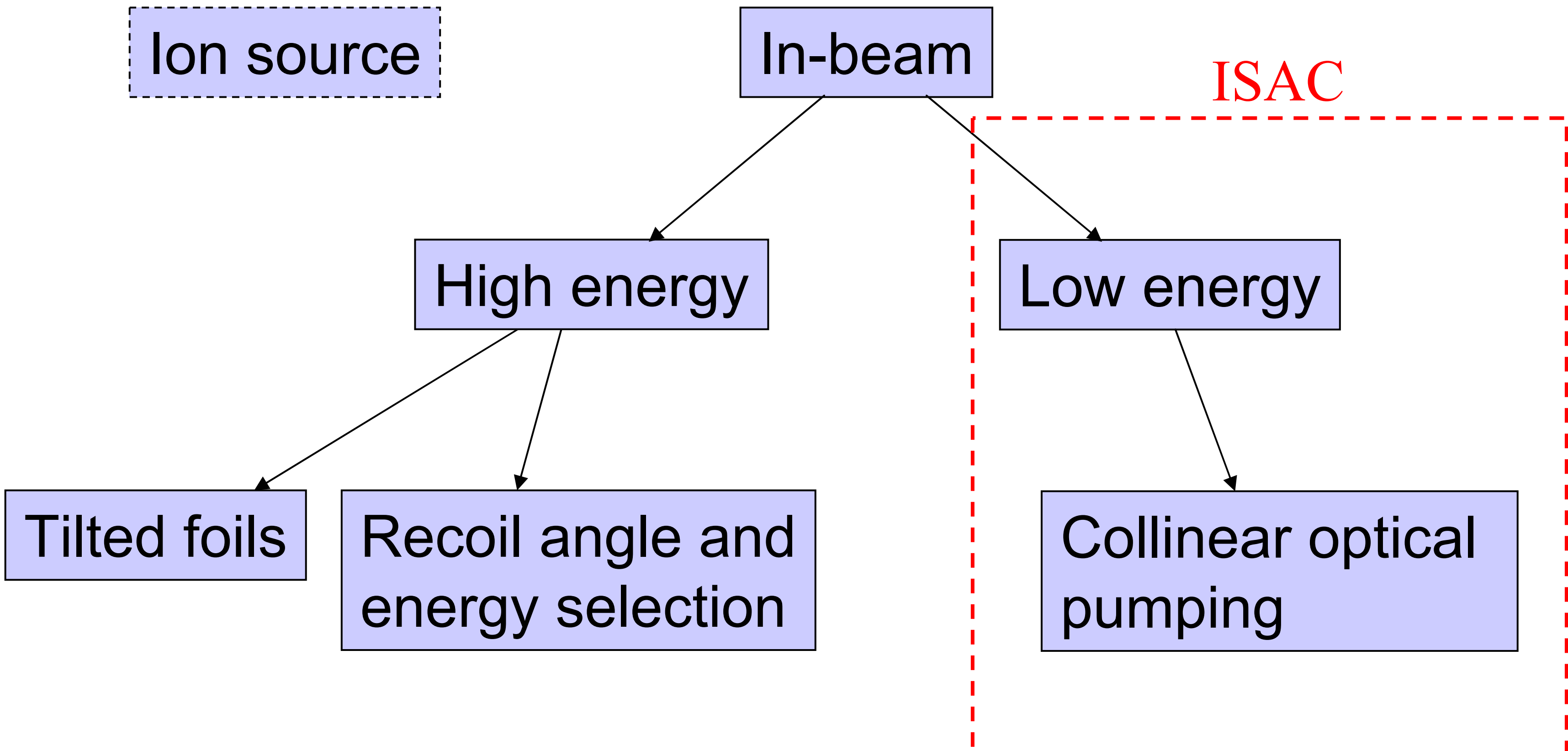
Polarized radioactive beams at TRIUMF-ISAC

Workshop on Atomic Physics with Rare Atoms

Ann Arbor, June 1-3, 2009

Phil Levy, TRIUMF

Methods of polarization



Physics at ISAC with polarized ion beams

Condensed matter β-detected NMR and NQR

Depth-controlled probing of ultrathin films with ^{8}Li i.e. of matter near surfaces and interfaces. [R.F. Kiefl, W.A. MacFarlane et al]

High resolution atomic spectroscopy

β-NMR and β-NQR → nuclear moment of ^{11}Li [M. Pearson spokesperson S1155]
→ electric quadrupole moments of $^{20,21}Na$ [K. Minamisono et al, Phys. Lett. B 672 120 (2009)]

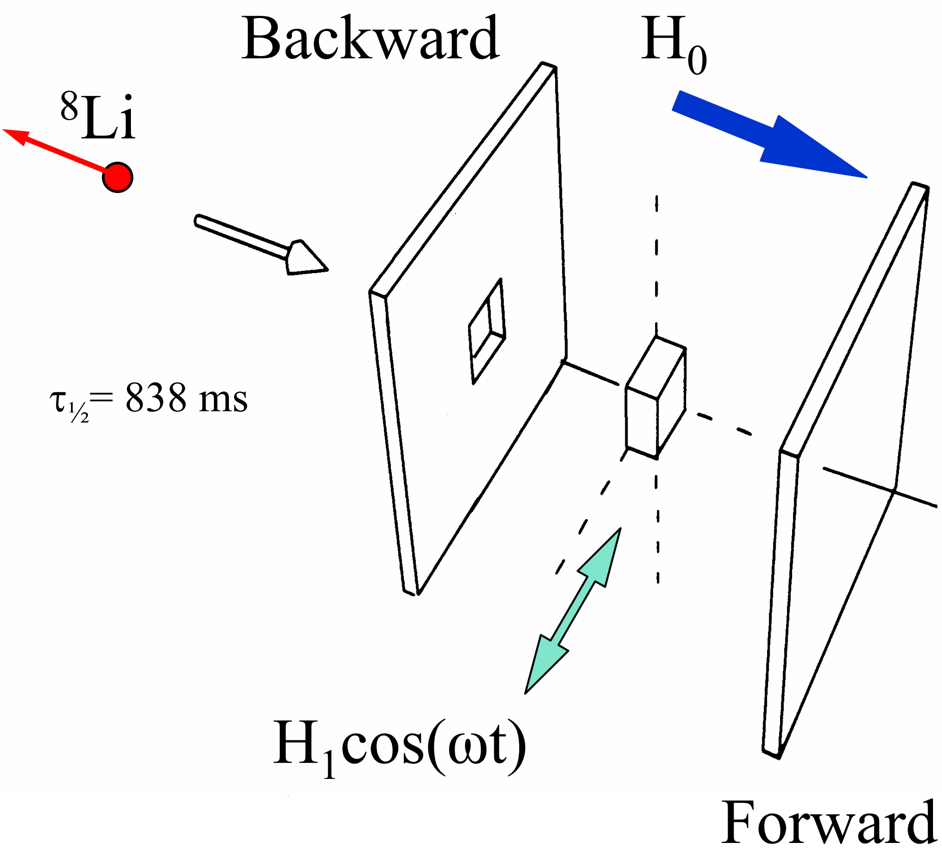
Fundamental symmetries

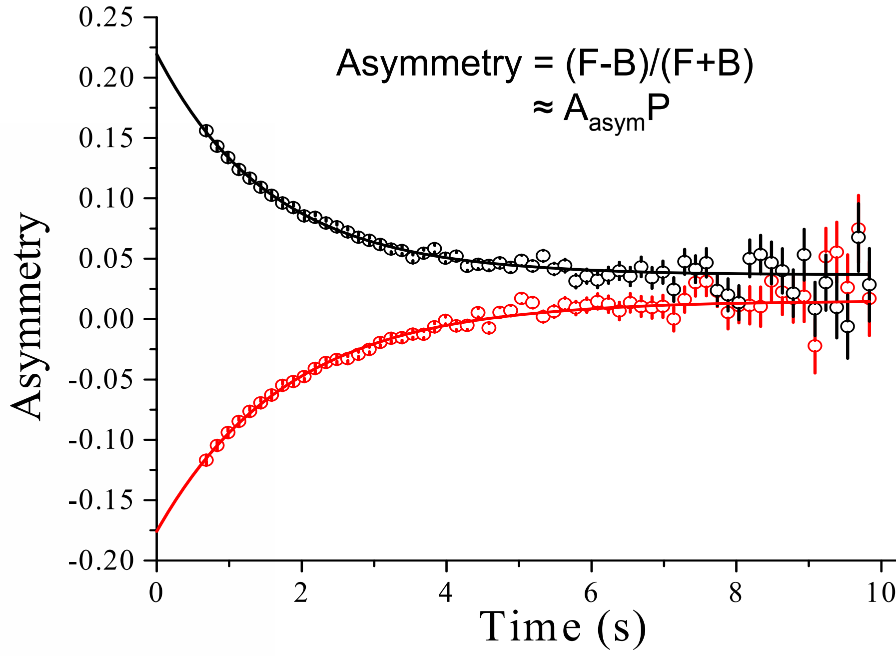
Search for time reversal symmetry violation → measure transverse polarization of β rays from ^{8}Li [J. Murata spokesperson S1183]
Comparison of β-decay alignment correlation terms of mirror nuclei ^{20}Na and ^{20}F (test of G-parity symmetry) → convert polarization to alignment.
[Minamisono et al, Hyperfine Interactions 159 (2004) 265]

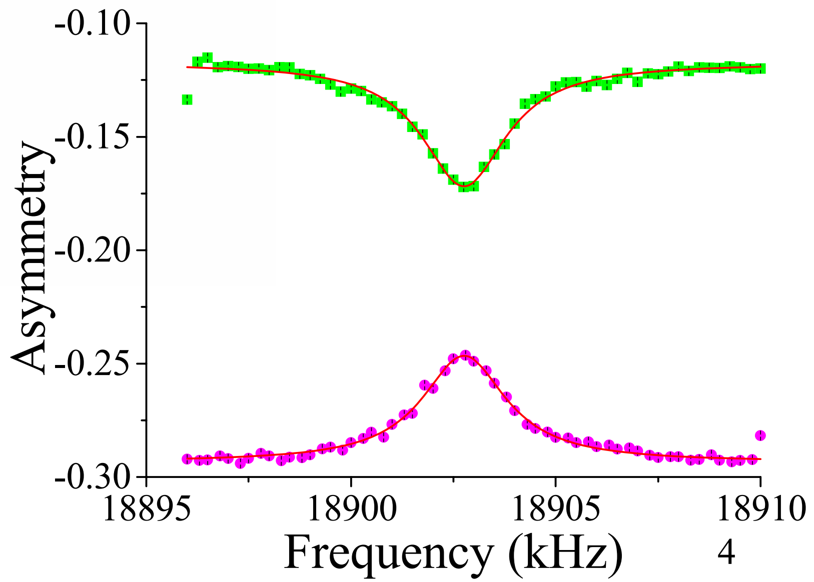
Nuclear structure

β-delayed nuclear spectroscopy → β-decay asymmetries measured in coincidence with delayed radiations to obtain spin and parity of daughter product excited levels
^{11}Li → ^{11}Be [T. Shimoda et al, Phys. Lett. B 611, 239-247 (2005)]
$^{28,29,30}Na$ → Mg [T. Shimoda spokesperson S1114]

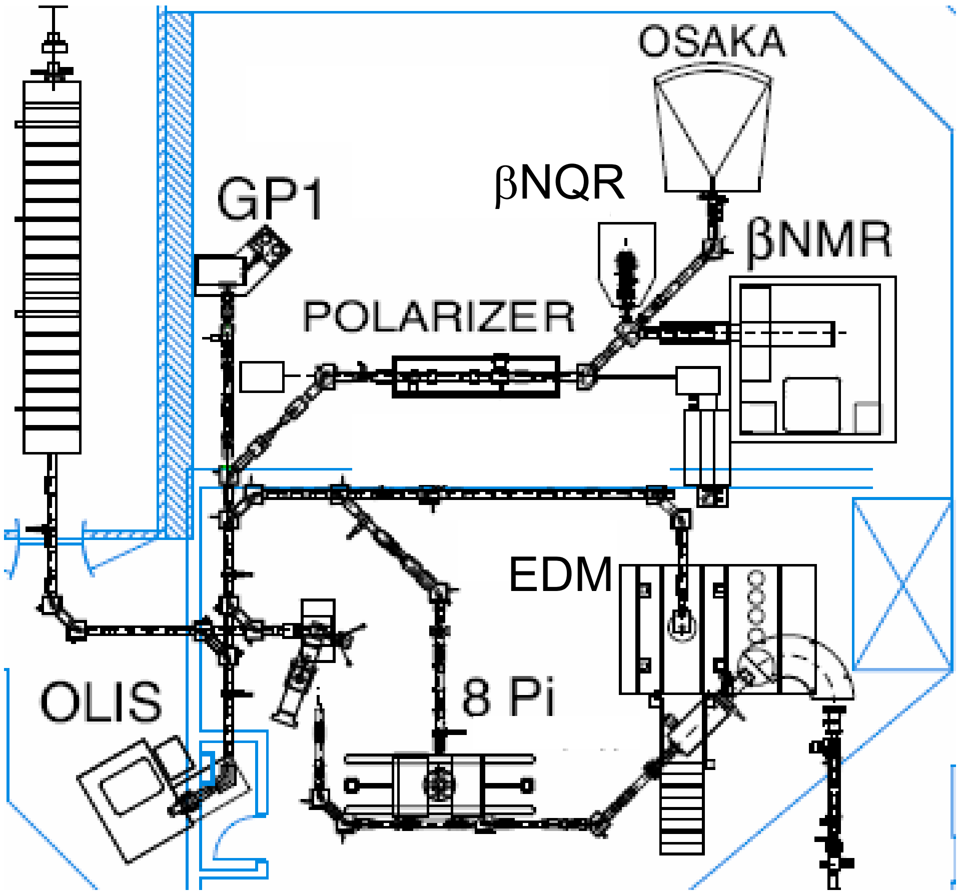
Geometry of a β-NMR Experiment





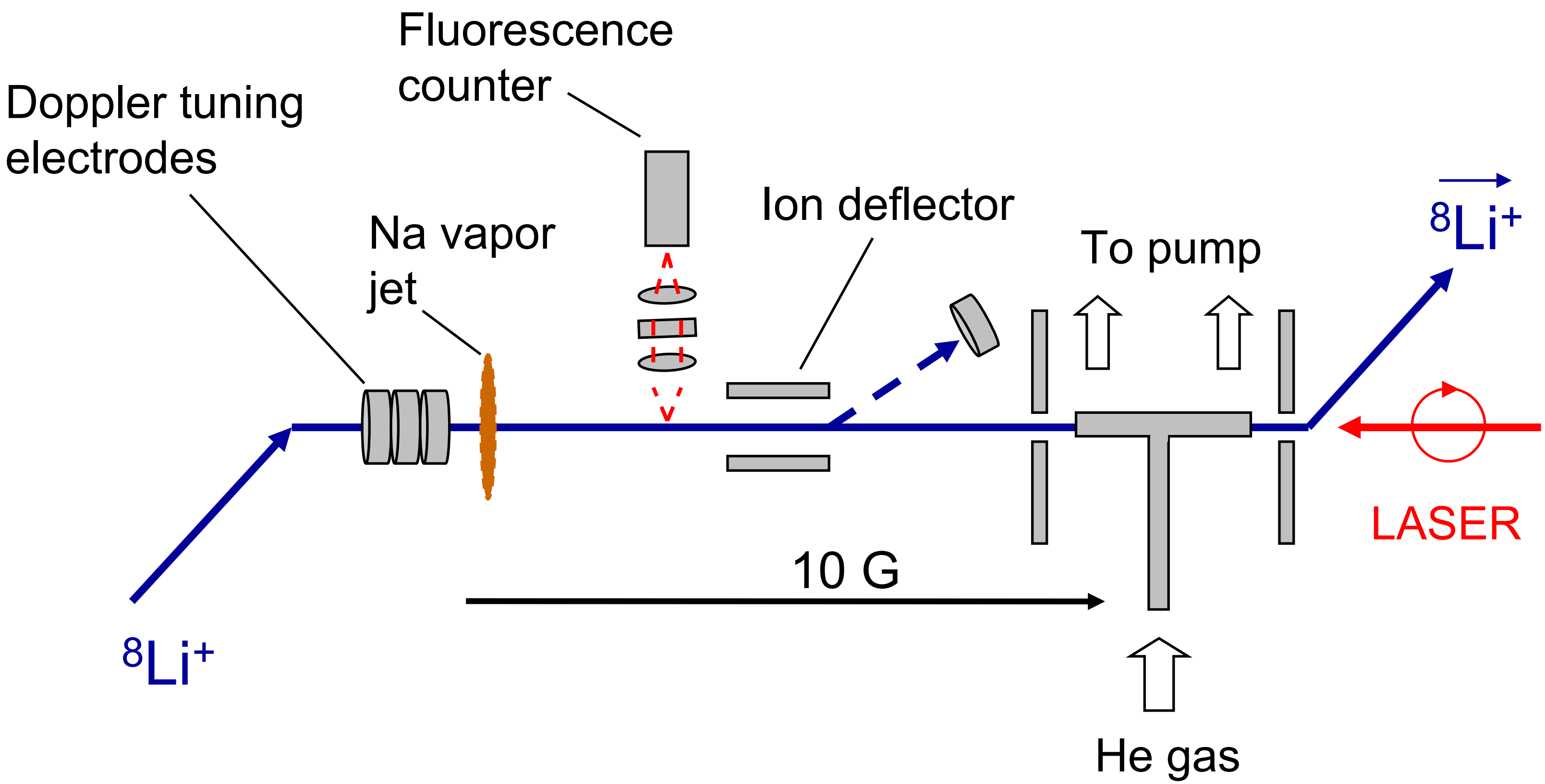


Low Energy Hall at ISAC

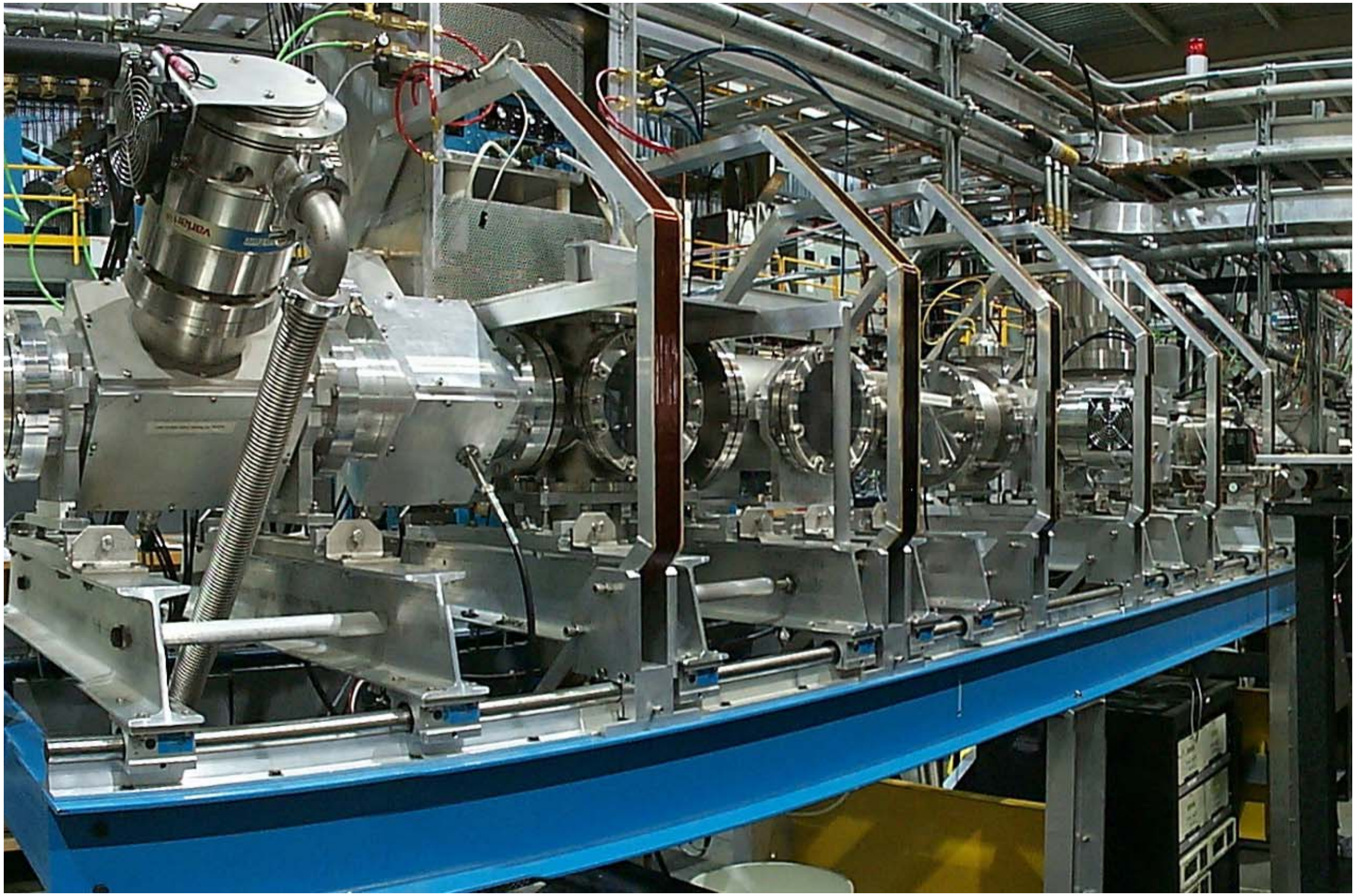


Collinear polarization method

Collinear Polarization



Collinear beam line at TRIUMF

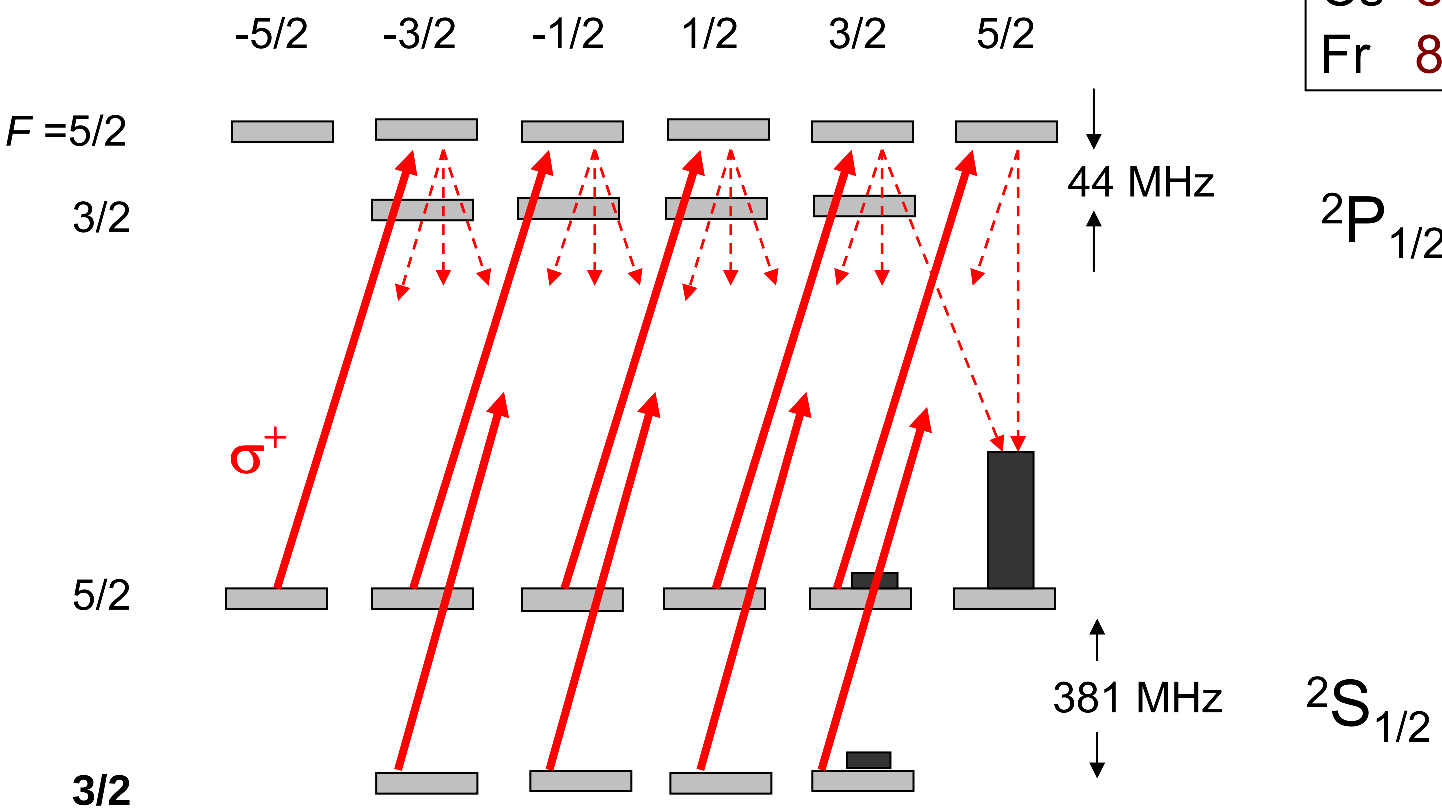


Optical pumping of alkali metals

Li	671 nm
Na	590
K	770
Rb	795
Cs	894
Fr	817

^{8}Li

I=2



Advantages of collinear geometry

- Allows long laser interaction time (microseconds) with fast beams
- Doppler width $\Delta\nu$ of beam is small → high resolution
  → low saturation powers

For beam energy spread $\Delta E = 2$ eV,
acceleration voltage U = 30 kV:

$$\Delta\nu = \frac{1}{\lambda}\sqrt{\frac{1}{2mqU}}\Delta E$$

Element	Transition wavelength λ *(nm)*	Natural linewidth *(MHz)*	Doppler width $\Delta\nu$ *(MHz)*
^{8}Li	671	6	42
^{210}Fr	817	5	7
^{11}Be	313	18	77
^{20}F	686	7	26

Other energy broadening mechanisms

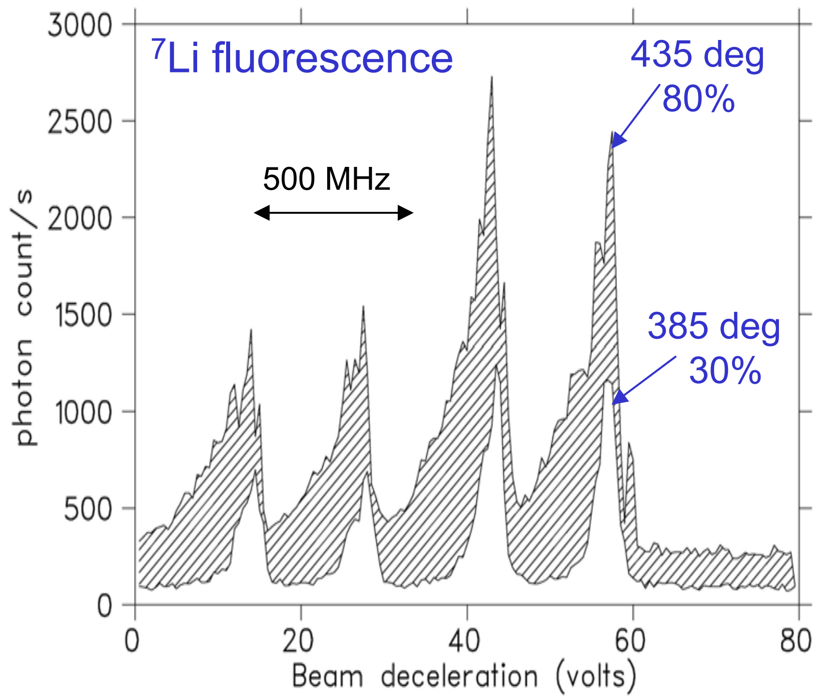
• Collisions in neutralizer cell

Li^+(beam) + Na (vapour)→ Li + Na^+

Changes in internal energy change the kinetic energy of the forward scattered lithium atom. This broadens the energy spread of the beam and limits the thickness of Na vapour to less than optimum for neutralization

Typically ~40% neutralization efficiency is used

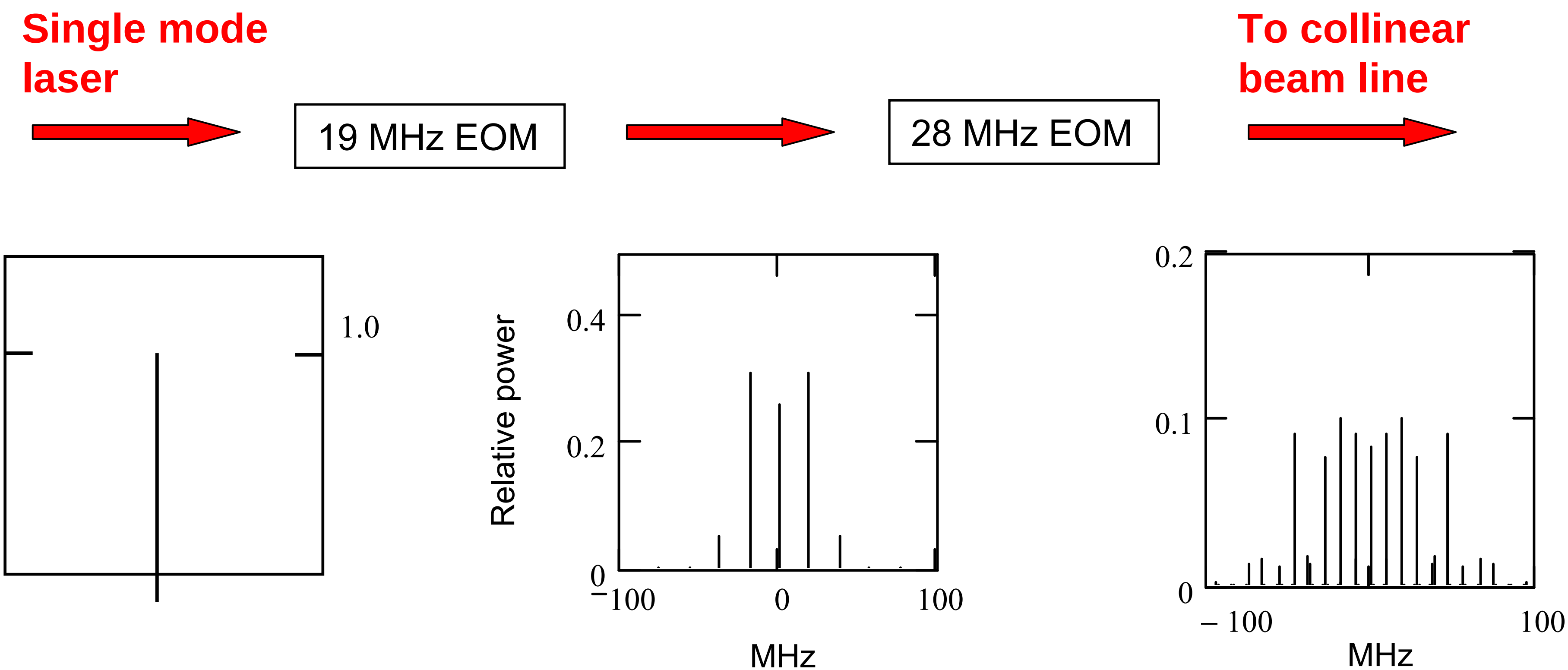
Collisions have negligible effect on transverse emittance



•Zeeman splitting of hyperfine magnetic substates (unimportant for guide fields < 10 gauss)

•Ion beam and laser divergences (unimportant for typical ~2 mrad)

EOM broadening of laser bandwidth

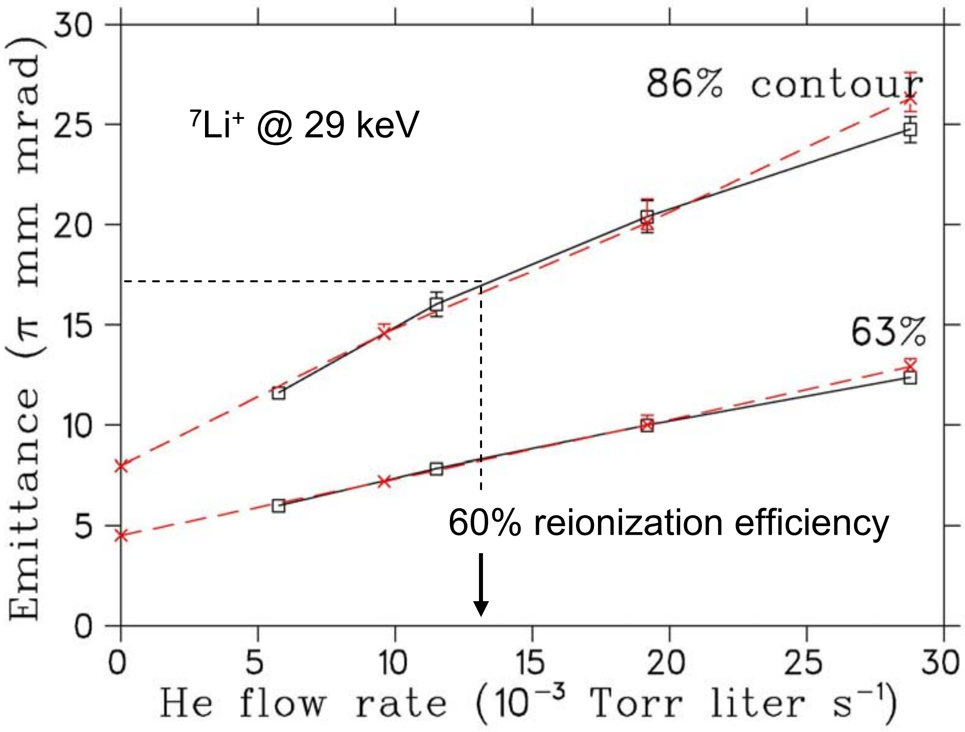


Beam emittance

Dashed line – Li^+ beam with neutralizer switched off, deflectors off

Solid line – “polarized” ion beam

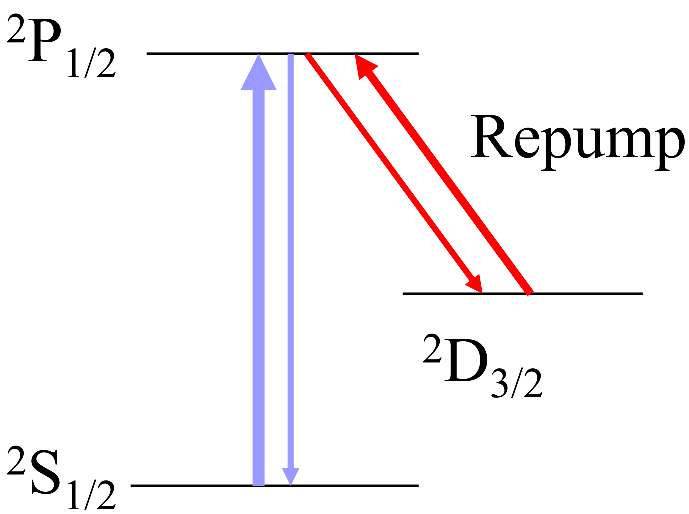
Shows scattering due to helium, no effect from sodium.



Beyond the alkali metals

Alkaline earths

- Ion has electronic structure similar to neutral alkalis.



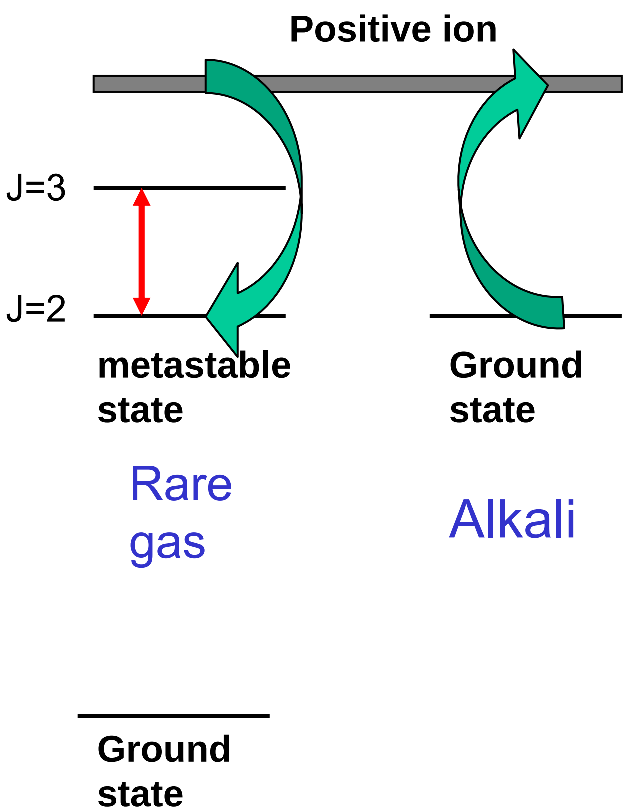
	Polarizing wavelength (nm)	Repump wavelength (nm)
Be	313	none
Mg	280	none
Ca	397	866
Sr	422	1092
Ba	494	650
Ra	468	1079

[M. Kowalska et al., Phys. Rev. C 77, 034307 (2008)]

Rare gases

- Closed transition uses metastable $1s_5(J=2)$ atomic state as lower level
- Rare gas$^+$ + alkali → rare gas + alkali$^+$
- Typical polarization = 20% ?

	Ionization potential (eV)
Na	5.14
K	4.34
Cs	3.89



	Polarizing wavelength (nm)	Binding energy of metastable state (eV)
He	1083	4.77
Ne	640	4.94
Ar	812	4.21
Kr	812	4.08
Xe	882	3.81
Rn	745	3.98

Other examples of closed transitions

Many other elements can be polarized through some combination of ground state or metastable pumping, with a repump laser if required. A small sample is listed below:

Element	Transition	Wavelength (nm)	Energy of metastable state (eV)	Binding energy of metastable state (eV)
O	$^5S_2 - {}^5P_3$	777	9.15	4.47
F	$^4P_{5/2} - {}^4D_{7/2}$	686	12.70	4.73
Si	$^3P_1 - {}^3P_0$	252	0.0095	8.14
Ge		271	0.069	7.81
Sn		304	0.21	7.13
Pb		368	0.97	6.44
Hg	$^1S_0 - {}^3P_1$	254	ground state transition	

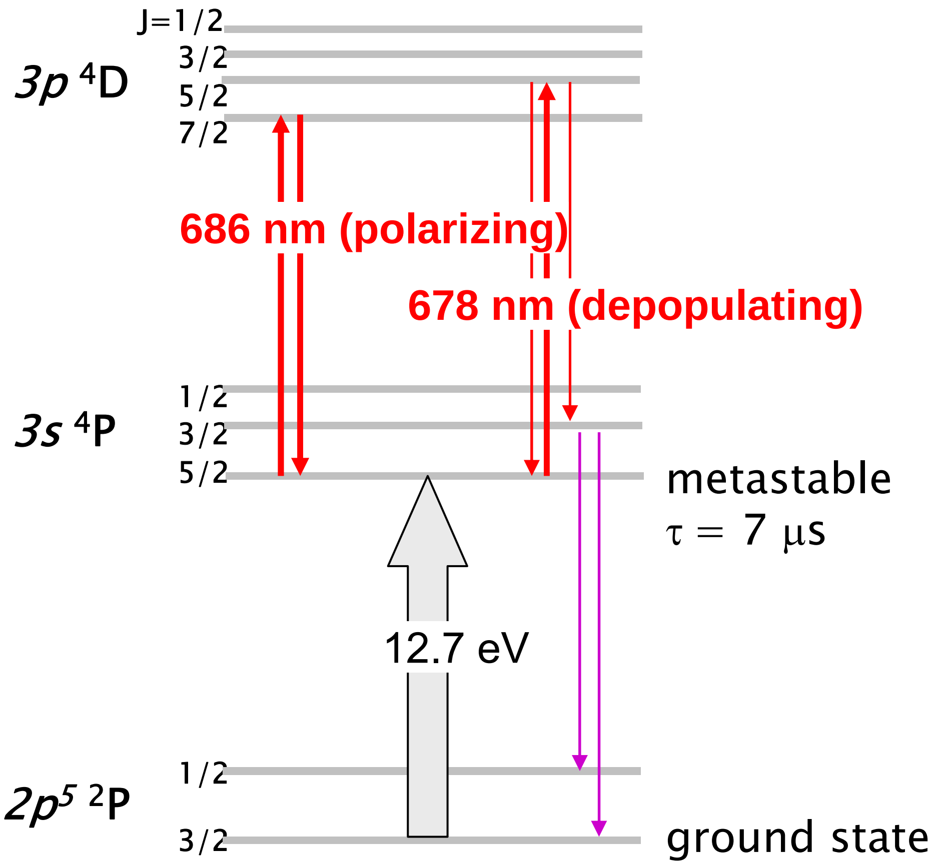
Feasibility study of polarizing ^{20}F

Development of polarized ^{20}F beam

- Required for continuation of G-parity studies begun with mirror nucleus ^{20}Na

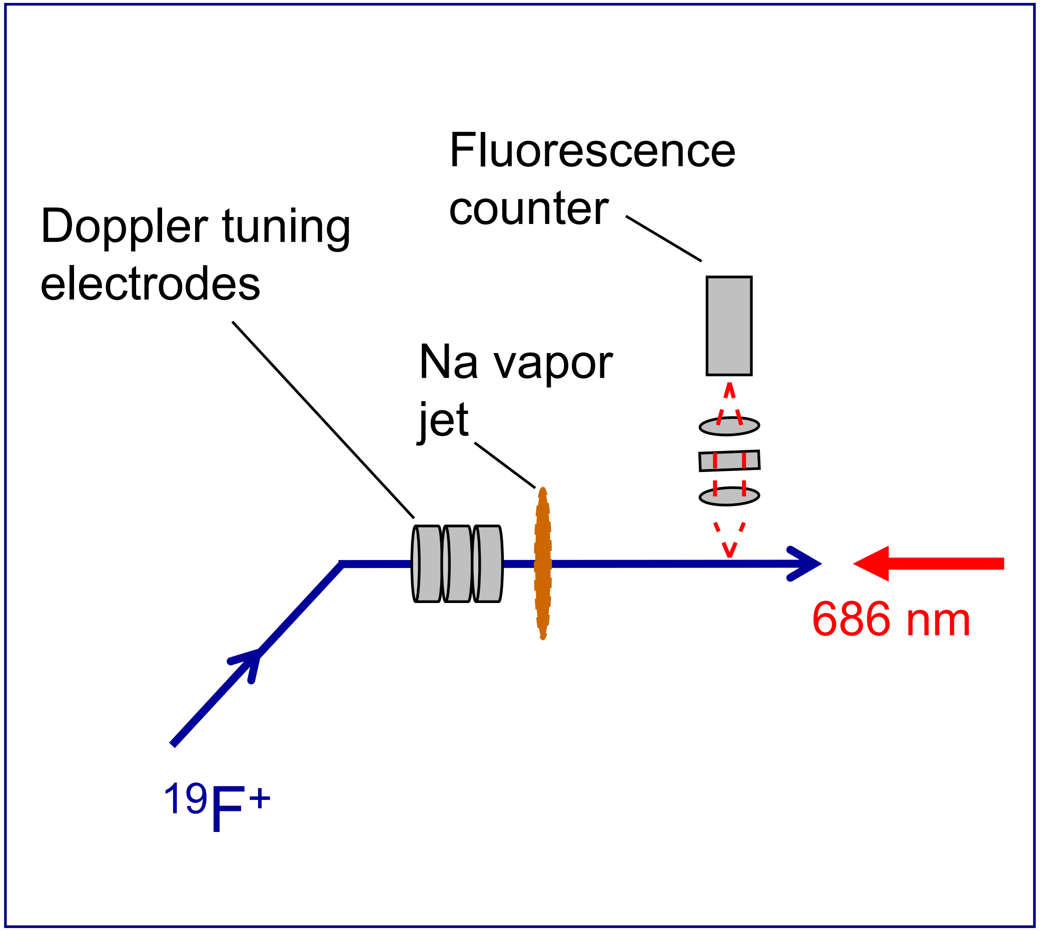
- Questions
- Metastable production efficiency and survival
- Hyperfine structure of ^{20}F (I =2)

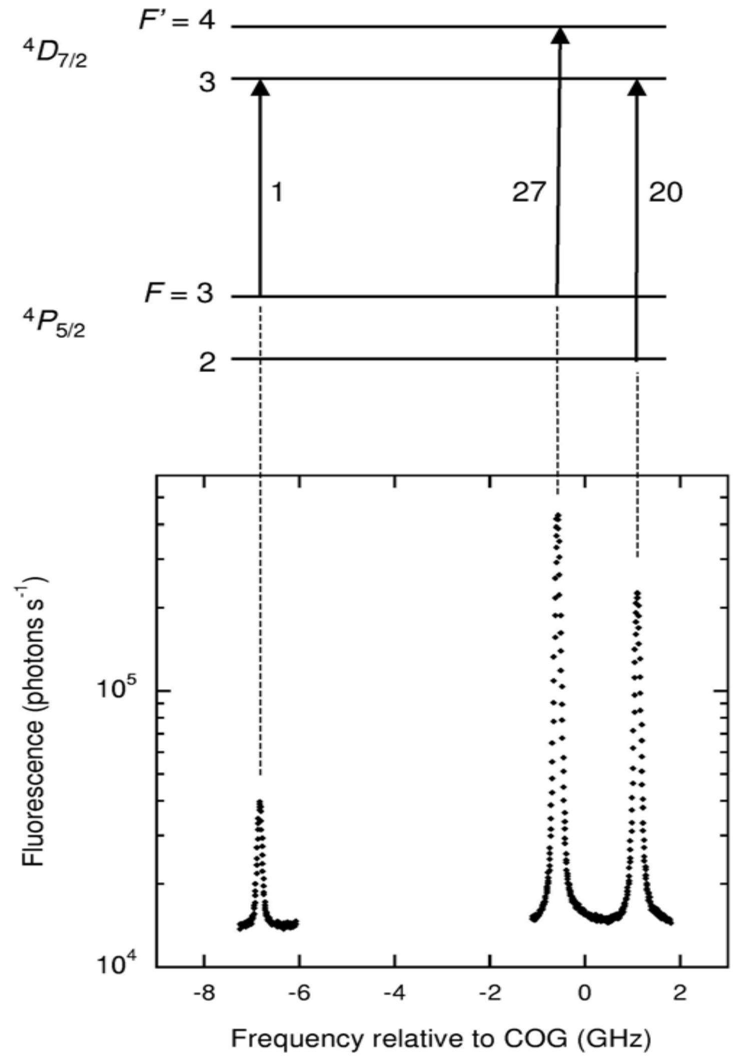
- Methods
- Used stable ^{19}F (I =1/2)
- Laser induced fluorescence $^4P_{5/2} \rightarrow {}^4D_{7/2}$
- Metastable depopulation pumping $^4P_{5/2} \rightarrow {}^4D_{5/2}$



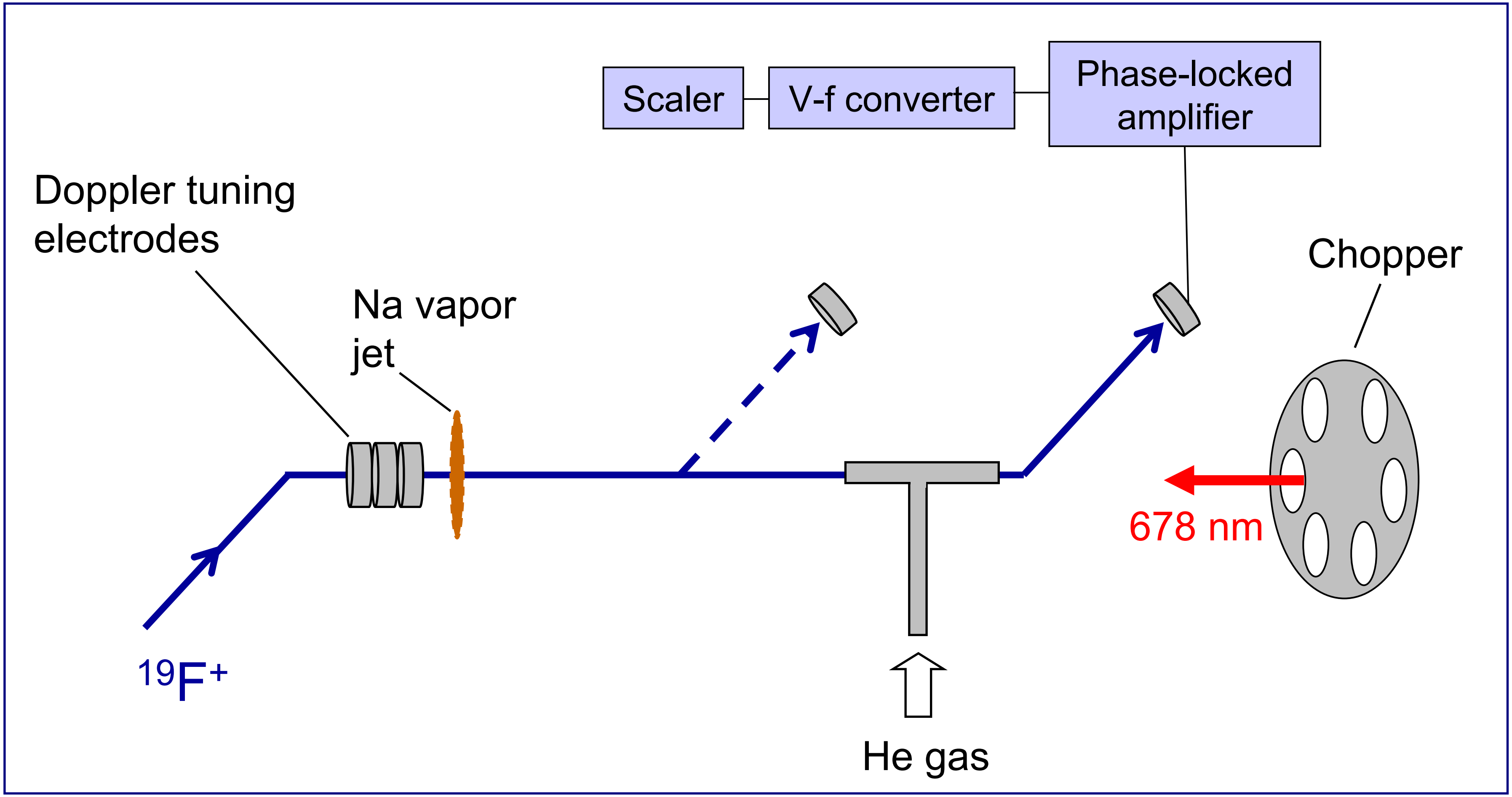
[C.D.P. Levy et al., NIM A 580, 1571 (2007)]

Polarizing transition $^4P_{5/2} \rightarrow {}^4D_{7/2}$

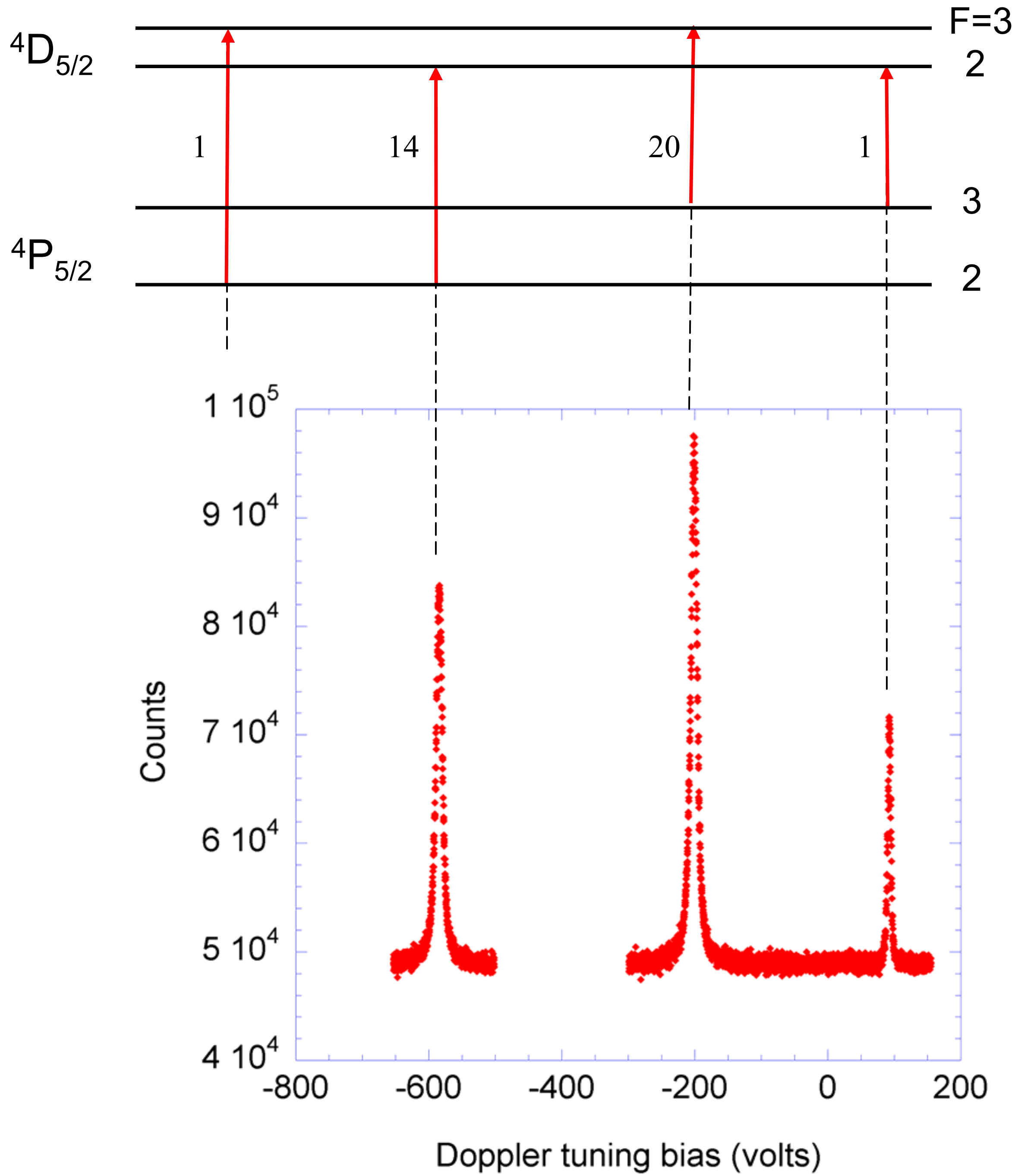




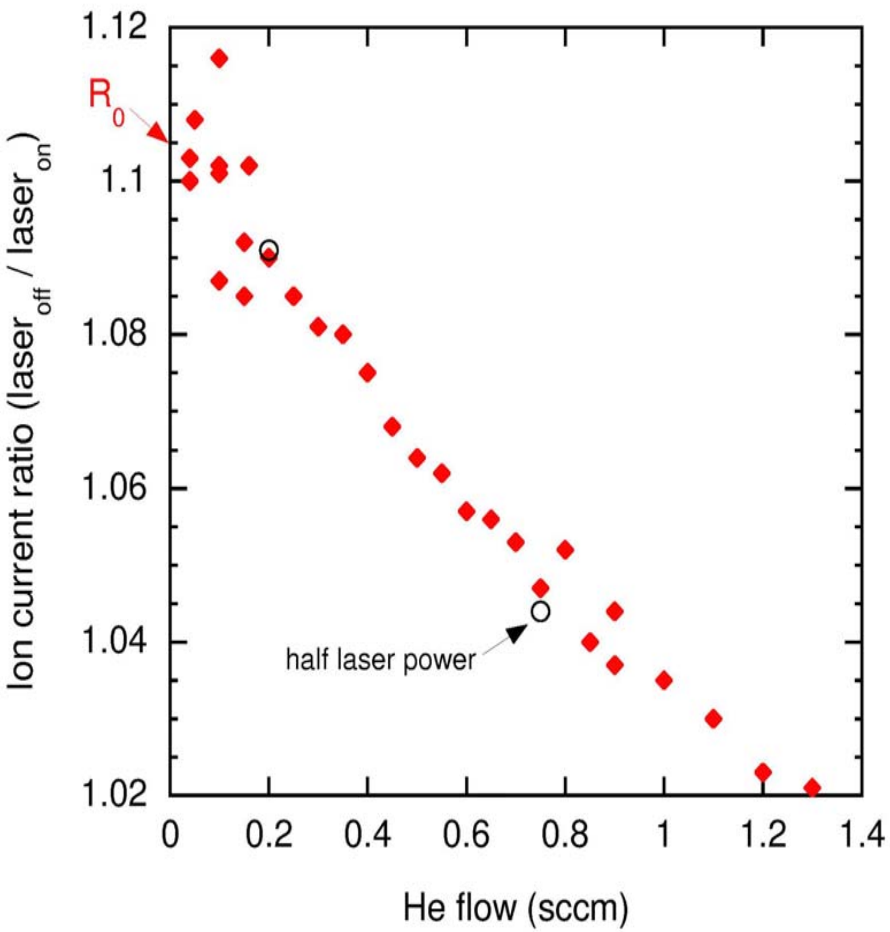
Depopulating transition $^4P_{5/2} \rightarrow {}^4D_{5/2}$



Faraday cup spectroscopy



Metastable yield



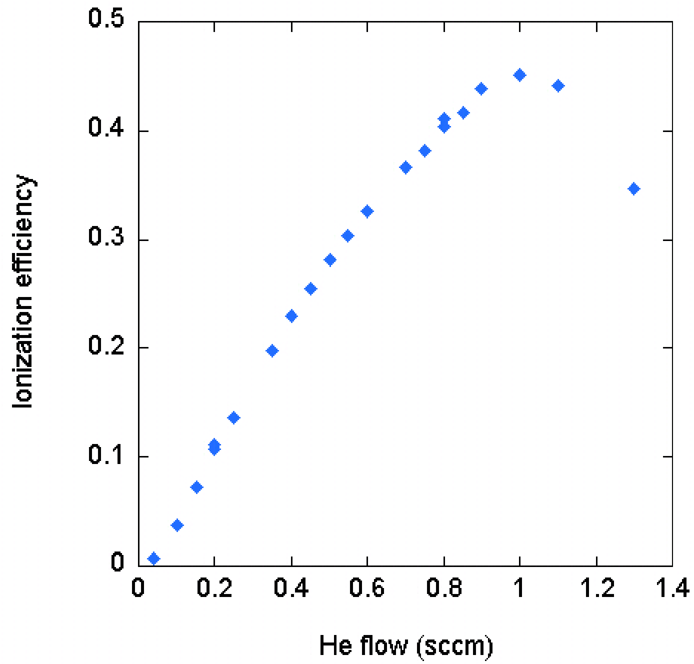
Metastable-derived ion beam fraction at low He flow

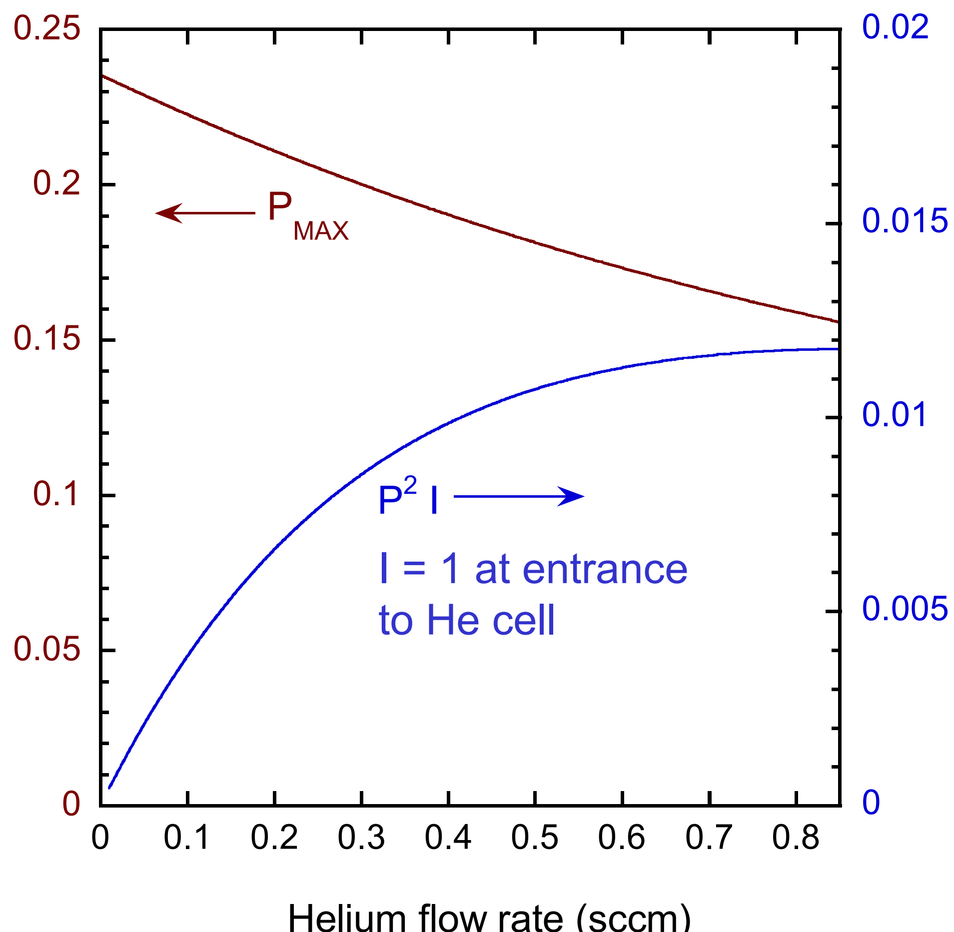
= 0.24 +0.16/-0.03

ρ = ionization cross section ratio
= 3.4 [O.B. Firsov, Soviet Phys. JETP 36 (1959) 1076]

Tuned to strongest transition, *F* = 3 → 3

Polarization and transmission efficiency





- P_{MAX} assumes 100% polarization of metastables
- Assumes no polarization loss during ionization

Polarization loss during ionization?

Sudden loss of excited electron does not reduce polarization:

$2s^2\,2p^4\,3s$ ($^4P_{5/2}$ metastable atom)

S=3/2

L=1

J=5/2

$2s^2\,2p^4\,3p$ ($^4D_{7/2}$ upper state atom)

S=3/2

L=2

J=7/2

Ionize

$2s^2\,2p^4$ ($^3P_2$ ionic ground state)

S=1

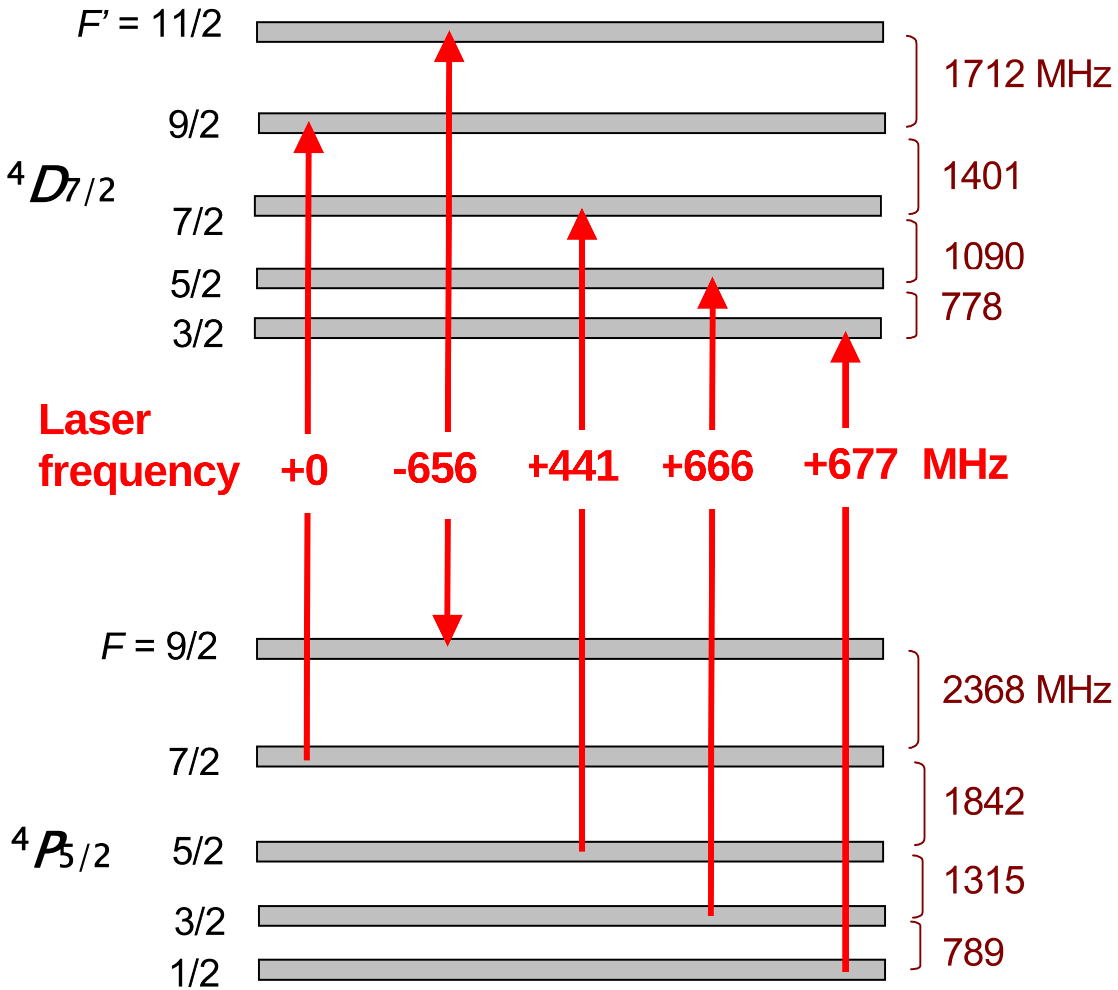
L=1

J=2

In each case, *J* remains fully stretched, and total angular momentum $F=I+J$ remains fully stretched. No radiative losses.

⇨ no changes in orientation of nuclear spin *I*.

Calculated ^{20}F hyperfine structure

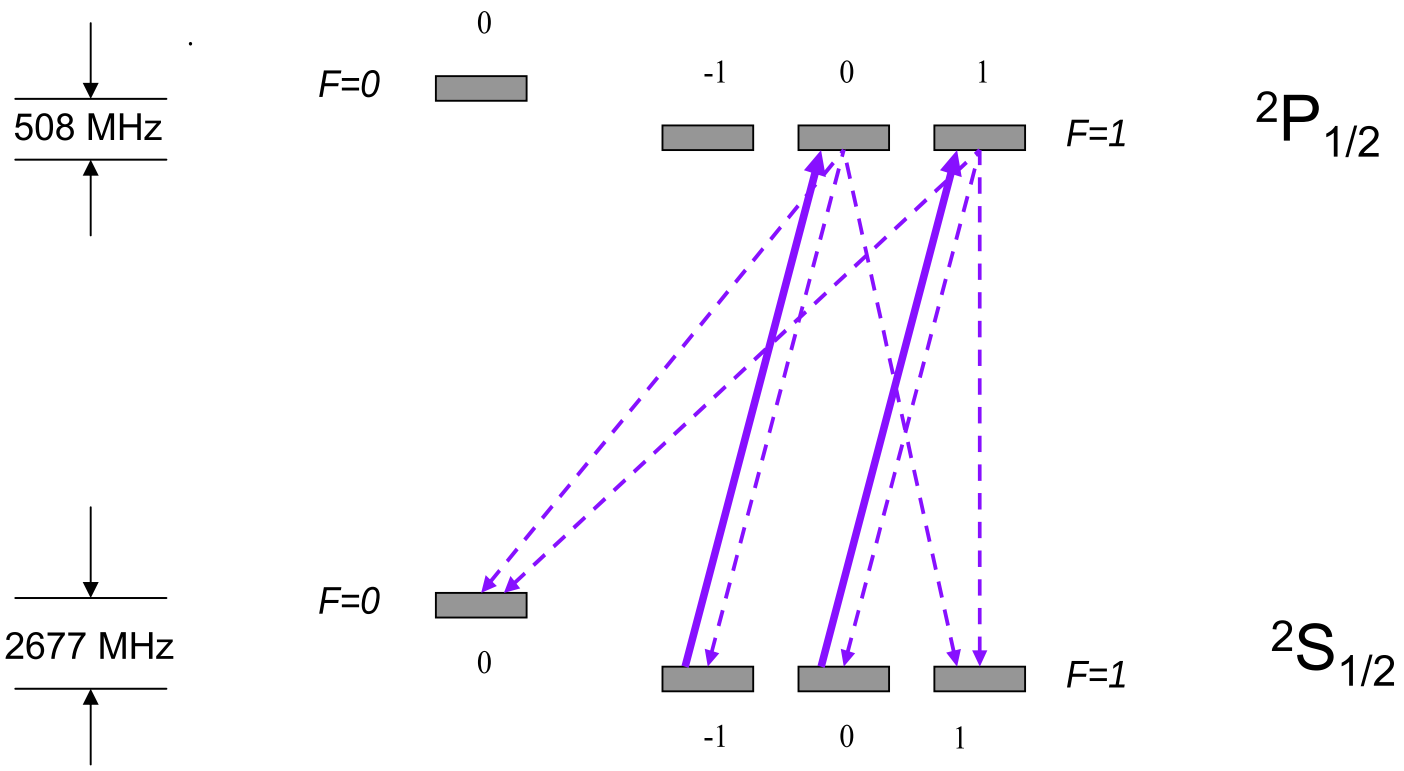


- Electric quadrupole shifts < 5 MHz (extrapolating from other halogens)
- 666 MHz EOM covers 80% of population

→ predicted beam polarization up to 14 - 17%

Polarized ^{11}Be

Optical pumping of $^{11}Be^{+}$



Pumping on F=1→1, all transitions are shown

Comparison of $^{11}Be^{+}$ and ^{8}Li

	Nuclear spin	Half-life *(s)*	Asymmetry parameter	$^{2}S_{1/2} \rightarrow {}^{2}P_{1/2}$ transition wavelength *(nm)*	Transition saturation intensity *(mW cm^{-2})*	Ion electronic structure
^{8}Li	2 Responds to electric field gradients and magnetic fields	0.84	-0.33	671 Dye laser	2.6	Closed shell
$^{11}Be^{+}$	½ A pure magnetic probe	13.8	?	313 Frequency-doubled dye laser	78	Paramag-netic

Previous ^{11}Be polarization:

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Measurement of the Magnetic Moment of the One-Neutron Halo Nucleus ^{11}Be

W. Geithner,[1] S. Kappertz,[1] M. Keim,[2] P. Lievens,[3] R. Neugart,[1] L. Vermeeren,[4] S. Wilbert,[1] V. N. Fedoseyev,[5] U. Köster,[6] V. I. Mishin,[5] V. Sebastian,[1] and ISOLDE Collaboration[2]

(Received 26 May 1999)

The magnetic moment of ^{11}Be ($T_{1/2} = 13.8$ s) was measured by detecting nuclear magnetic resonance signals in a beryllium crystal lattice. The experimental technique applied to a ^{11}Be^{+} ion beam from a laser ion source includes in-beam optical polarization, implantation into a metallic single crystal, and observation of rf resonances in the asymmetric angular distribution of the β decay (β-NMR). The nuclear magnetic moment $\mu(^{11}\text{Be}) = -1.6816(8)\ \mu_N$ provides a stringent test for theoretical models describing the structure of the $1/2^{+}$ neutron halo state.

[Geithner et al]

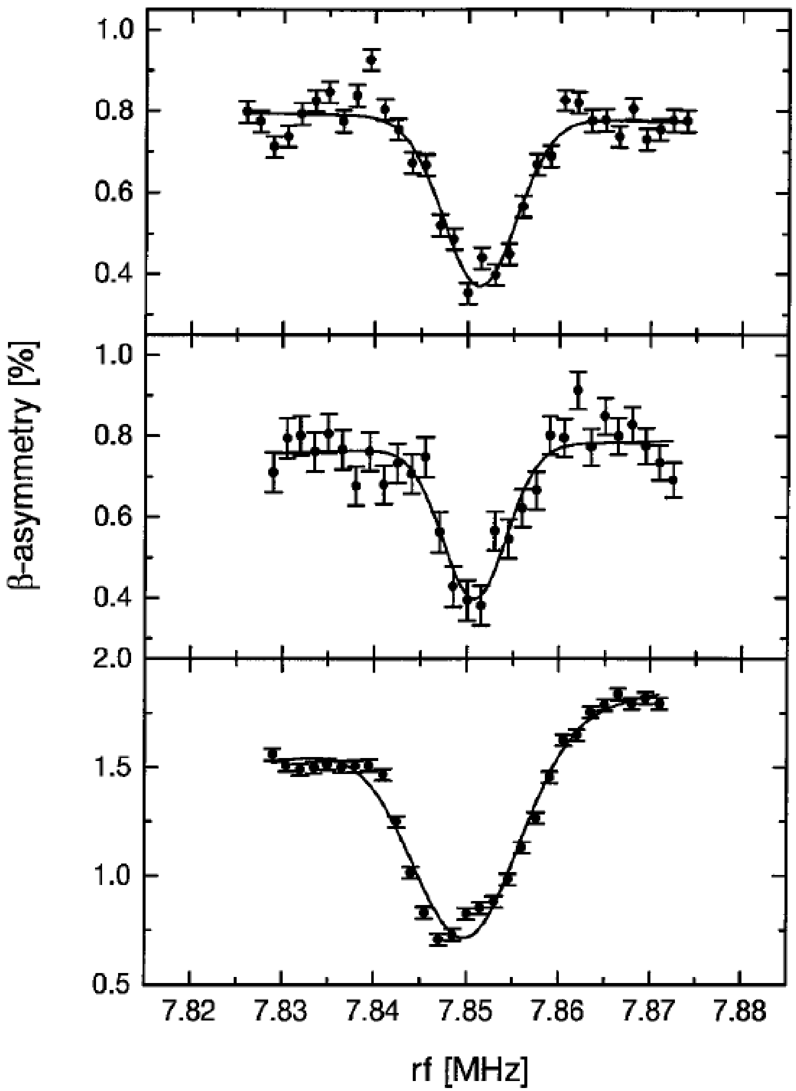


FIG. 1. Examples of β-NMR signals of ^{11}Be nuclei in a beryllium host crystal.

^{11}Be yield = a few 10^6 ions/s

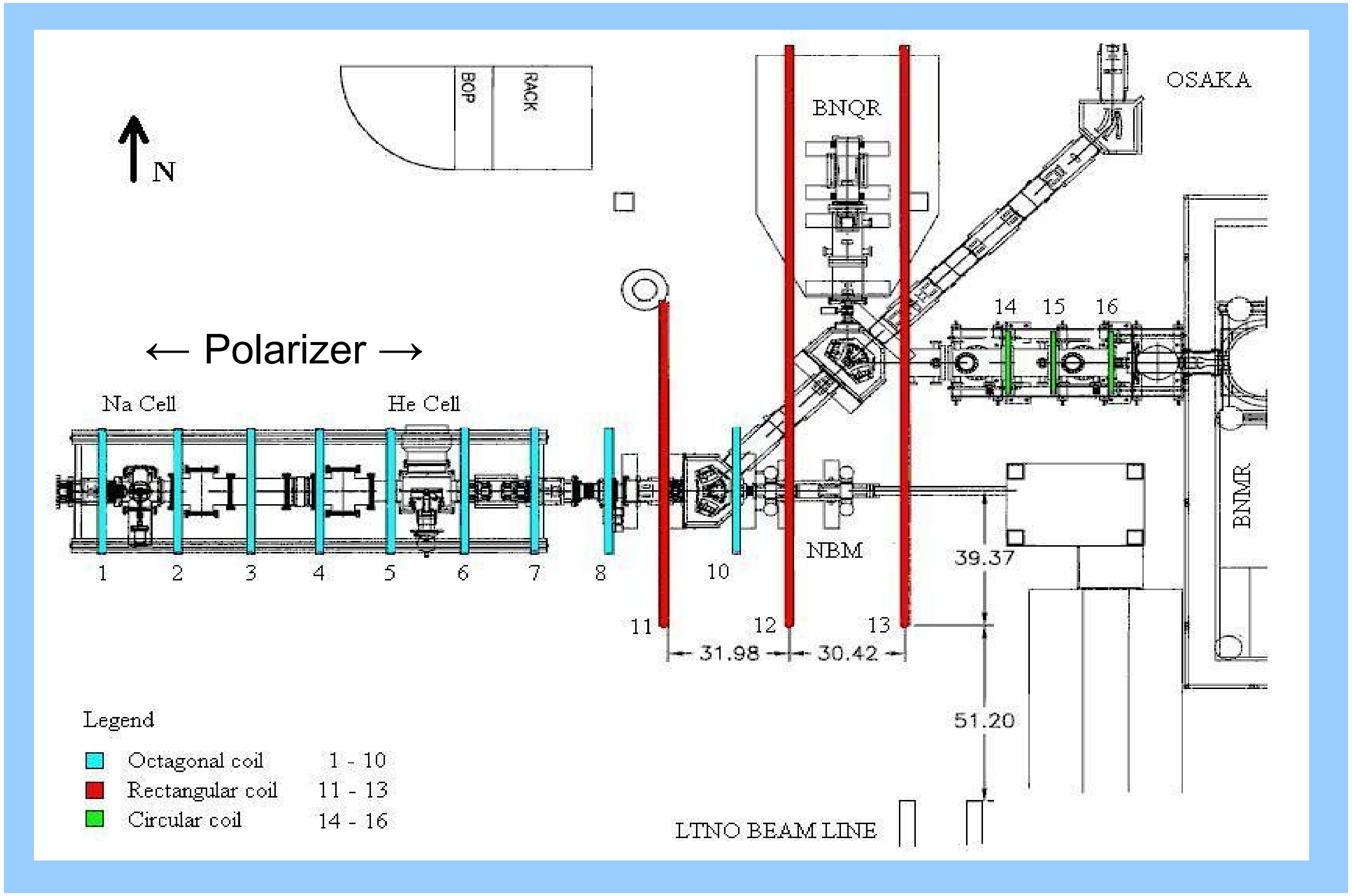
Time-averaged asymmetry ≈ 1%
(too low for condensed matter studies)

Laser power ≈ 1mW
(far below saturation intensity)
single frequency
(many ions can't "see" the light)

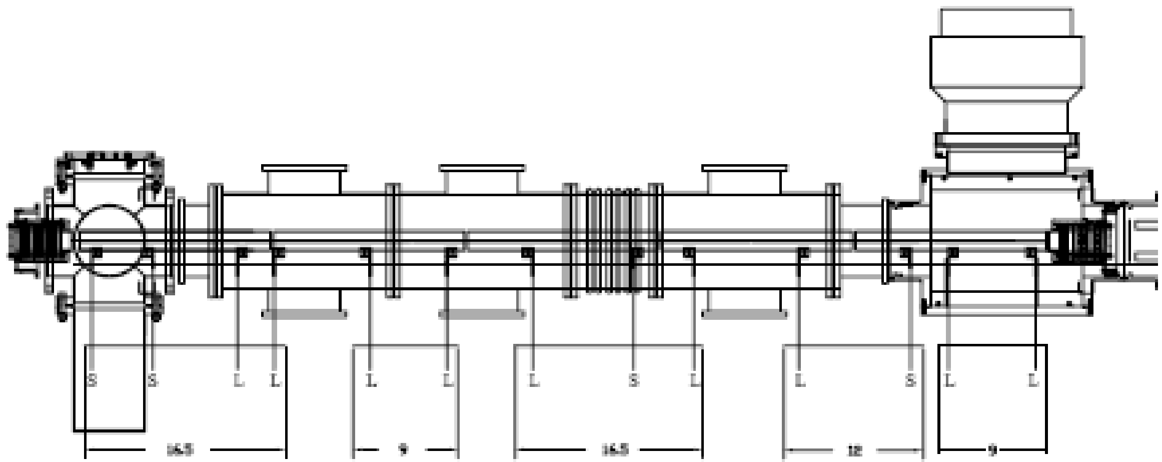
Transport coils

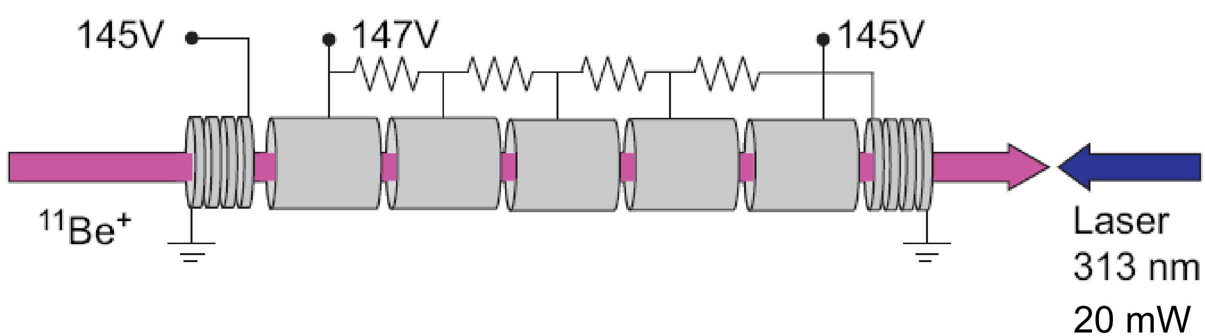
• $^{11}Be^{+}$ is paramagnetic. The electron magnetic moment precesses rapidly in the Earth's field, destroying nuclear polarization.

⇨Extend guide magnetic field to experiments

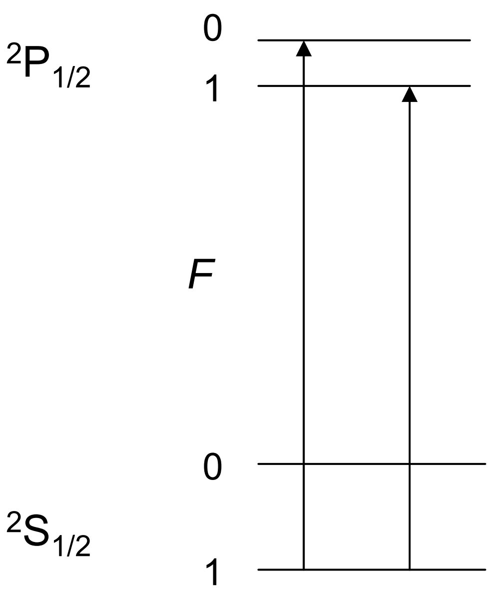


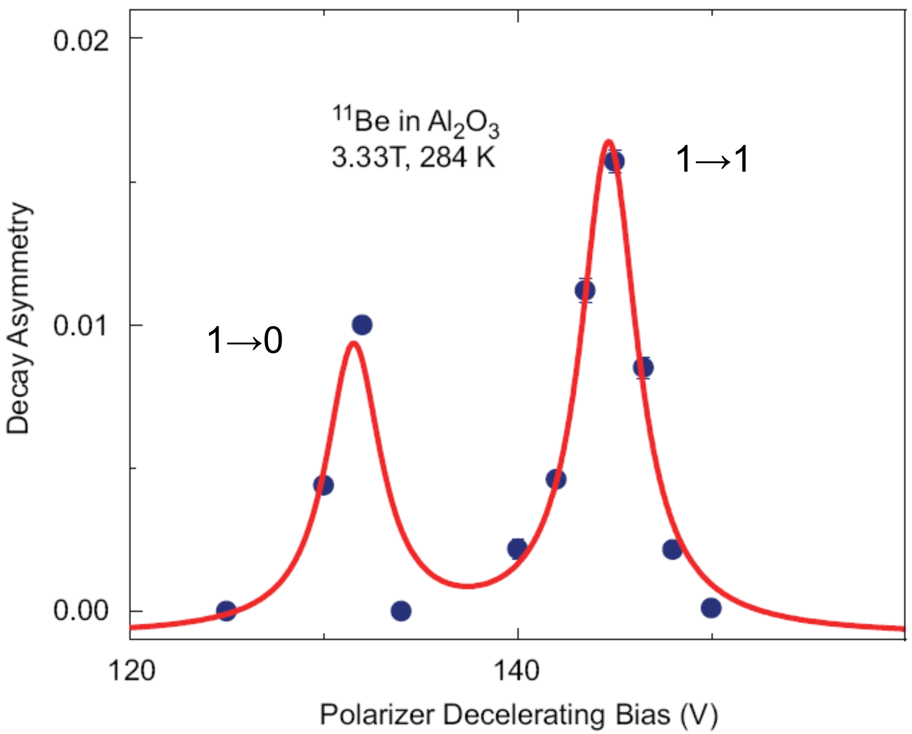
Doppler tuning and bandwidth matching





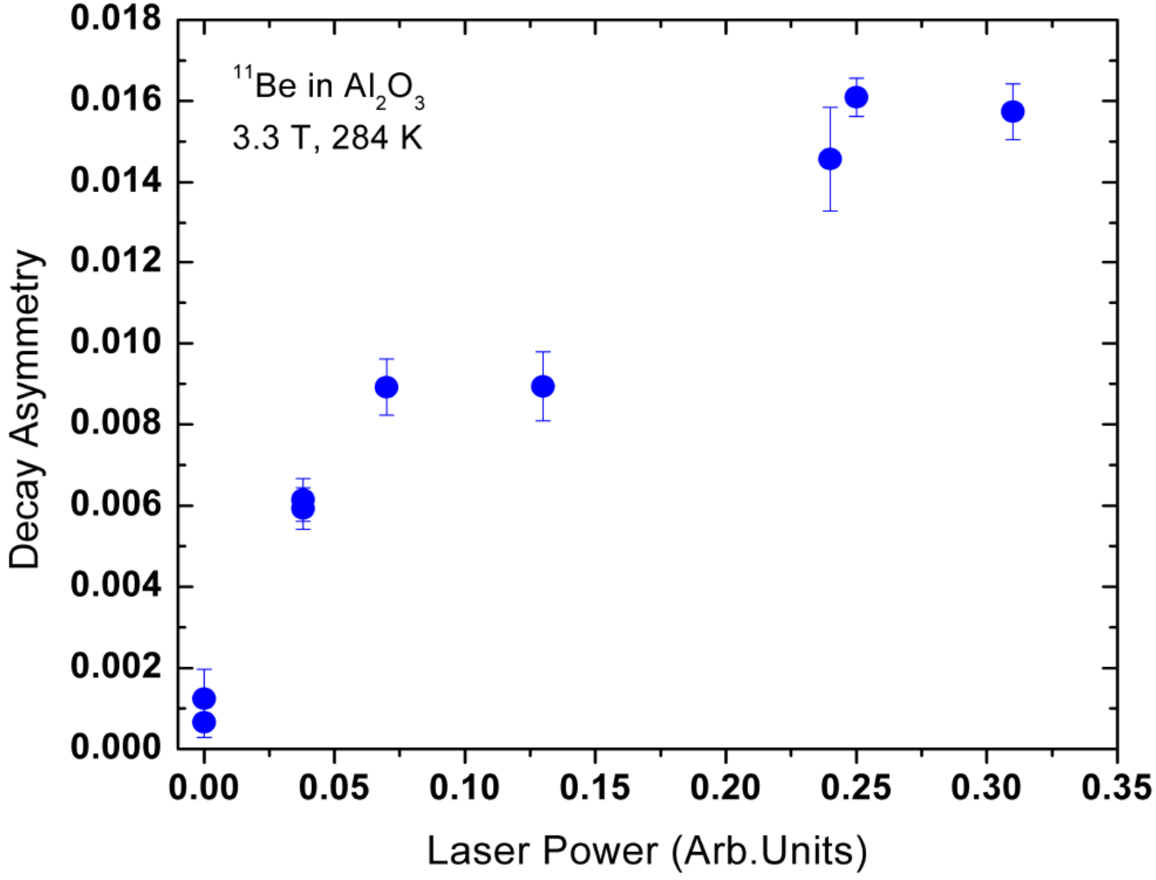
Result





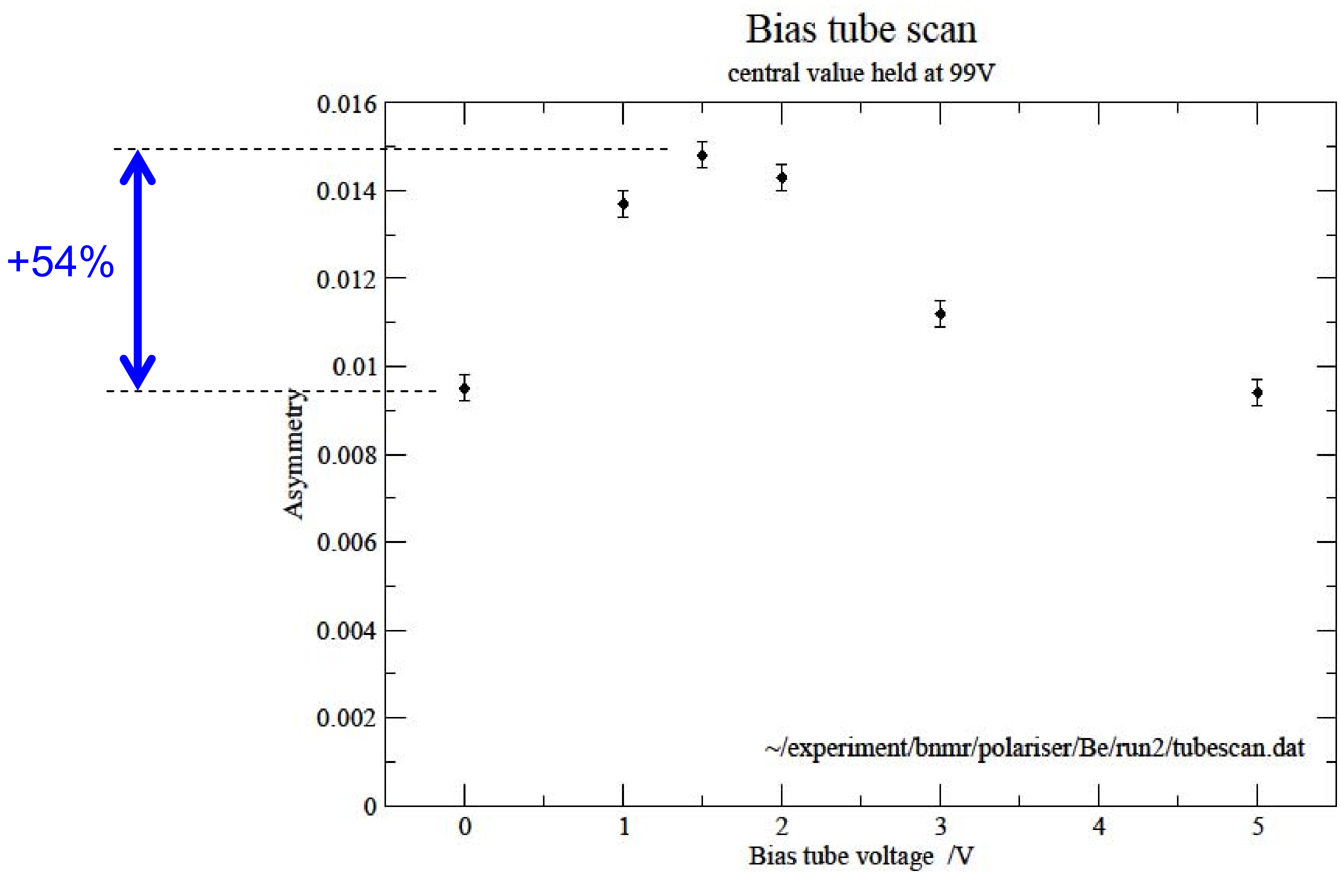
30% increase in asymmetry due to 2 V applied across the segmented tube.

Saturation curve



Drift tube segmentation

- increased to 7, lengths tailored to Doppler profile



Interpreting the results

- Asymmetry is not much better. Why not?

- An optical pumping cycle produces one scattered fluorescence photon
- The saturation intensity I_S for an atomic transition is defined as

$$I_S = \frac{\pi h c}{3\lambda^3 \tau}$$

where τ is the lifetime of the excited state and λ is the wavelength of the transition. The scattering rate on resonance γ at a laser intensity I is given by

$$\gamma = \frac{I/I_S}{2\tau\left(1 + I/I_S\right)} \quad \text{/atom/s}$$

Optical pumping parameters

	Geithner et al (^{11}Be)	TRIUMF (^{11}Be)
Laser power (mW)	1	20
γ (s^{-1})	7.27 E5	1.17 E7
Mean length/cycle on resonance (cm)	142	5.1
Mean number of cycles	1	6
Maximum observed asymmetry	0.008	.016

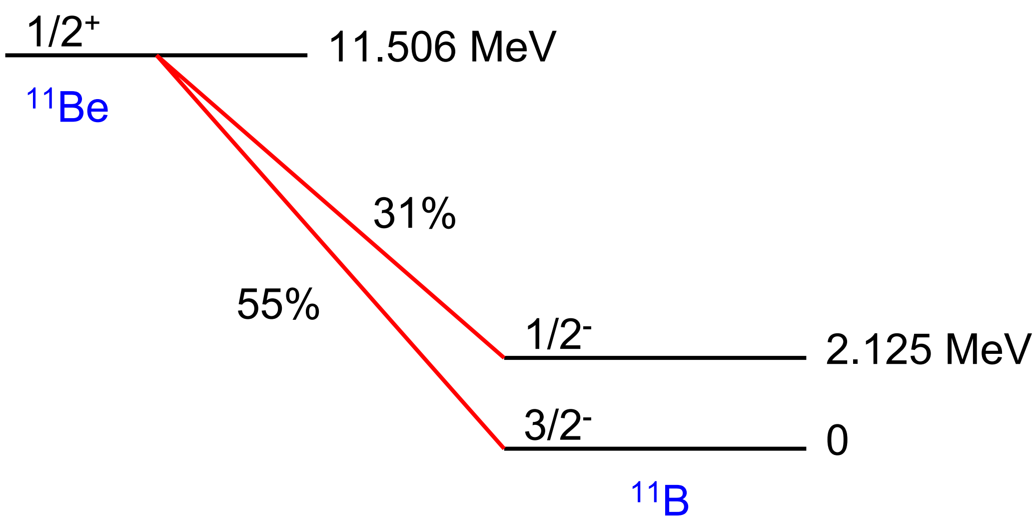
Conclusion

- Spin ½ atom takes only 2-3 optical pumping cycles to saturate polarization. Even far below the transition saturation intensity, the polarization begins to saturate.

⇨ ^{11}Be beta-decay asymmetry parameter is small.

Future options

- Increase polarization twofold by pumping both g.s. hyperfine levels → 3% asymmetry. Uses more complex drift tube arrangement.
- Discriminate on beta detection? Two strongest transitions tend to cancel, so count betas above 9 MeV.



Summary

- Many elements can be polarized in a collinear beam line
  - alkalis
  - alkaline earths
  - rare gases
  - O, F, Si, Ge, Sn, Pb, …..

- Suited to low emittance, low energy beams of beta-emitters, of course applicable to stable isotopes as well

- Development can proceed with stable beams

- Besides initial motivation of condensed matter physics, polarized radioactive beams are useful in low-energy studies of nuclear structure and fundamental symmetries.

Collaborators

TRIUMF
Matt Pearson, Gerald Morris, John Behr, Jens Lassen (and the rest of the Laser Ion Source group), Keerthi Jayamanna, Rick Baartman, Kei Minamisono, Larry Root, Miguel Olivo, Geoff Wight, Dick Yuan

βNMR group
Rob Kiefl, Andrew MacFarlane, Kim Chow, Mike Smadella, MD Hossain, Terry Parolin, Dong Wang, Hassan Saadaoui, Susan Song

Université Laval
Richard Labbé

McGill University
Thomas Cocolios

University of Tokyo
Atsushi Hatakeyama

Osaka University
Yoshikazu Hirayama