



NuPEERS Lecture

Electron Scattering and the Nuclear Matter

Paul Guèye
Associate Professor
gueye@frib.msu.edu

June 13-15, 2024



MICHIGAN STATE
UNIVERSITY



U.S. DEPARTMENT OF
ENERGY

Office of
Science

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

Who Am I?



Once Upon a Time
... the (real) twins



Second Upon a Time
... the (virtual) twins

▪ Influence

- Mame (grand-mother)
- Wife: Mornetka
- Daughter: Yannick (December 8)

▪ Twin brother: René

- Son: Yoann (!)
- Daughter: Maeva (December 8!)

▪ Whole family ...



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 2

Education ...

▪ High School

- Lycée Lamine Gueye

▪ College

- Université Cheikh Anta Diop (UCAD)
 - » BS: Physics & Chemistry (1987)
 - » MS: Physics & Chemistry (1990)
- Université de Clermont-ferrand II (France)
 - » PhD: Nuclear Physics (1994)

▪ Positions

- Hampton University/Jefferson Lab (VA)
 - » Researcher; Professor; Chair of Physics
- Michigan State University (MI)



Cheikh Anta Diop

(Student of Pierre Joliot-Curie)

- 1923-1986
- 7 PhDs!
- ^{14}C (dating) lab



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 3

Research Interest [1]

▪ Nuclear Physics

- Correction to the Born Approximation
- Jefferson Lab (4-6-12 GeV era) – 1995+
- Michigan State University: NSCL/FRIB (MoNA Collaboration) – 2012+

▪ Accelerator Physics

- Beamline instrumentation: from beam to physics to patients
- Low energy electron accelerator (LELIA) @ HU
- US Particle Accelerator School
- Polarized $e^\pm$ scattering off rare isotopes (<https://indico.jlab.org/event/680>)

▪ Ultrafast Lasers (high power)

- University of Michigan (Gérard Mourou, 1997+ - 2018 Nobel Laureate)
 - » K. Assamagan *et al*, NIM, **A438** (1999)
- High energy electrons from laser wakefield acceleration



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 4

Research Interest [2]

■ Medical Physics

- <https://www.jlab.org/conference/amc-dps-22>
- Improving cancer treatments
 - » Scintillating fibers, 2001+
- Brachytherapy (Curie therapy),
- Proton therapy (HU Proton Therapy Institute)
- Head Medical Physics Program 2011-2012
- Patents:
 - » 9351691, 9028390, 8568285, 8133167, 7662083
- G4DNA: Geant4 radiation damages to the DNA
 - » physics+biology+chemistry

Real time dosimetry monitoring for radiotherapy treatment

Developed by Jefferson Lab and Hampton University scientists; licensed to Radiadyne; R&D100 award, MedTech Breakthrough award



Active Catheter Development for Brachytherapy

In-vivo dose measurements would allow for real time evaluation of dose delivered to patient



ADVANCING MEDICAL CARE THROUGH DISCOVERY IN THE PHYSICAL SCIENCES 2023



Jefferson Lab

HOME ABOUT SCIENCE CAREERS

Funding

The Oartrac® system was designed and built by Radiadyne, a subsidiary of AngioDynamics. Research involving the scintillating fiber technology and its adaptation for medical applications was supported by Hampton University and DOE's Thomas Jefferson National Accelerator Facility.

Publications

P. Gueye, C. Keppel, L. Tynes, D. Kieper, "Apparatus and method for radiation distribution mapping." U.S. Patent 8,133,167 (2012).

P. Gueye, C. Keppel, L. Tynes, D. Kieper, "Apparatus and method for brachytherapy radiation distribution mapping." U.S. Patent 7,662,083 (2010).

P. Gueye, C. Keppel, C. Sinesi, "Apparatus and method for external beam radiation distribution mapping." U.S. Patent Application US20140018675A1 (2005).

Related Links

2018 R&D 100 Award Winners

2018 MedTech Breakthrough Awards

November 2018

RESOURCES

FOR THE PUBLIC

Diversity
Electron-Ion Collider
Job Openings
News
Press Room
Research Highlights
Visiting

FOR RESEARCHERS

Accelerator Science
EIC Center
EIC Partner Project
Engineering
Nuclear Physics
Publications
Theory Center
User Information

FOR EDUCATION

Games & Puzzles
Postdoc/Grad Students
Program & Events
Science Cinema
Student Zone
Teacher Tools

FOR BUSINESS

Community Impact
Emergency Preparedness
Event Services
Partnerships
Phone Book
Procurement
Small Business Program
Technology Transfer

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY IS MANAGED BY JEFFERSON SCIENCE ASSOCIATES, LLC FOR THE U.S. DEPARTMENT OF ENERGY

THOMAS JEFFERSON

NATIONAL ACCELERATOR FACILITY

12000 Jefferson Avenue, Newport News, VA
Phone: 757-269-7100 Fax: 757-269-7363

INSIGHT FOR EMPLOYEES

PRIVACY AND SECURITY NOTICE
VULNERABILITY DISCLOSURE PROGRAM
SITE MAP

CONTACT JLAB

JLAB STATUS
REPORT A PROBLEM



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 5

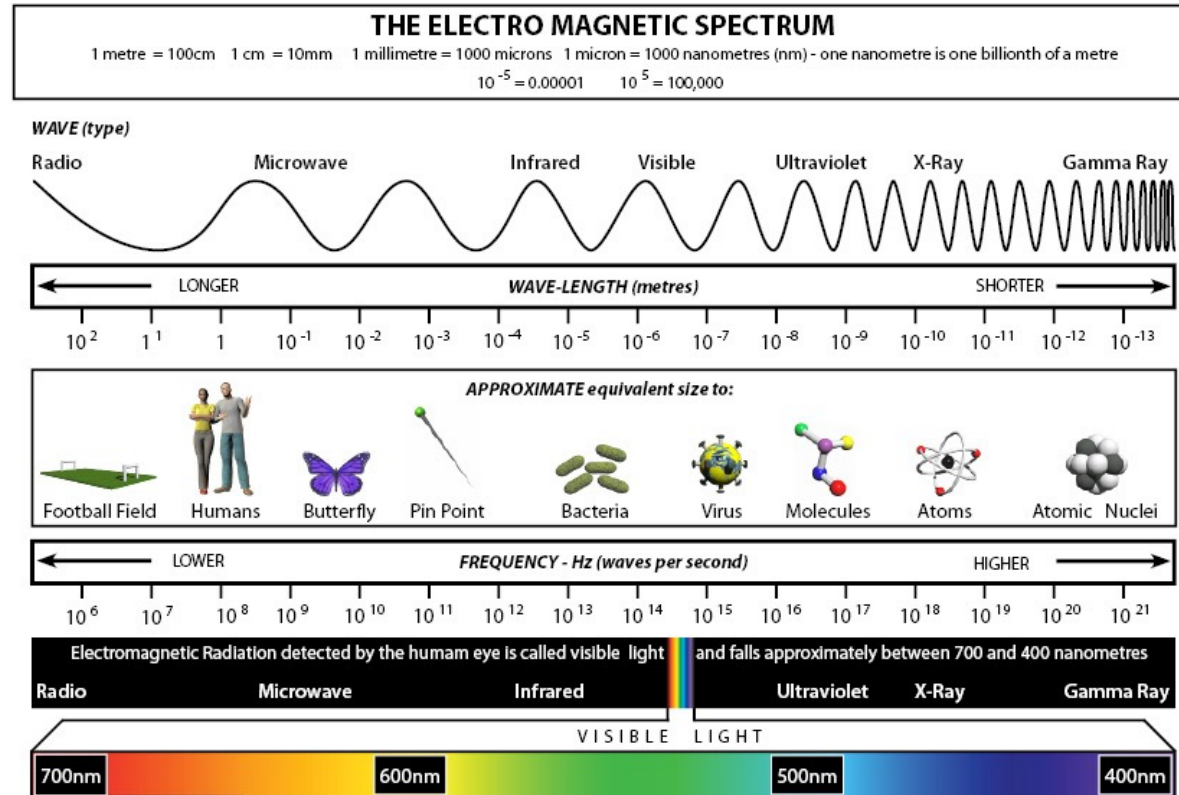
How Good Is Our Eyesight?

$$E = hc/\lambda$$

$$hc \approx 200 \text{ MeV fm}$$

$$\lambda \approx 2 \text{ fm} \rightarrow E \approx 100 \text{ MeV}$$

$$1 \text{ fm} = 10^{-15} \text{ m!}$$



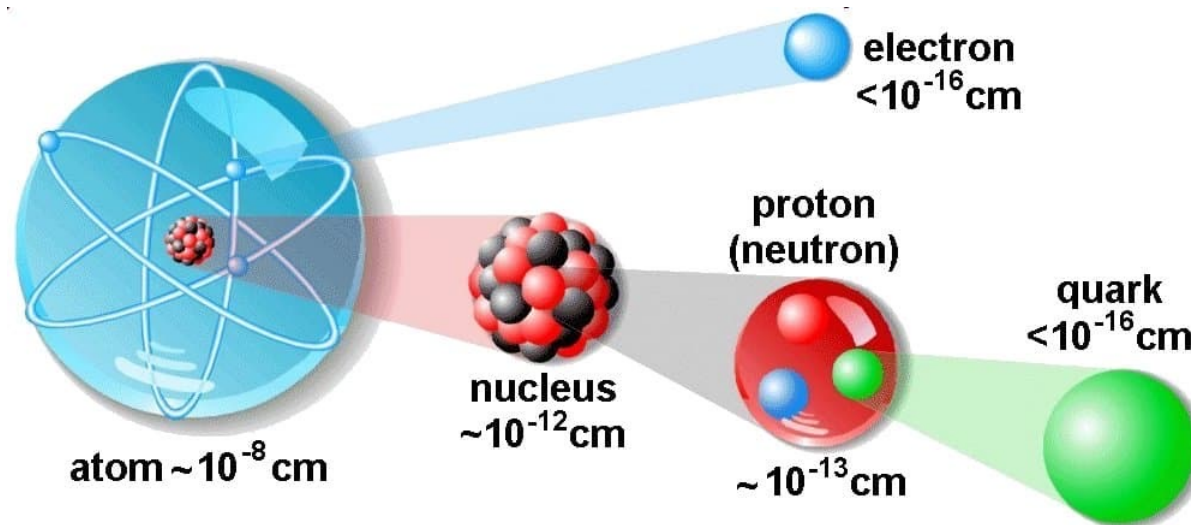
© Copyright ColourTherapy Healing 2010 - www.colourtherapyhealing.com



Facility for Rare Isotope Beams
 U.S. Department of Energy Office of Science | Michigan State University
 640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 6

Making Atoms ...



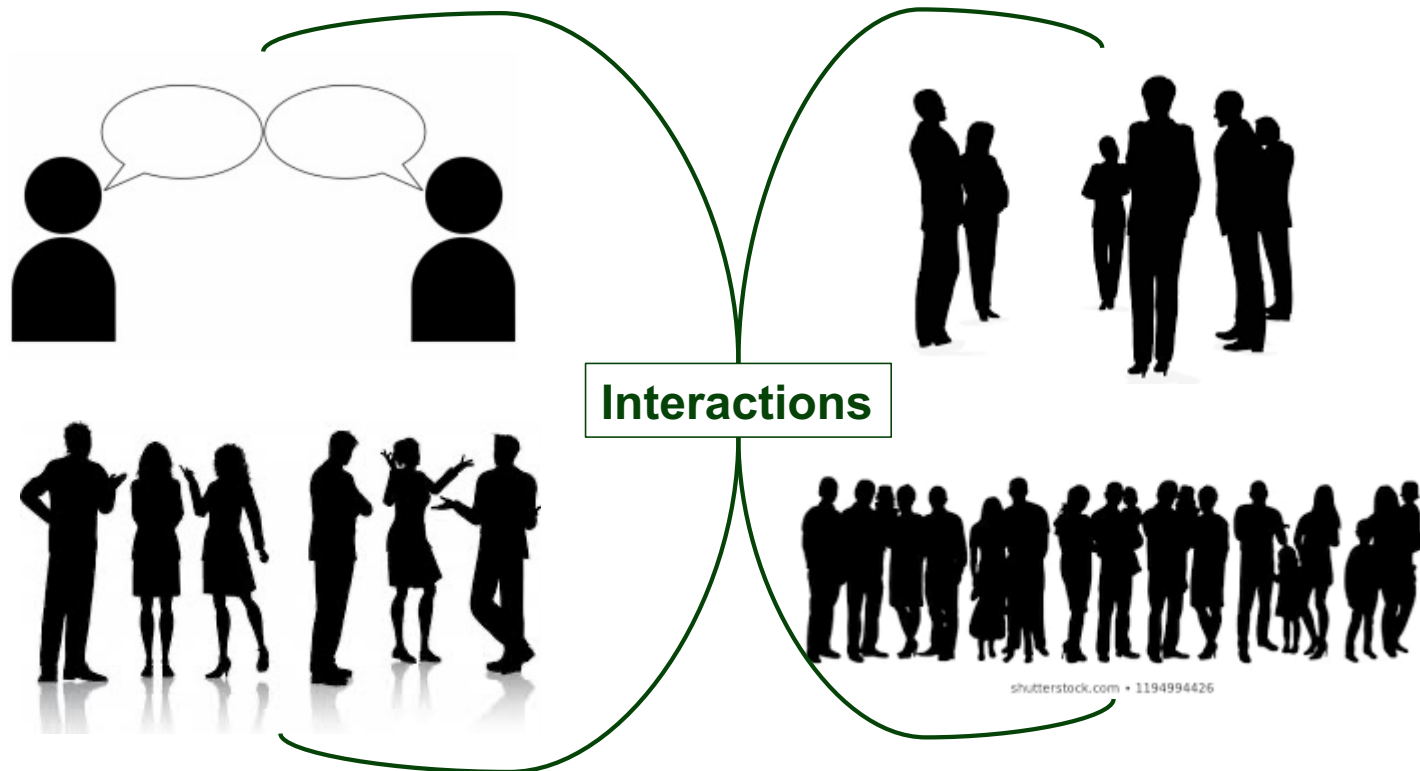
periodictable.org



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 7

2, 3, 4 ... Too Many



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 8

Making More Atoms ...

period	group																	18		
	1*																	2		
1		1																	2	
2		3	4																	10
3		11	12																	18
4		19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
5		37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	
6		55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	
7		87	88	89	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	
		Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og	
lanthanoid series		6	58	59	60	61	62	63	64	65	66	67	68	69	70	71				
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu				
actinoid series		7	90	91	92	93	94	95	96	97	98	99	100	101	102	103				
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr				

Alkali metals

Alkaline-earth metals

Transition metals

Other metals

Other nonmetals

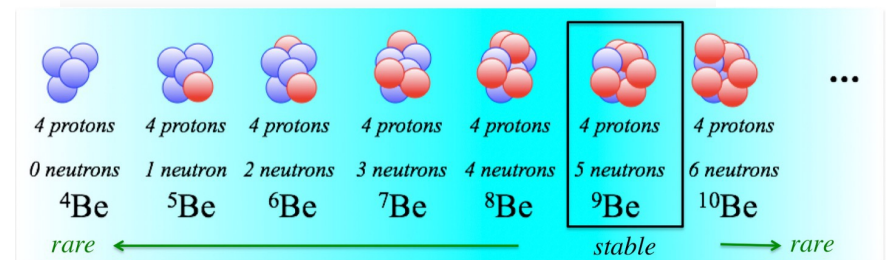
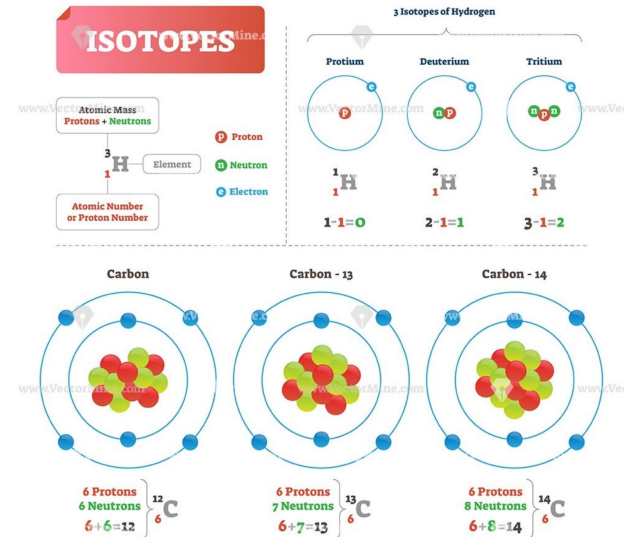
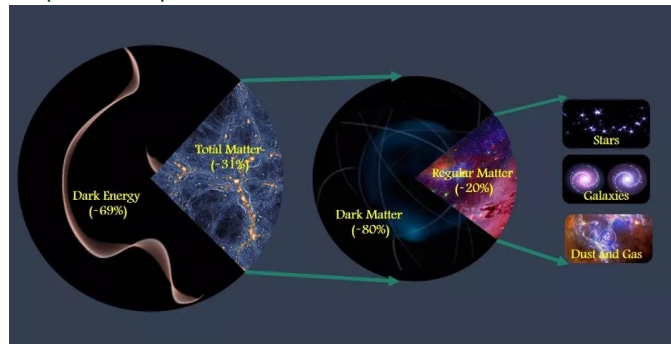
Halogens

Noble gases

Rare-earth elements (21, 39, 57-71) and lanthanoid elements (57-71 only)

Actinoid elements

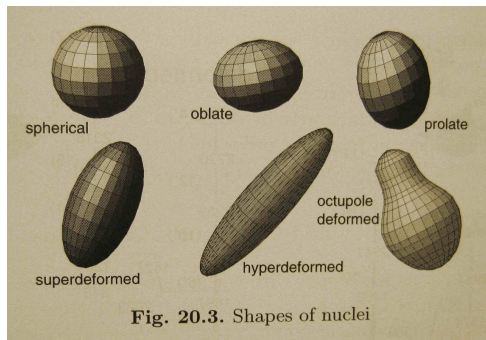
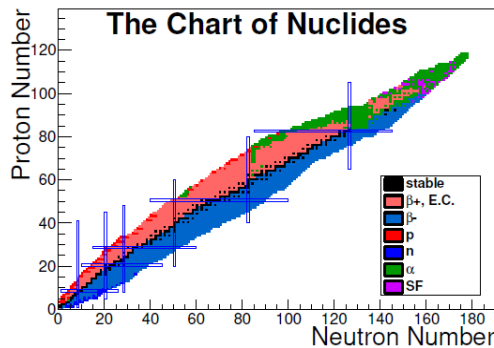
<https://www.space.com/universe-total-amount-matter-measured>



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

Nuclear Chart & Nuclear Science

Data from G. Audi, *et al.*, Chinese Physics C, 41(3),030001, 2017

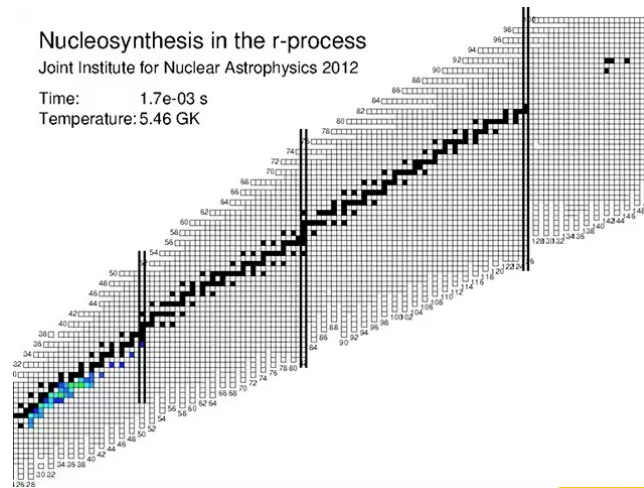


<https://web2.ph.utexas.edu/~coker2/index.files/rotation2.htm>

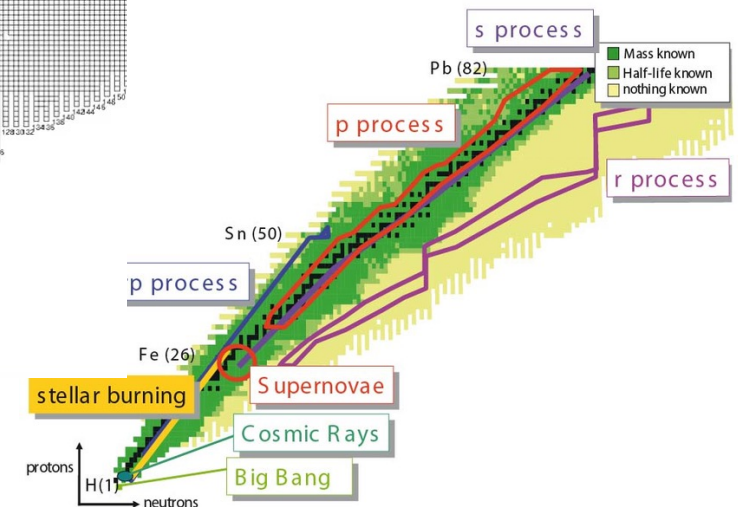
Nucleosynthesis in the r-process

Joint Institute for Nuclear Astrophysics 2012

Time: 1.7×10^{-3} s
Temperature: 5.46 GK



- 288 stables ($T_{1/2} > \text{life of the solar system}$)
- 3,308 different isotopes have been discovered (2019)



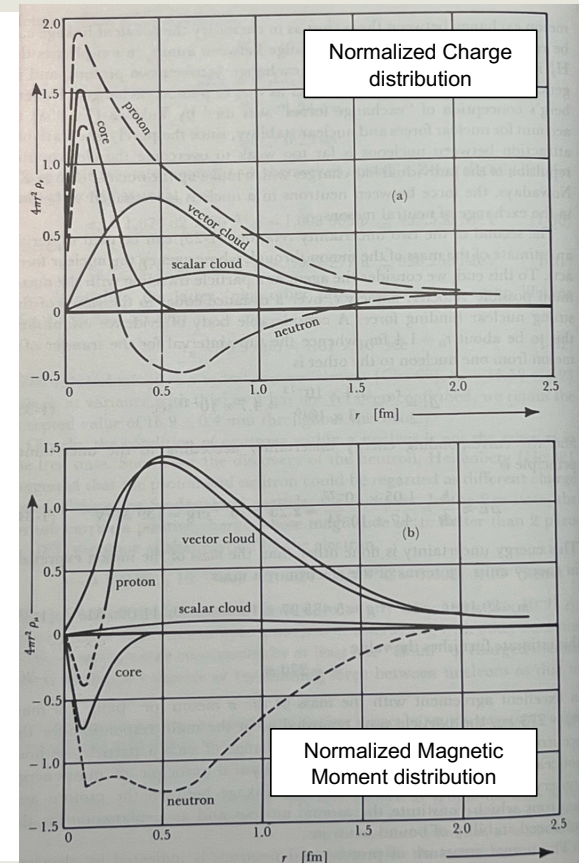
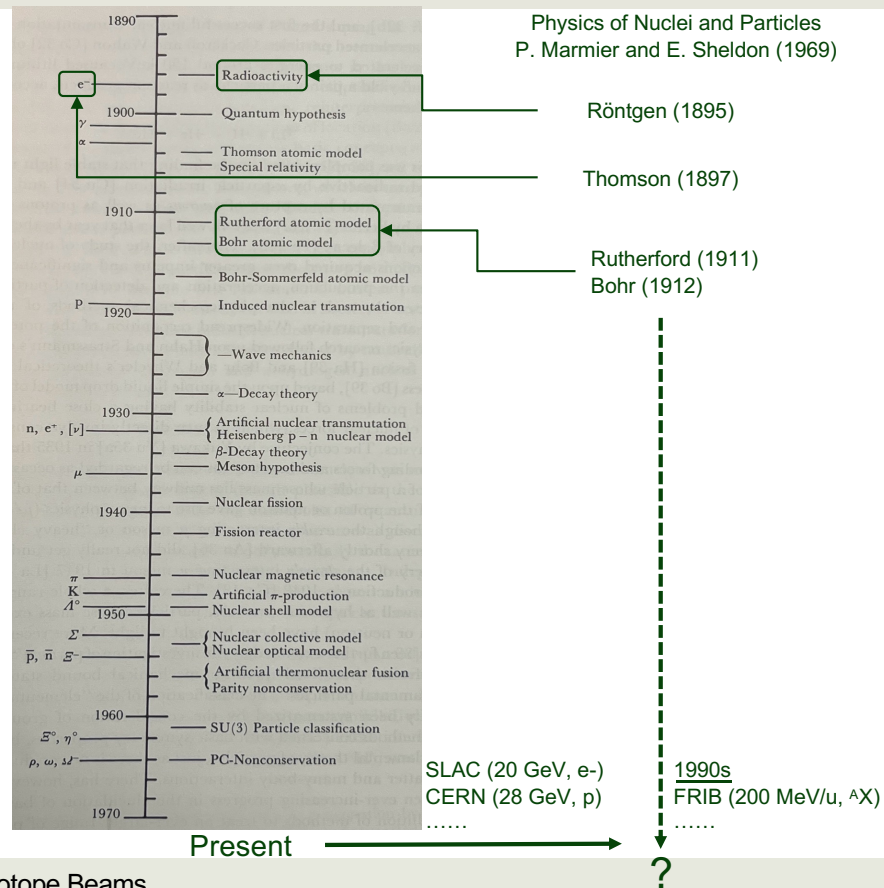
K.Blaum *et al.*, Contemporary Physics, **51**, 149-175 2010



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 10

Nuclear Physics – Brief History



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

Peeking Inside Closed Rooms



*Can you really tell
what is inside?*

<https://www.vecteezy.com/free-vector/house-cross-section>



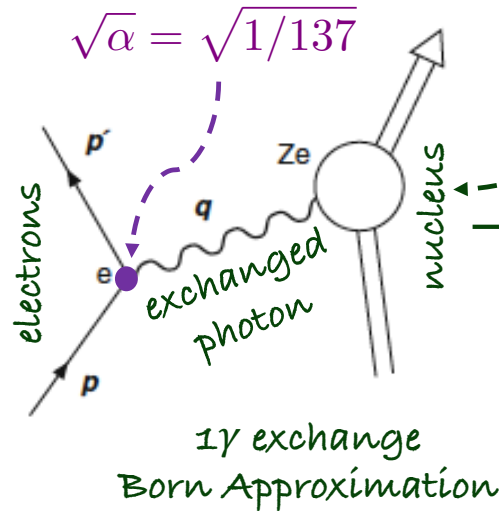
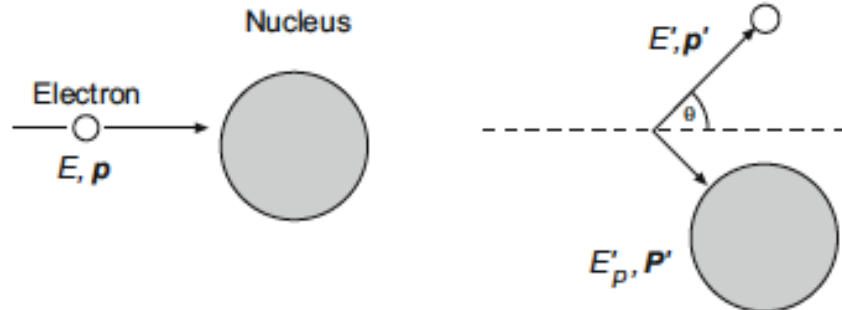
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 12

Peaking Inside Nuclei

e: electron ; Ze: nucleus

$\mathbf{p}$ incident electron momentum
 $\mathbf{p}'$ outgoing electron momentum
 $\mathbf{q}$ momentum transferred to the nucleus ($\mathbf{q} = \mathbf{p} - \mathbf{p}'$)



Feynman Diagram!!

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(\mathbf{q}^2)|^2$$

$$\text{Prob(scatt. off target)} = \text{Prob(scatt. off point charge)} |F(\mathbf{q}^2)|^2$$



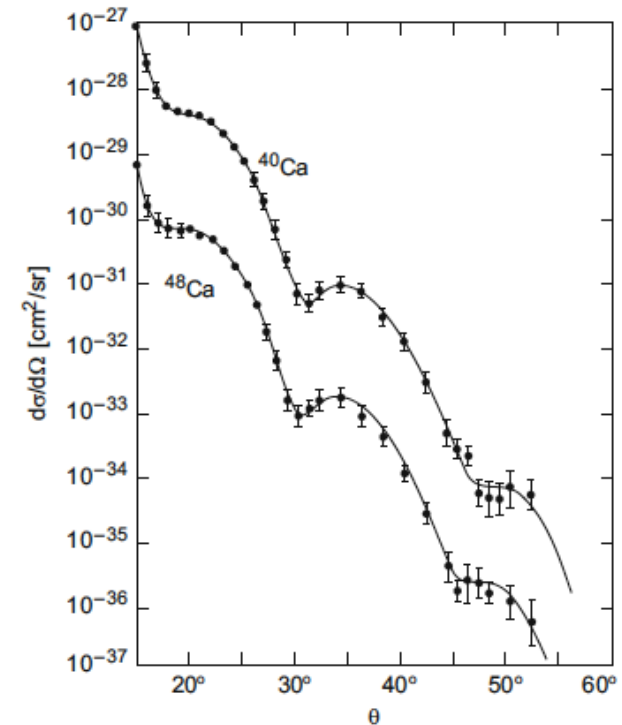
Facility for Rare Isotope Beams
 U.S. Department of Energy Office of Science | Michigan State University
 640 South Shaw Lane • East Lansing, MI 48824, USA
 frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 13

Most Important Quantity: The Nuclear Radius!

$\rho(r)$	$ F(q^2) $	Example
pointlike	constant	Electron
exponential	dipole	Proton
gauss	gauss	${}^6\text{Li}$
homogeneous sphere	oscillating	—
sphere with a diffuse surface	oscillating	${}^{40}\text{Ca}$

$r \rightarrow$ $|q| \rightarrow$



Bogdan Povh, Klaus Rith, Christoph Scholz, Frank Zetsche • Werner Rodejohann
 Particles and Nuclei: An Introduction to the Physical Concepts



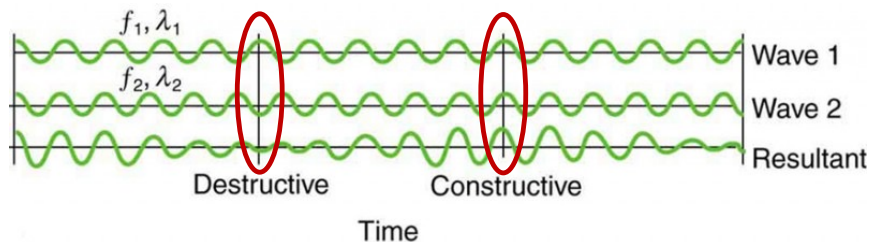
Facility for Rare Isotope Beams
 U.S. Department of Energy Office of Science | Michigan State University
 640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 15

Waves Interference

- Microscopic objects
 - Electrons: point particles
 - Nucleons: ~ 1 fm (1×10^{-15} m)
- World of probability!!
 - Quantum mechanics
- Everything is energy = wave

$$E = mc^2$$



<https://courses.lumenlearning.com/suny-physics/chapter/16-10-superposition-and-interference/>



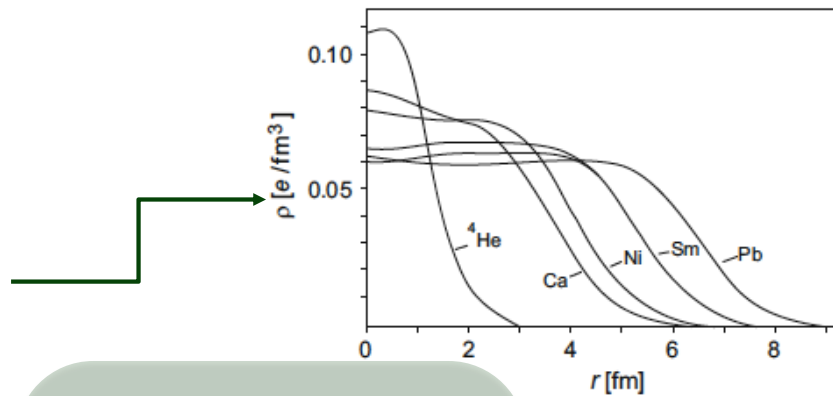
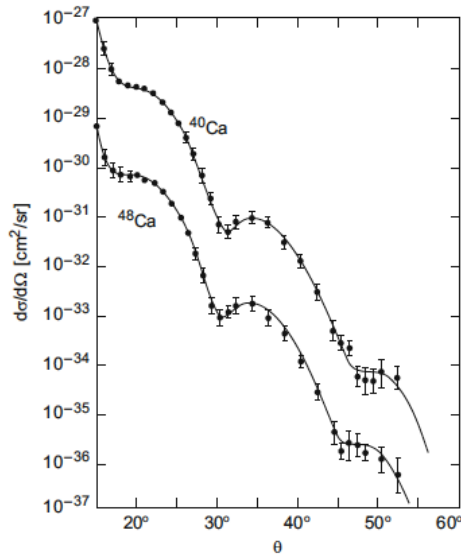
<https://studymind.co.uk/notes/interference/>



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 16

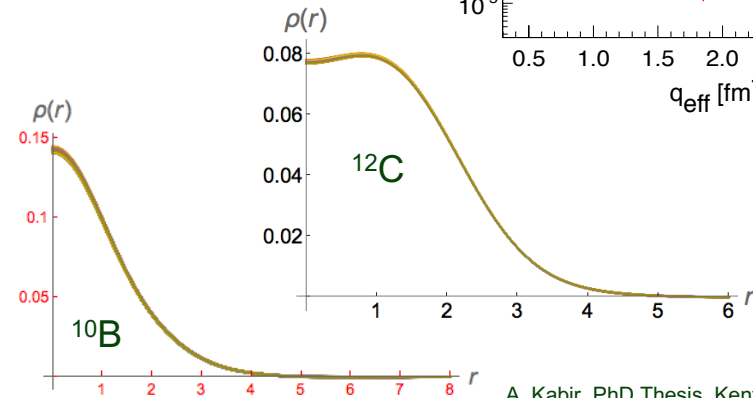
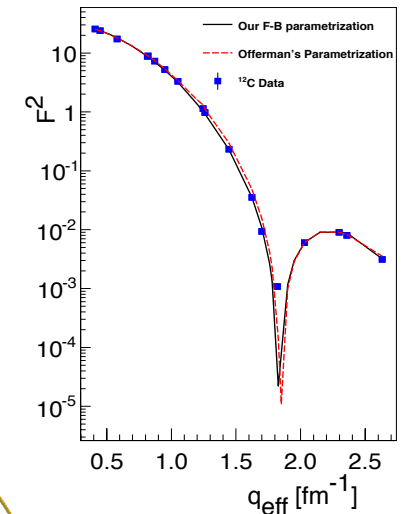
Extracting Nuclear Radii



$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(\mathbf{q}^2)|^2$$

$$F_p(q^2) = \frac{1}{4\pi} \int d^3r j_0(qr) \rho_p(r)$$

$$ZF_p = 4\pi \int_0^\infty \rho_p r^2 dr = \sum_{\nu=1}^\infty (-1)^{\nu+1} \frac{4\pi R_p}{q_\nu^2} a_\nu$$



A. Kabir, PhD Thesis, Kent State (2015)



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

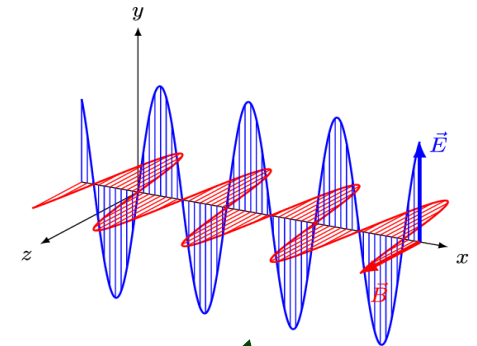
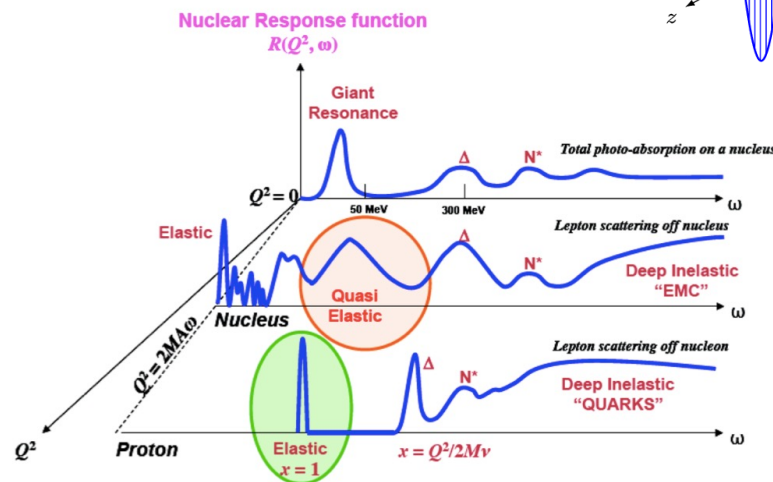
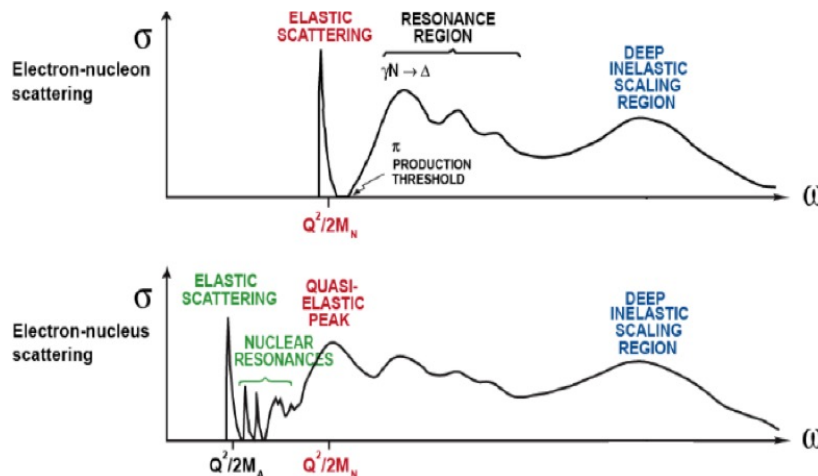
P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 17

Probing nuclei and nucleons with electrons

<https://commons.wikimedia.org/wiki/File:EM-Wave.gif>

The power of (electron) scattering experiments as a microscope

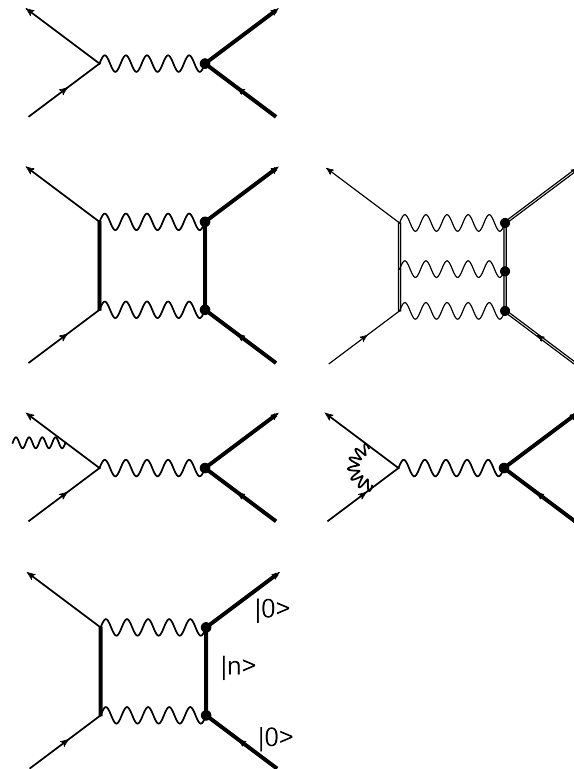
- A [beam] + B [target] = inside view of the nuclear matter!!
- **Invariant mass** technique probing **new particles/states**
- **Missing mass** technique probing **reaction mechanisms**



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 18

Beyond the Born Approximation



Born Approximation

+ ... Coulomb Corrections

+ ... Radiative Corrections

+ ... Dispersive Corrections

partial-wave
analysis

static
analysis

dynamic
corrections

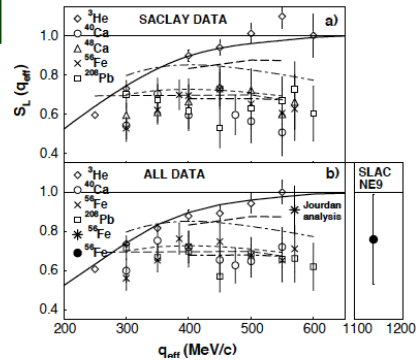


What's going on with >1γ?

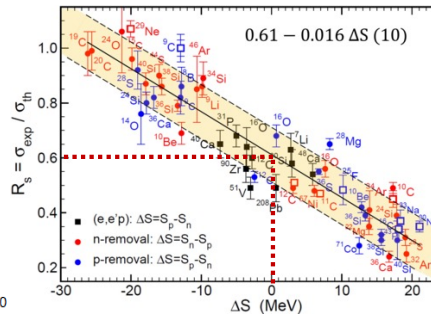
In-medium nucleons & the Coulomb Sum Rule (CSR)

$$S_L(|\mathbf{q}|) = \int_{\omega>0} |\mathbf{q}| \frac{R_L(\omega, |\mathbf{q}|)}{ZG_{Ep}^2(Q^2) + NG_{En}^2(Q^2)} d\omega$$

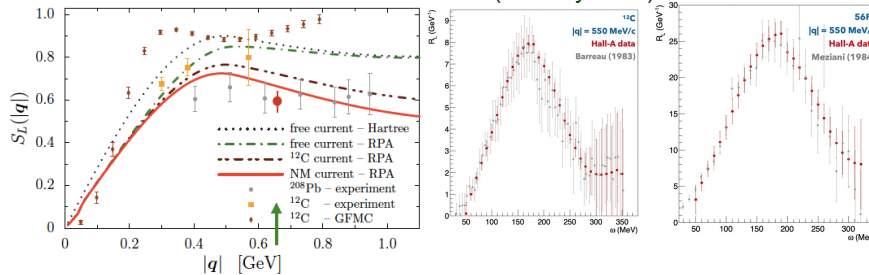
J. Morgenstern & Z. Meziani.
EPJ, **A17**, 451–455, (2003)



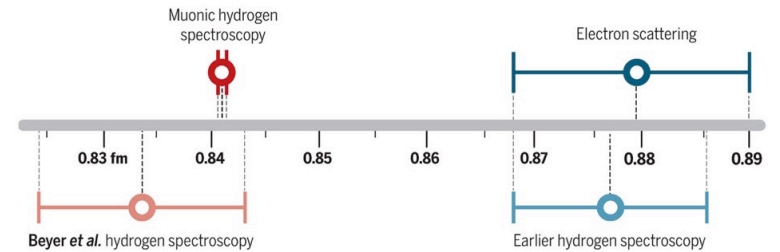
J. A. Tostevin and A. Gade
Phys. Rev. C **103**, 054610 (2021)



M. Paolone, JLab e05-110; CSR quenching?
Hall A/C Collaboration (January 2022)



Proton radius



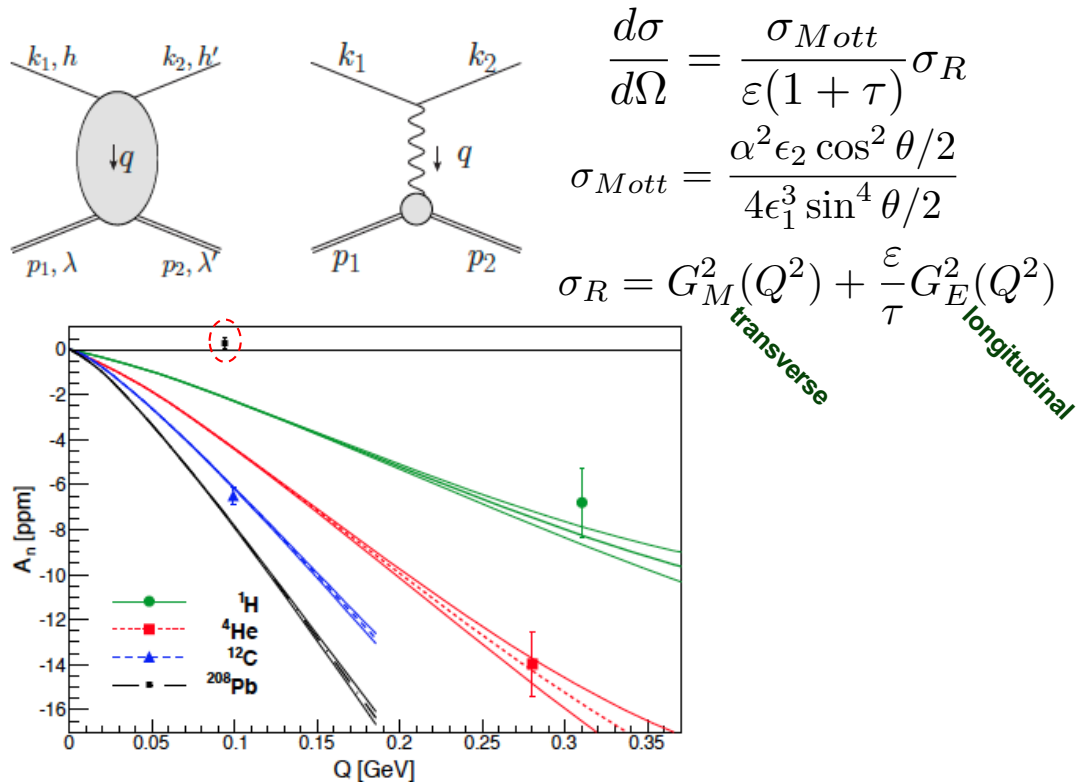
W. Vassen, Science, **358**, 6359, pp. 39-40 (2017)
R. Pohl, Nature, **466** (2010)



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 20

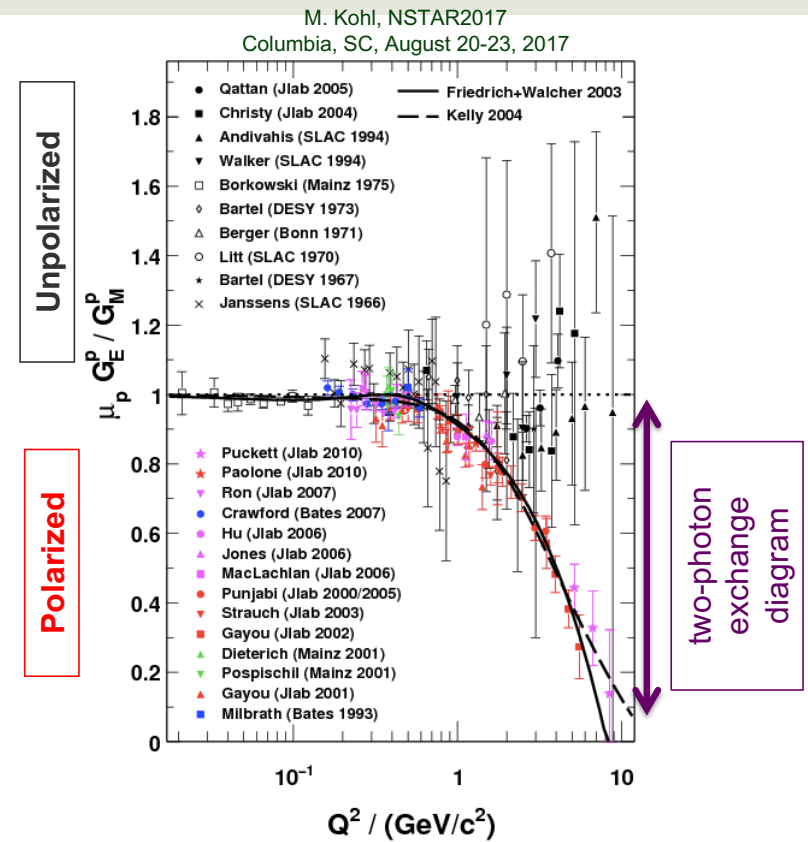
G_E/G_M puzzle: the role of two-photon exchange



S. Abrahamyan *et al.* (HAPPEX and PREX Collaborations)
Phys. Rev. Lett. **109**, 192501 (2012)



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

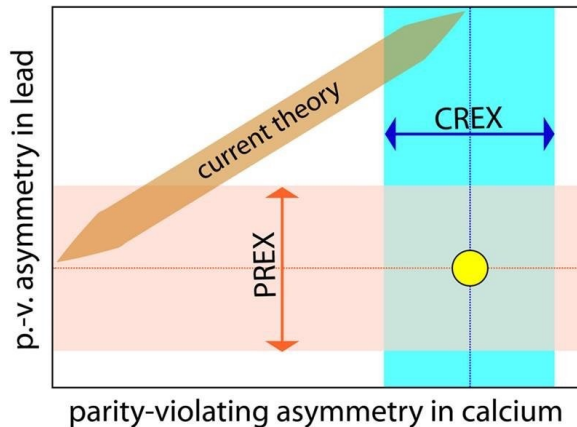


P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 21

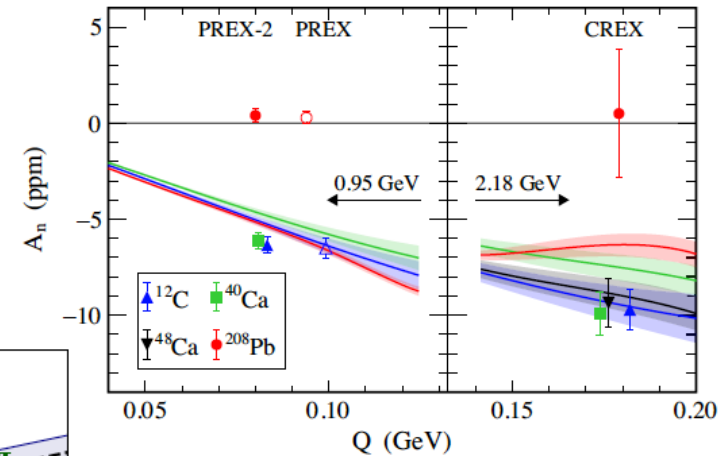
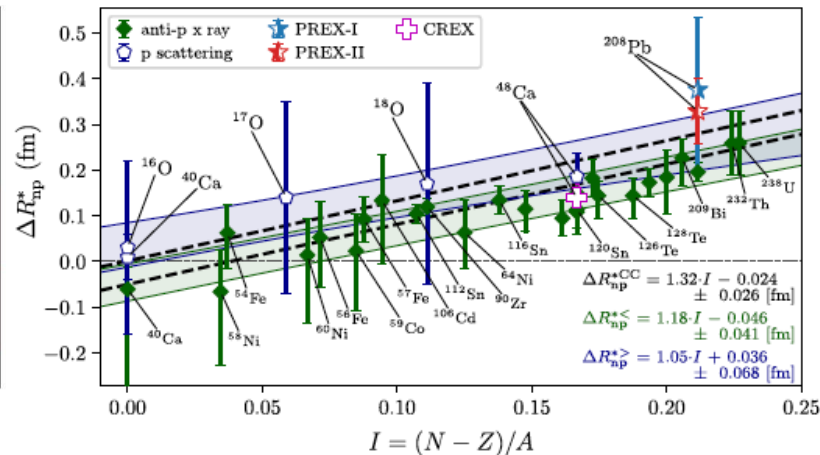
Neutron skin puzzle: the role of virtual excitations [1] (see L. Broussard talk)

- **PREX:** D. Adhikari et al., PRL, **126**, 172502 (2021)
 - ^{208}Pb : $R_n - R_p = 0.283 \pm 0.071$ fm
- **CREX:** D. Adhikari et al., PRL, **129**, 042501 (2022)
 - ^{48}Ca : $R_n - R_p = 0.121 \pm 0.026$ (exp) ± 0.024 (model) fm

P.-G. Reinhard, X. Roca-Maza, and W. Nazarewicz
PRL**129**, 232501 (2022)



S. J. Novario, D. Lonardoni, S. Gandolfi, and G. Hagen
PRL**130**, 032501 (2023)



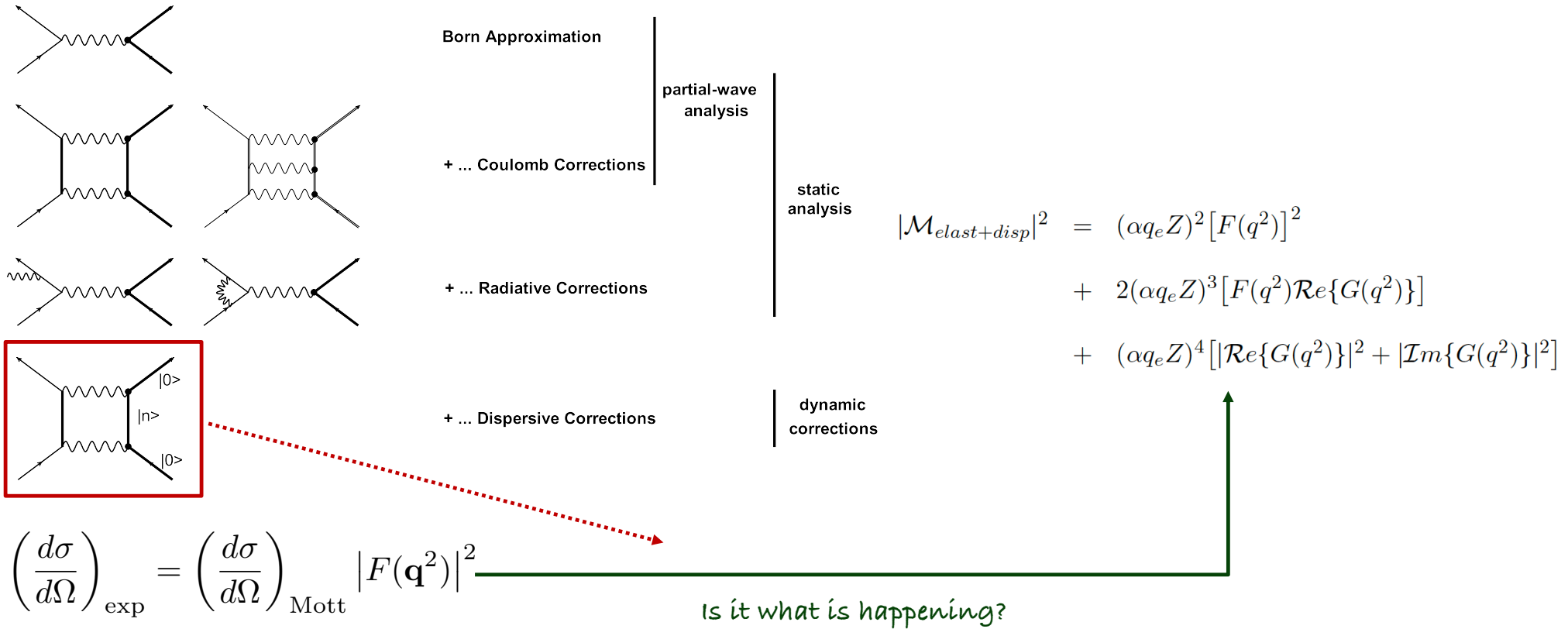
Adhikari et al, PRL 128, 142501 (2022)



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 22

Neutron skin puzzle: the role of virtual excitations [2]



Wait ... There is More!!

Nuclear Tomography & Polarization?

Meson electro-production

$$\begin{aligned} \frac{d\sigma_v}{d\Omega_\eta} = & \frac{|\mathbf{k}|}{k_\gamma^{cm}} P_\alpha P_\beta \{ R_T^{\beta\alpha} + \varepsilon_L R_L^{\beta\alpha} \\ & + [2\varepsilon_L(1+\varepsilon)]^{1/2} ({}^c R_{TL}^{\beta\alpha} \cos \phi_\eta + {}^s R_{TL}^{\beta\alpha} \sin \phi_\eta) \\ & + \varepsilon ({}^c R_{TT}^{\beta\alpha} \cos 2\phi_\eta + {}^s R_{TT}^{\beta\alpha} \sin 2\phi_\eta) \\ & + h[2\varepsilon_L(1-\varepsilon)]^{1/2} ({}^c R_{TL'}^{\beta\alpha} \cos \phi_\eta + {}^s R_{TL'}^{\beta\alpha} \sin \phi_\eta) \\ & + h(1-\varepsilon^2)^{1/2} R_{TT'}^{\beta\alpha} \} \end{aligned}$$

G. Knöchlein, D. Drechsel, L. Tiator
Z. Phys. **A352**, 327-343 (1995)

3D nucleon tomography!!
(DVCs, parton distributions ...)

Table 1. Polarization observables in pseudoscalar meson electroproduction. A star denotes a response function which does not vanish but is identical to another response function via a relation in App. A

		Target			Recoil			Target + Recoil								
β	α	x	y	z	x'	y'	z'	x	y	z	x'	y'	z'	x	y	z
T	R_T^{00}	0	R_T^{0y}	0	0	$R_T^{y'0}$	0	$R_T^{x'x}$	0	$R_T^{x'z}$	0	*	0	$R_T^{z'x}$	0	$R_T^{z'z}$
L	R_L	0	R_L^{0y}	0	0	*	0	$R_L^{x'x}$	0	$R_L^{x'z}$	0	*	0	*	0	*
${}^c TL$	${}^c R_{TL}^{00}$	0	${}^c R_{TL}^{0y}$	0	0	*	0	${}^c R_{TL}^{x'x}$	0	*	0	*	0	${}^c R_{TL}^{z'x}$	0	*
${}^s TL$	0	${}^s R_{TL}^{0x}$	0	${}^s R_{TL}^{0z}$	${}^s R_{TL}^{x'0}$	0	${}^s R_{TL}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^c TT$	${}^c R_{TT}^{00}$	0	*	0	0	*	0	*	0	*	0	*	0	*	0	*
${}^s TT$	0	${}^s R_{TT}^{0x}$	0	${}^s R_{TT}^{0z}$	${}^s R_{TT}^{x'0}$	0	${}^s R_{TT}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^c TL'$	0	${}^c R_{TL'}^{0x}$	0	${}^c R_{TL'}^{0z}$	${}^c R_{TL'}^{x'0}$	0	${}^c R_{TL'}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^s TL'$	${}^s R_{TL'}^{00}$	0	${}^s R_{TL'}^{0y}$	0	0	*	0	${}^s R_{TL'}^{x'x}$	0	*	0	*	0	${}^s R_{TL'}^{z'x}$	0	*
TT'	0	$R_{TT'}^{0x}$	0	$R_{TT'}^{0z}$	$R_{TT'}^{x'0}$	0	$R_{TT'}^{z'0}$	0	*	0	*	0	*	0	*	0

unpolarized

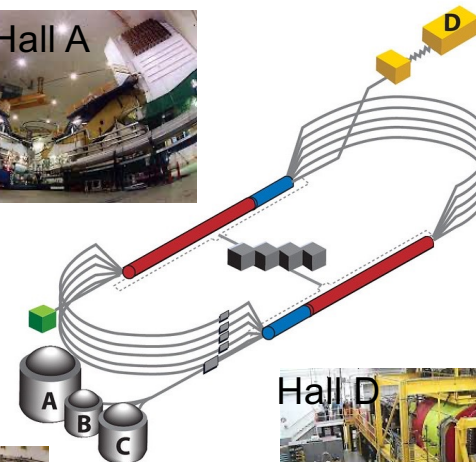
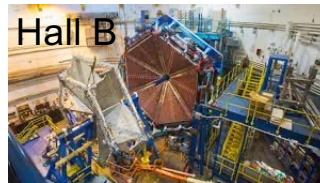
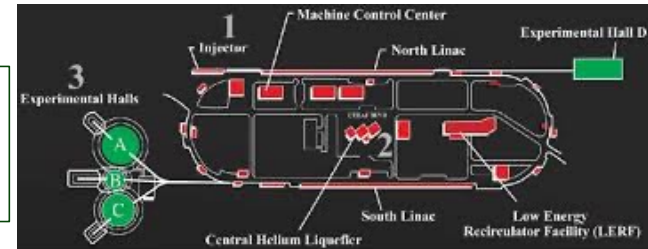
polarized



Thomas Jefferson National Accelerator Facility (Jefferson Lab)



12 GeV, 14 kW
Polarized e^-
CW (1.5 GHz)



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

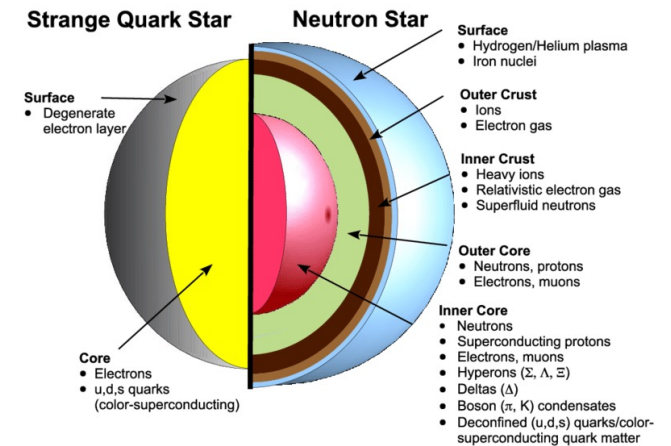
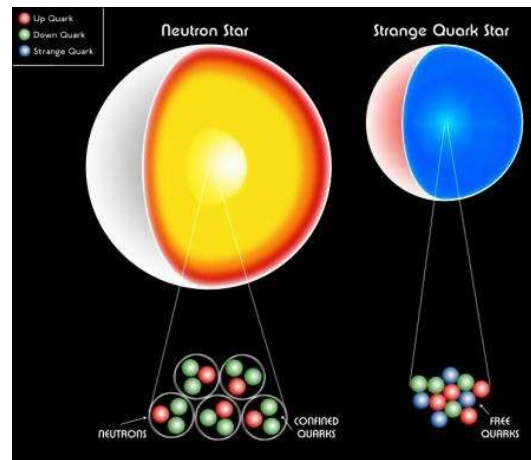
P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 25

Neutron Stars And Strange Stars?

(see P. Giuliani, B. Ramson, B. Dongwi talks)

- Need to understand elementary process
- Start with lightest ones
 - uds: $\Lambda(1115)$, $\Sigma^0(1192)$
 - uus: $\Sigma^+(1189)$
 - dds: $\Sigma^0(1197)$
- Formation of hypernuclei: $A X \rightarrow A^{-1} X_Y = [\Lambda, \Sigma]$
 - Interactions: NN, ΛN , ΣN , $\Lambda N N$...

F. Weber et al., Mod. Phys. Lett. A **29**, 23 (2014)



Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

P. Guèye, NuPEERS, June 13-15, 2024, Dillard University, Slide 26

Homework

- Calculate the elastic scattering kinematics (use relativistic kinematics)

- Known : incident electrons (E_{inc} , $\mathbf{P}_{\text{inc}}$), scattering angle (Θ)
- Unknown : outgoing electrons (E_{out} , $\mathbf{P}_{\text{out}}$)

- Assuming a homogenous sphere of radius R

- Known density

$$\rho(r) = \begin{cases} \frac{3}{4}\pi R^3 & \text{for } r \leq R \\ 0 & \text{for } r > R \end{cases}$$

- Replacing the density $\rho(r)$ to show that the form factor $F(\mathbf{q}^2)$ is

$$F(\mathbf{q}^2) = 4\pi \int \rho(r) \frac{\sin(|\mathbf{q}|r/\hbar)}{|\mathbf{q}|r/\hbar} r^2 dr = \frac{3}{\alpha^3} (\sin \alpha - \alpha \cos \alpha) ; \alpha = |\mathbf{q}|R/\hbar$$

