Francium and Fundamental Symmetries

Physics Colloquium
University of Texas at Austin
April 2023

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The periodic Table

ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4.
			Fe=56	Rn=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

Д. Менделѣевъ

Tentative System of Elements, Mendeleev 1869

The periodic table of elements

Reihen	Gruppe I. — R^2O	Gruppe II. — RO	Gruppe III. — R^2O^3	Gruppe IV. RH^4 RO^2	Gruppe V. RH^3 R^2O^5	Gruppe VI. RH^2 RO^3	Gruppe VII. RH R^2O^7	Gruppe VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

Mendeleev 1871

Only the atomic weight known.

Moved the elements around to make their chemical properties similar.

Named eka- (ekasilicon, *germanium*; ekaaluminium, *gallium*, ekaboron, *scandium*) and predicted some properties for those elements missing but that should in the table.

People started looking for eka-caesium.

Eka-cesium appearances

- 1925 D. K. Dobroserdov, a soviet chemist, proposes Russium
- 1926 G. J. F. Druce and F. H. Loring (UK) analyzed X ray spectra of manganese sulfate, propose Alkalinium.
- 1931 F. Allison and E. J. Murphy from Alambama Polyyechnic Institute, analize some pollucite, Virginium.
- 1936 H. Hulubei and Y. Cauchois analyzed pollucite using X ray spectra. Moldaviu

The discovery of Francium

Marguerite Perey (1909-1975)

- Born in Villemomble, east of Paris, youngest of 5 children.
- She studied at Lycée Victor Duruy.
- She wanted to study medicine, but the dead of her father made her look for something more immediate.
- Studied in a vocational college chemistry laboratory technician.
- The Curies often hired the top student from the school as an assistant, and Perey at 19 was called in for an interview.

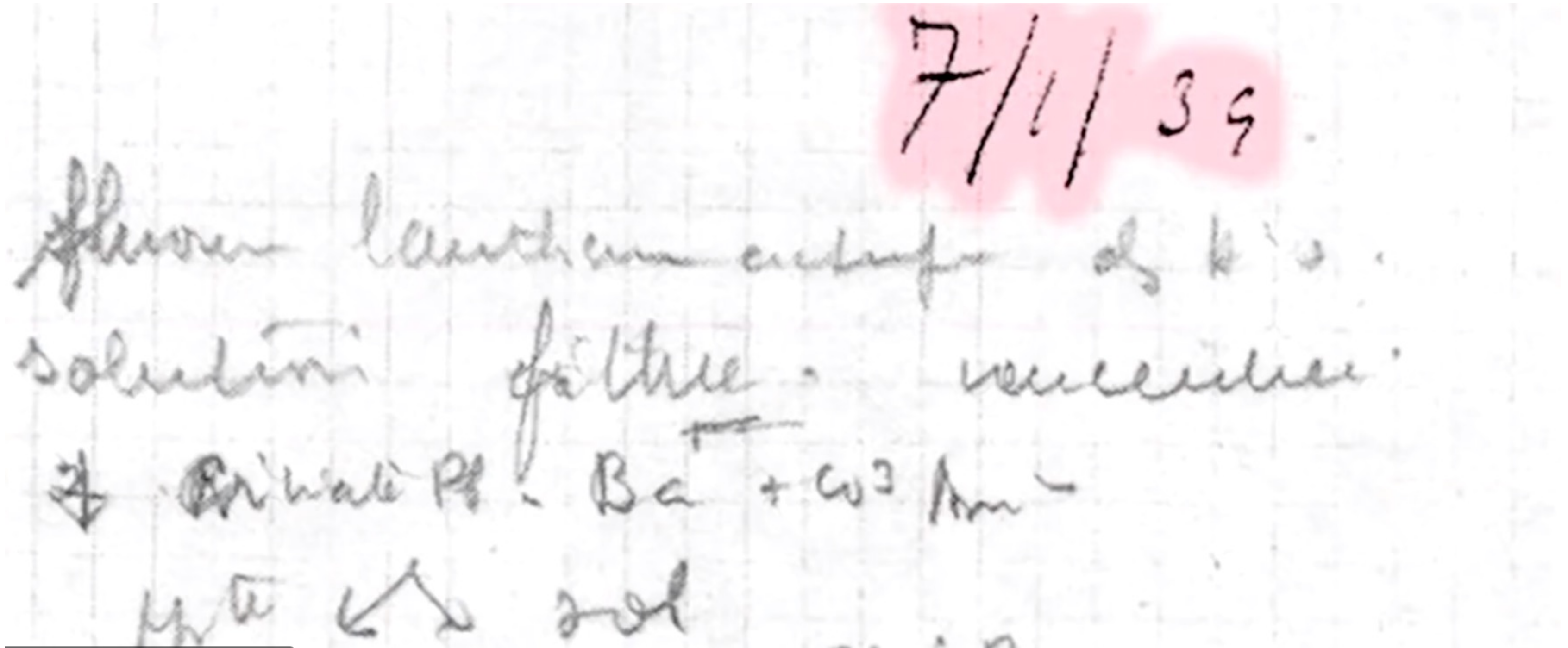
Chemical Group Block

PubChem

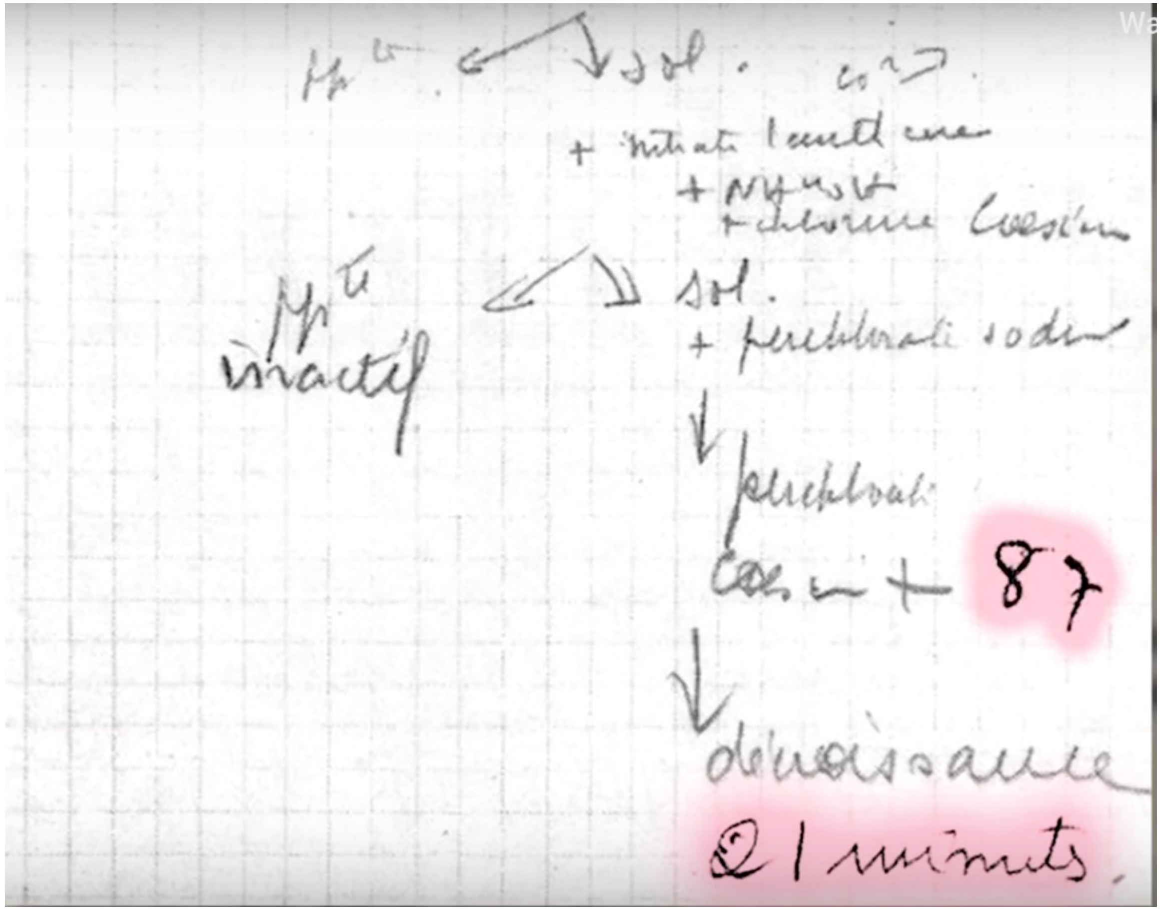
Atomic Number: 17 · Atomic Mass, u: 35.45 · Symbol: Cl · Name: Chlorine · Chemical Group Block: Halogen

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 1.0080 H Hydrogen Nonmetal																	2 4.00260 He Helium Noble Gas
2	3 7.0 Li Lithium Alkali Metal	4 9.012183 Be Beryllium Alkaline Earth Me...											5 10.81 B Boron Metalloid	6 12.011 C Carbon Nonmetal	7 14.007 N Nitrogen Nonmetal	8 15.999 O Oxygen Nonmetal	9 18.9984... F Fluorine Halogen	10 20.180 Ne Neon Noble Gas
3	11 22.989... Na Sodium Alkali Metal	12 24.305 Mg Magnesium Alkaline Earth Me...											13 26.981... Al Aluminum Post-Transition M...	14 28.085 Si Silicon Metalloid	15 30.973... P Phosphorus Nonmetal	16 32.07 S Sulfur Nonmetal	17 35.45 Cl Chlorine Halogen	18 39.9 Ar Argon Noble Gas
4	19 39.0983 K Potassium Alkali Metal	20 40.08 Ca Calcium Alkaline Earth Me...	21 44.95591 Sc Scandium Transition Metal	22 47.867 Ti Titanium Transition Metal	23 50.9415 V Vanadium Transition Metal	24 51.996 Cr Chromium Transition Metal	25 54.93804 Mn Manganese Transition Metal	26 55.84 Fe Iron Transition Metal	27 58.93319 Co Cobalt Transition Metal	28 58.693 Ni Nickel Transition Metal	29 63.55 Cu Copper Transition Metal	30 65.4 Zn Zinc Transition Metal	31 69.723 Ga Gallium Post-Transition M...	32 72.63 Ge Germanium Metalloid	33 74.92159 As Arsenic Metalloid	34 78.97 Se Selenium Nonmetal	35 79.90 Br Bromine Halogen	36 83.80 Kr Krypton Noble Gas
5	37 85.468 Rb Rubidium Alkali Metal	38 87.62 Sr Strontium Alkaline Earth Me...	39 88.90584 Y Yttrium Transition Metal	40 91.22 Zr Zirconium Transition Metal	41 92.90637 Nb Niobium Transition Metal	42 95.95 Mo Molybdenum Transition Metal	43 96.90636 Tc Technetium Transition Metal	44 101.1 Ru Ruthenium Transition Metal	45 102.9055 Rh Rhodium Transition Metal	46 106.42 Pd Palladium Transition Metal	47 107.868 Ag Silver Transition Metal	48 112.41 Cd Cadmium Transition Metal	49 114.818 In Indium Post-Transition M...	50 118.71 Sn Tin Post-Transition M...	51 121.760 Sb Antimony Metalloid	52 127.6 Te Tellurium Metalloid	53 126.9045 I Iodine Halogen	54 131.29 Xe Xenon Noble Gas
6	55 132.90... Cs Cesium Alkali Metal	56 137.33 Ba Barium Alkaline Earth Me...		72 178.49 Hf Hafnium Transition Metal	73 180.9479 Ta Tantalum Transition Metal	74 183.84 W Tungsten Transition Metal	75 186.207 Re Rhenium Transition Metal	76 190.2 Os Osmium Transition Metal	77 192.22 Ir Iridium Transition Metal	78 195.08 Pt Platinum Transition Metal	79 196.96... Au Gold Transition Metal	80 200.59 Hg Mercury Transition Metal	81 204.383 Tl Thallium Post-Transition M...	82 207 Pb Lead Post-Transition M...	83 208.98... Bi Bismuth Post-Transition M...	84 208.98... Po Polonium Metalloid	85 209.98... At Astatine Halogen	86 222.01... Rn Radon Noble Gas
7	87 223.01... Fr Francium Alkali Metal	88 226.02... Ra Radium Alkaline Earth Me...		104 267.1... Rf Rutherfordium Transition Metal	105 268.1... Db Dubnium Transition Metal	106 269.1... Sg Seaborgium Transition Metal	107 270.1... Bh Bohrium Transition Metal	108 269.1... Hs Hassium Transition Metal	109 277.1... Mt Meitnerium Transition Metal	110 282.1... Ds Darmstadtium Transition Metal	111 282.1... Rg Roentgenium Transition Metal	112 286.1... Cn Copernicium Transition Metal	113 286.1... Nh Nihonium Post-Transition M...	114 290.1... Fl Flerovium Post-Transition M...	115 290.1... Mc Moscovium Post-Transition M...	116 293.2... Lv Livermorium Post-Transition M...	117 294.2... Ts Tennessine Halogen	118 295.2... Og Oganesson Noble Gas
				57 138.9055 La Lanthanum Lanthanide	58 140.116 Ce Cerium Lanthanide	59 140.90... Pr Praseodymium Lanthanide	60 144.24 Nd Neodymium Lanthanide	61 144.91... Pm Promethium Lanthanide	62 150.4 Sm Samarium Lanthanide	63 151.964 Eu Europium Lanthanide	64 157.2 Gd Gadolinium Lanthanide	65 158.92... Tb Terbium Lanthanide	66 162.500 Dy Dysprosium Lanthanide	67 164.93... Ho Holmium Lanthanide	68 167.26 Er Erbium Lanthanide	69 168.93... Tm Thulium Lanthanide	70 173.05 Yb Ytterbium Lanthanide	71 174.9668 Lu Lutetium Lanthanide
				89 227.02... Ac Actinium Actinide	90 232.038 Th Thorium Actinide	91 231.03... Pa Protactinium Actinide	92 238.0289 U Uranium Actinide	93 237.04... Np Neptunium Actinide	94 244.06... Pu Plutonium Actinide	95 243.06... Am Americium Actinide	96 247.07... Cm Curium Actinide	97 247.07... Bk Berkelium Actinide	98 251.07... Cf Californium Actinide	99 252.0830 Es Einsteinium Actinide	100 257.0... Fm Fermium Actinide	101 258.0... Md Mendelevium Actinide	102 259.1... No Nobelium Actinide	103 266.1... Lr Lawrencium Actinide

- Purified a mineral (about ten tons) in about ten years containing actinium (a few milligrams).
- She discovered that the actinium had two decays after she finished the purification, one at 220 KeV corresponding to actinium and the other at 80 KeV of the daughter with half-life of 21 minutes.



- Saw that the activity of the daughter behaved like an alkali as it precipitated with some cesium salts.
- She was doing nuclear chemistry of the highest quality.



Discovery of Francium as a product of alpha decay of actinium in 1939 (Marguerite Perey)

$$^{227}_{89}\mathrm{Ac} \longrightarrow {}^{223}_{87}\mathrm{Fr} + {}^{4}_{2}\alpha$$

Marguerite Perey, Institut du Radium, Paris~1939

Comptes rendus a L'Academie de Sciences, **208**, 87 (1939)
Séance du 9 Janvier 1939

RADIOACTIVITÉ. — *Sur un élément* 87, *dérivé de l'actinium.* Note de M^lle **Marguerite Perey**, présentée par M. Jean Perrin.

Afin de connaître avec précision l'évolution de l'activité du rayonnement β émis par l'actinium privé de ses dérivés, nous en avons suivi l'accroissement, en nous efforçant de mesurer le plus tôt possible après la dernière purification l'activité β propre à l'actinium, avant que celle de ses successeurs intervienne.

...

Nous sommes donc amenée à penser que cet élément *radioactif naturel*, de période 21 minutes, a le numéro atomique 87 et dérive, par rayonnement α, de l'actinium; soit que l'actinium possède un faible embranchement α, ou qu'il soit un mélange de deux isotopes se désintégrant l'un par rayonnement β, l'autre par rayonnement α.

- She was given a fellowship to study her PhD at La Sorbonne. Finished in 1946.
- Professor at Strasbourg, head of Nuclear Chemistry (1949).
- First woman elected as a corresponding member of the French Academy of Sciences (1962).

Veronique Greenwood, “My Great-Great-Aunt Discovered Francium. and It Killed Her.” New York Times Magazine Dec. 3, 2014; photographs provided by Jean Trouchaud.

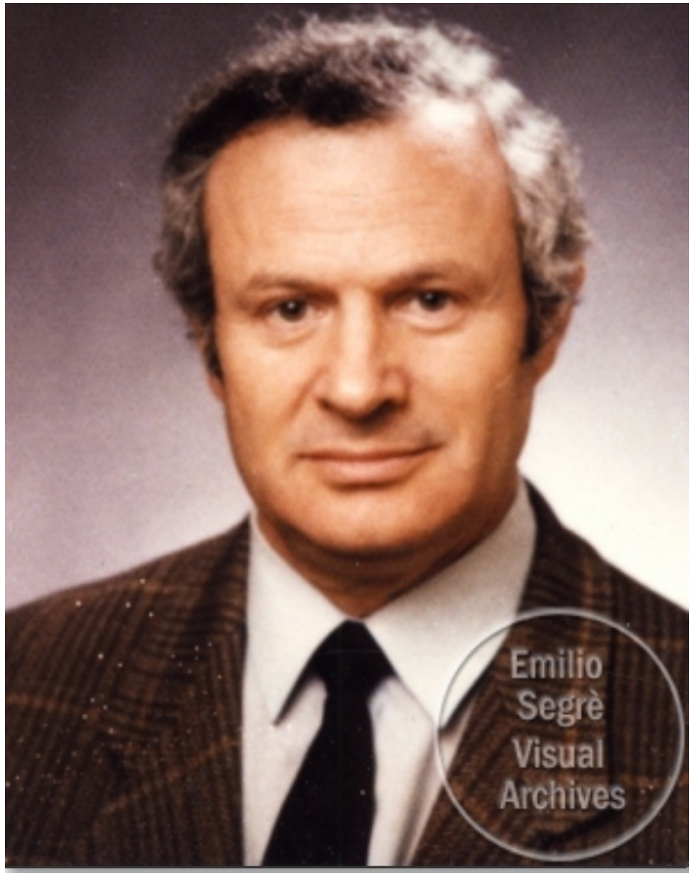
The entrance to atomic physics

SPECTROSCOPIE ATOMIQUE. — *Première mise en évidence d'une transition optique dans l'atome de francium.* Note (*) de Sylvain Liberman, Jacques Pinard, Hong Tuan Duong, Patrick Juncar, Jean-Louis Vialle, Pierre Jacquinot, Membre de l'Académie, Gerhard Huber, François Touchard, Stephan Büttgenbac' Annie Pesnelle, Catherine Thibault, Robert Klapisch et Collaboration ISOLDE.

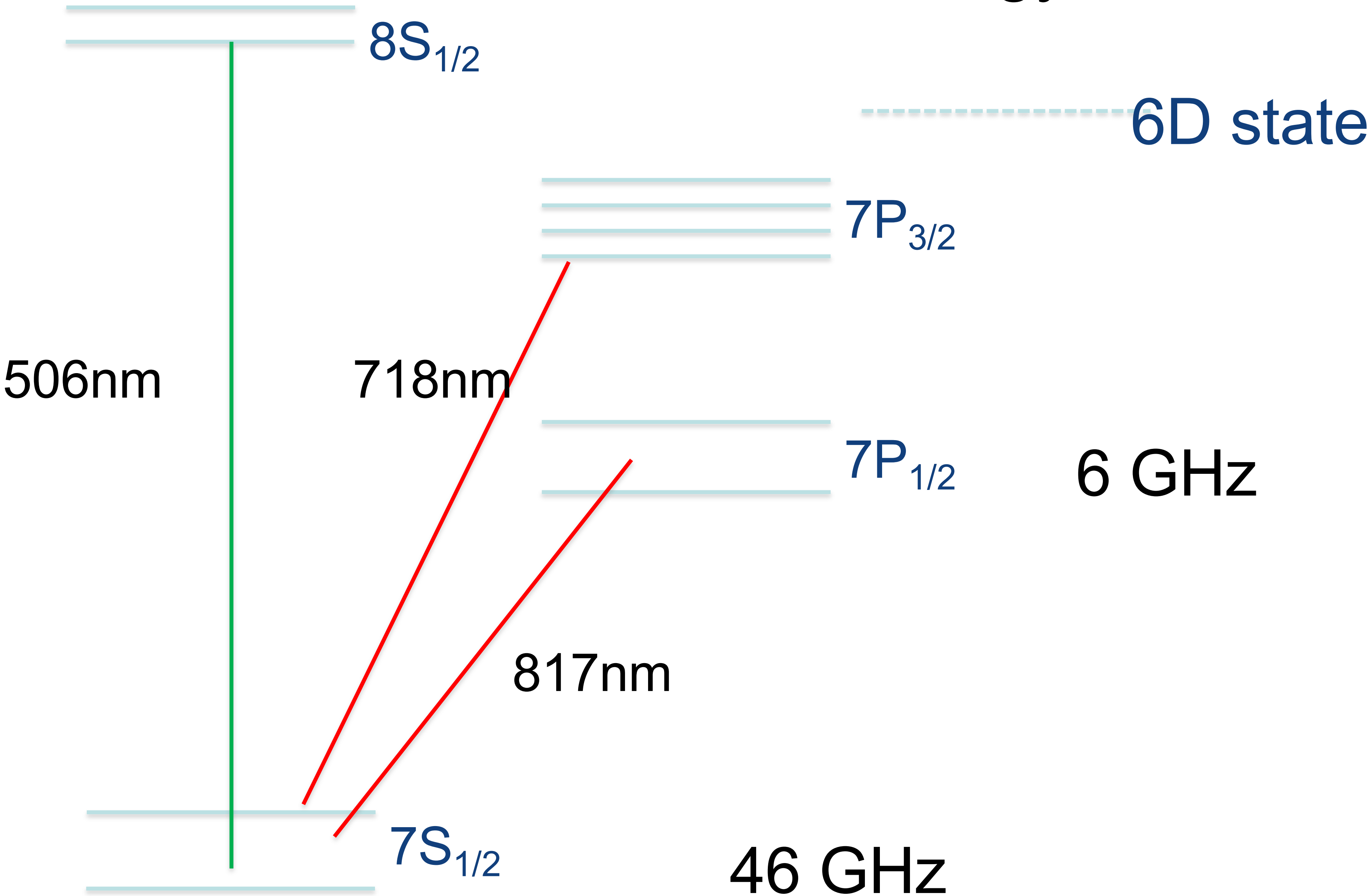
Sylvain Liberman
(1934-1988)

Found the D2 line of Fr (718 nm), working at CERN.

Try to find a Euro coin between Paris and Marseille

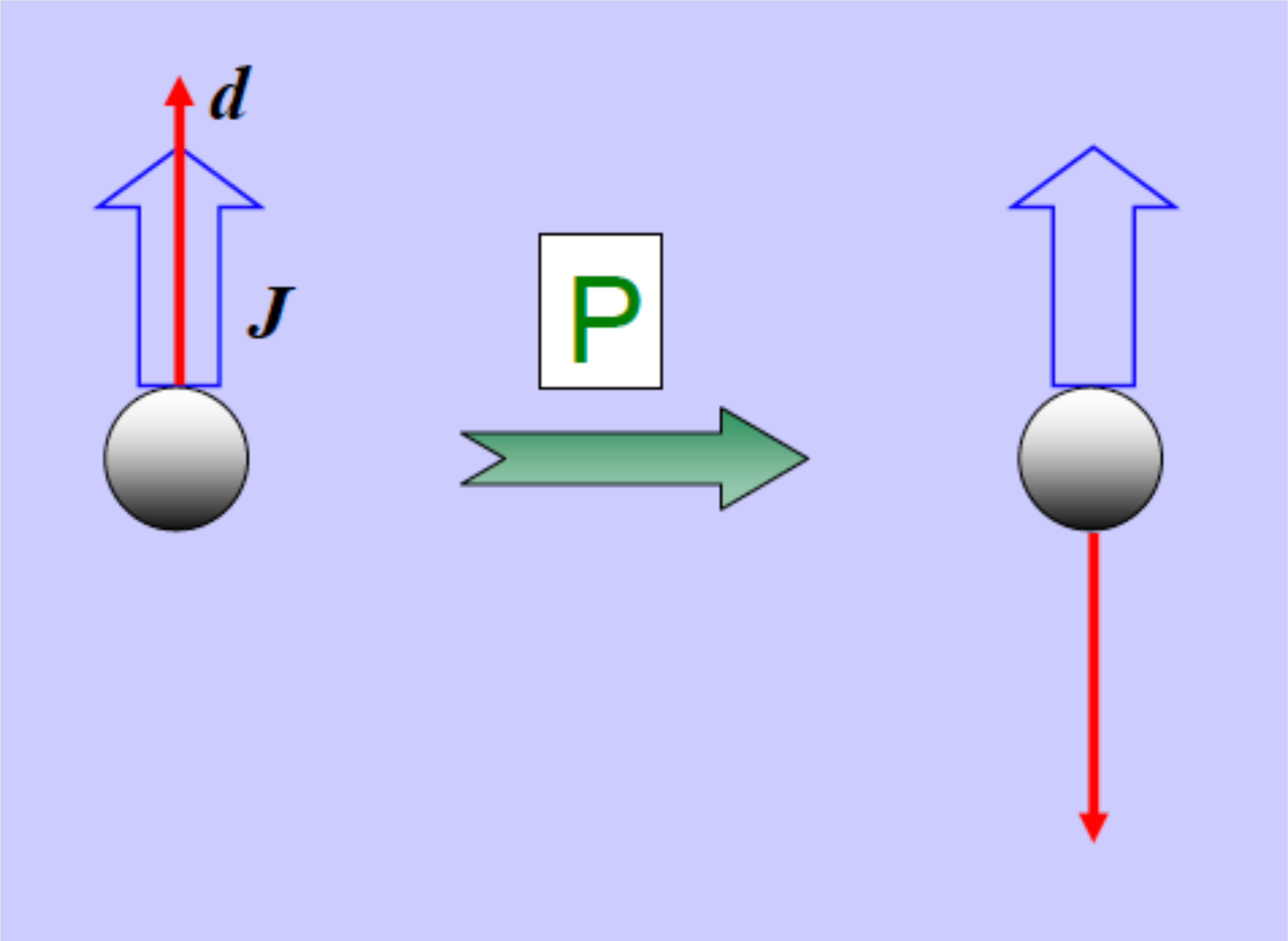


Francium ^{210}Fr Atomic Energy Levels



Weak interaction

- Fermi: Theory of beta decay, the neutrino
- The weak interaction changes the flavor of a particle: a down quark becomes an up quark, converting a neutron into a proton.
- Weinberg Salam: Electroweak unification: Four force carriers three heavy and one light $W^{\pm}$, Z^0, γ
- The inverse process a proton becomes a neutron is the beginning of the solar cycle.
- The weak interaction violates parity (1956)
- The weak interaction violates charge-parity (1964).
- Neutrinos have mass and oscillate (~1990-2010).
- …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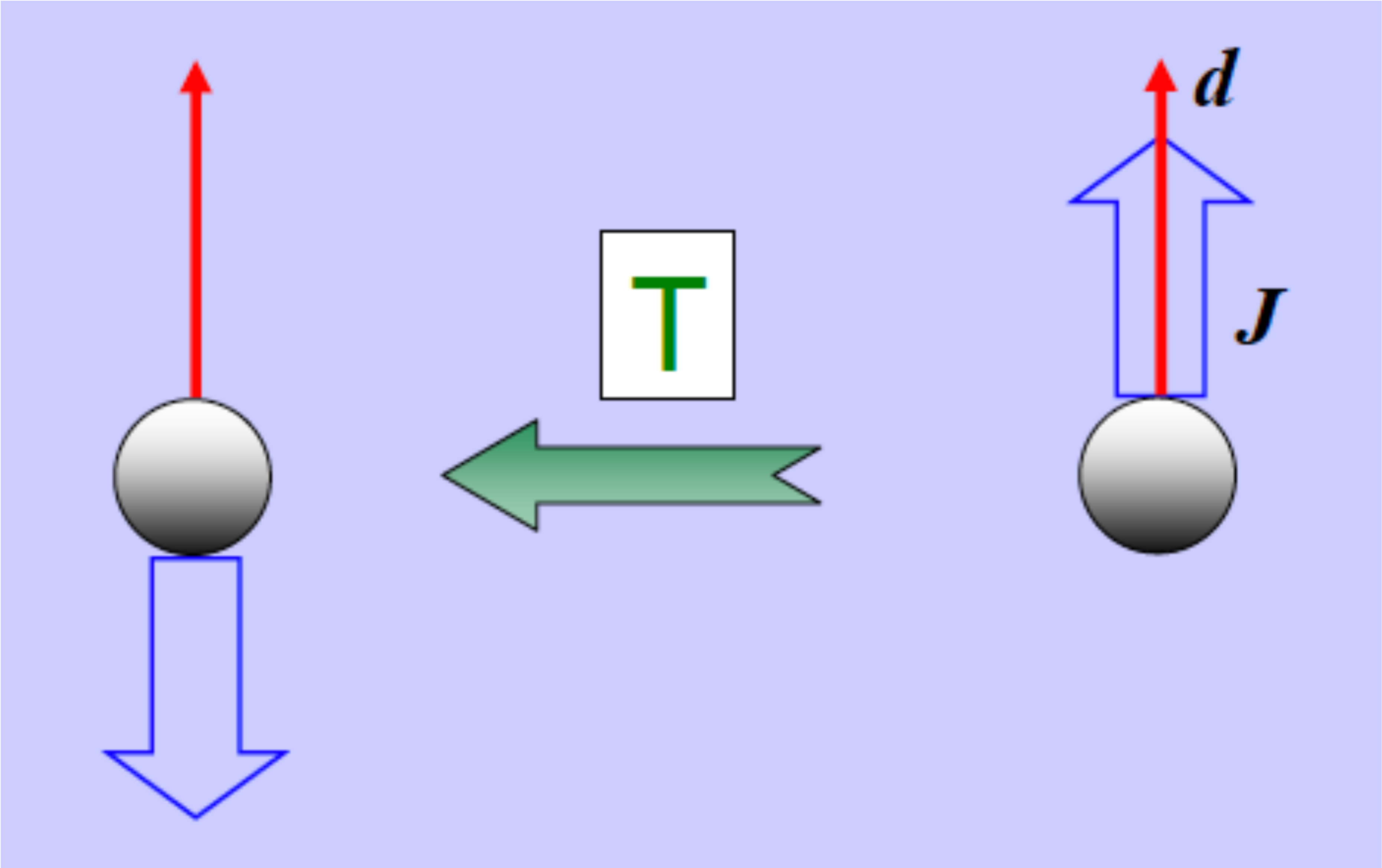

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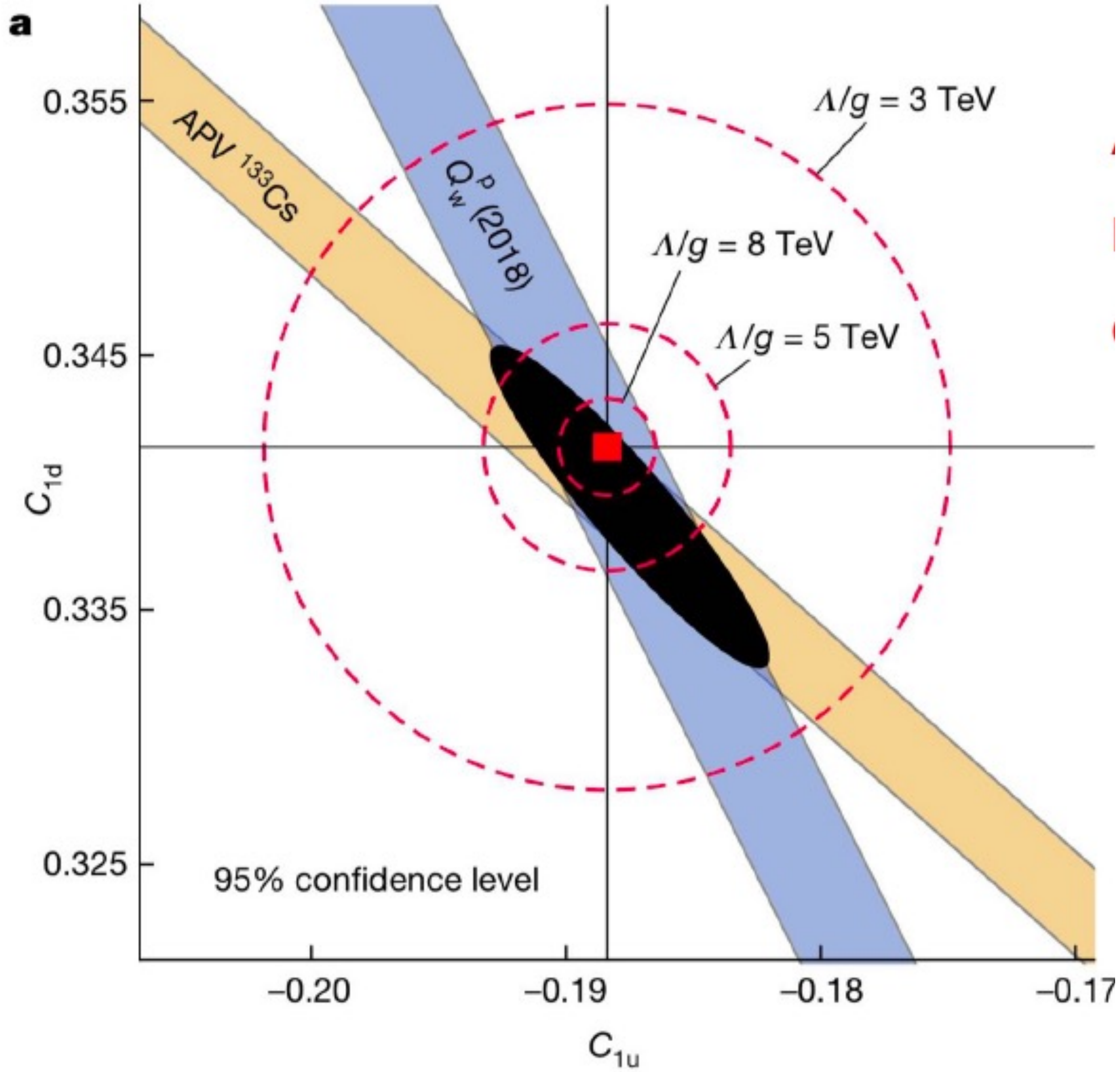
Francium at Stony Brook

Measure Atomic Parity non Conservation and compare to predictions of the SM and study if the weak interaction gets affected by the presence of lots of nucleons.

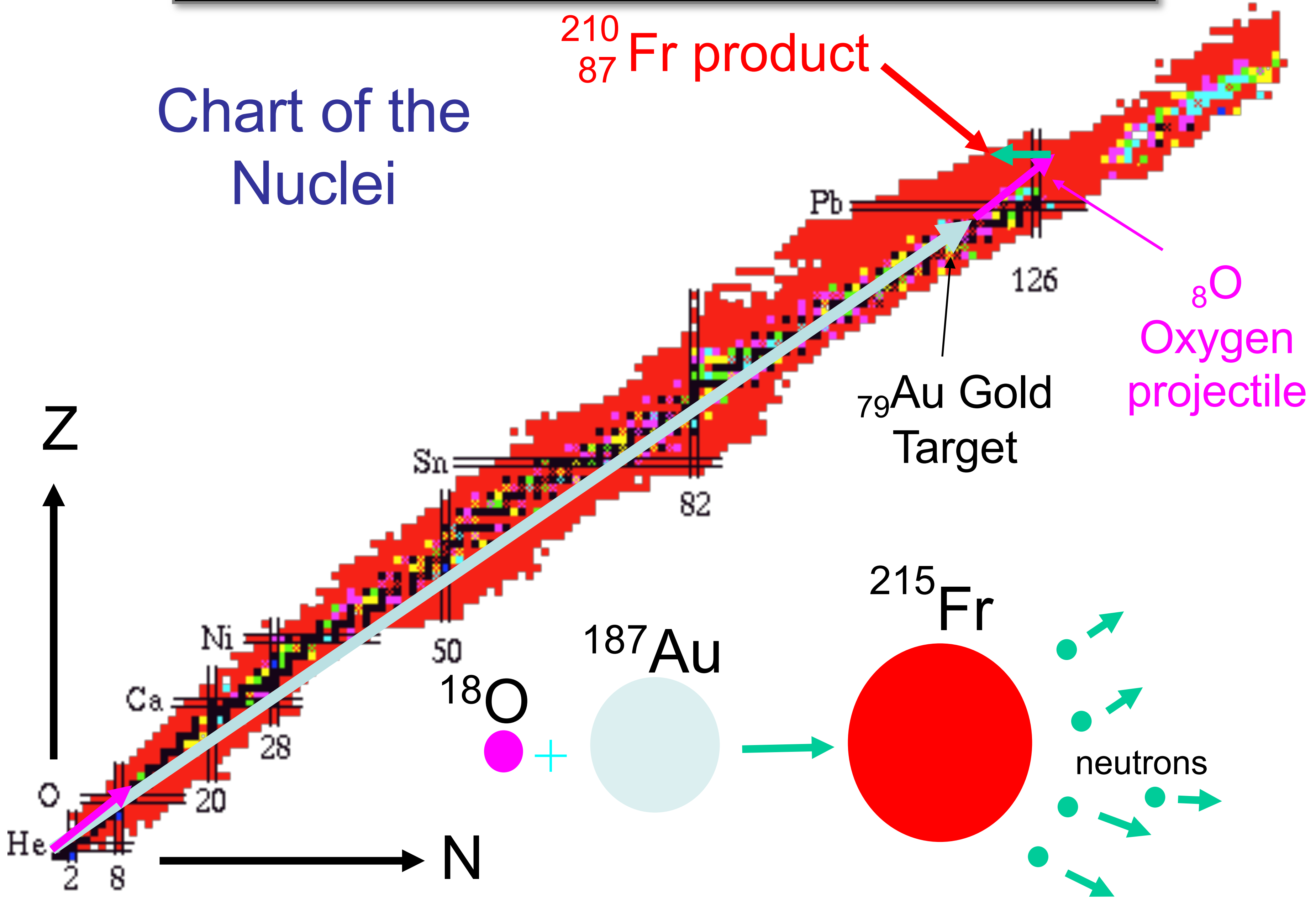
Use a heavy atom as the measurements scale faster than Z^3 and $Z^{8/3}$

Weak PV electron-quark couplings



Q_{weak} 2018

How did we make Fr at Stony Brook ?

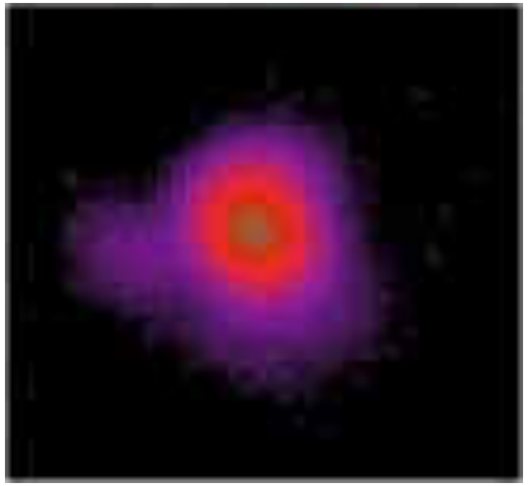


Francium at Stony Brook with Gene D. Sprouse

1991-94: Construction of 1st production and trapping apparatus.

1995: Produced and Trapped Francium in a MOT.

1996-2000: Laser spectroscopy of Francium.



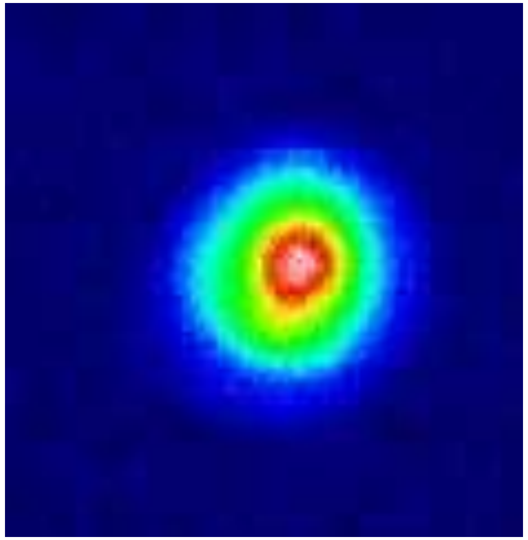
2,000 atoms

2000-2002: High efficiency trap.

2003: Spectroscopy.

2004: Lifetime of 8S level.

2007: Magnetic moment ^{210}Fr .



250,000 atoms

PHYSICAL REVIEW A, VOLUME 62, 052507

Energies and hyperfine splittings of the $7D$ levels of atomic francium

J. M. Grossman,* R. P. Fliller III, T. E. Mehlstäubler,† L. A. Orozco, M. R. Pearson, G. D. Sprouse, and W. Z. Zhao‡
Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800
(Received 5 May 2000; published 12 October 2000)

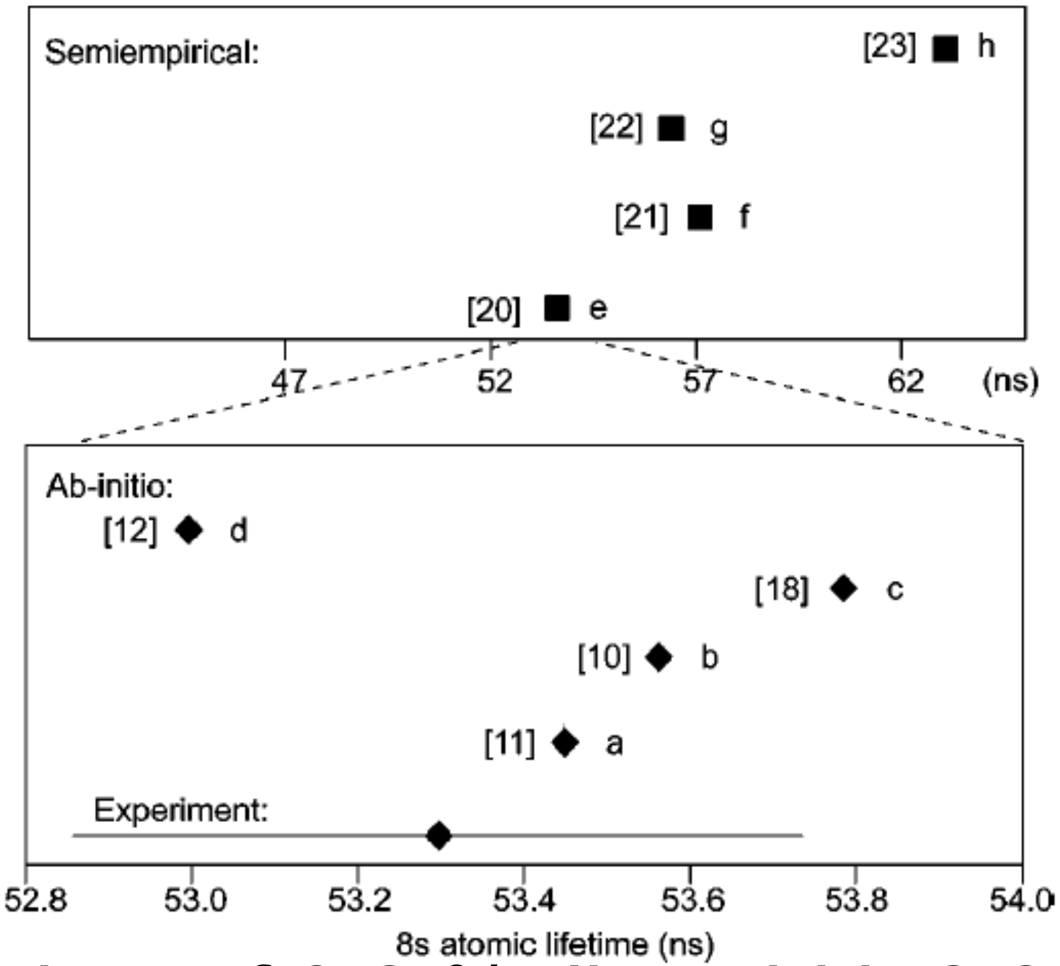
TABLE IV. Comparison of measured and predicted center-of-gravity energy difference to ground state

Source	$E(7D_{3/2})$ (cm^{-1})	$E(7D_{5/2})$ (cm^{-1})
This work	**24 244.831(4)**	**24 333.298(4)**
Ref. [28] (MBPT)	24 235(120)	24 325(120)
Ref. [3] (MBPT)	24186	24275
Ref. [27] (MBPT)	24253	24343
Ref. [29] (second order QDF)	24 244.03(3)	24 332.93(3)
Second-order QDF, using δ from [13]	24 244.070	24 332.766
Third-order QDF, using $E(nD_J)$ from [13]	24 244.303	24 334.211

Theory from 20% (1978) to about $1/10^5$ (2000).

PHYSICAL REVIEW A **71**, 062504 (2005)

Lifetime measurement of the 8*s* level in francium



Uncertainty of 0.8 %, linewidth 2.8 MHz

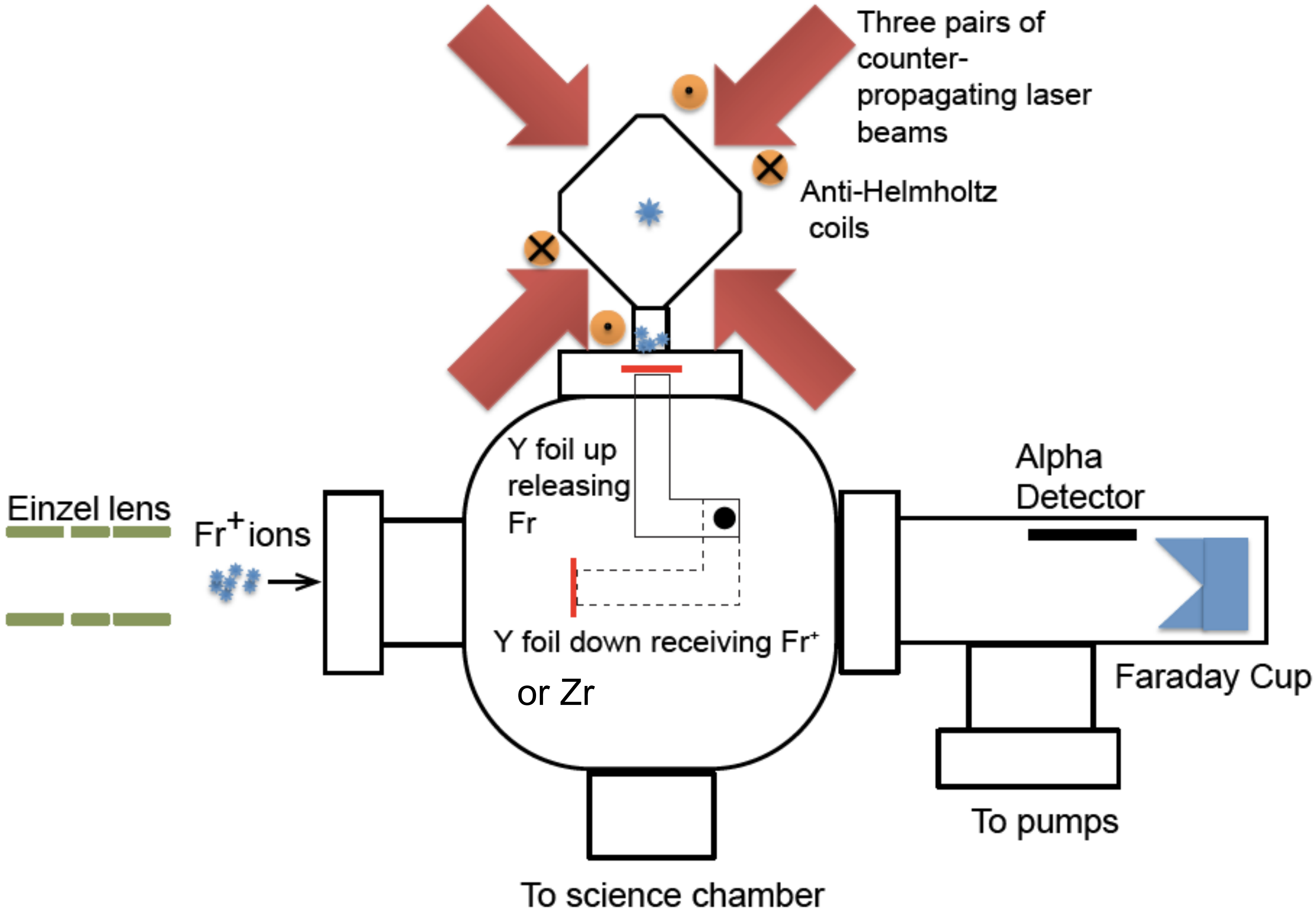
Francium at TRIUMF

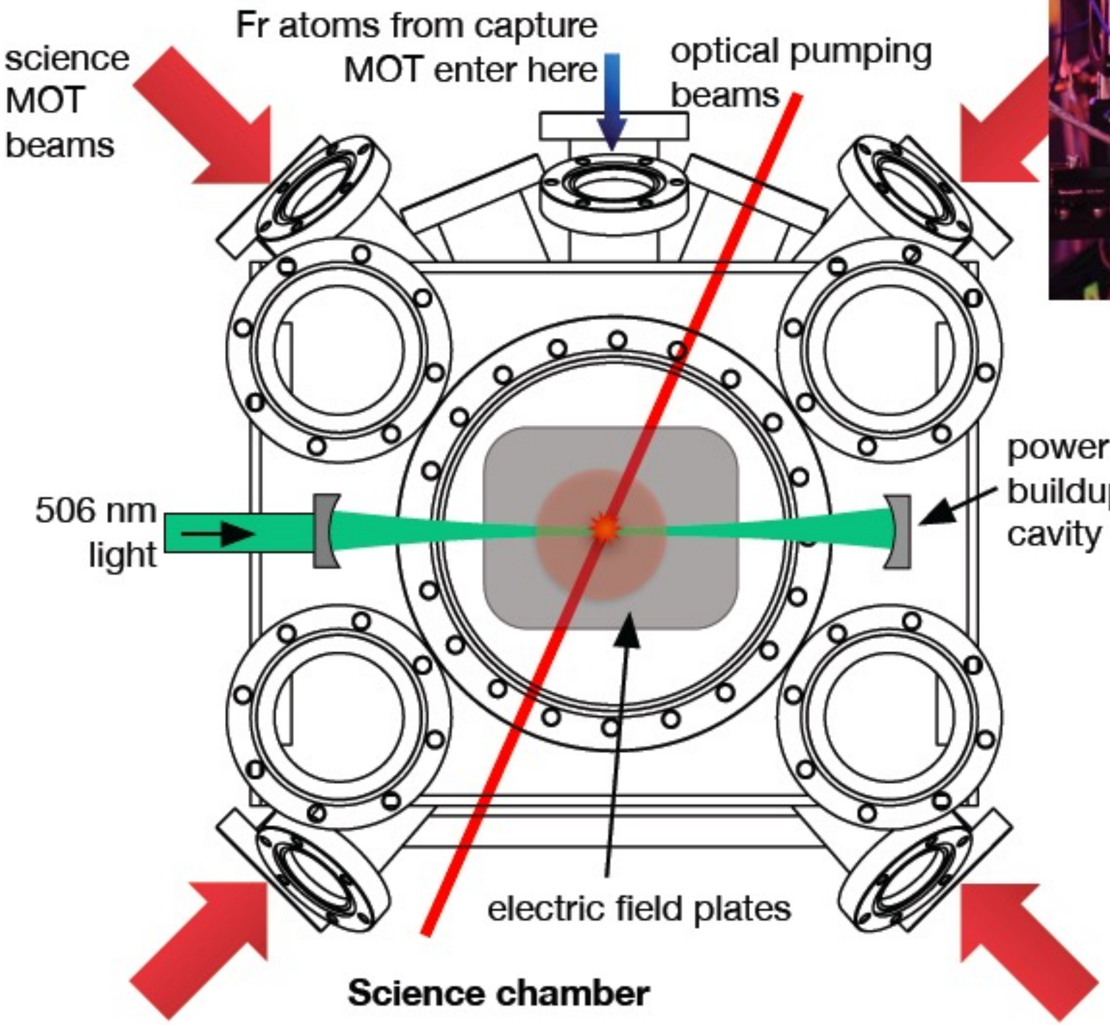
FrPNC Colaboration (Fall-2022)

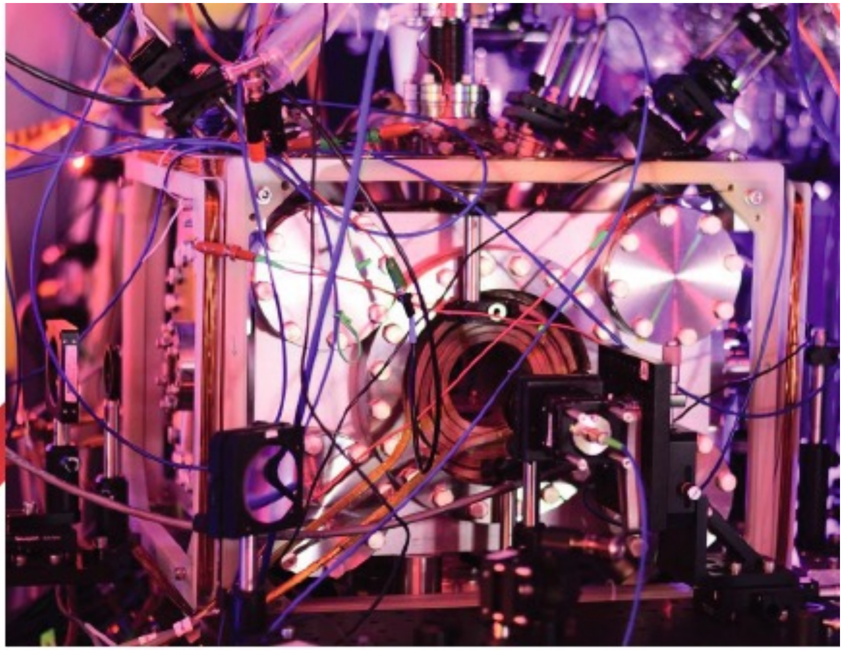
Seth Aubin; College of William and Mary, USA.
John A. Behr, Alexander Gorolov, Andrea Teigelhoefer, Liam Xie ; TRIUMF, Canada.
Victor V. Flambaum; University of New South Wales, Australia.
Eduardo Gómez; Universidad Autónoma de San Luis Potosí, México.
Gerald Gwinner SPOKESPERSON Timothy Hucko, Anima Sharma ; University of Manitoba, Canada.
Luis A. Orozco University of Maryland, USA.

Work has been supported by: NRC, TRIUMF, and NSERC from Canada, DOE, and NSF of USA, y CONACYT from Mexico.

Fr Trapping Facility capture MOT







Coordinate system (handedness)

E_{DC}

B_{DC}

$\sigma^{\pm}$ polarization

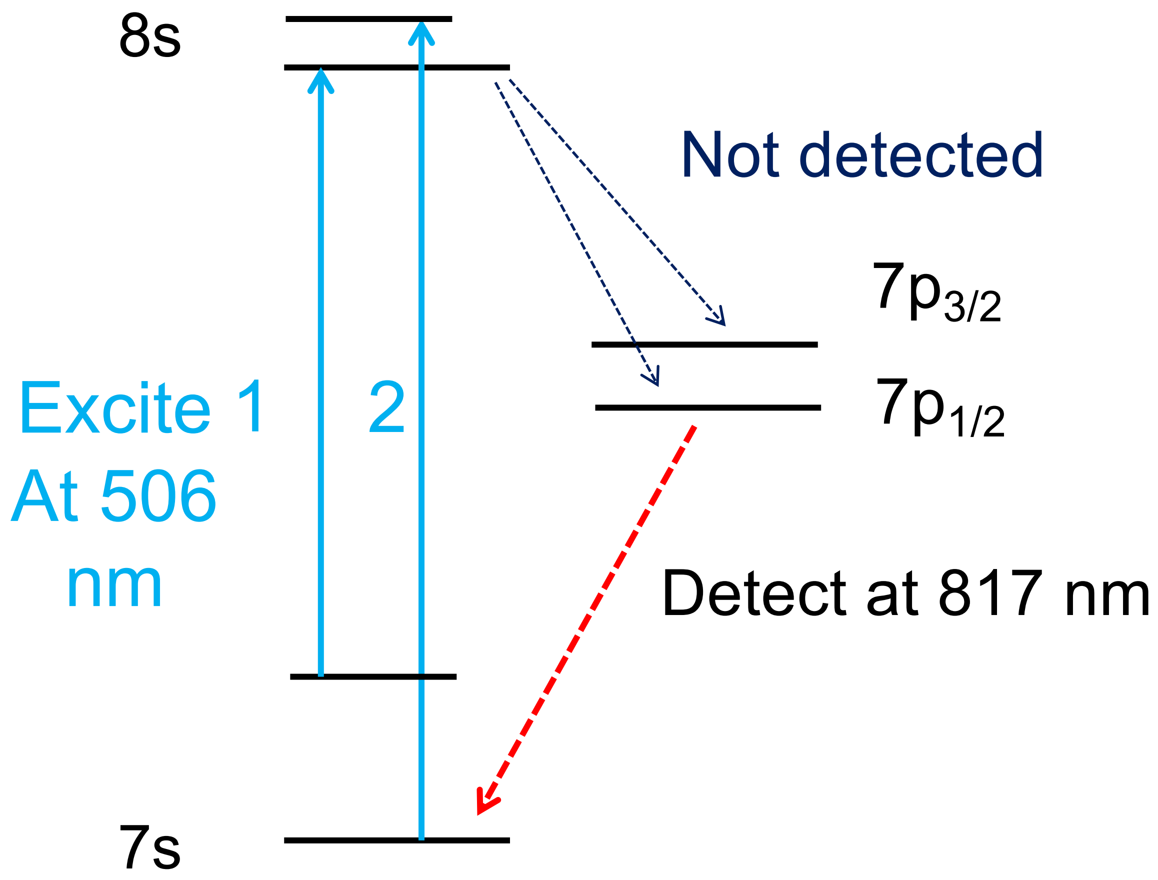
Pseudo scalar ~ $\sigma \cdot \vec{p}$

APNC with Stark-induced 7s → 8s transition in Fr

- Electric dipole forbidden.
- Small transition rate due to PNC effect, and M1 (hyperfine mixing) geometry supressed.
- Use Stark Interference technique.

$$R \propto |A_{stark}+A_{PNC}+A_{M1}|^2 \approx (A_{stark})^2 \pm 2(A_{stark}A_{PNC}^{*})$$

Interference term changes sign upon parity reversal



$$S \approx (R^{+}- R^{-})/ (R^{+}+ R^{-})$$
$$\approx Im(A_{PNC})/(A_{stark})$$

Average of 1 and 2: nuclear spin independent APNC

The apparatus:

We need a system of coordinates.

The observable (pseudoscalar, P odd, T even).

$$\vec{S} \cdot \vec{E} \times \vec{B}$$

E Electric Field for Stark Mixing

B Magnetic Field (needs to resolve the m sublevels)

S polarization of excitation light

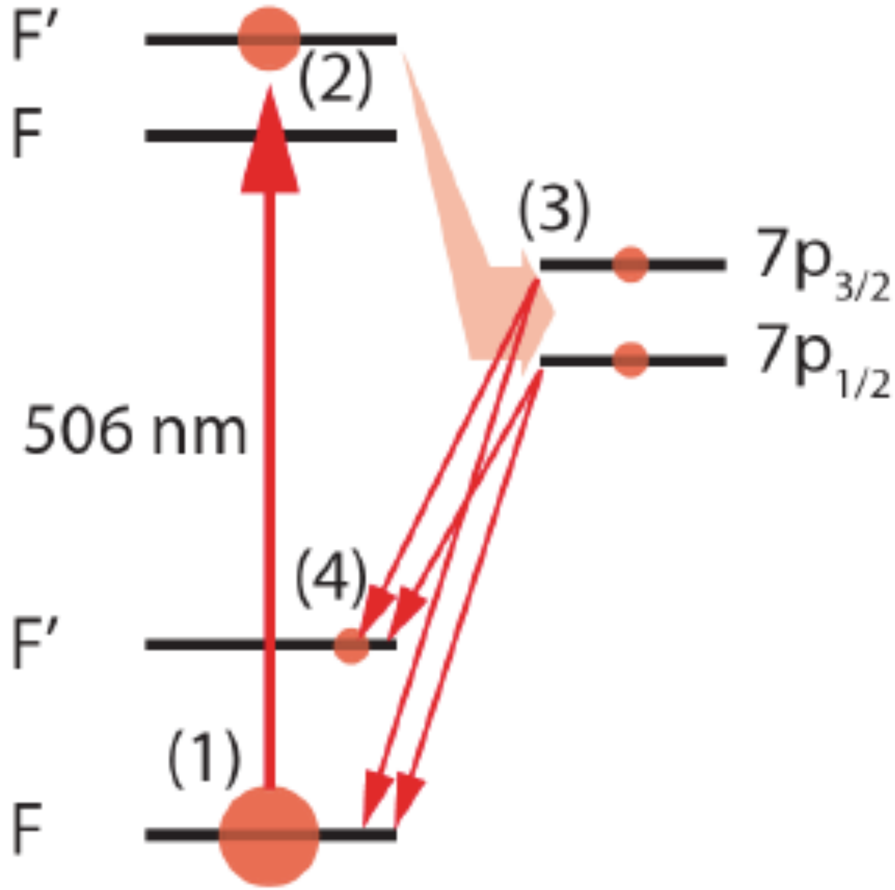
The M1 transition between 7S and 8S

How we measure M1?

$\overline{|8s>} = |8s + \varepsilon p>$

$|E1_{Stark} + M1 + E1_{PNC}|^2$

$\overline{|7s>} = |7s + \varepsilon p>$



Geometry that suppresses $E1_{PNC}$

transition rate proportional to:

$$|E1_{Stark} + M1|^2 = |E1_{Stark}|^2 + 2\mathrm{Re}(E1_{Stark} \cdot M1) + |M1|^2$$

$$E1_{Stark} \sim \beta\, E_{DC}$$

M1 has two contributions: HF mixing and relativistic.

$$R_{7s-8s} = \frac{2}{c\epsilon_0 \hbar^2} \tau I |A_{\text{Stark}} + A_{\text{PV}} + A_{M1}|^2$$

I is the intensity of the electric field (laser in the cavity)

$$\vec{\epsilon} = \epsilon \hat{x}$$

$$A_{\text{Stark}} = i\beta(\vec{E} \times \vec{\epsilon}) \langle F' M'_F | \vec{\sigma} | F M_F \rangle$$

DC Field: $\vec{E} = E\hat{z}$, Polarization $\vec{\epsilon} = \epsilon \hat{x}$

By geometry A_{PV} is not accessible

M1 must be between the same N states:

$$A_{M1} = M(\hat{k} \times \hat{\epsilon}) \langle F' M'_F | \vec{\sigma} | F M_F \rangle$$

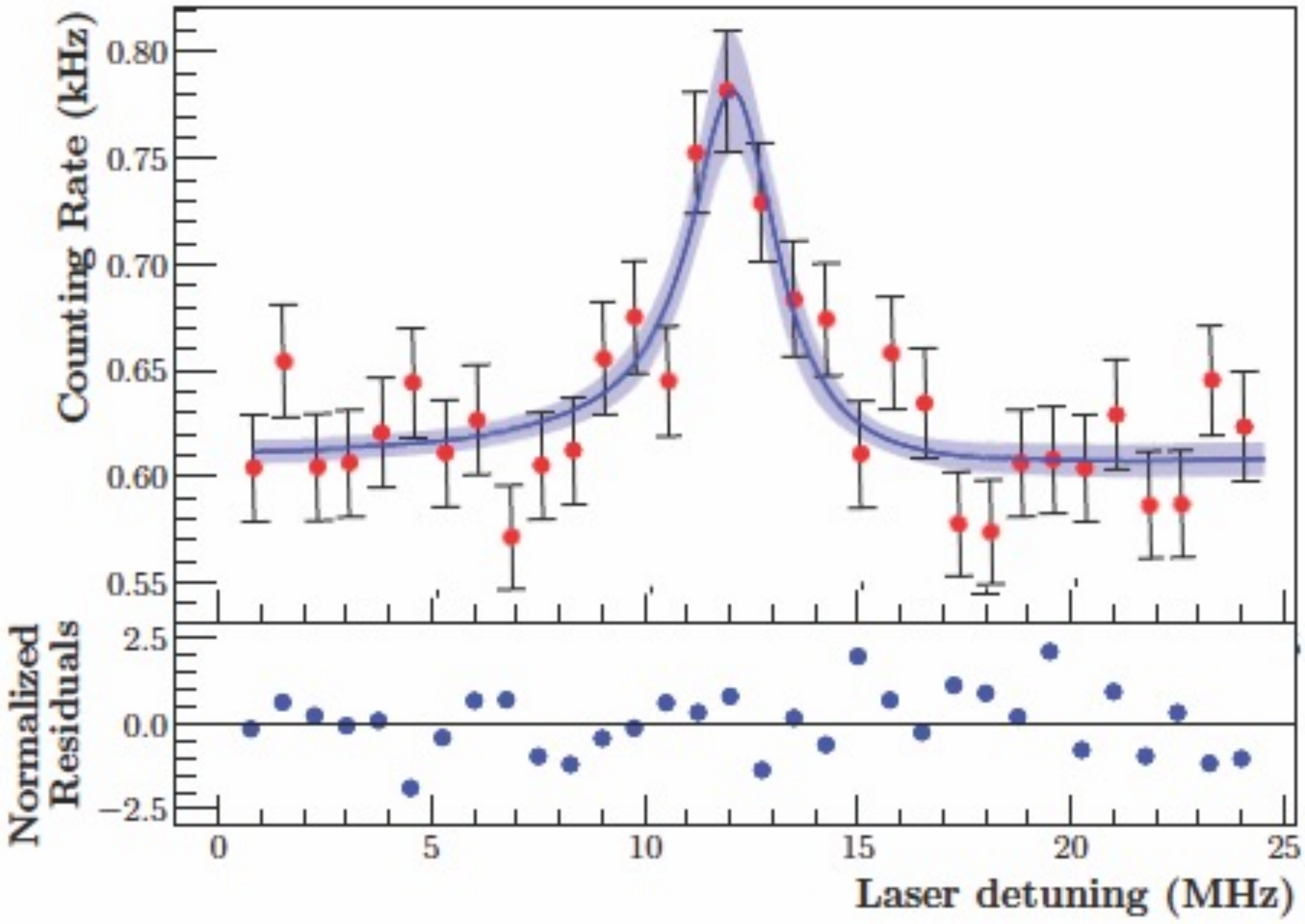
However, thanks to hyperfine mixing of levels:

$$M_{hf} = \frac{\sqrt{\Delta E_{hf}^{7s} \Delta E_{hf}^{8s}}}{E_{7s} - E_{8s}} \frac{\mu_B}{c}$$

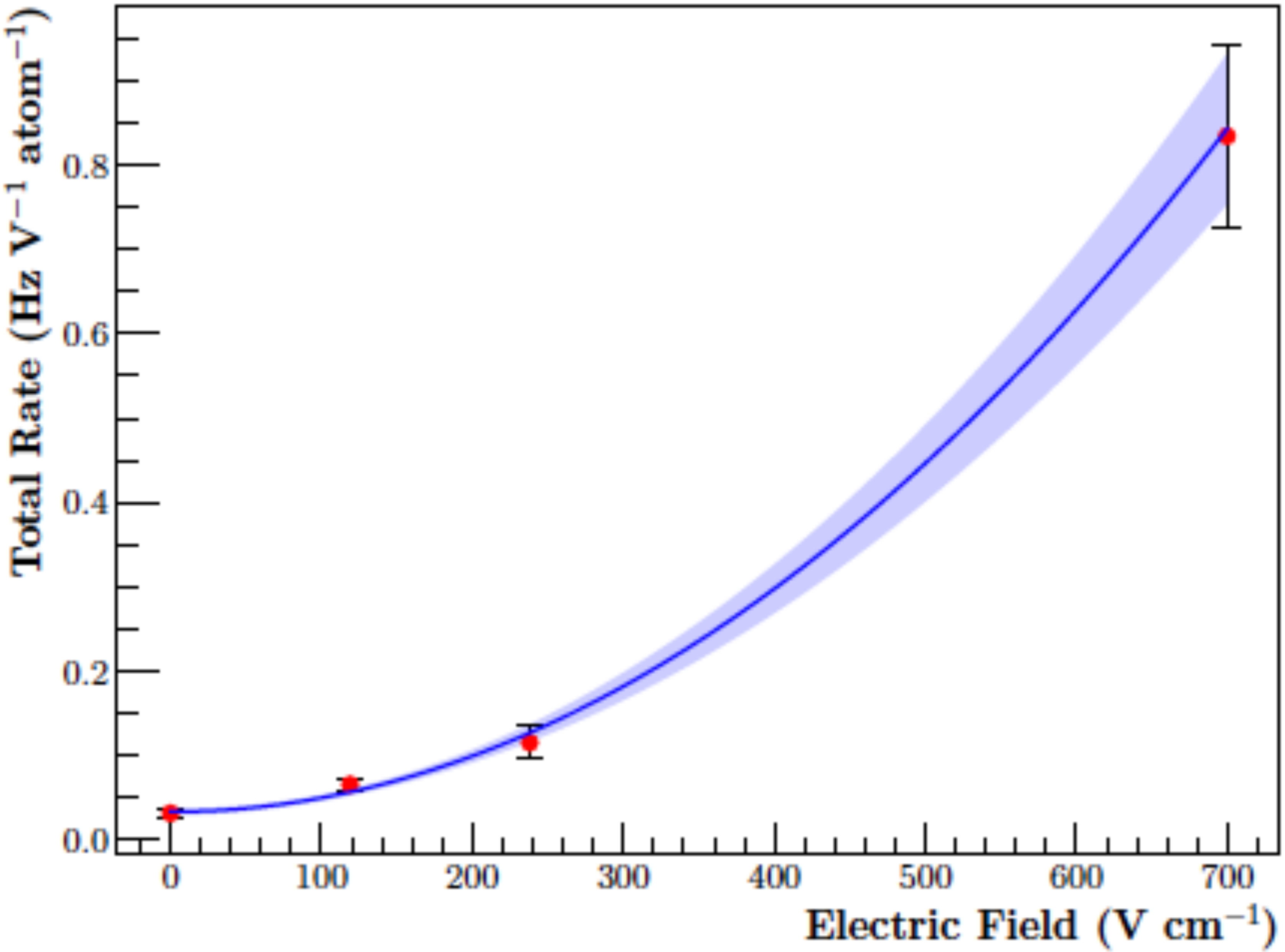
The rate depends on the applied electric field (βE_{DC}) vector polarizability

$$R_{7s-8s} = \frac{2}{c\epsilon_0 \hbar^2} \tau I [\beta^2 E^2 \epsilon^2 + (M_{\text{rel}} \pm M_{\text{hf}} \delta_{FF' \pm 1})^2 \epsilon^2] \cdot | \langle F' M'_F | \vec{\sigma} | F M_F \rangle |^2.$$

Signal at a 0 V/cm in ^{211}Fr 7S, F=5 → 8S, F=4



Signal as a function of the DC electric field



Errors:

Statistics: counting (dominates)

Systematic: hyperfine saturation

Based on the total rate.

Extrapolate to zero electric field (quadratic dependence) to get $M1/\beta$

$M1/\beta = 143 \pm 11$ V/cm
$\beta = (74.3 \pm 0.7) a_0^3$
$M_{HF} = 3.45 \times 10^{-5}\ \mu_B/c$

The relativistic value is :
$M_{rel} = (53 \pm 4) \times 10^{-5}\ \mu_B/c$
M_{rel} reduced $= (130 \pm 10) \times 10^{-5}\ \mu_B/c$
Mrel calculated $= 137.4 \times 10^{-5}\ \mu_B/c$ Safranova 2017

TABLE I. A comparison of the relativistic component for the Fr $7s-8s$ reduced $M1$ matrix element between theory and experimental values.

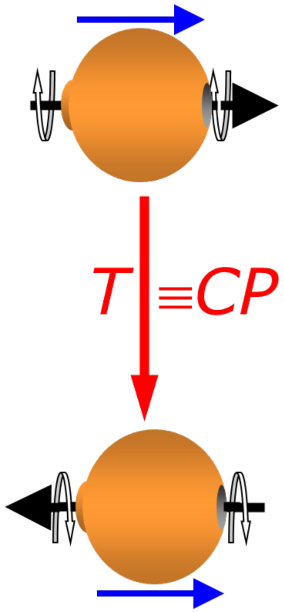
References	$M_{\mathrm{rel}}(\times 10^{-5}\mu_{\mathrm{B}}/\mathrm{c})$
Theory	
Savukov *et al.*[13], 1999	113
Gossel *et al.*[12], 2013	176.5
Safronova *et al.*[11], 2017	No Breit: 139.9
	Breit: 137.4
Experimental	
This work	130 ± 10

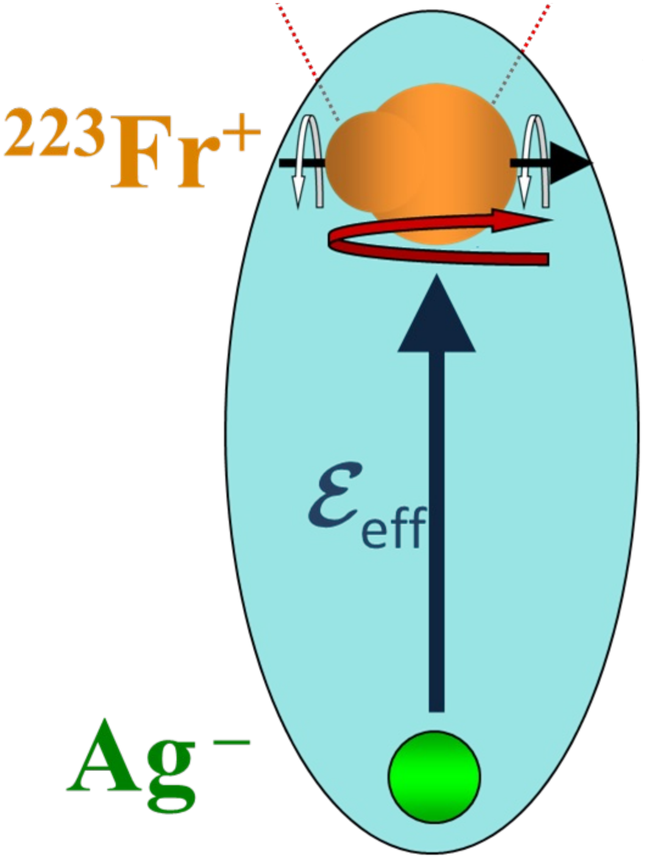
A possible future avenue

10^4x gain on the proton EDM ssensitivity, related to the Shift moment.

Use ^{223}Fr with octupolar nuclear deformation

Use molecules ^{223}FrAr





S2139LOI: Fr molecules:

Goal:

Improve the sensitivity to a CP violating proton Schiff moment / EDM, using ^{223}FrAg.

Team:

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Thanks

Bibliography:

G Gwinner and, L. A. Orozco, "Studies of the weak interaction in atomic systems: Towards measurements of atomic parity non-conservation in francium," Special Issue on, "Quantum sensors for new-physics discoveries." Quantum Science and Technology **7**, 024001 (2022).