Spin Polarized (Metastable) Highly Charged Ions A Probe for the Magnetic Structure of Nuclei?

Or

What you can do with a 100% spin polarized electron target?

GSI, 11.12.2002

Idea 1:
Prepare spin-polarized nuclear beams

Highly stripped ions capture
several spin-oriented electrons

Transfer shell polarisation on nucleus

magnetic structure of ionic shell : dipole moment

Can create by electron capture *any* species of metastable ionic states:

e.g. He-like $^3S_1$(1s,2s)

or

Li-like $^4P_{1/2,3/2,5/2}$ (1s,2s,2p)

or

Be-like $^3P_{0,1,2}$ ($1s^2$, 2s,2p)

etc

only $\Delta F=1$ transitions

Idea 2:
use hyperfine interaction
and measure the hyperfine energy splitting
and hyperfine quenching (decay time)
of spin polarized metastable shell states

Atomic lifetimes for highly charged ions

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Abstract

In this talk I give an overview of the present status of our theoretical understanding of Lifetimes. I discuss a few examples and describe the latest measurement of Hyperfine Quenching of gold at GSI. I discuss prospects for new experiments with applications to nuclear physics

Experiment:

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Hyperfine Splitting

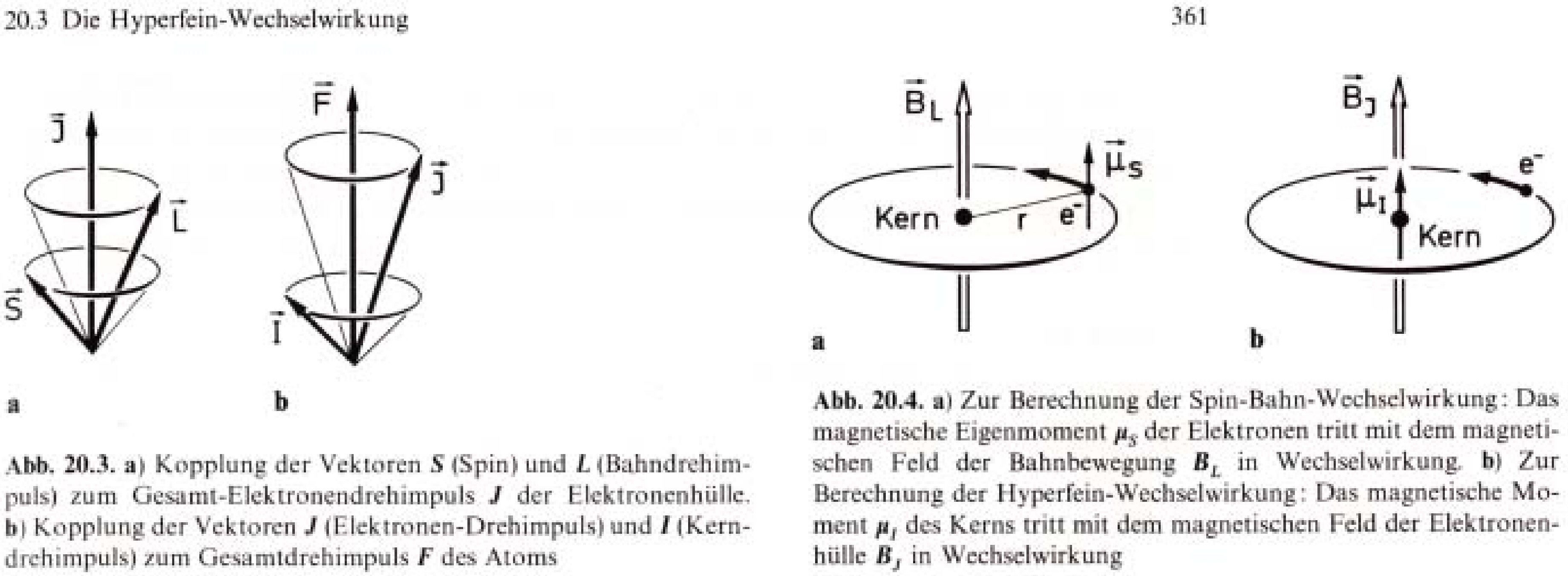

20.3 Die Hyperfein-Wechselwirkung 361

Abb. 20.3. a) Kopplung der Vektoren ***S*** (Spin) und ***L*** (Bahndrehimpuls) zum Gesamt-Elektronendrehimpuls ***J*** der Elektronenhülle. **b)** Kopplung der Vektoren ***J*** (Elektronen-Drehimpuls) und ***I*** (Kerndrehimpuls) zum Gesamtdrehimpuls ***F*** des Atoms

Abb. 20.4. a) Zur Berechnung der Spin-Bahn-Wechselwirkung: Das magnetische Eigenmoment $\boldsymbol{\mu}_S$ der Elektronen tritt mit dem magnetischen Feld der Bahnbewegung $\boldsymbol{B}_L$ in Wechselwirkung. **b)** Zur Berechnung der Hyperfein-Wechselwirkung: Das magnetische Moment $\boldsymbol{\mu}_I$ des Kerns tritt mit dem magnetischen Feld der Elektronenhülle $\boldsymbol{B}_J$ in Wechselwirkung

Hyperfine Splitting

$$V_{HFS} = -\mu_I B_J$$

$$= -|\mu_I| B_J \cos(\boldsymbol{\mu}_I, \boldsymbol{B}_J) =$$

$$-|\mu_I| B_J \{F(F+1)-I(I+1)-J(J+1)\}/(2 \text{ square root}\{J(J+1)I(I+1)\})$$

Depends NOT on the multipole character of the nuclear magnetic moment

Total Angular Momenta F

Example:

J=S=1(L=0) and I=3

=> F= 2,3,4

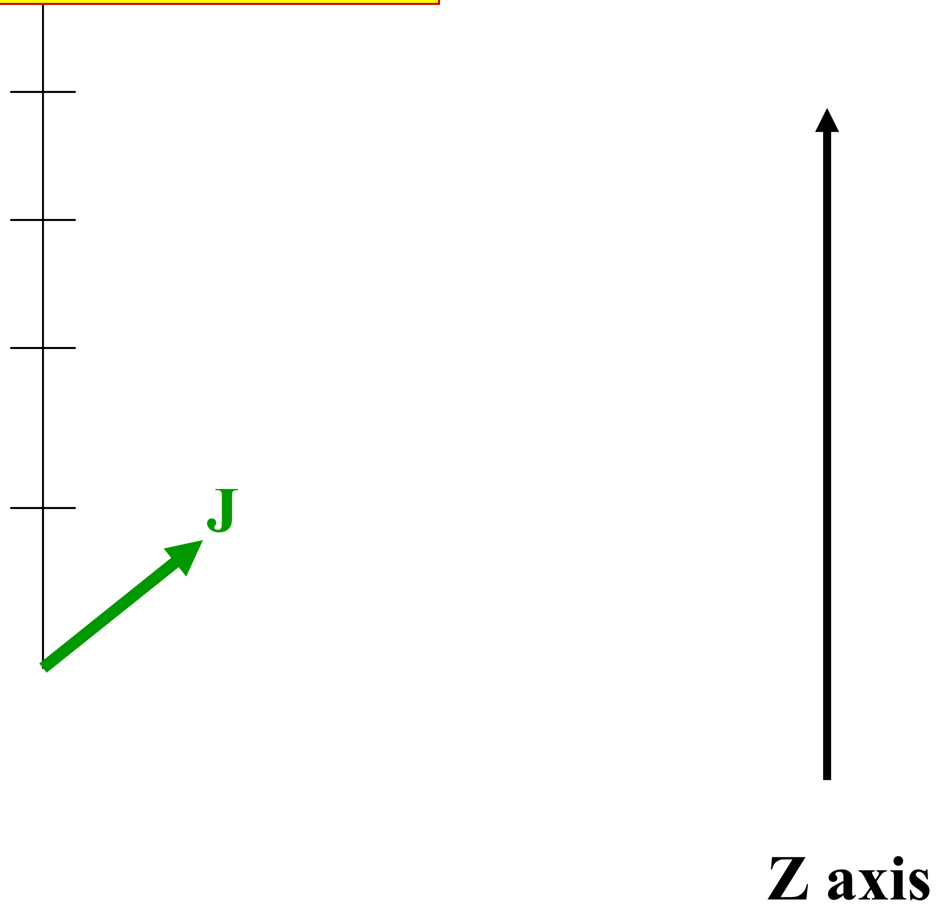
Total Angular Momenta F
Example:

J=S=1(L=0) and I=3

=> F= 2,3,4

J=S=1

S is fixed in space with respect to z-axis



Total Angular Momenta F

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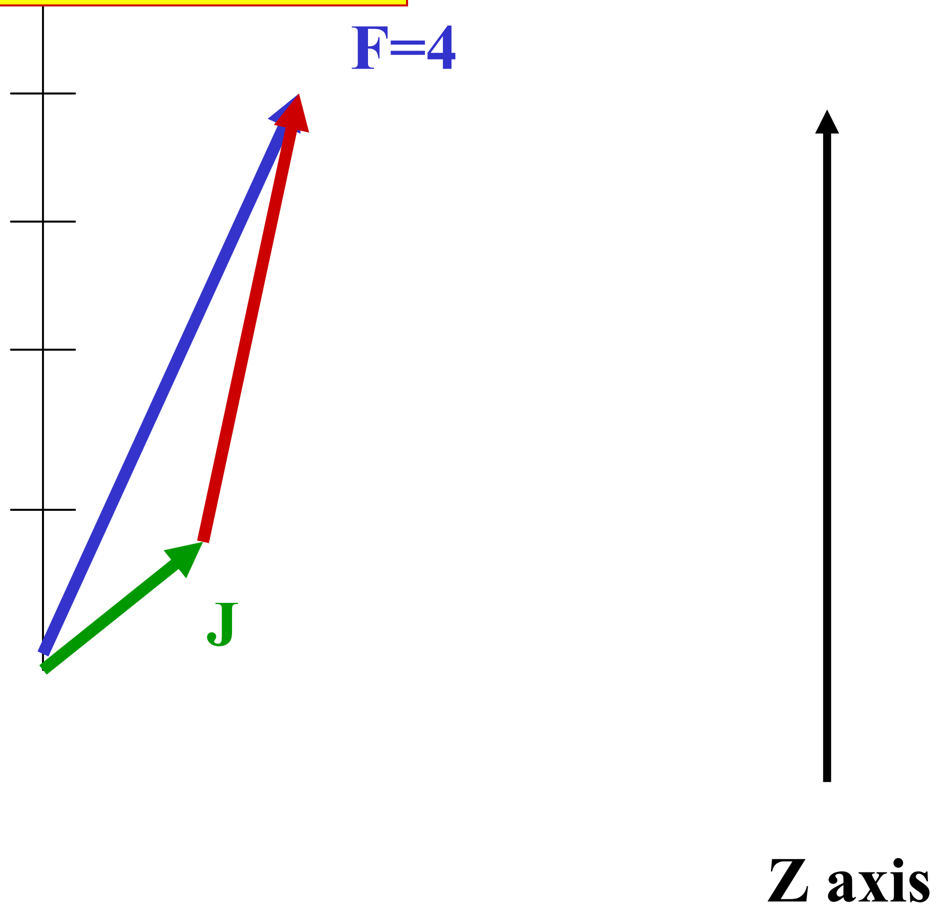
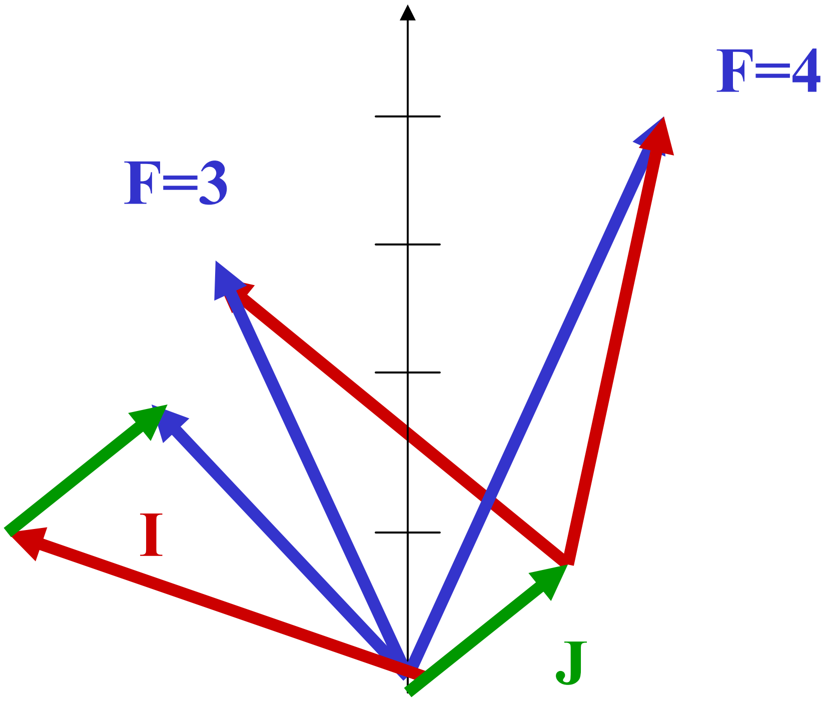


Total Angular Momenta F
=> F= 2,3,4

J=S=1

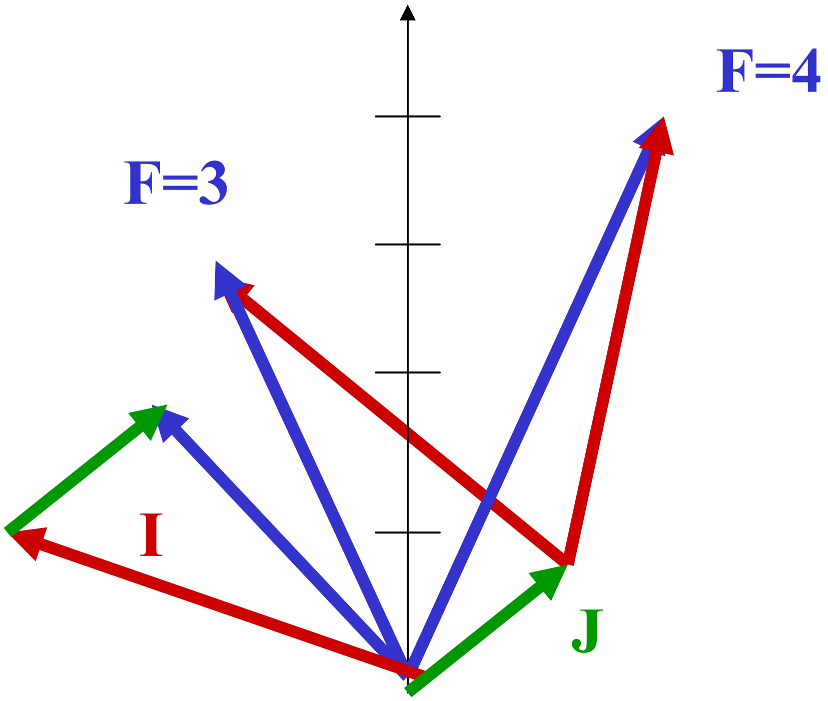
S is fixed in space with respect to z-axis



Total Angular Momenta F for J=S=1(L=0) and I=3 => F= 2,3,4

J=S=1

S is fixed in space with respect to z-axis



In case of F=4

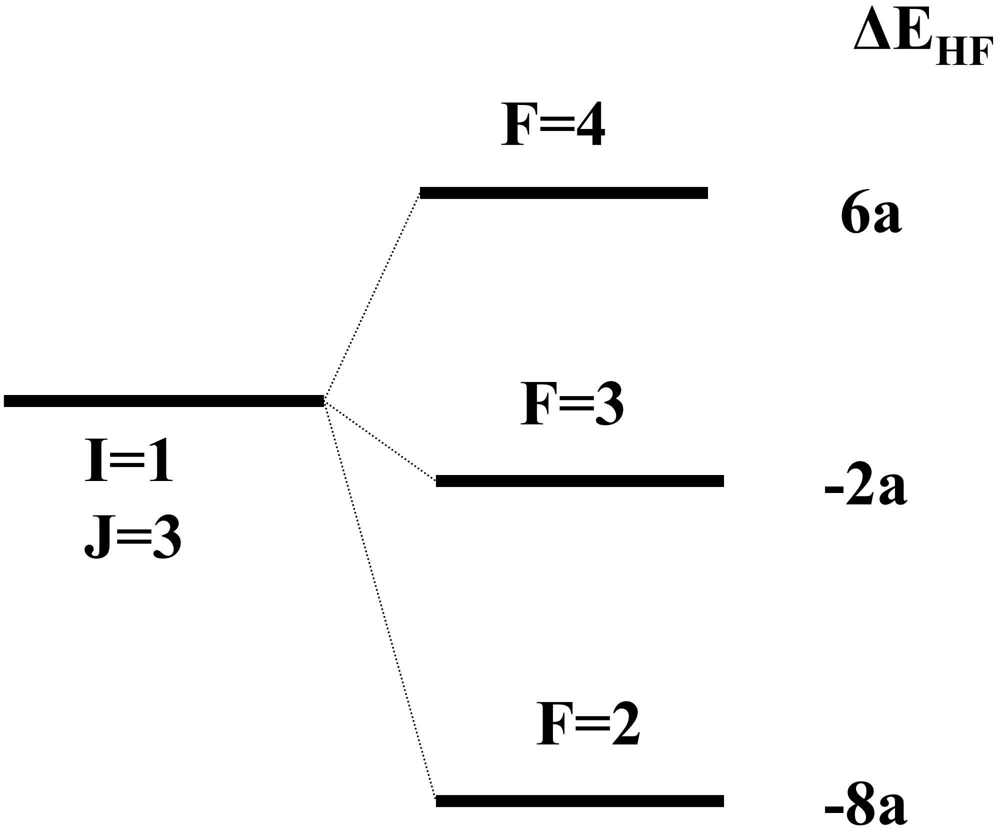
⇒I can only be parallel to S

In case of F=2

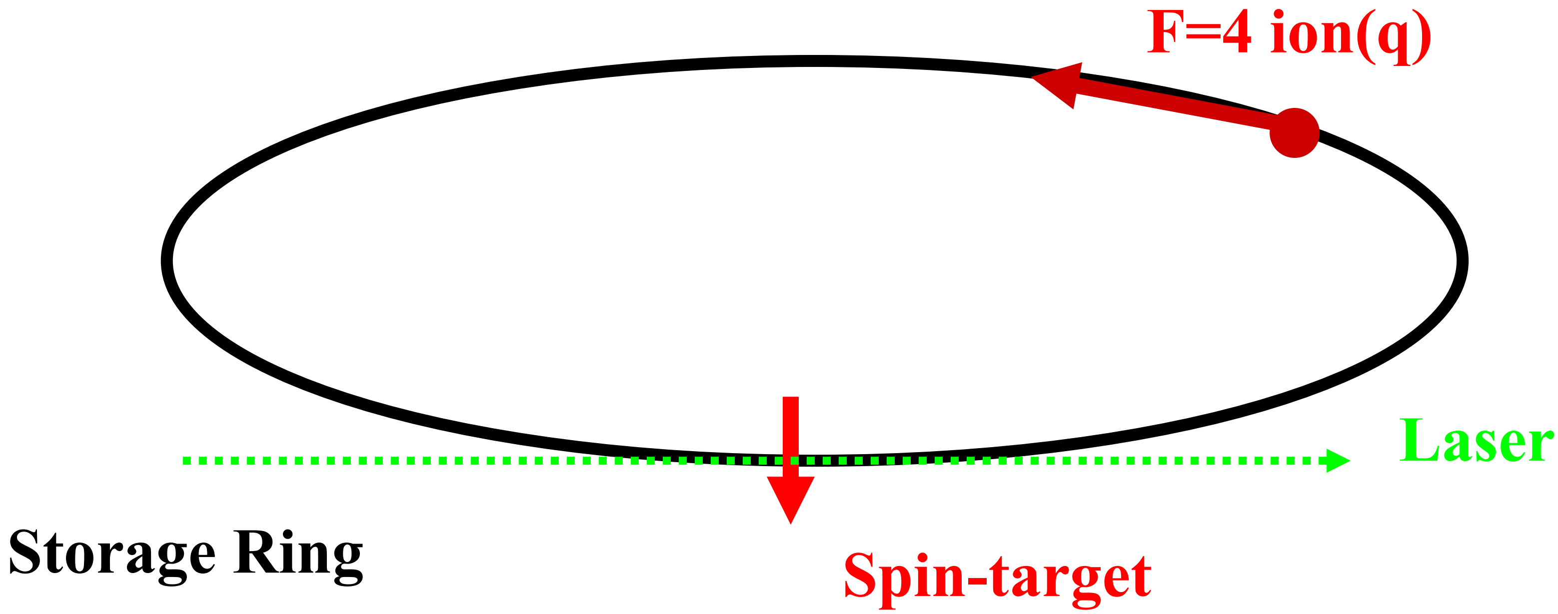
=> I can only be antiparallel to S

Z axis

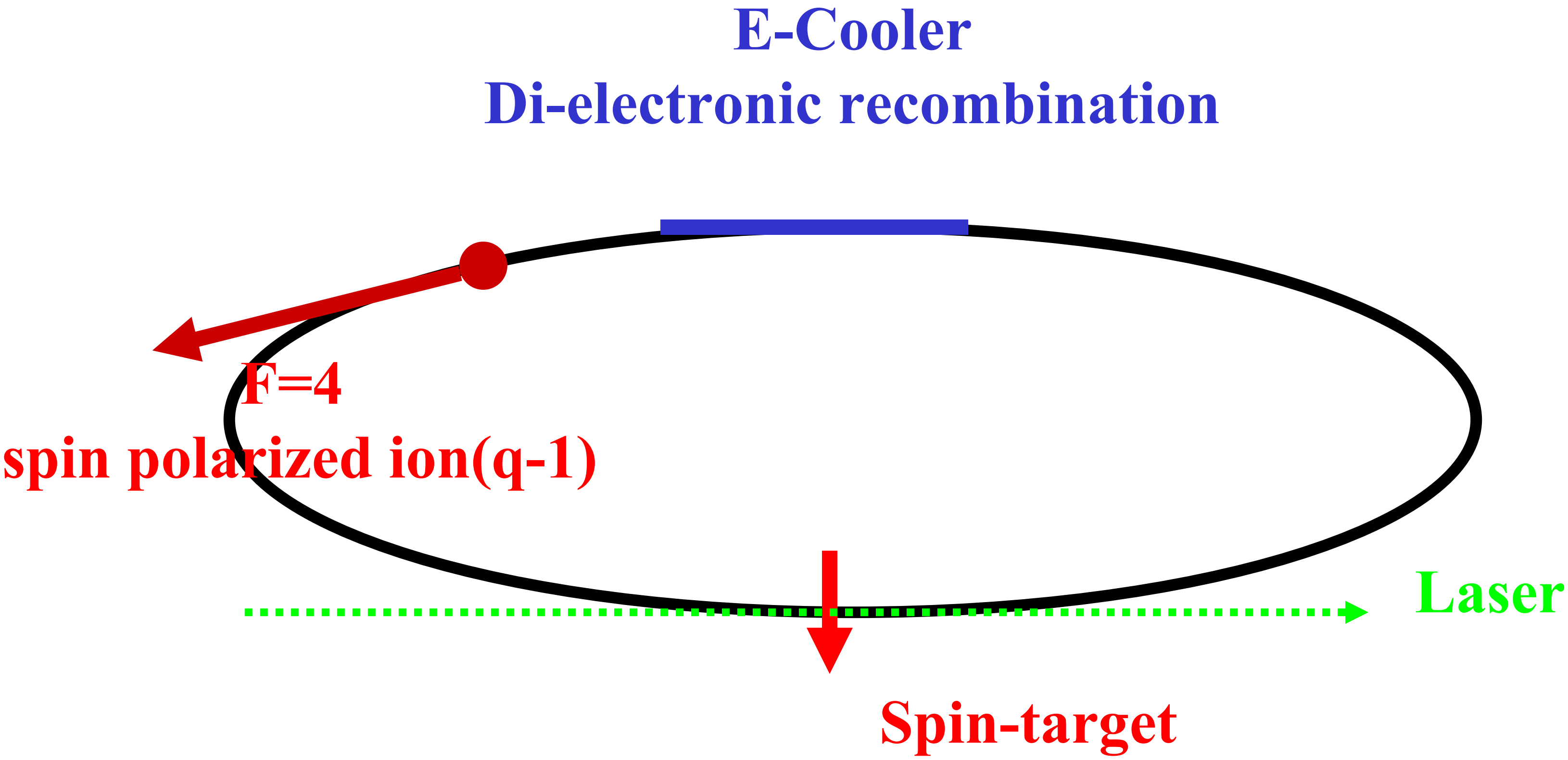
Hyperfine Splitting



Can pump all F by circular photon (laser, maser)
into max F state
Since orientation of S in Lab system is fixed
=>
Ionic beam is *100%* spin polarized



Can pump all F by circular photon (laser, maser) into max F state



E-Cooler

Di-electronic recombination

F=4

spin polarized ion(q-1)

Laser

Spin-target

What can one learn about the **Magnetic Structure of Nuclei** when measuring the hyperfine quenching of **Meta-stable Highly Charged Ions with high S quantum number**?

magnetic structure of ionic shell : dipole moment

Metastable state:

He-like $3S_1(1s,2s)$ or Be-like $^3P_{0,1,2}$ $(1s^2, 2s,2p)$ ….

only $\Delta F=1$ transitions

Why studying lifetimes in heavy ions?

1. Not sensitive to the same correlation contribution as energies (e.g., single excitations)
2. Not sensitive to the same part of the wave function (can be adjusted by choosing different multipoles)
3. Metastable levels can be very sensitive to weak perturbations $\Rightarrow$ good tool to study energy differences that cannot be reached directly, nuclear magnetic moments, parity violation. . .
   - Measurement of 2s Lamb shift in H-like Ar by measurement of the $2s$ lifetime in an electric field (Marrus and Gould, 1974).
   - Measurement of $1s2p\,^3P_0 - 1s2p\,^3P_1$ separation when nuclear magnetic moment is known by Hyperfine Quenching.
   - Measurement nuclear magnetic moment assuming $1s2p\,^3P_0 - 1s2p\,^3P_1$ separation is known.
   - Negative energy continuum and other relativistic/QED effects

Indelicato et al. GSI report

All metastable ionic shell states can only decay by spin flip.

Only the nuclear magnetic moment does induce spin flip in the ionic shell.

Dependent on the I,J,F and m-values, different magnetic multipoles will contribute to the quenching process

Hyperfine quenching

$$1/\tau \sim$$

$$<\Psi_{If,Jf,F}\,|\text{magnetic multipole}|\Psi_{Ii,Ji,F}>$$

Depends on the multipole character!

Fig. 1: The level scheme of the first excited states in Be-like ions

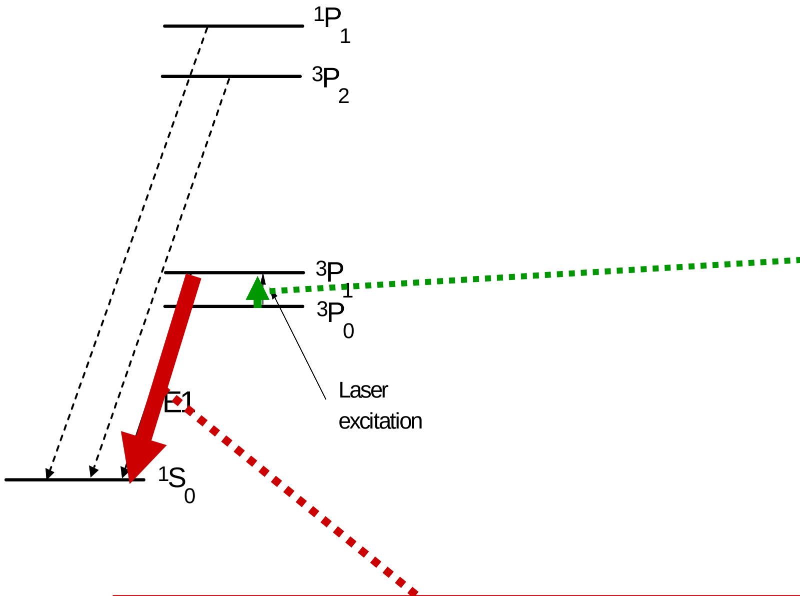
$^{S}L_{F}$

Δn=0 transitions in Be-like Kr

Excitation energy $^3P_0$ - $^3P_1$: 10.36 eV

Fluorescence radiation E1: 72.98 eV

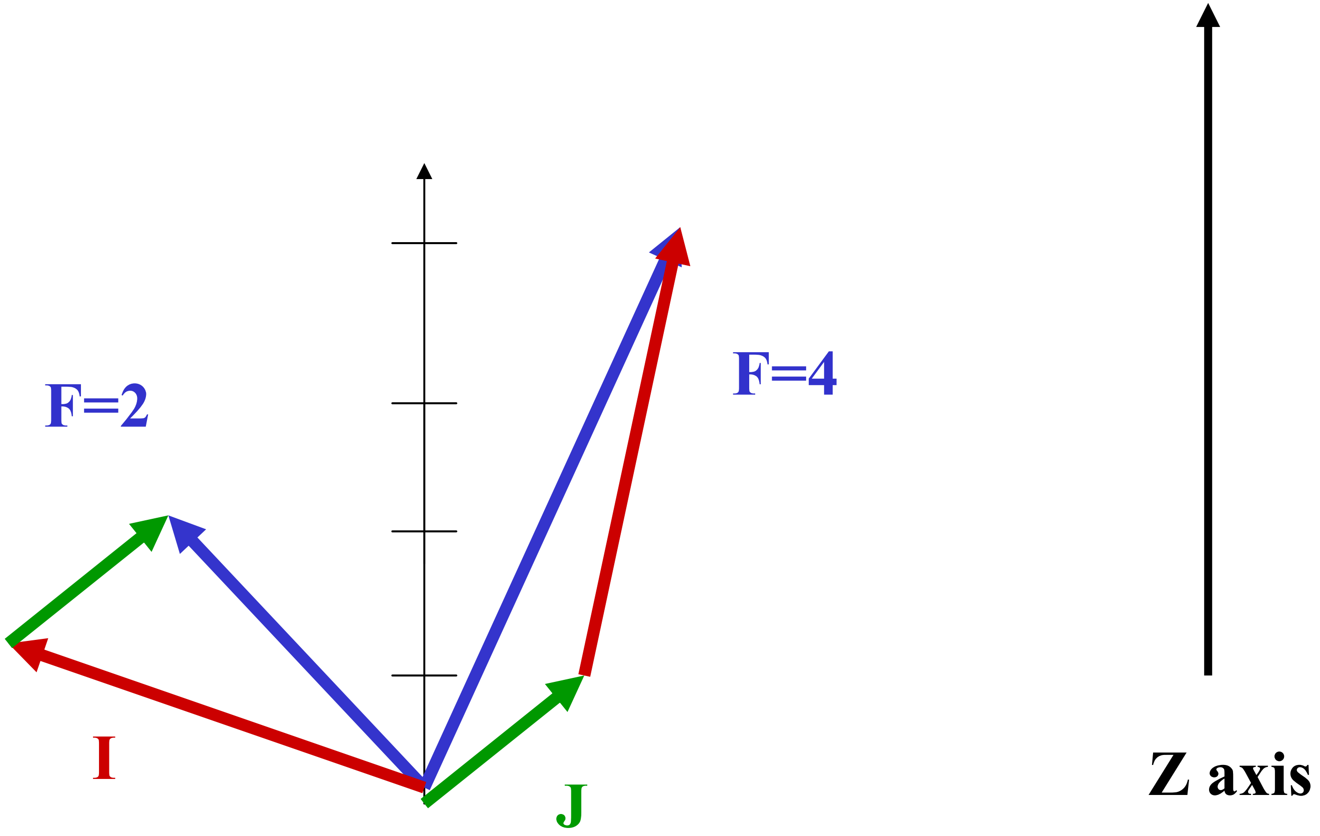
The transition from the **$^3P_1$ to the $^3P_0$ state is a M1-transition with an associated decay time of about 100 µs in the case of the 10.4 eV level spacing in krypton.** A typical frequency-doubled dye laser pulse of 5 ns duration and 20mJ of power at 0.1 cm-1 bandwidth will suffice to transfer 50% of those ions that match the laser bandwidth within their Doppler width into the 3P1 state. **From $^3P_1$ they will decay to the ground state within about 1 ns,** emitting a photon of 73 eV. For the numbers given above (3*10 8 ions, 10 % in the metastable state, Δp/p < 10-4 and a bunch length of 15 meters) this will imply the emission of more than 106 photons after resonant excitation of the fine structure transition.



M1 transition

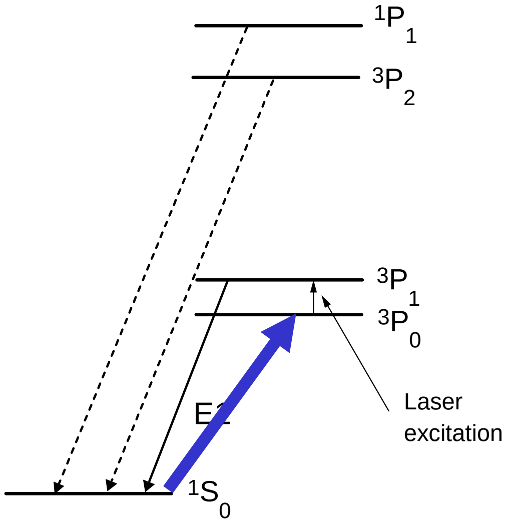
E1 with spin flip due to hyperfine quenching

Decay rate of metastable ionic state due to hyperfine quenching depends on relative orientation of axial vectors (F, I, and J)

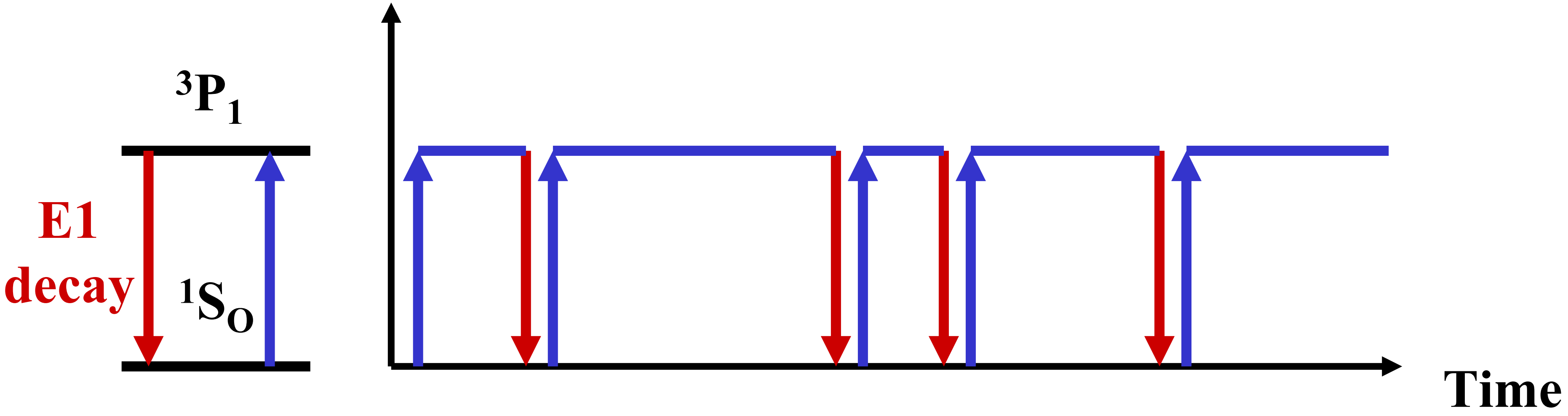


Preparing the ion in different S and different F states one probes different magnetic features of the nuclear moment

Can store one ion in HITRAP and pump with circular polarized lasers (one or two photon absorption) ion back into excited state



Can excite $^1S_0$ state to $^3P_0$ state after each decay by two circular polarized photons



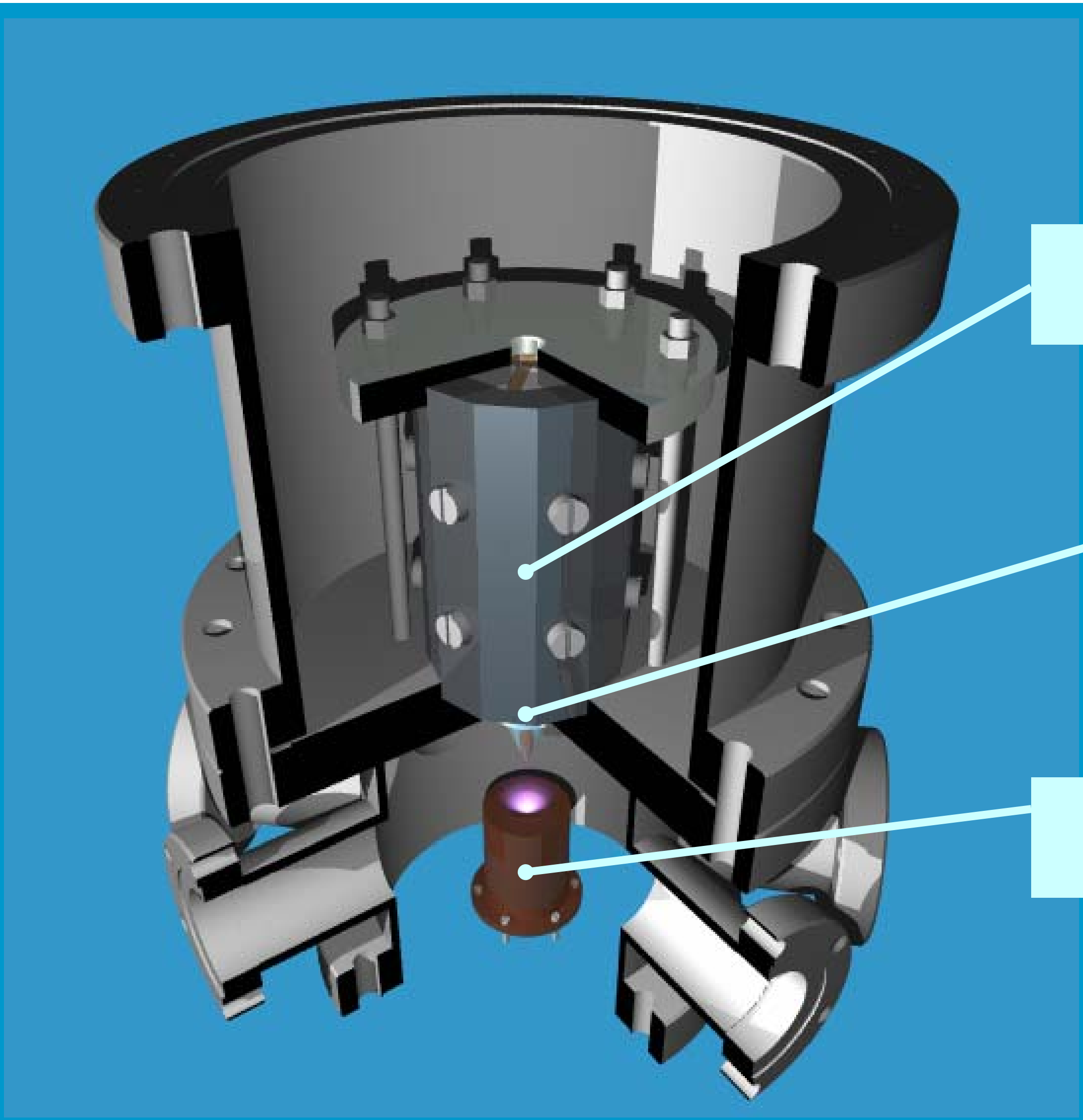
Pumping by
circular polarized
Laser excitation

$$\tau_{decay} = (\Delta'\Omega_{\gamma}\ /4\pi)/\ N_{\gamma}\ (1-\ 1/\ \sigma_{exc}\ \ N_{\gamma})$$

Where Laser excitation time is short compared to τ_{decay}

1. How to get 100% spin polarized electron target?

1. Creation of 100% spin oriented matter (gas target)



Stern-Gerlach Hexapole magnet

Skimmer

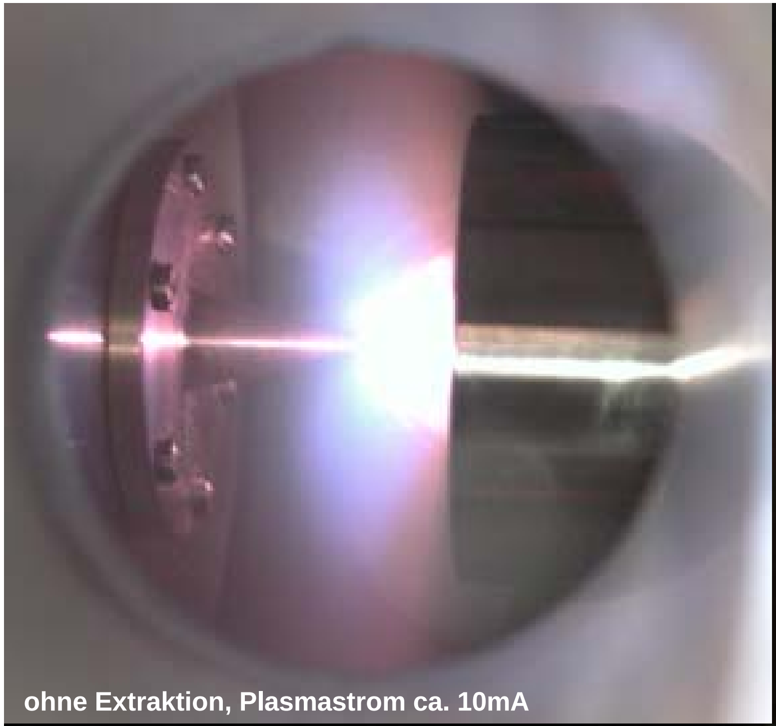
Micro Plasma source (80K)

Plasmaquelle zur Erzeugung metastabiler He-Atome

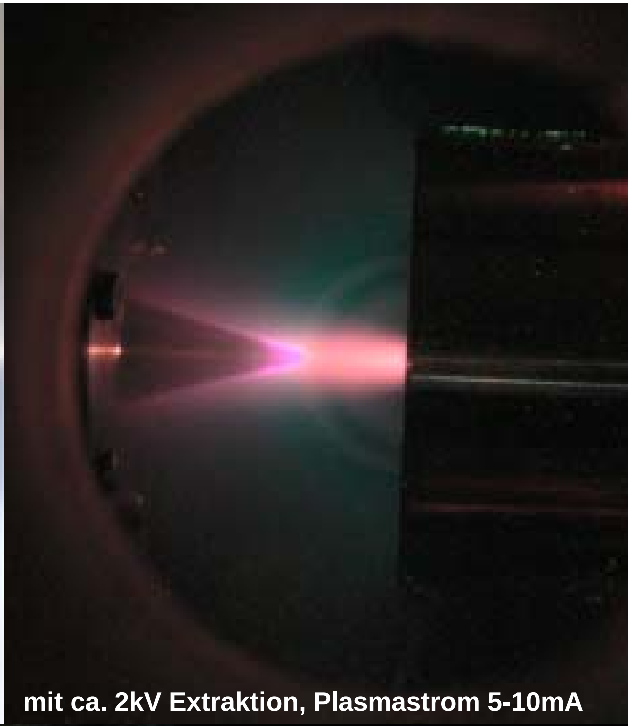
+

Separation der verschiedenen Zustände für Jetgeschwindigkeiten <1200m/s (He)

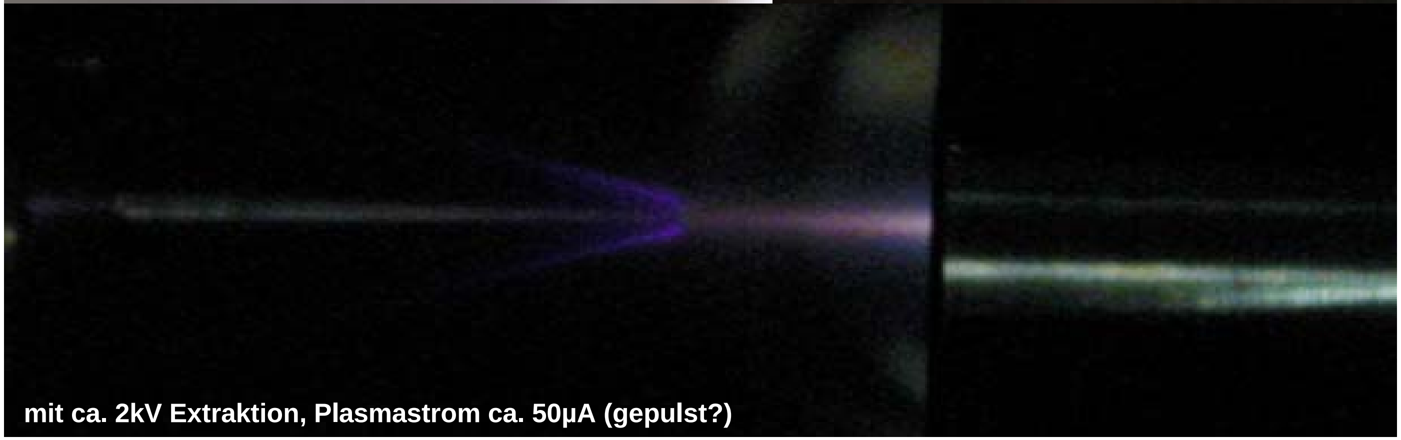
Compact source for polarized He* or H°



ohne Extraktion, Plasmastrom ca. 10mA



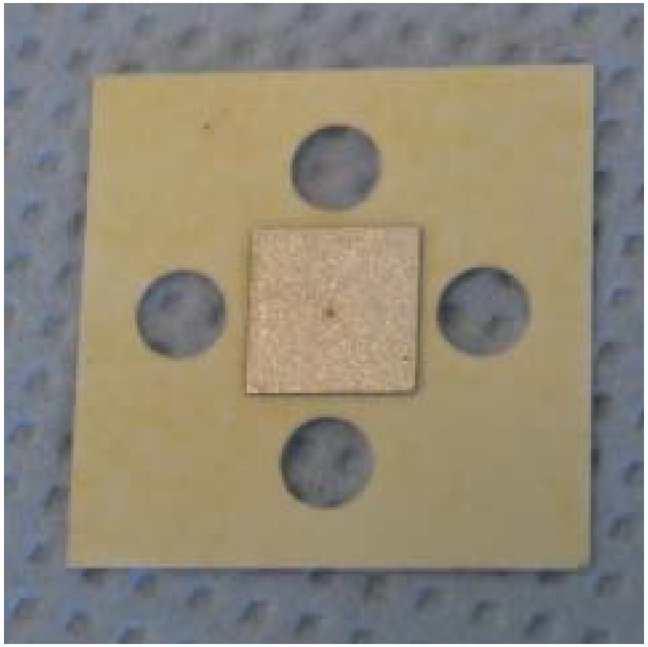
mit ca. 2kV Extraktion, Plasmastrom 5-10mA



mit ca. 2kV Extraktion, Plasmastrom ca. 50µA (gepulst?)

3D-MSE auf Keramik-Basis

neue MSE mit Keramik als Isolator



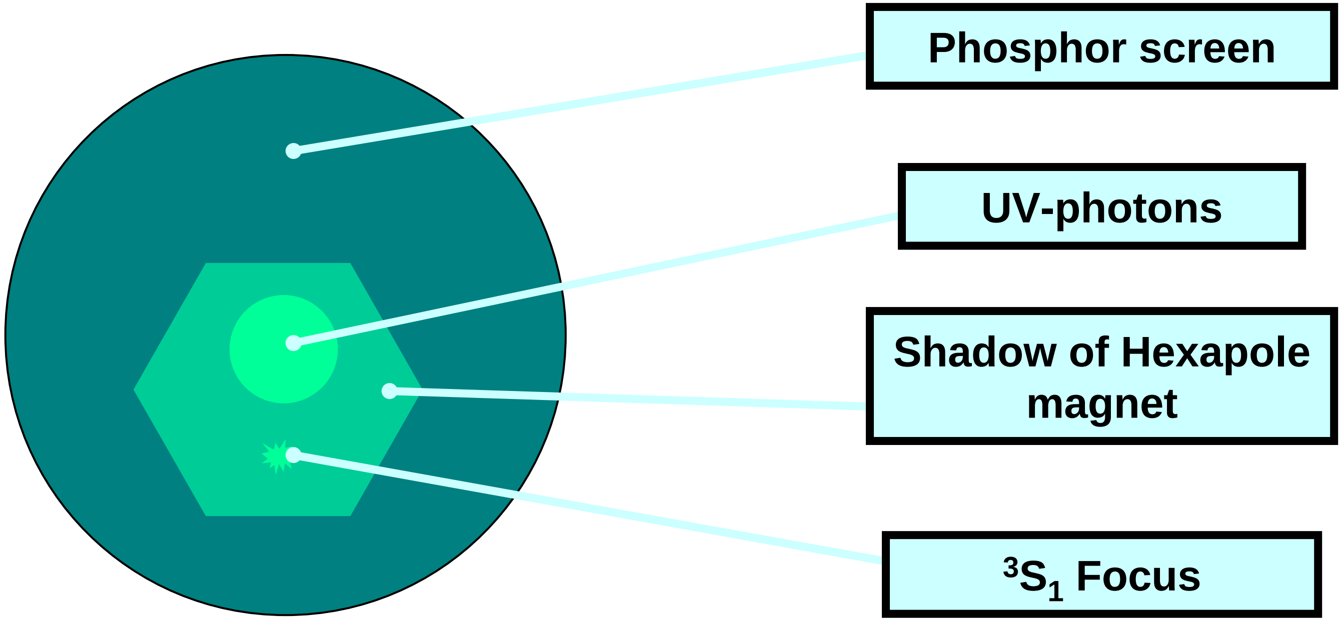
Vorteile der Keramik:

- **robustes Mehrschichtsystem**
- **höhere Wärmeleitfähigkeit**
- **unempfindlich gegen Sputtering und UV-Strahlung**
- **lange Lebensdauer**
- **sauberes Material**

Nachteile:

- **erhältliche Keramikfolie ist 5x bzw. 2x stärker**
- **aufwendige Lasertechnik zur Bearbeitung**
- **lange Bearbeitungszeiten für großflächige Systeme mit vielen Poren**
- **hoher Stückpreis**

Detector: Phosphor screen with Microchannelplates



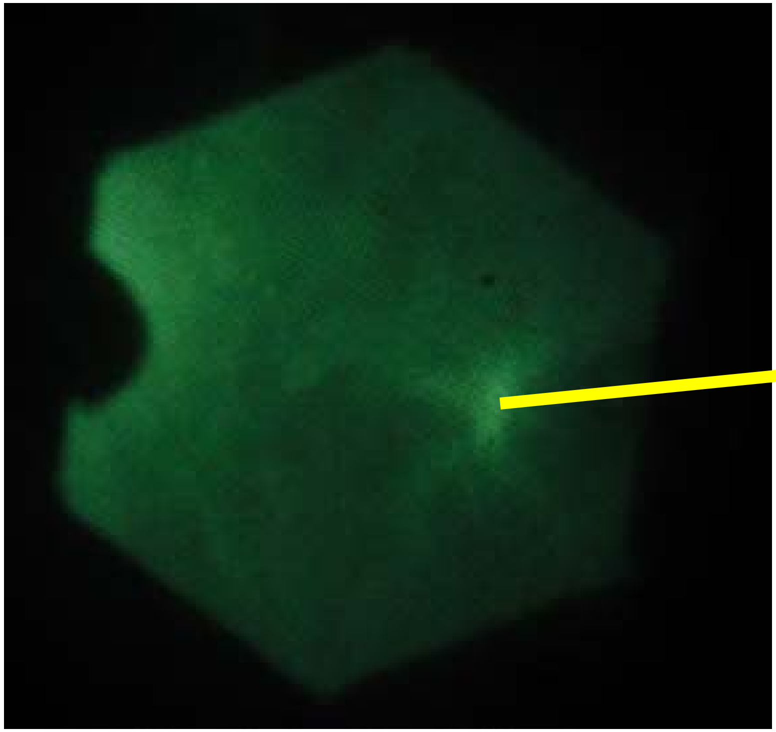
Phosphor screen

UV-photons

Shadow of Hexapole magnet

$^3S_1$ Focus

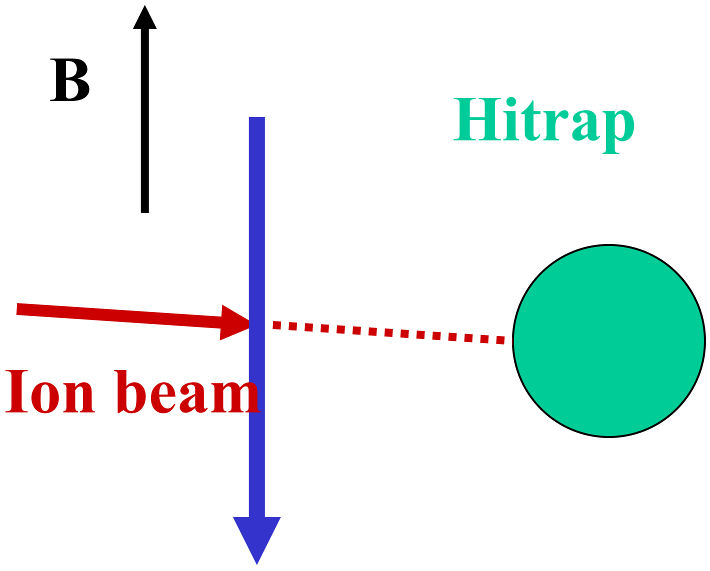
Phosphor screen



Focus of He* $^3S_1(1s,2s)$ atomic jet

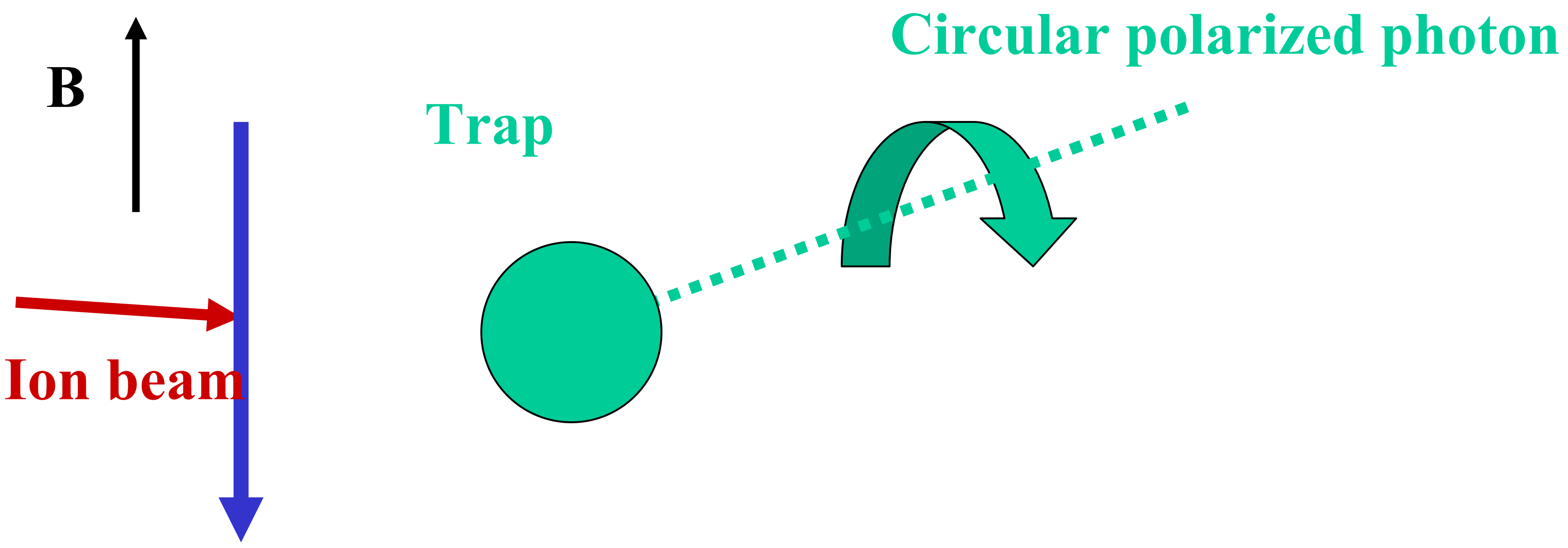
100% in m_S=+1

Typical Trap experiment

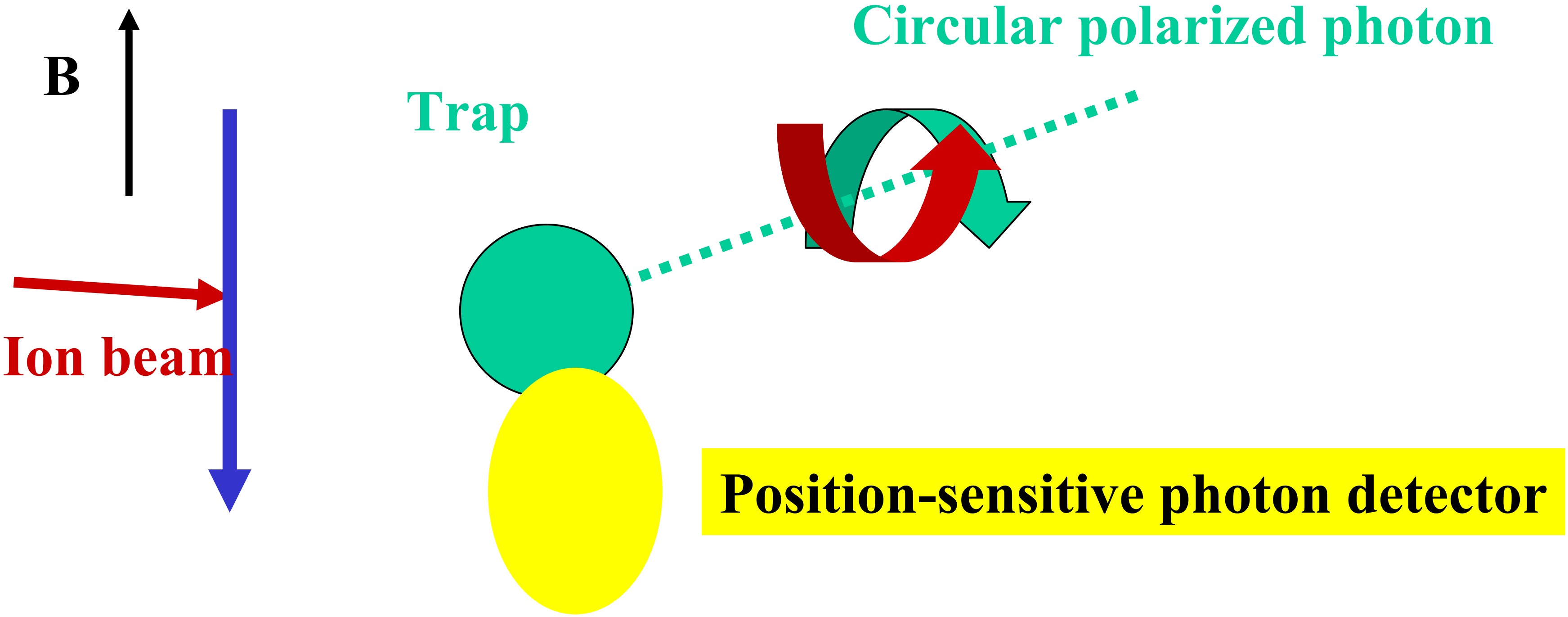


Electron capture
in gas jet of spin
oriented atoms

Typical Trap experiment



Typical Trap experiment



Circular polarized photon

B

Trap

Ion beam

Position-sensitive photon detector

Conclusion:

1. Using a 100% spinpolarized electron target
   One can prepare spin-polarized metastable highly charged ions

2. Can prepare spin-polarized nuclei

3. Can measure decay rates (hyperfine quenching) of ΔF=1 transitions for different metastable states and for different cos(*J*,*I*)

4. One can probe the different magnetic multipole moments of nuclei

5. Measuring the photon decay distribution for different relative F and Z orientations one can make symmetry tests in nuclear transitions

Coworkers:
Till Jahnke, Sven Schößler,
Olliver Hohn, Angela Bräuning-Demian,
Lutz Spielberger, Matthias Smolarski,
Reinhard Dörner, Siegbert Hagmann,
Thomas Stöhlker, Joachim Ullrich et al.

We do control the orientation of F and
the photon polarization Z
in the lab system and
can vary the angle between the two axial vectors

We can measure the distribution of the polar momentum vector p_γ of the emitted photons with respect to the orientation of the above vectors

the excitation and decay rate in the lab system should depend on the orientation of these axial vectors

Measure the photon emission rate (N_γ) in the lab system with respect to F and Z

Similar to the Wu experiment

We measure $N(p_\gamma)$ with respect to *F and Z*

Is $N(p_\gamma)$ for F x Z

Equal to

$N^*(p_\gamma)$ for ($-F$) x ($-Z$) ?

Sensitive to symmetries in transitions, since two or more axial vectors are controled