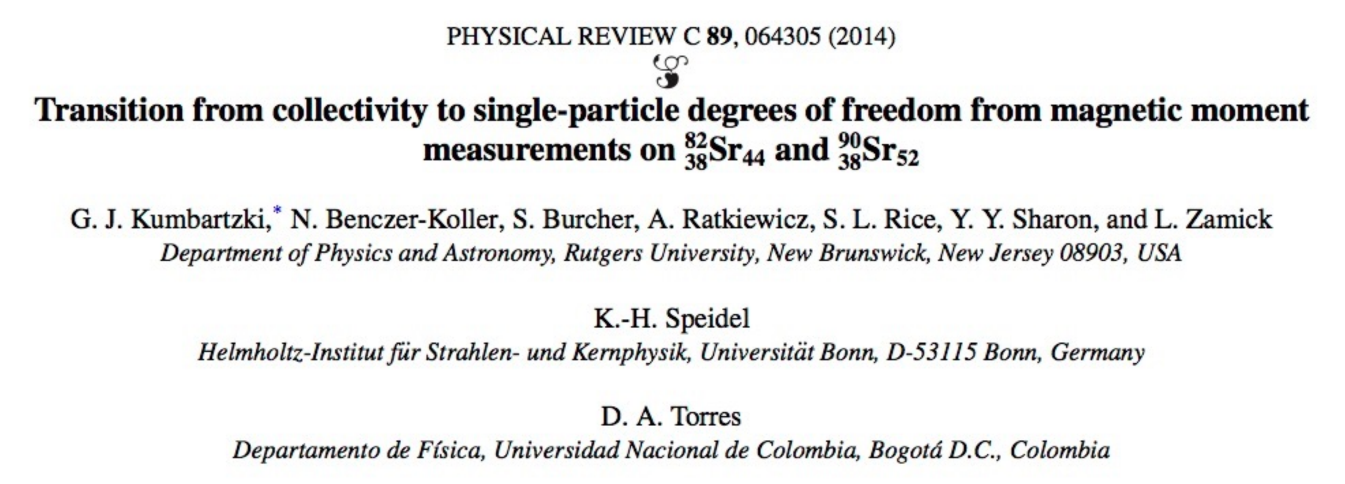
$^{88}_{38}\mathrm{Sr}_{50}$

What is better as a closed core for shell model calculations?

$^{88}_{40}\mathrm{Zr}_{50}$

……

$$^{12}\mathrm{C}(^{78,86}\mathrm{Kr},{}^{8}\mathrm{Be})^{82,90}\mathrm{Sr}^{*}$$



PHYSICAL REVIEW C **89**, 064305 (2014)

Transition from collectivity to single-particle degrees of freedom from magnetic moment measurements on $^{82}_{38}\mathrm{Sr}_{44}$ and $^{90}_{38}\mathrm{Sr}_{52}$

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The semi-magic core ^{88}Sr Vs. ^{90}Zr

^{88}Sr and ^{90}Zr have been utilized as closed shell cores for large scale shell model calculations in the $28 < Z < 50$ region.

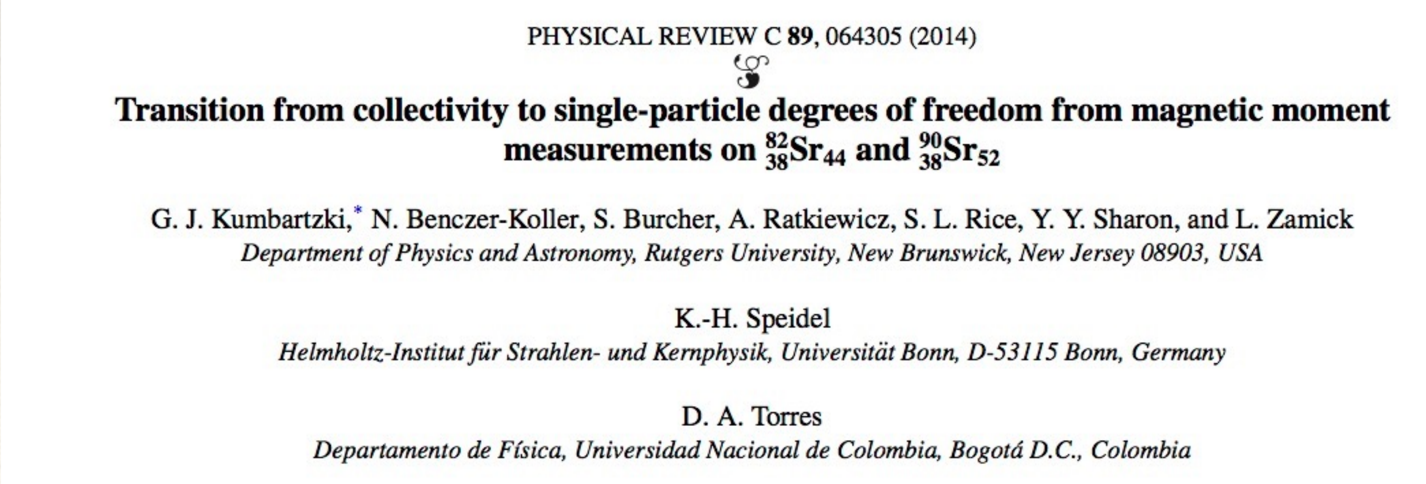
$${}^{88}_{38}\mathrm{Sr}_{50}$$

What is better as a closed core for shell model calculations?

$${}^{88}_{40}\mathrm{Zr}_{50}$$

……

- **For ^{82}Sr both g factors are in agreement with the collective value Z/A expected for nuclei in the middle of a major shell.**
- **The *g* factors in ^{90}Sr are negative but smaller than in the isotone ^{92}Zr.**
- **The results also indicate that ^{88}Sr is a proton-soft core nucleus and perhaps even softer than ^{90}Zr.**



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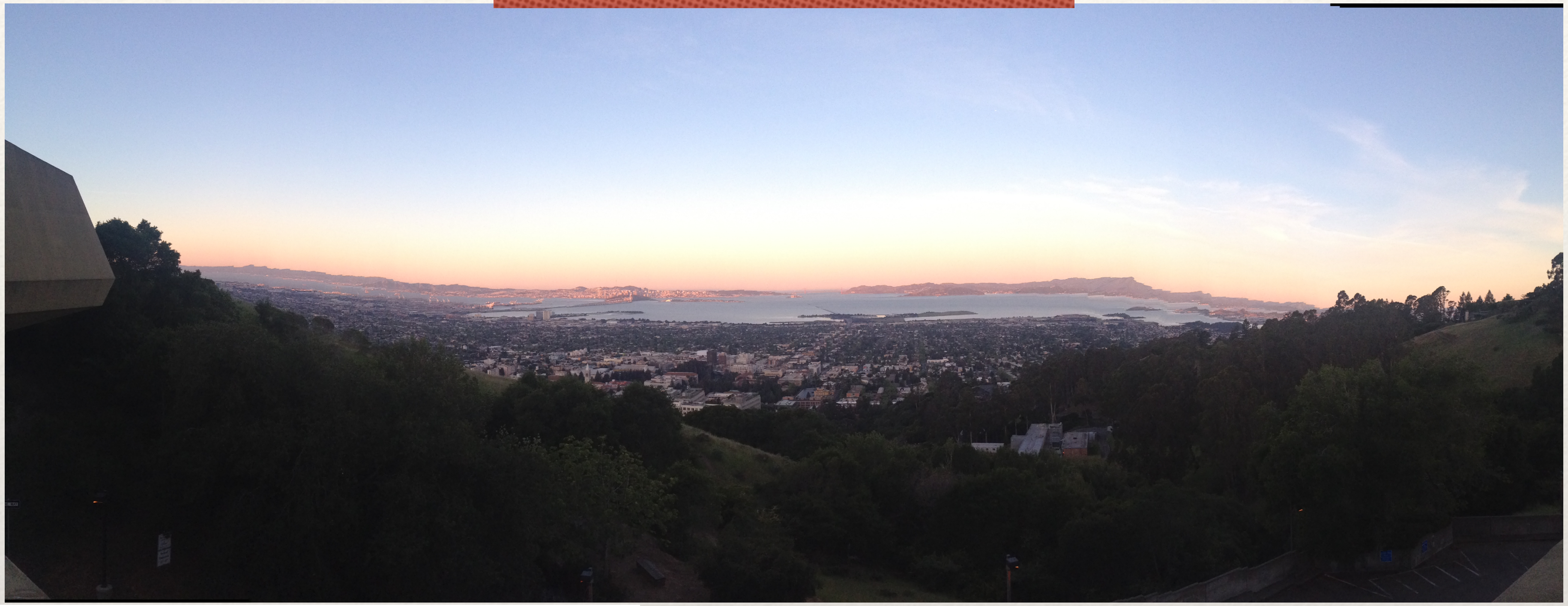
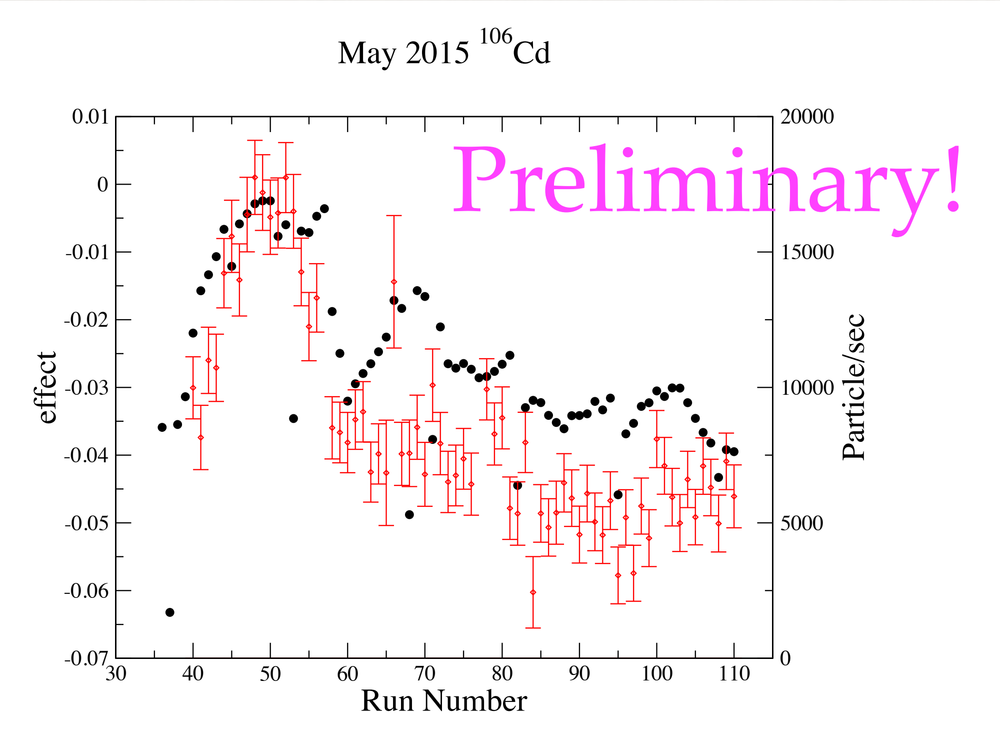
Our current efforts and the next frontiers

$^{12}C(^{106}Cd, ^{12}C)^{110}Sn^*$





Results coming soon!

Summary

- *Most of g-factor values for even-even nuclei are positive.*
- *Negative g factors are "very" rare:*
    - ^{46}Ca (2^+), 92,94Zr (2^+,4^+) isotopes: $f_{7/2}$
    - ^{16,20}O isotopes: $d_{5/2}$
- *Positive g factors in the $f_{7/2}$ shell*
    - g(^{42,44}Ca,2^+)
- The TF technique has been implemented with radioactive beams
    - ^{126}Sn
    - Every case is different, contamination and lifetime drive the experiment.
- **Alpha transfer reactions must be investigated to improve magnetic moment measurements.**
- **The Transient Field must be also studied from a first principle base to replace the current parameterizations.**

In the 7th day you go Kraków and thanks the audience

ありがとう

Gracias

kiitos

tack

Thank you.

धन्यवाद

Dziękuję

danke

merci

תודה

감사합니다

شكرا

obrigado

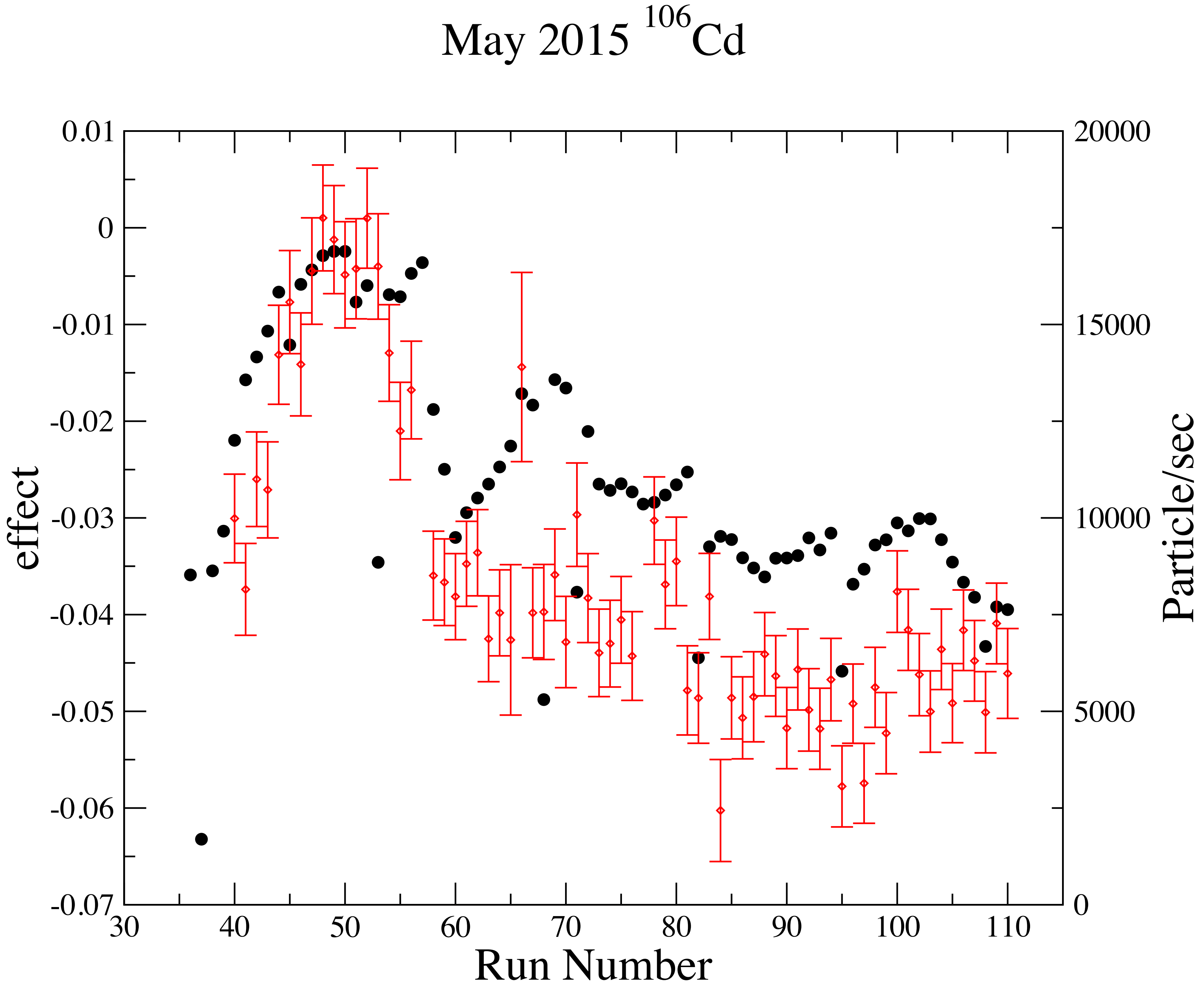
grazie

dankjewel

Some History

$$\Delta\theta^{exp} = \frac{\epsilon}{S(\theta)}$$

Radiation Damage



Alpha Transfer Vs. Coulex