Laser Trapping and Probing of Exotic Helium Isotopes

Peter Müller

Argonne NATIONAL LABORATORY

... for a brighter future

U.S. Department of Energy

UChicago Argonne LLC

Office of Science
U.S. DEPARTMENT OF ENERGY

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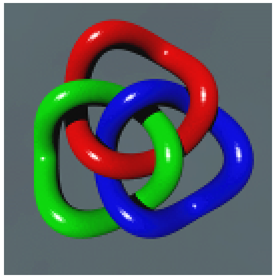
Outline

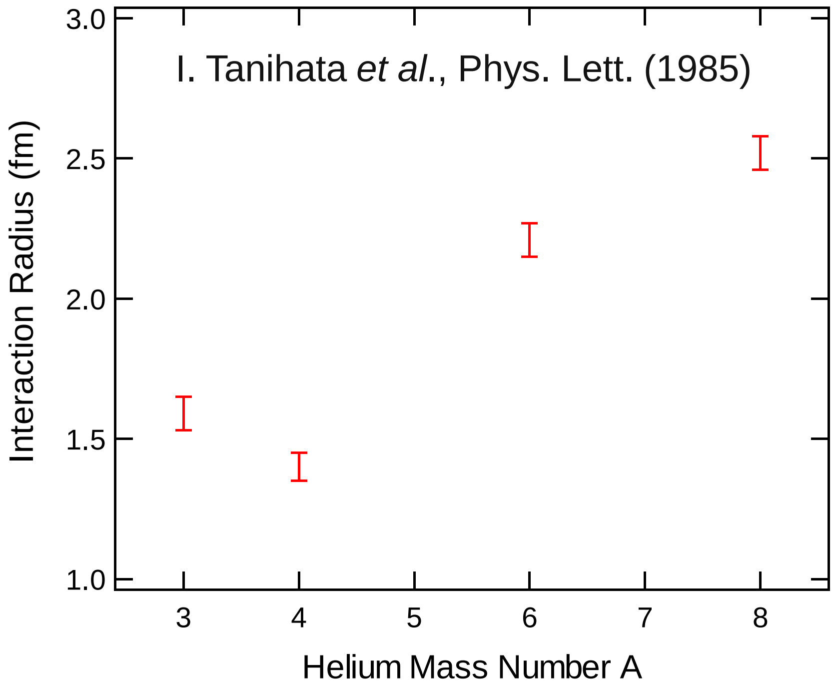
- Nuclear Charge Radii of ^{8}He
- Beta-neutrino correlation study of ^{6}He
- Laser Spectroscopy at CARIBU

Neutron Halo Nuclei ^{6}He and ^{8}He

Isotope	Half-life	Spin	Isospin	Core + Valence
He-6	807 ms	0^+	1	α + 2n
He-8	119 ms	0^+	2	α + 4n



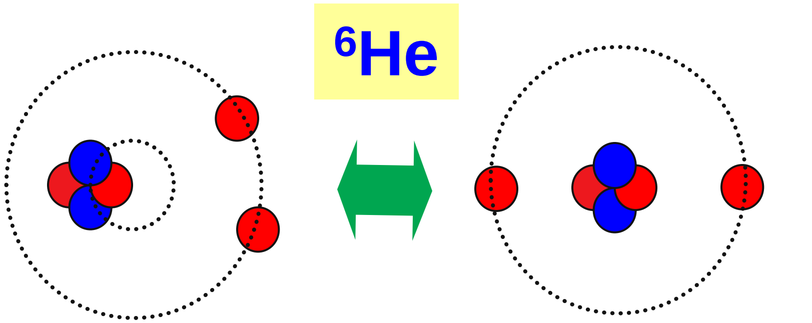
Borromean



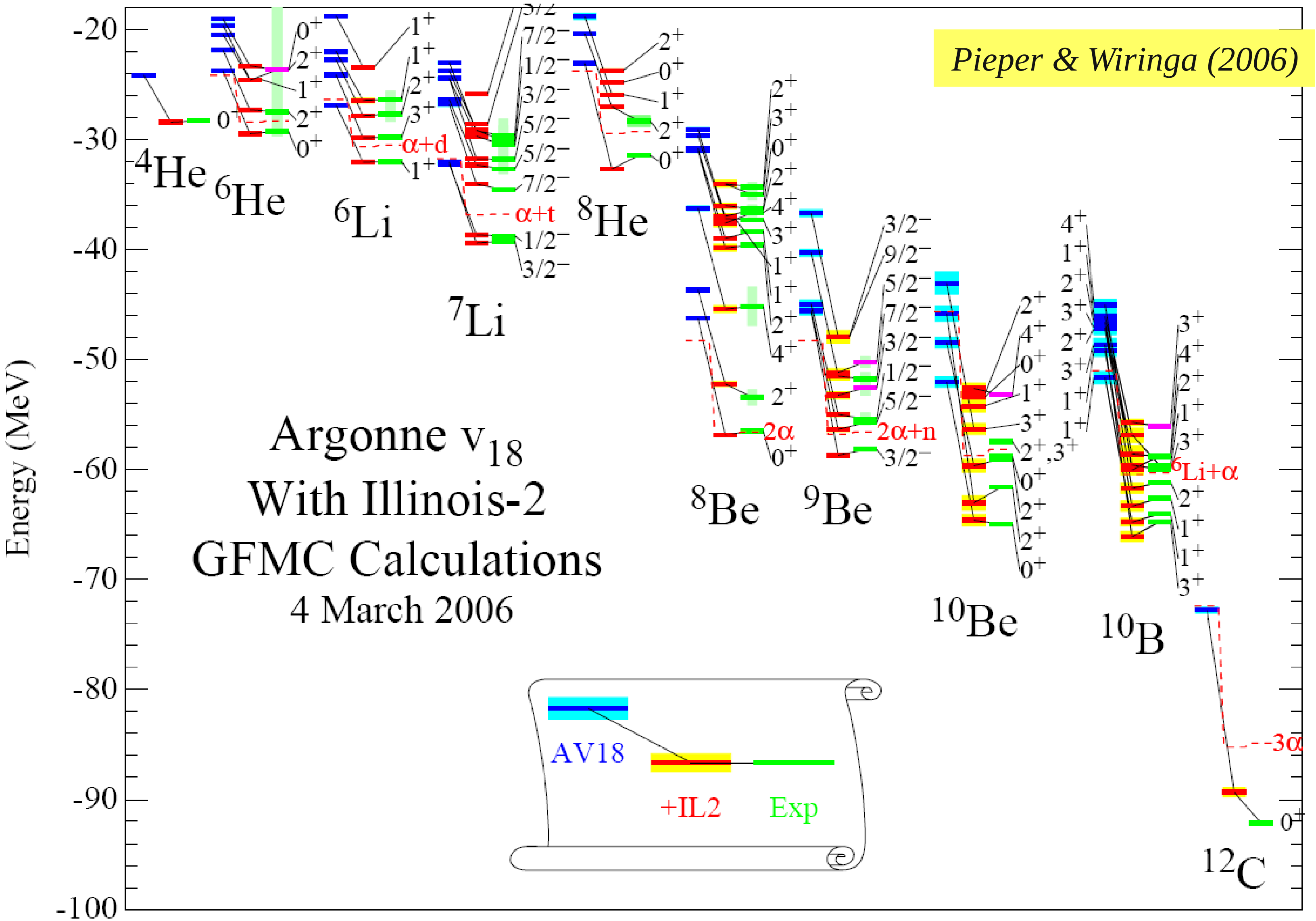
Core-Halo Structure

$$\sigma_I(6He) - \sigma_I(4He) = \sigma_{-2n}(6He)$$

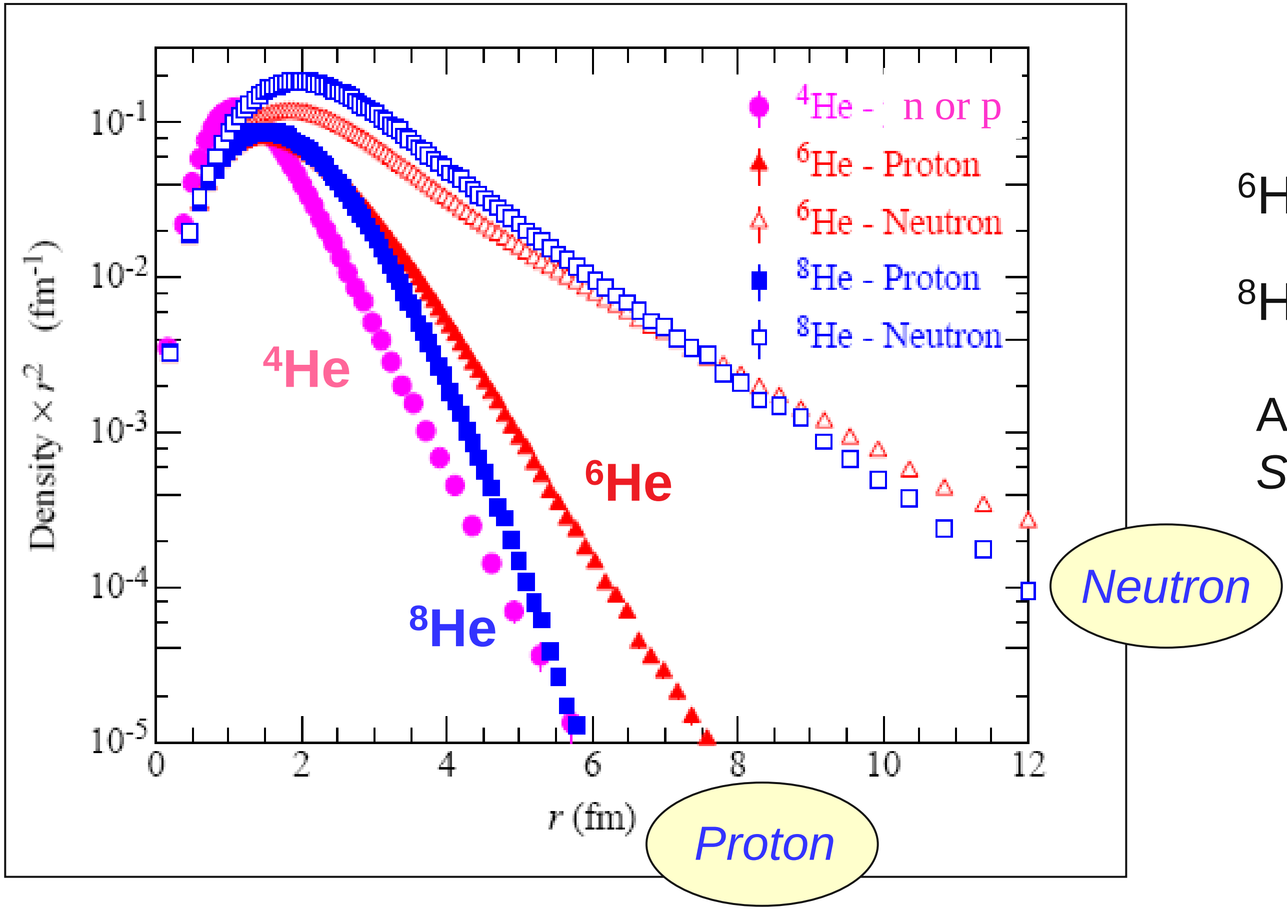
I. Tanihata *et al*., Phys. Lett. (1992)



Green's Function Monte Carlo



GFMC – Neutron and Proton Densities in Helium-4,6,8



$\sqrt{<r^2>}_{pp}$

^{6}He: 1.92(4) fm

^{8}He: 1.82(2) fm

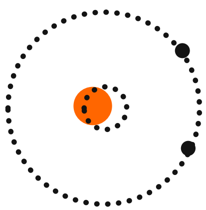
Av18+IL7
S. Pieper 2007

Atomic Isotope Shift

Isotope Shift $\delta\nu = \delta\nu_{MS} + \delta\nu_{FS}$

Mass shift:

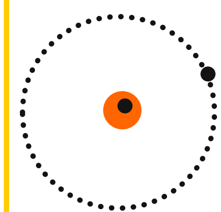
due to nucleus recoil



$$\delta\nu_{MS} \propto \frac{A - A'}{AA'}$$

Field shift:

due to nucleus size



$$\delta\nu_{FS} \propto Z \times \Delta[\Psi(0)]^2 \times \delta\langle r^2\rangle$$

For $2^3S_1 - 3^3P_2$ transition @ 389 nm:

$$\delta\nu = \delta\nu_{MS} + C_{FS} \; \delta\langle r^2\rangle$$

^{6}He - ^{4}He : $\delta\nu_{6,4}$ = 43196.202(16) MHz + 1.008 ($\langle r^2\rangle_{He4}$ - $\langle r^2\rangle_{He6}$) MHz/fm^2

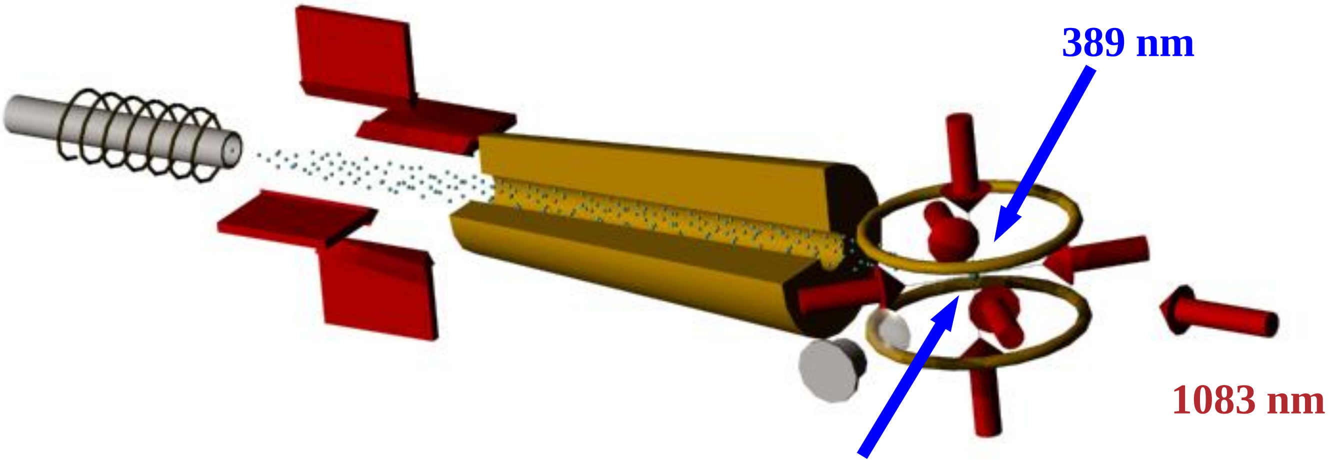
^{8}He - ^{4}He : $\delta\nu_{8,4}$ = 64702.519(1) MHz + 1.008 ($\langle r^2\rangle_{He4}$ - $\langle r^2\rangle_{He8}$) MHz/fm^2

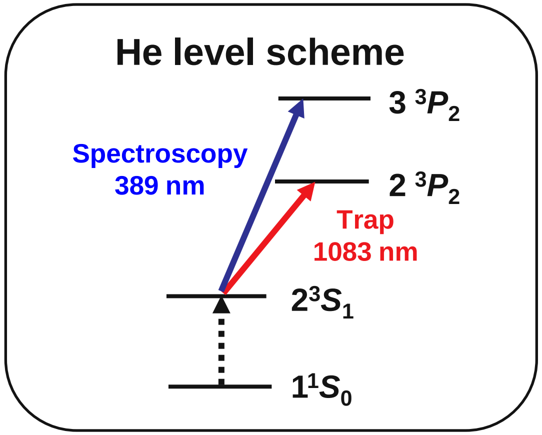
G.W.F. Drake, Univ. of Windsor, *Nucl. Phys. A737c, 25 (2004)*

100 kHz error in IS ←→ ~ 1% error in radius

Atom Trapping of ^{6}He & ^{8}He at GANIL

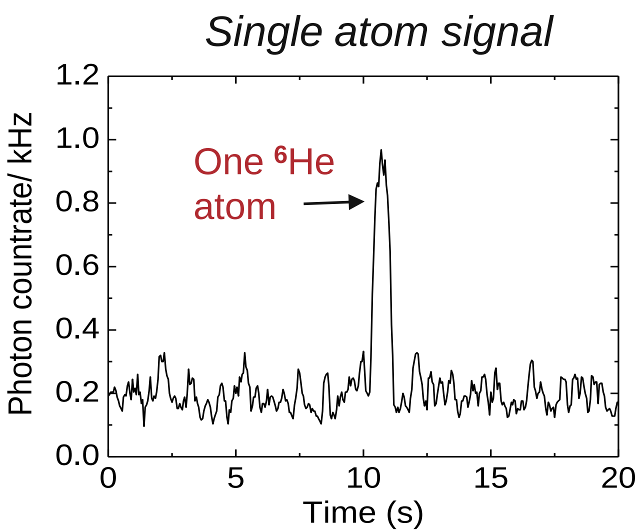
Atom Trap Setup



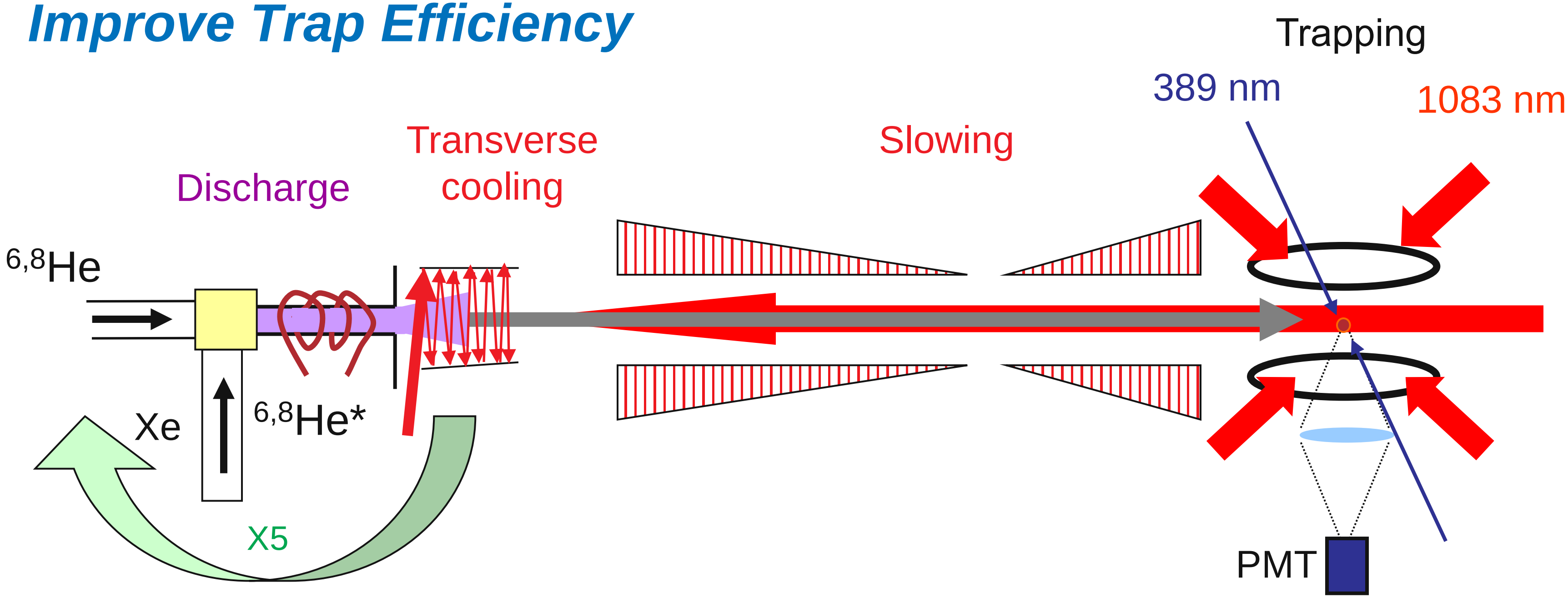


Helium Rates

	^{6}He	^{8}He
@ source	$5 \times 10^{7}\ s^{-1}$	$1 \times 10^{5}\ s^{-1}$
Efficiency = 1×10^{-7}		
@ trap	$5\ s^{-1}$	$30\ hr^{-1}$



Improve Trap Efficiency



7x10^{-5} • 0.2 • 0.5 • 0.28 = **2x10^{-6}**

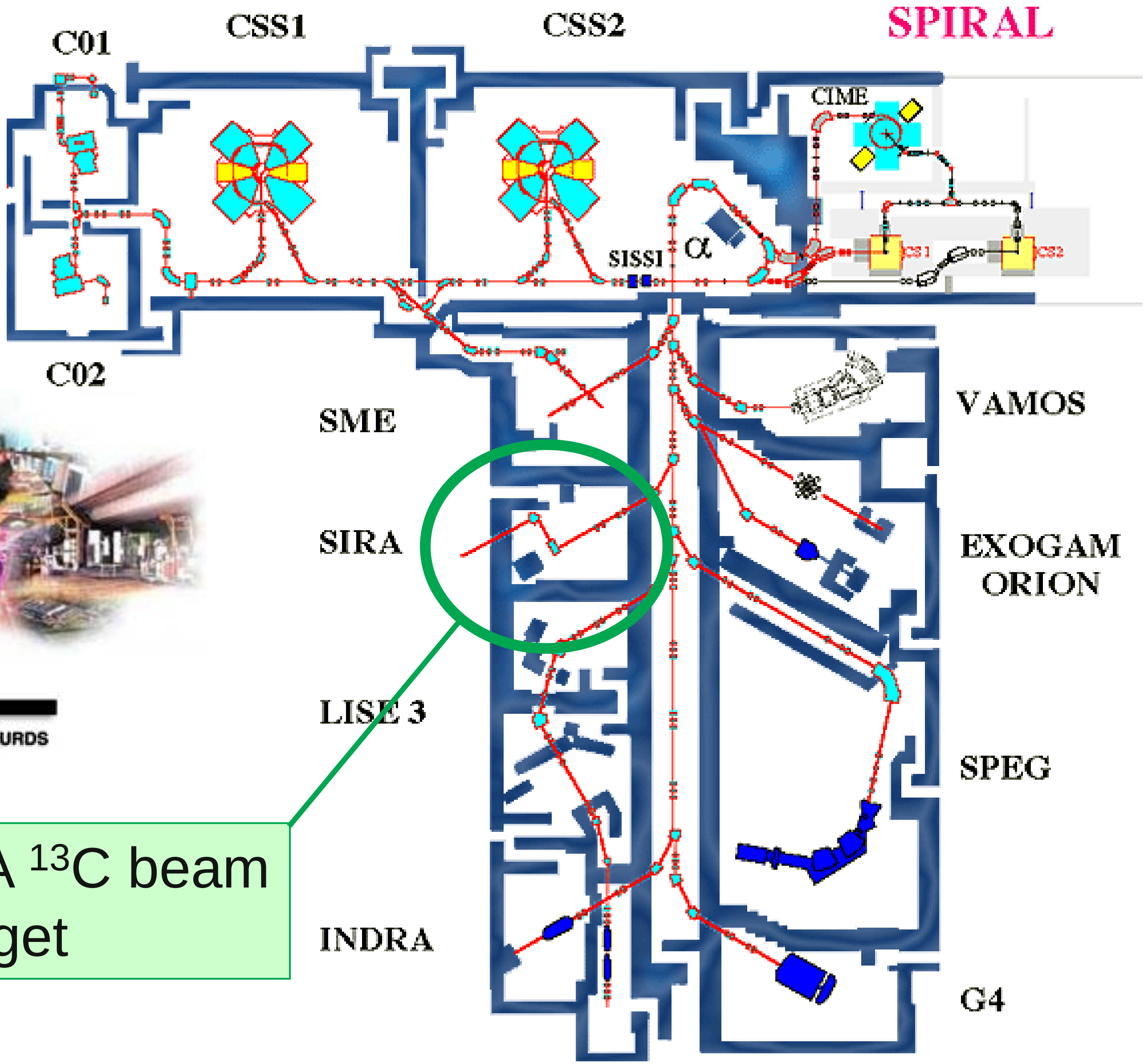
X1.4 X10 X1.4

- Use xenon discharge x 1.4
- More laser power 0.5 W->4 W x 3.5
- Longer transverse cooling x 4

for ^{6}He !

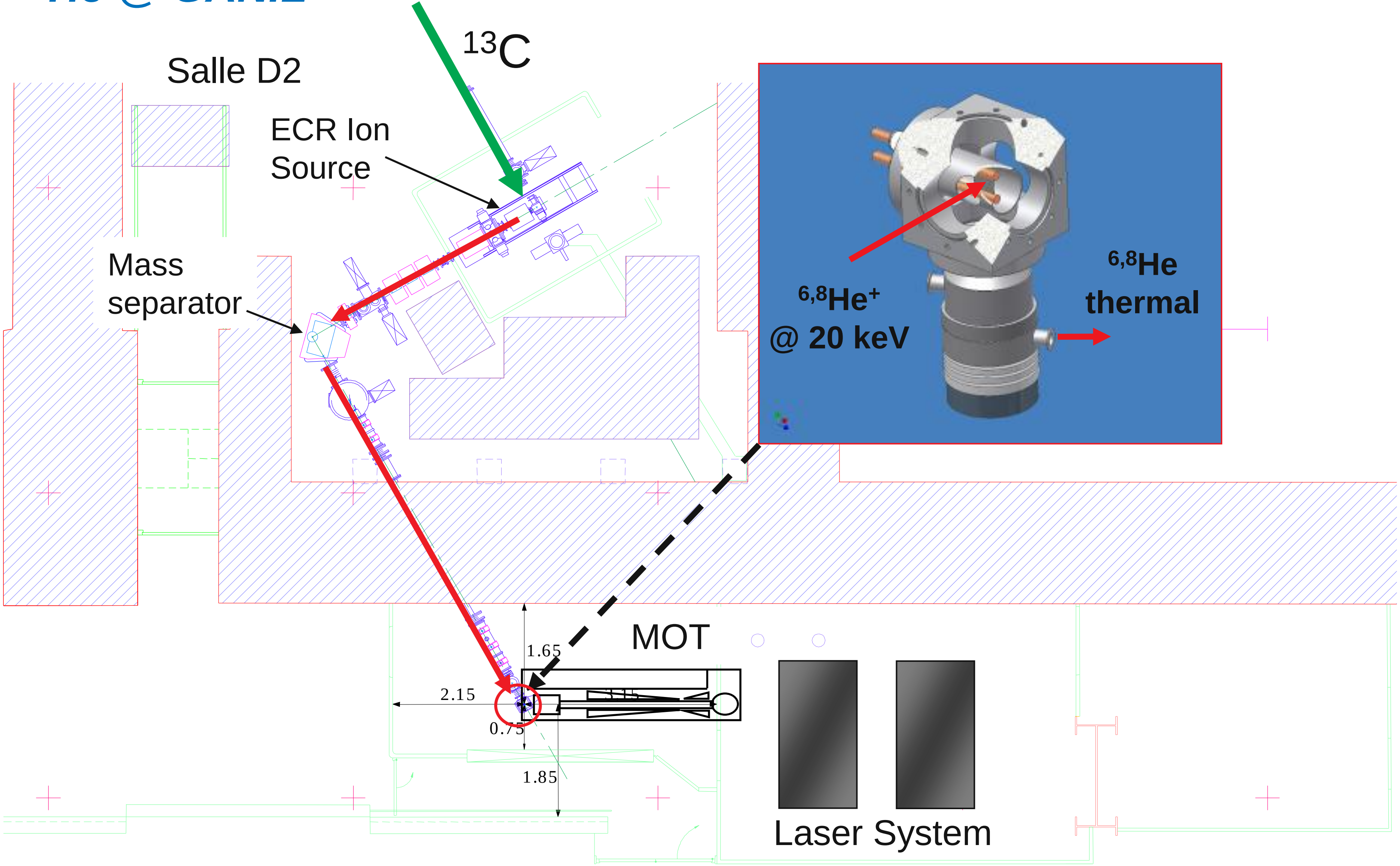
- Recirculation x 5 -> **Total x 100**

He-8 @ GANIL



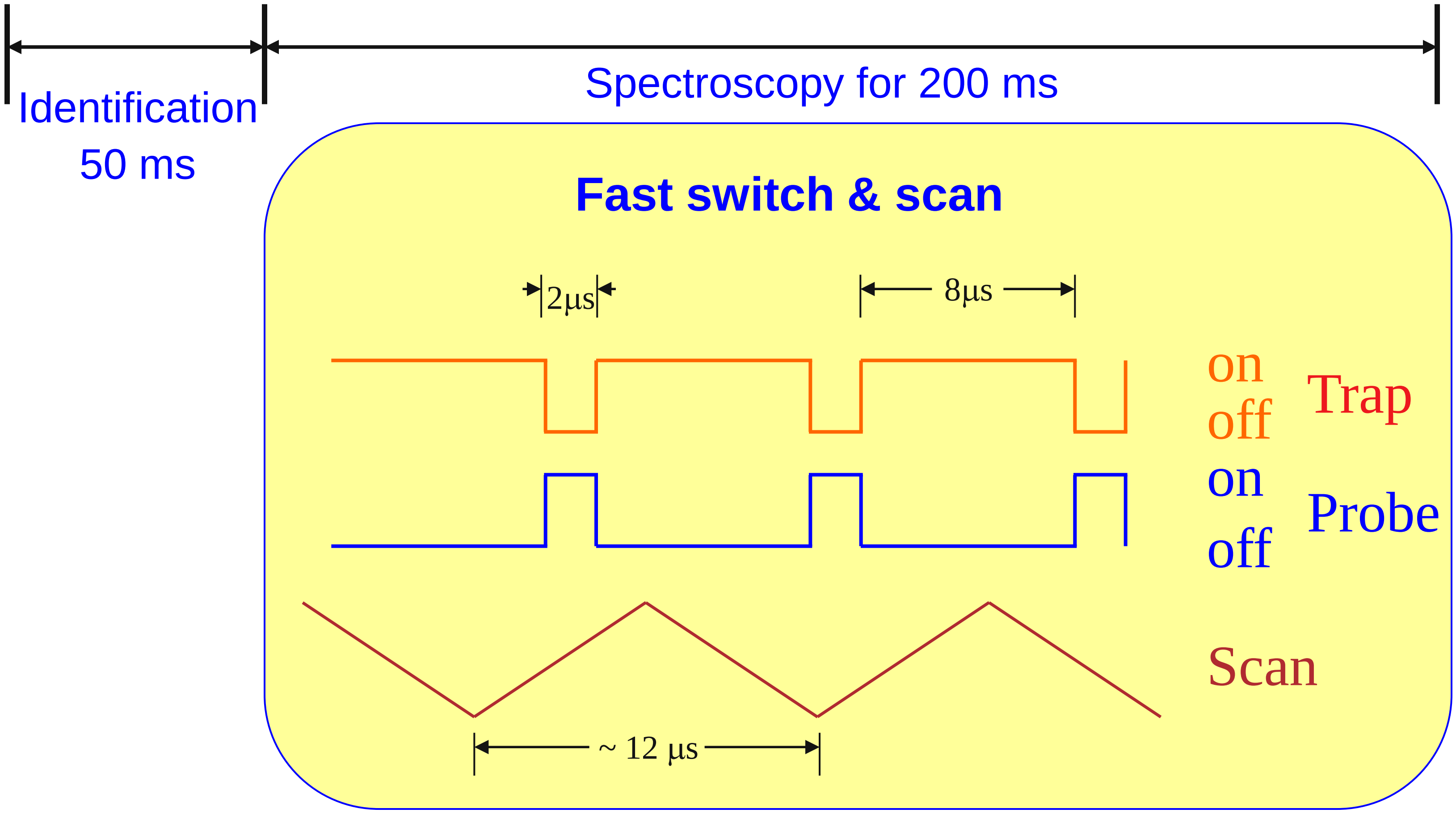
75 MeV/u, 0.4 pμA ^{13}C beam on ^{12}C target

^{8}He @ GANIL



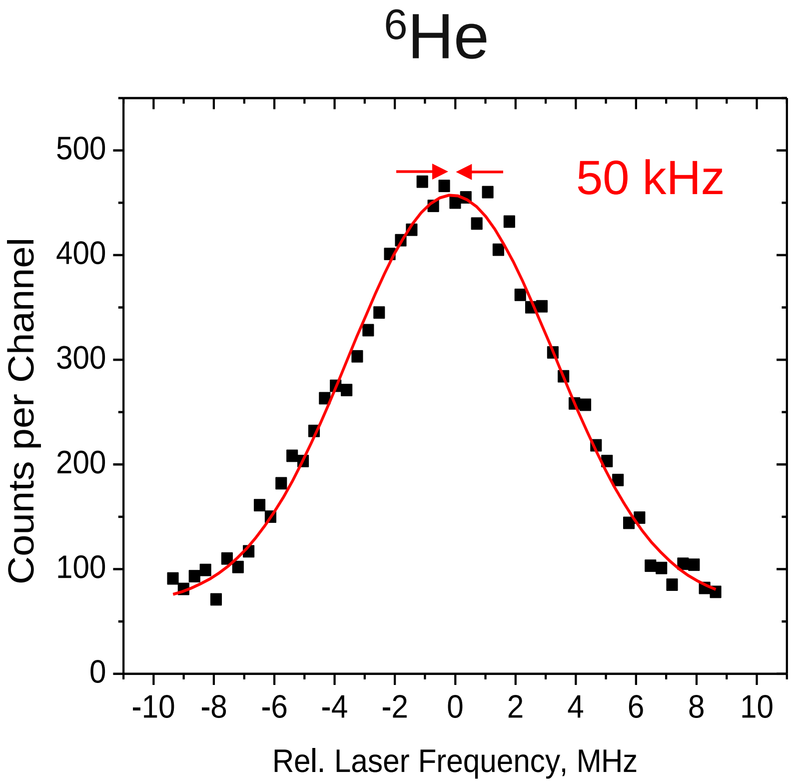
13C
Salle D2
ECR Ion Source
Mass separator
6,8He+
@ 20 keV
6,8He
thermal
MOT
1.65
2.15
0.75
1.85
Laser System

Switch & Scan

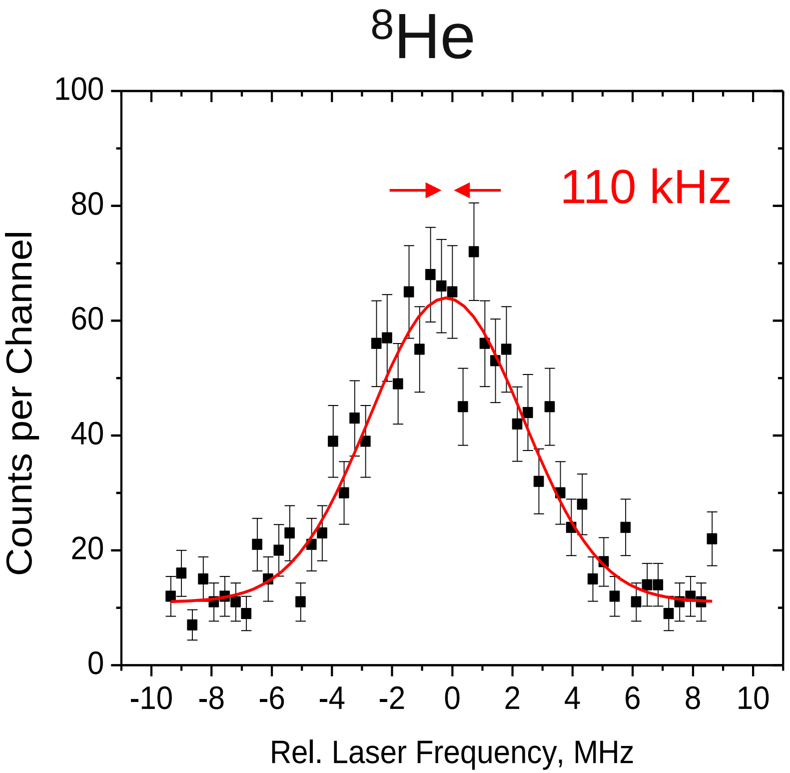


- Two-detuning trap (hot and cold)
- Power balance between the two opposing probe beams

June 15th…. ^{6}He + ^{8}He Sample Spectra

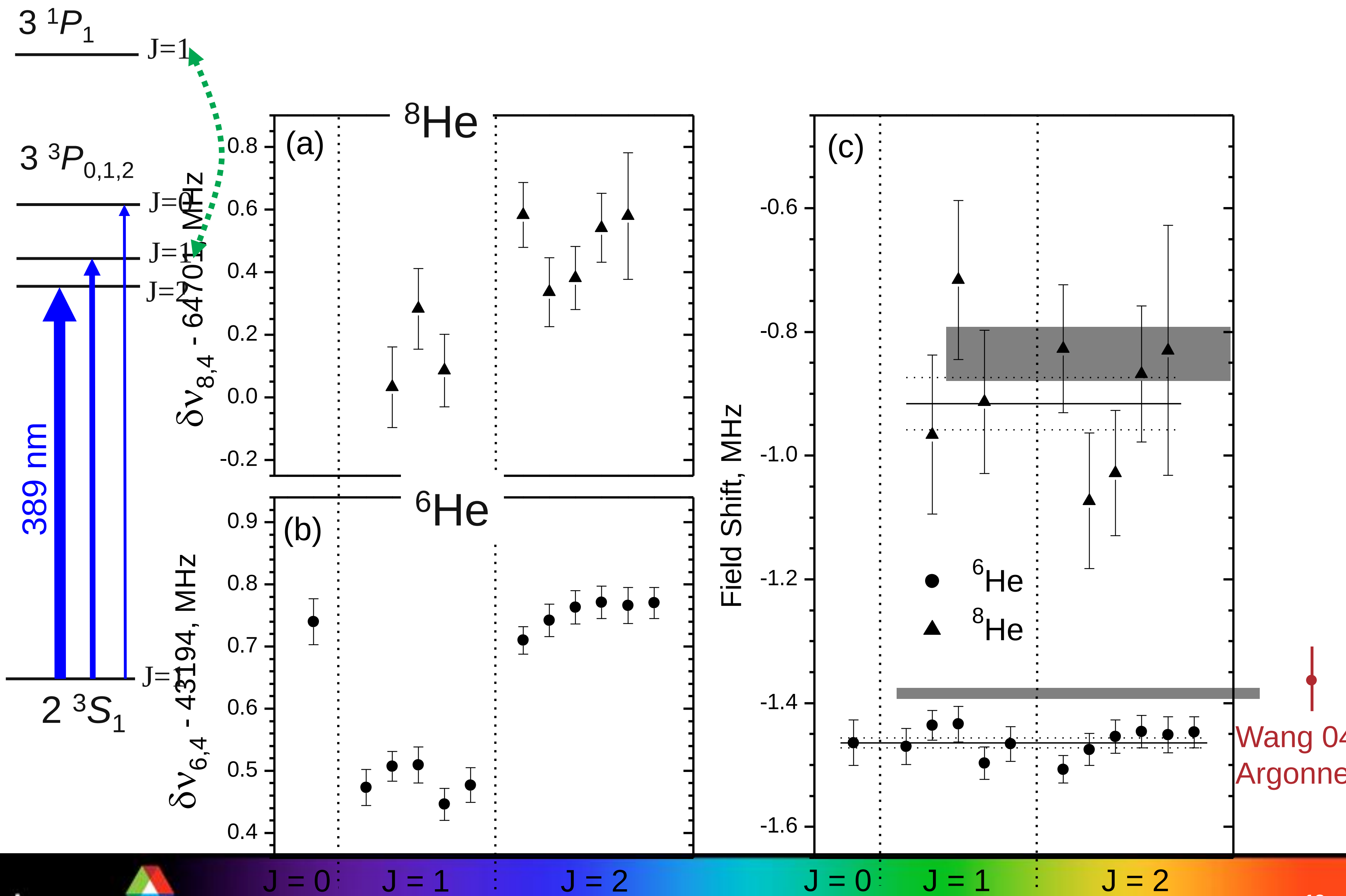


~ 5 ^{6}He atoms/s
2 minutes



~ 30 ^{8}He atoms/hr
2 hours

Isotope Shift and Field Shift : J - Dependence?



Experimental Uncertainties and Corrections

		^{6}He	^{8}He
Statistical	Photon Counting	8 kHz	32 kHz
	Laser Alignment	2 kHz	12 kHz
	Reference Laser	2 kHz	24 kHz
Systematic	Probing Power Shift	0 kHz	15 kHz
	Zeeman Shift	**30 kHz**	45 kHz
	Nuclear Mass	15 kHz	**1 kHz**
	TOTAL	**35 kHz**	**63 kHz**

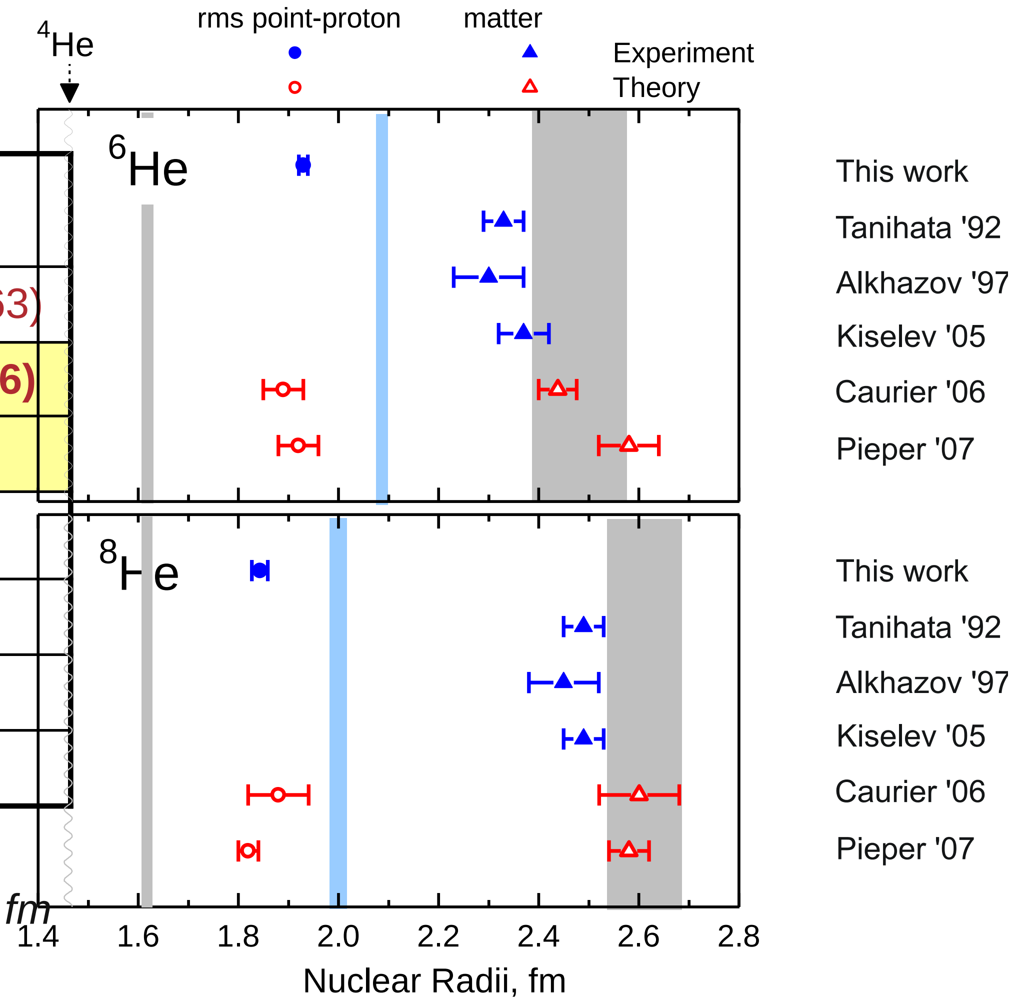
Corrections	Recoil Effect	+110(0) kHz	+165(0) kHz
	Nuclear Polarization	-14(3) kHz	-2(1) kHz

TITAN Penning Trap @ TRIUMF, V. L. Ryjkov *et al.*, PRL **101**, 012501 (2008)

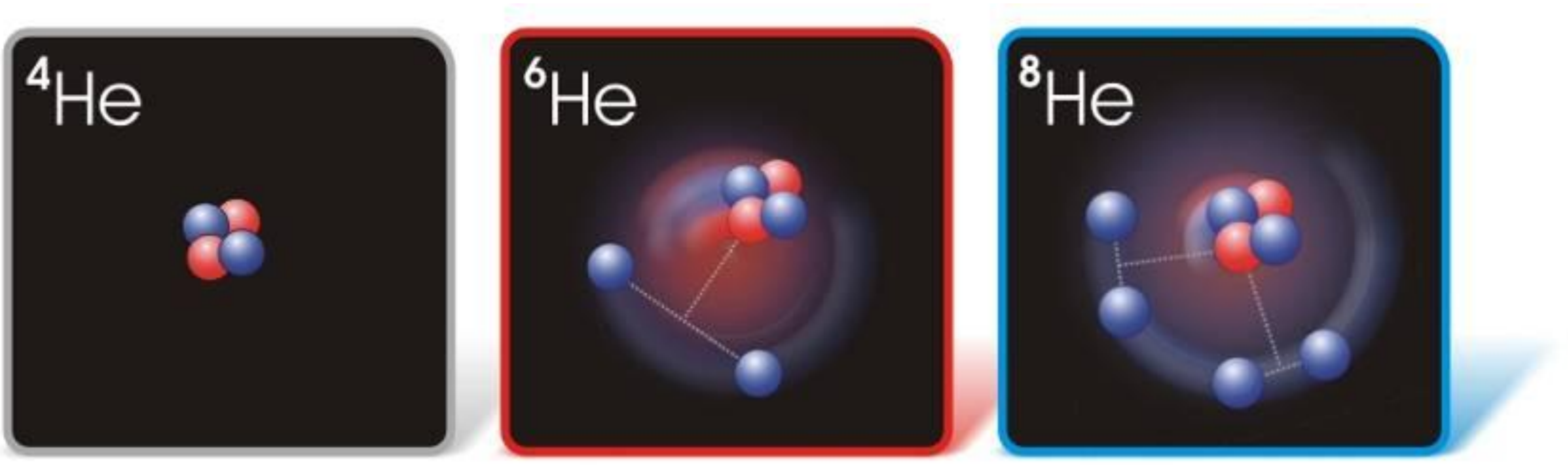
^{6}He & ^{8}He RMS Point Proton and Matter Radii

	^{6}He	^{8}He
Field Shift, MHz	-1.464(34)	-1.026(63)
RMS R_{pp}, fm	**1.930(9)**	**1.843(16)**
Total Uncertainty	**0.4 %**	**0.9 %**
- Statistical	*0.1 %*	*0.6 %*
- Trap Systematics	*0.3 %*	*0.6 %*
- Mass Systematics	*0.2 %*	*0.0 %*
- He-4: 1.465(4) fm	*0.1 %*	*0.1 %*

Pieper 2007 *1.92(4) fm* *1.82(2) fm*
GFMC Av18+IL7

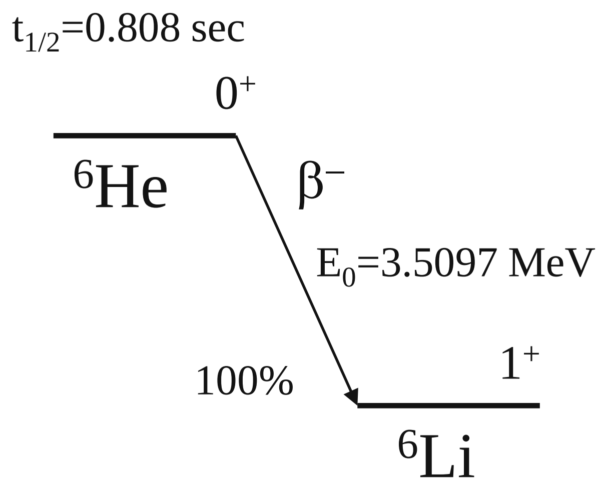


RMS Charge Radii : ^{4}He - ^{6}He - ^{8}He



1.681(4) fm   2.072(9) fm   1.961(16) fm

Beta-Neutrino Correlation in the Decay of ^{6}He



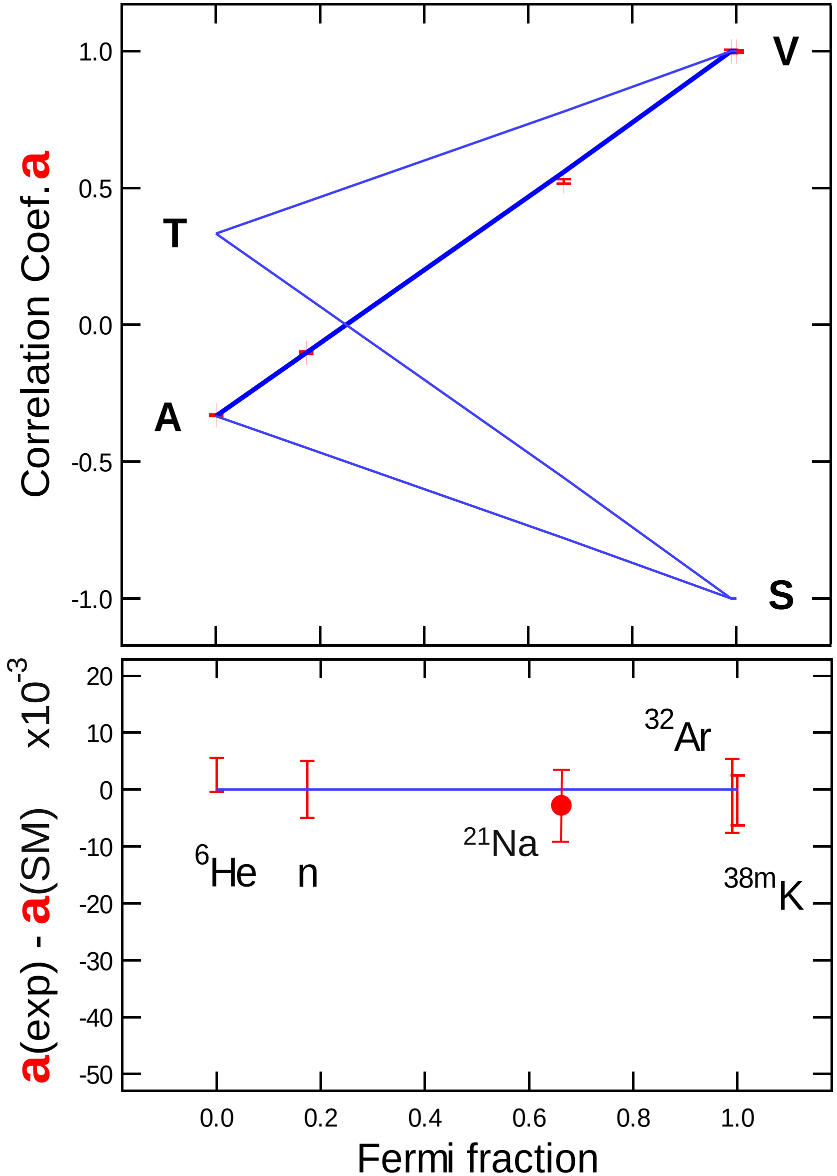
$$N\left(E_\beta,\theta_{\beta\nu}\right) \propto 1 + a \cdot \frac{p_\beta}{E_\beta} \cos\theta_{\beta\nu}$$

Best experimental limit:

a = - 0.3343 ± 0.0030

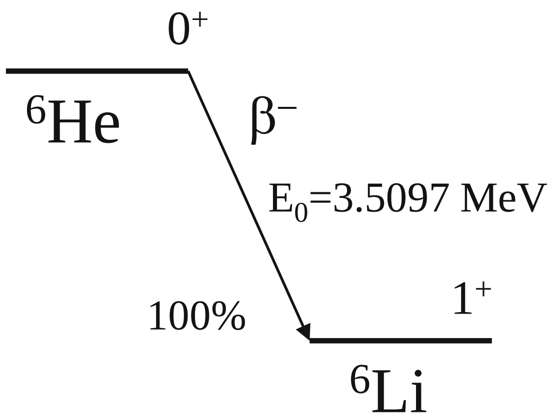
$$\frac{\left|C_T\right|^2 + \left|C'_T\right|^2}{\left|C_A\right|^2 + \left|C'_A\right|^2} \le 0.4\%$$

Johnson et al., Phys. Rev. (1963)



Beta-Neutrino Correlation in the Decay of ^{6}He

$t_{1/2}$=0.808 sec



$$N\left(E_\beta,\theta_{\beta\nu}\right)\propto 1+a\cdot\frac{p_\beta}{E_\beta}\cos\theta_{\beta\nu}$$

Best experimental limit:

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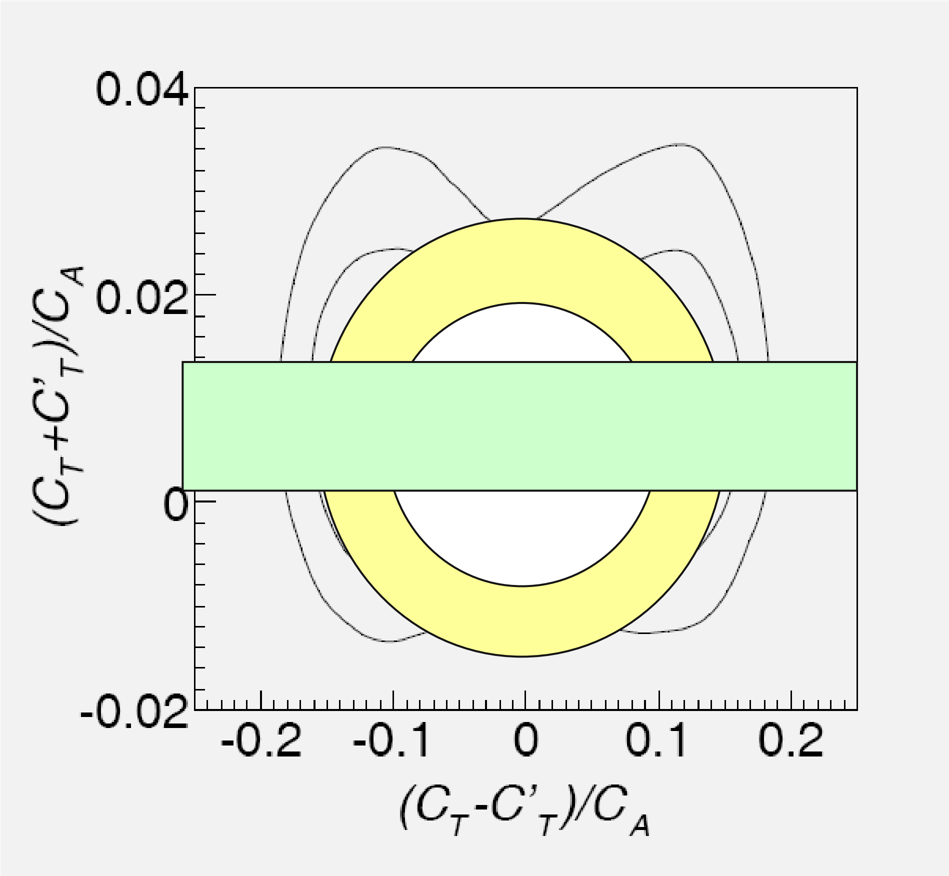
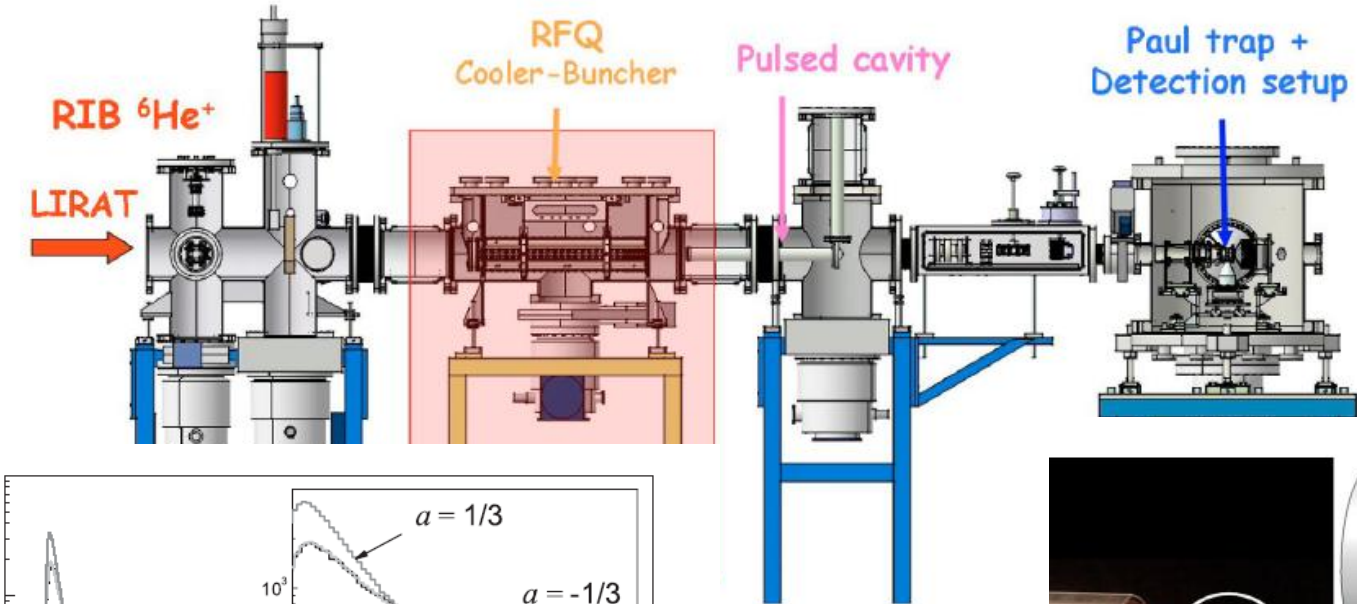
$$\frac{|C_T|^2+|C_T'|^2}{|C_A|^2+|C_A'|^2}\leq 0.4\%$$

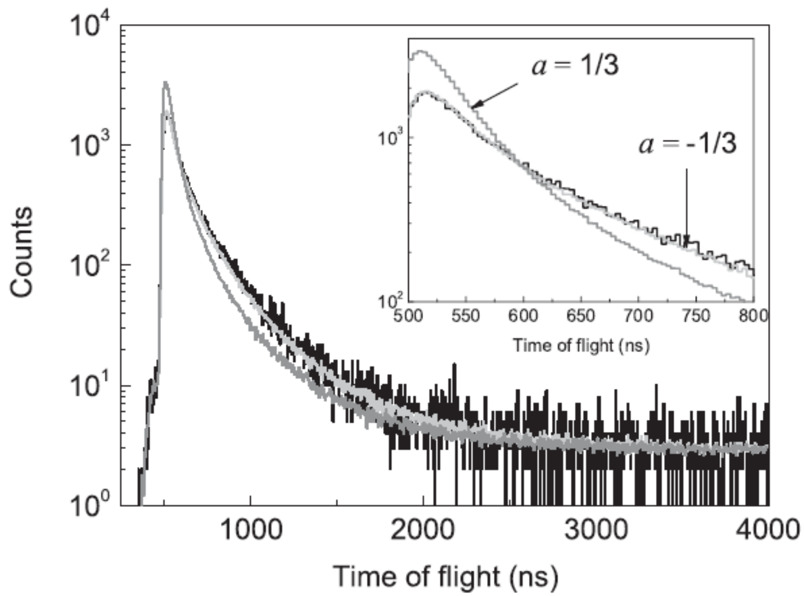
Johnson et al., Phys. Rev. (1963)

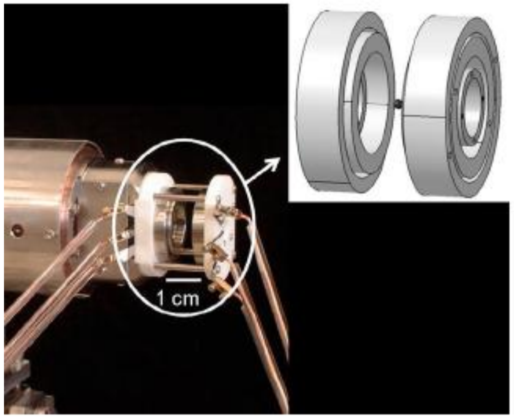


Severijns et al, Rev. Mod. Phys. 78, 991 (2006).

LPC TRAP @ GANIL



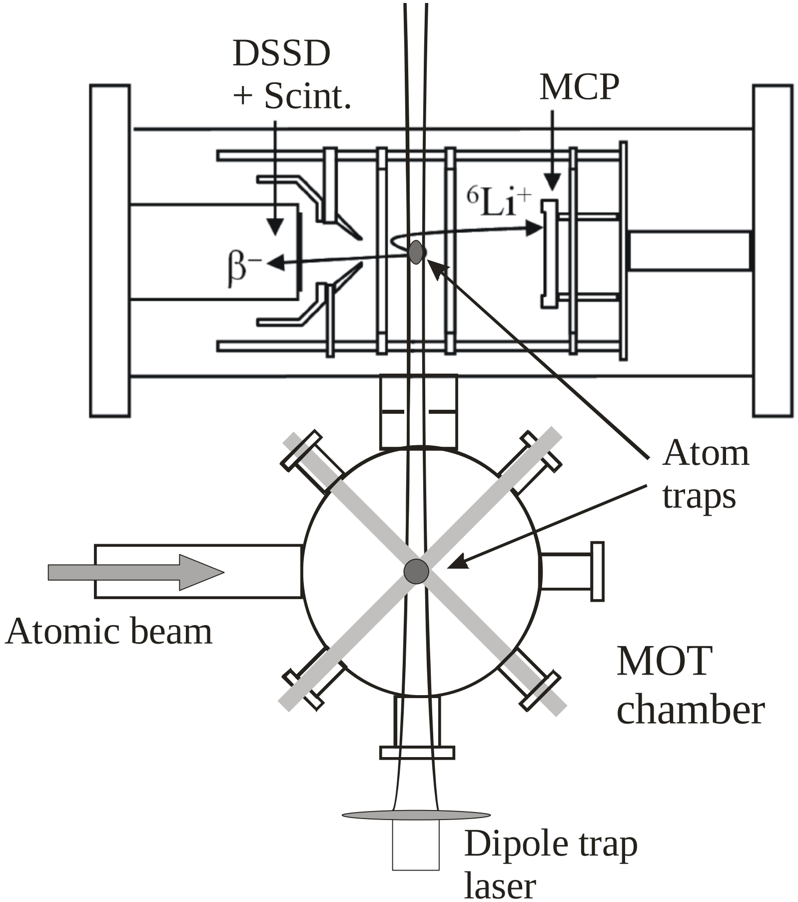


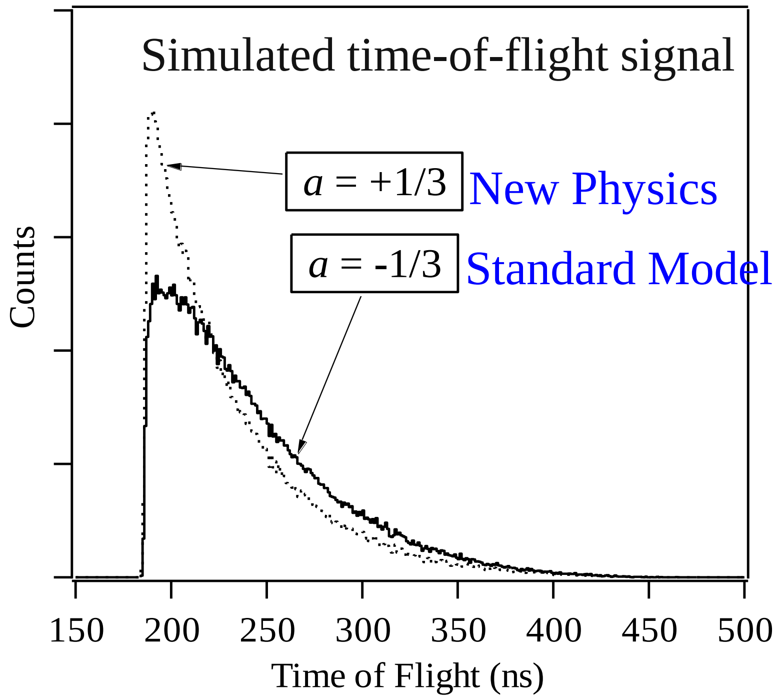


- data collection completed in 2008
- statistically: $\delta a/a$ ~0.5%
- systematic under investigation

X. Flechard *et al.* PRL **101**, 212504 (2008)

Beta-Decay Study with Laser Trapped ^{6}He





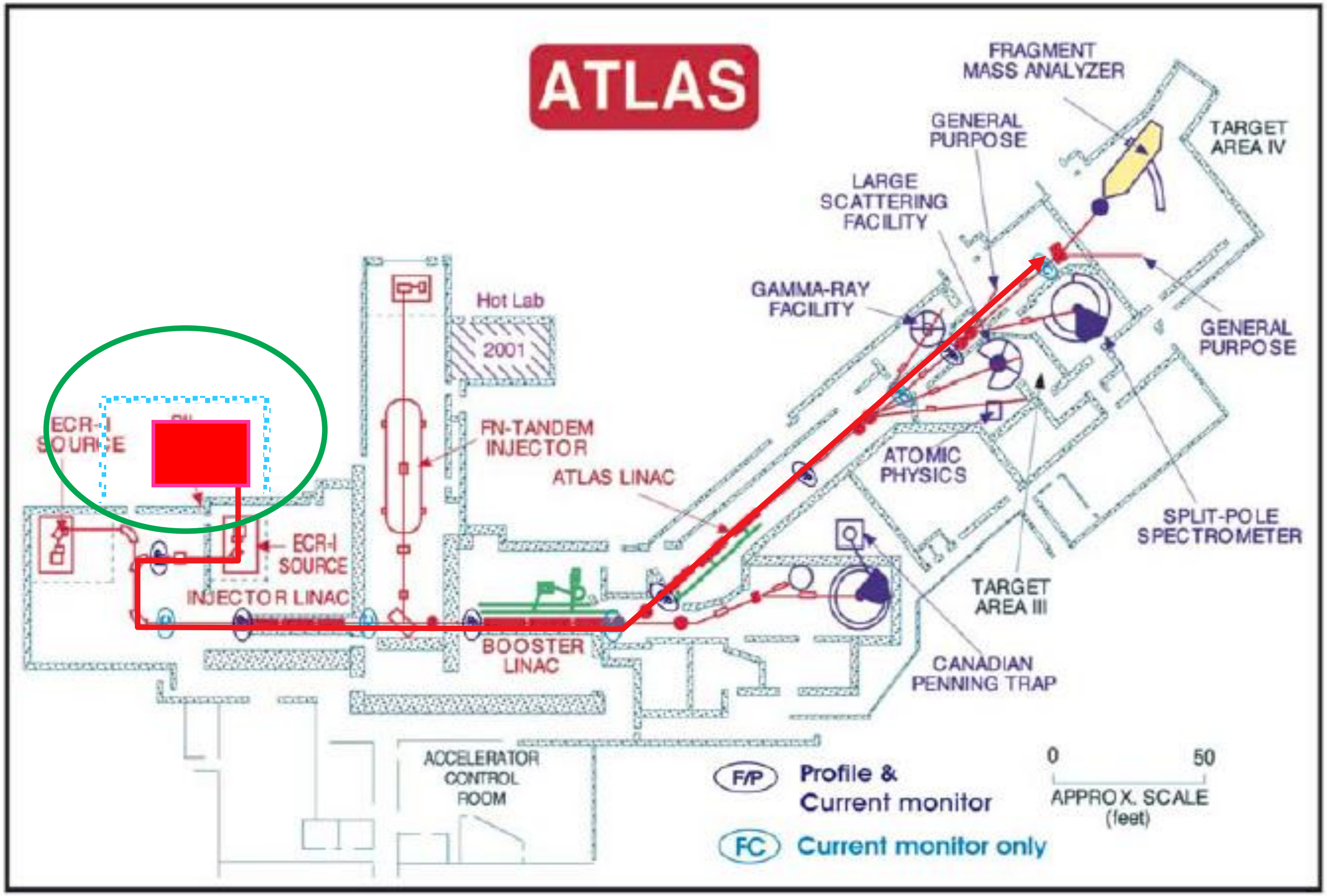
^{6}He yields:

- ATLAS: 1×10^7 s^{-1}
- CENPA: ~1×10^9 s^{-1}
- SARAF / SPIRAL2: ~1×10^{12} s^{-1}

- ^{6}He trapping rate: 1×10^4 s^{-1},
- 2×10^5 coincidence events in 15 min: $\delta a = \pm 0.008$
- 1 week: $\delta a/a = 0.1\%$

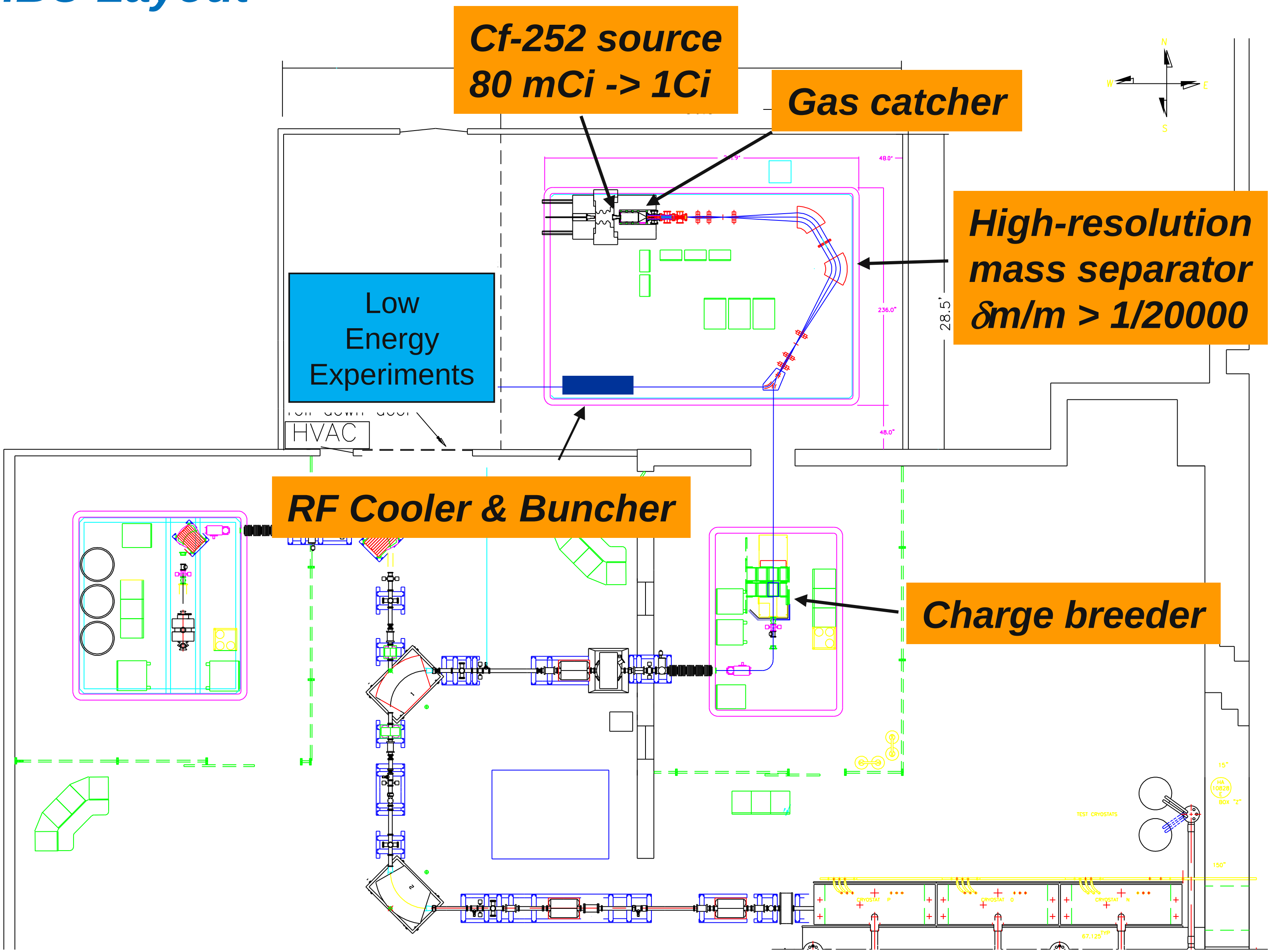
CARIBU: Californium Rare Isotope Breeder Upgrade

Contact: Guy Savard, Richard Pardo, Physics Division, Argonne

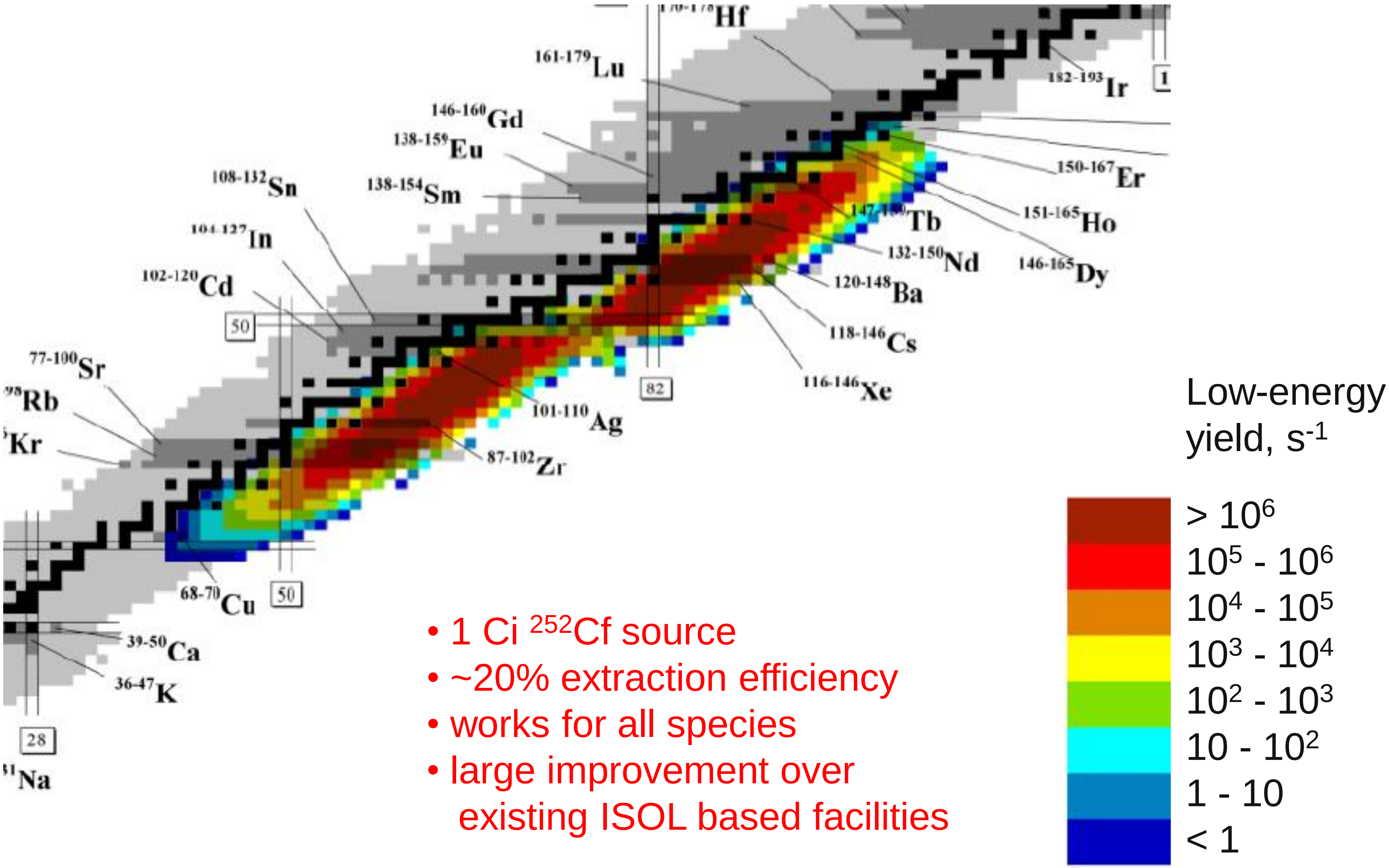


http://www.phy.anl.gov/atlas/caribu.html

CARIBU Layout



Isotopic Menu for Laser Spectroscopy



- 1 Ci ^{252}Cf source
- ~20% extraction efficiency
- works for all species
- large improvement over existing ISOL based facilities

Isotopic Menu – "Low Mass"

		Wavelengths, nm		Laser Spectroscopy		CARIBU	
		I	II	LS	Method	Range > 100/s	
30	Zn	589.4				75	79
31	Ga	417.2				76	83
32	Ge	*265.16				77	86
33	As	197.2				79	89
34	Se	207.48				80	92
35	Br	*827.47				83	94
36	Kr	*811.52		72 .. 96	CS	85	97
37	Rb	780.0		76 - 96	CS	87	97
38	Sr	460.86	421.7	77 - 100	CS	89	102
39	Y	414.4		JYFL .. 102	CS	91	104
40	Zr	388.65		87 … 102	CS	94	106
41	Nb	492.45		.. 103	CS	97	109
42	Mo	390.41		… 108	CS	100	112
43	Tc	429.82				101	113
44	Ru	392.7				103	115
45	Rh	369.34				105	118
46	Pd	276.39				109	124
47	Ag	328.16		101 … 110	CS	111	125
48	Cd	326.1	214.5	102 … 120	CS	112	126
49	In	451.3	236.5	104 - 127	CS	115	133
50	Sn	452.5		108 - 132	CS, RIMS	124	136

MOT

Collinear

N = 50

Refractory elements

N = 82

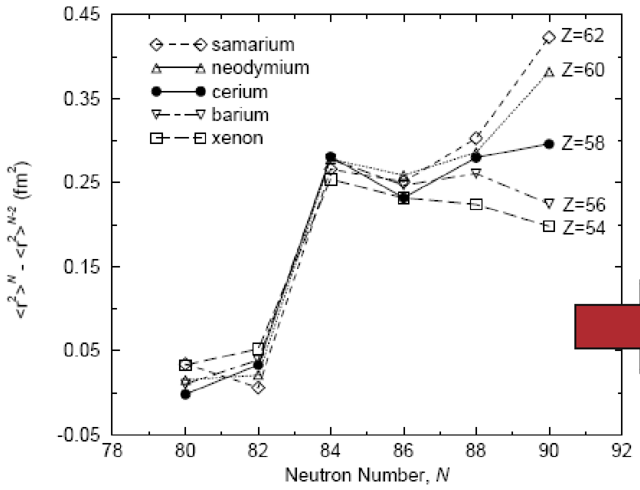
Menu of Isotopes – “High Mass”

		Wavelengths, nm		Laser Spectroscopy		CARIBU	
		I	II	LS	Method	Range > 100/s	
51	Sb	231.22				124	138
52	Te	214.35				129	140
53	I	183.04				131	142
54	Xe	*882.18		116 … 146	CS	133	146
55	Cs	455.65		118 - 146	CS	135	148
56	Ba	553.7	455.4	120 – 146,148	CS	137	150
57	La	418.84		… @ TRIUMF	CS	139	152
58	Ce	450.64	331	… @ JYFL	CS	141	155
59	Pr	495.14	590			144	157
60	Nd	468.34	590	132 … 150	RIS	146	159
61	Pm	?				149	161
62	Sm	471.71		138 - 154	RIS	151	164
63	Eu	459.4	604.9	138 - 159	RIS	154	166
64	Gd	432.71		146 - 160	RIS	156	168
65	Tb	432.64		147 ... 159	RIS	159	169
66	Dy	404.71		146 … 165	RIS	162	171
67	Ho	410.38		151 … 165	RIS	166	171
68	Er	415.23		150 … 167	RIS	169	172

MOT

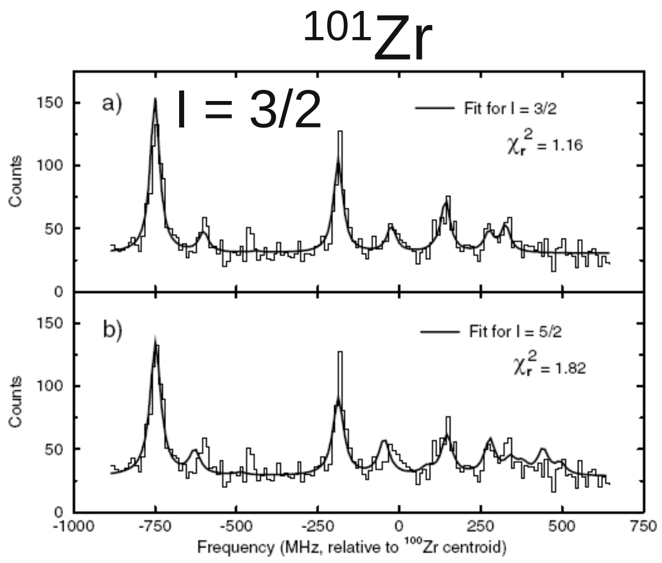
Collinear

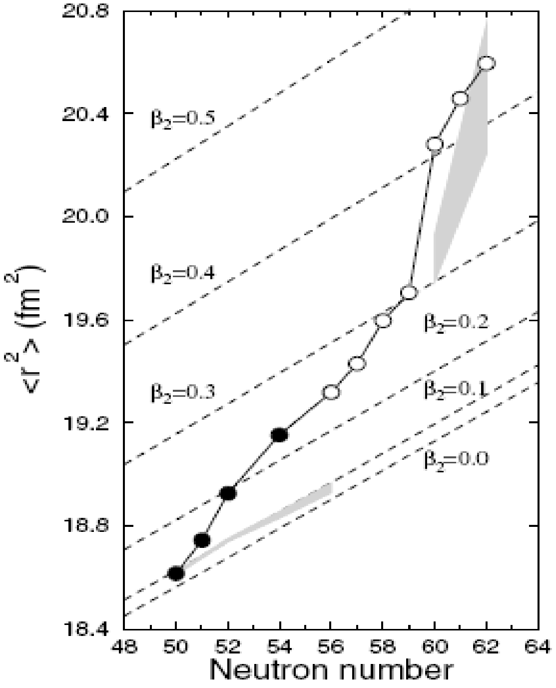
N = 82



Laser Spectroscopy of Refractory Elements

Laser Spectroscopy of Cooled Zirconium Fission Fragments, P. Campbell *et al., PRL 89, 082501 (2002)*



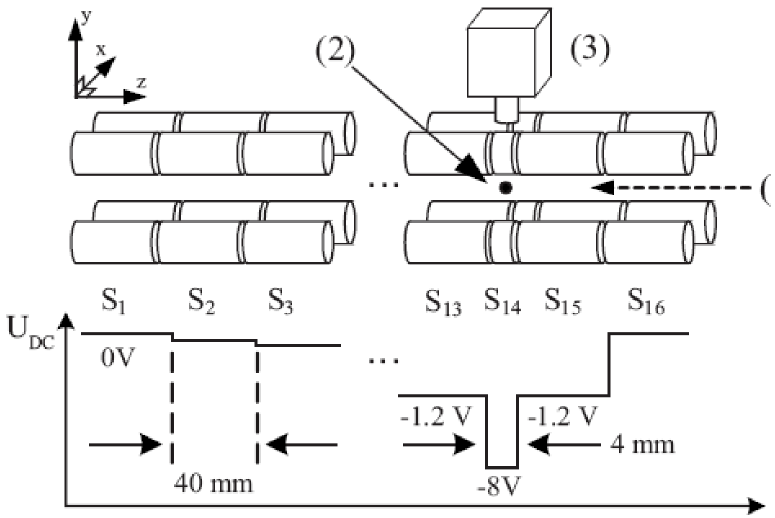


Charge radius vs. deformation: $\delta\langle r^2\rangle = \langle r^2\rangle_s \frac{5}{4\pi}\sum_i \delta\langle\beta_i^2\rangle,$

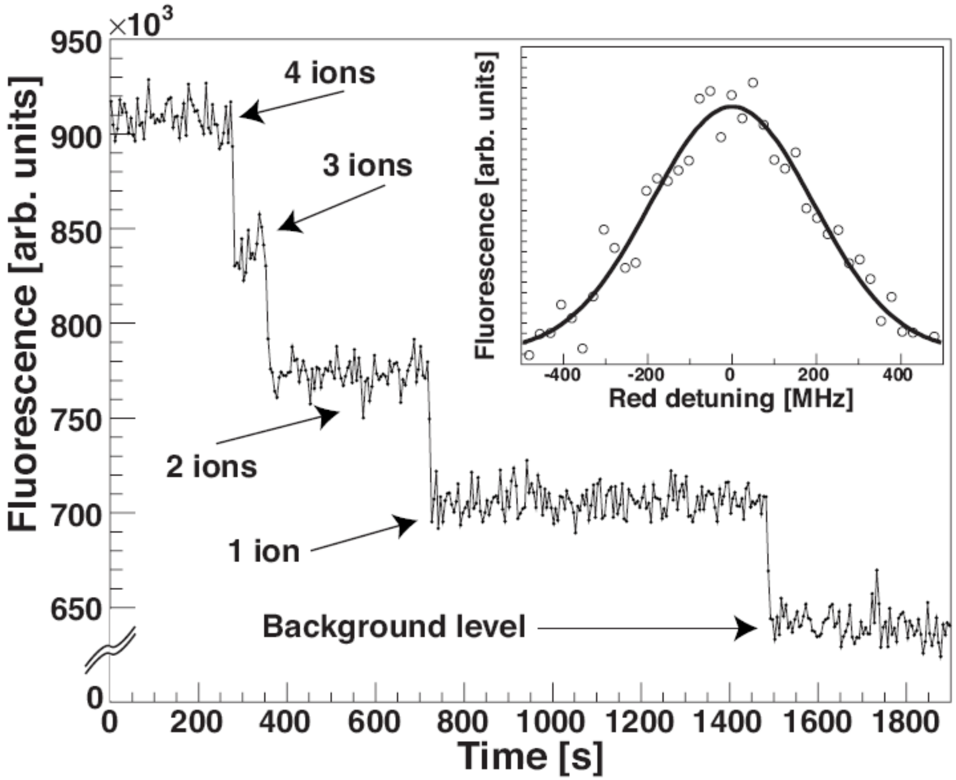
- Measured $^{96–102}Zr$ with yields > 500 s^{-1} -> @ CARIBU: ^{106}Zr ~ $1x10^4$ s^{-1}
- N=60 shape transition for higher Z: Nb, Mo … -> ^{109}Mo, ^{112}Nb

Barium Ion Spectroscopy for EXO

EXO Collaboration



PHYSICAL REVIEW A **76**, 023404 (2007)



With He as buffer gas and repumping

Ion Trap Spectroscopy at CARIBU

Develop linear Paul trap for spectroscopy of neutron-rich Ba isotopes at CARIBU.

To investigate:

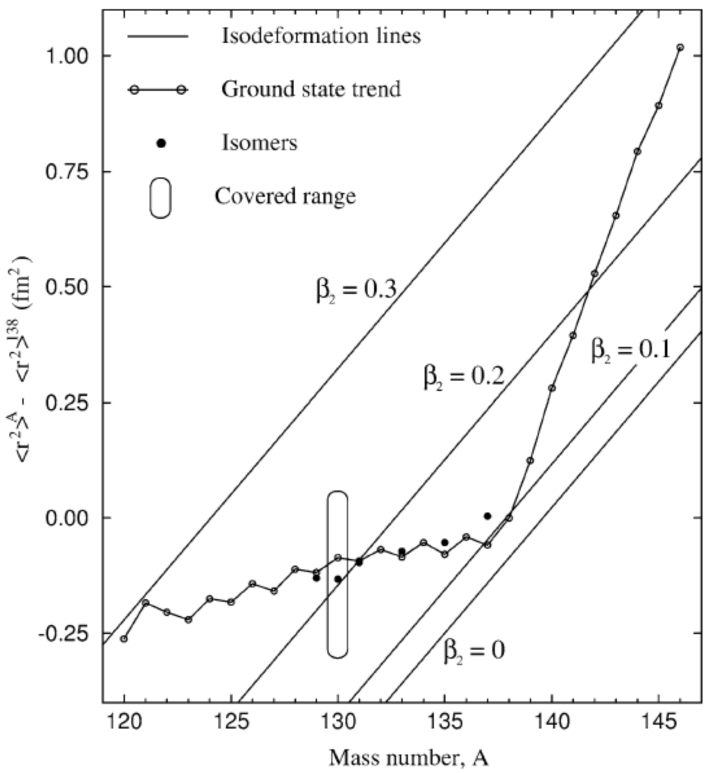
- optimized trap geometry and detection system (ion trap simulations)
- Buffer gas cooling + quenching (with H_2)
- Cooling of trap with LN_2

More considerations …

- Use RF cooler / buncher & transfer line
- Also …
  - other CARIBU beams (Sr, Y, Zr ..)
  - Yb^+, No^+
  - $^{229}Th^{3+}$ (isomer from gas catcher)
  - Sympathetic cooling

Ba Isotopes

A		t_1/2	yield, 1/s
139	1.45E-01	1.396h	3.22E+05
140	5.16E-01	12.75d	1.15E+06
141	1.11E+00	18.3 m	2.46E+06
142	2.70E+00	10.7 m	5.99E+06
143	4.40E+00	14.3 s	9.77E+06
144	3.37E+00	11.4 s	7.48E+06
145	2.06E+00	4.0 s	4.57E+06
146	9.81E-01	2.20 s	2.18E+06
147	2.50E-01	0.892s	5.55E+05
148	4.80E-02	0.64 s	1.07E+05
149	4.04E-03	0.36 s	8.97E+03
150	3.27E-04	0.962s	7.26E+02
152	3.77E-07	0.420s	8.37E-01



Thank You!

^{8}He Collaboration

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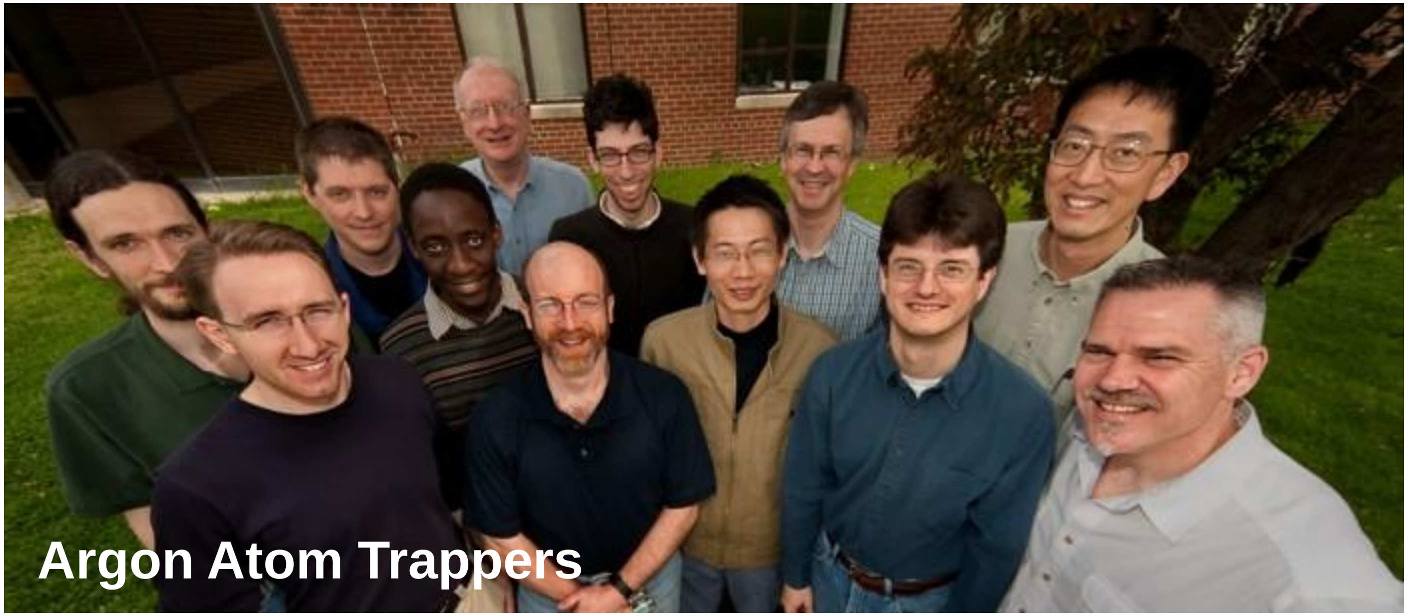

www.phy.anl.gov/mep/atta/