Hyperfine anomaly and nuclear g-factor measurements of Ba isotopes

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Outline

- Hyperfine anomaly and motivation for the measurement
- TITAN setup
- Current status
- Summary

Hyperfine anomaly

Magnetic dipole interaction is the source of hyperfine energy W_{hfs}:

$$W_{hfs} = A\, I\cdot J$$

For point – like nucleus:

$$A = \mu_I B(0) \sim \mu_I |\psi(0)|^2$$

In reality:

$$A_{ex} = A\,(1-\varepsilon_{BW})(1-\varepsilon_{BR})$$

ε_{BW}: Bohr-Weisskopf effect. Reflects distributuon of magnetization in extended nucleus

ε_{BR}: Breit-Rosenthal effect. Reflects change of electronic wavefunction by nuclear extension

Order of magnitude: $\varepsilon_{BW} \sim 10^{-1} – 10^{-3}$, $\varepsilon_{BR} << \varepsilon_{BW}$

$$A_{ex} = A\,(1-\varepsilon_{BW})\xcancel{(1-\varepsilon_{BR})}$$

What to measure

- ε_{BW} can not be measured directly since there is no point-like nucleus for comparison

- Instead, compare two isotopes :

$$\frac{A_{ex}(1)}{A_{ex}(2)} = \frac{\mu_I(1)}{\mu_I(2)} \frac{1-\varepsilon_{BW}(1)}{1-\varepsilon_{BW}(2)} = \frac{\mu_I(1)}{\mu_I(2)} (1-\varepsilon_{BW}(1)-\varepsilon_{BW}(2))$$

$$= \frac{\mu_I(1)}{\mu_I(2)} (1-\Delta^{1,2})$$

- **Measure $\Delta^{1,2}$: differential hyperfine anomaly**

Typical values

- $\Delta^{1,2}$ is typically $10^{-1} - 10^{-3}$
- In order to determine $\Delta^{1,2}$ to 1% accuracy one needs to measure A and μ_I for two isotopes to $10^{-3} - 10^{-5}$.

- Values for $\Delta^{1,2}$ are known for all pairs of stable nuclei with non-zero spin. That is not a good sample for nuclear studies. Understanding in terms of nuclear models is poor.

- Systematic measurement of $\Delta^{1,2}$ for unstable isotopes will help to improve understanding of this effect.

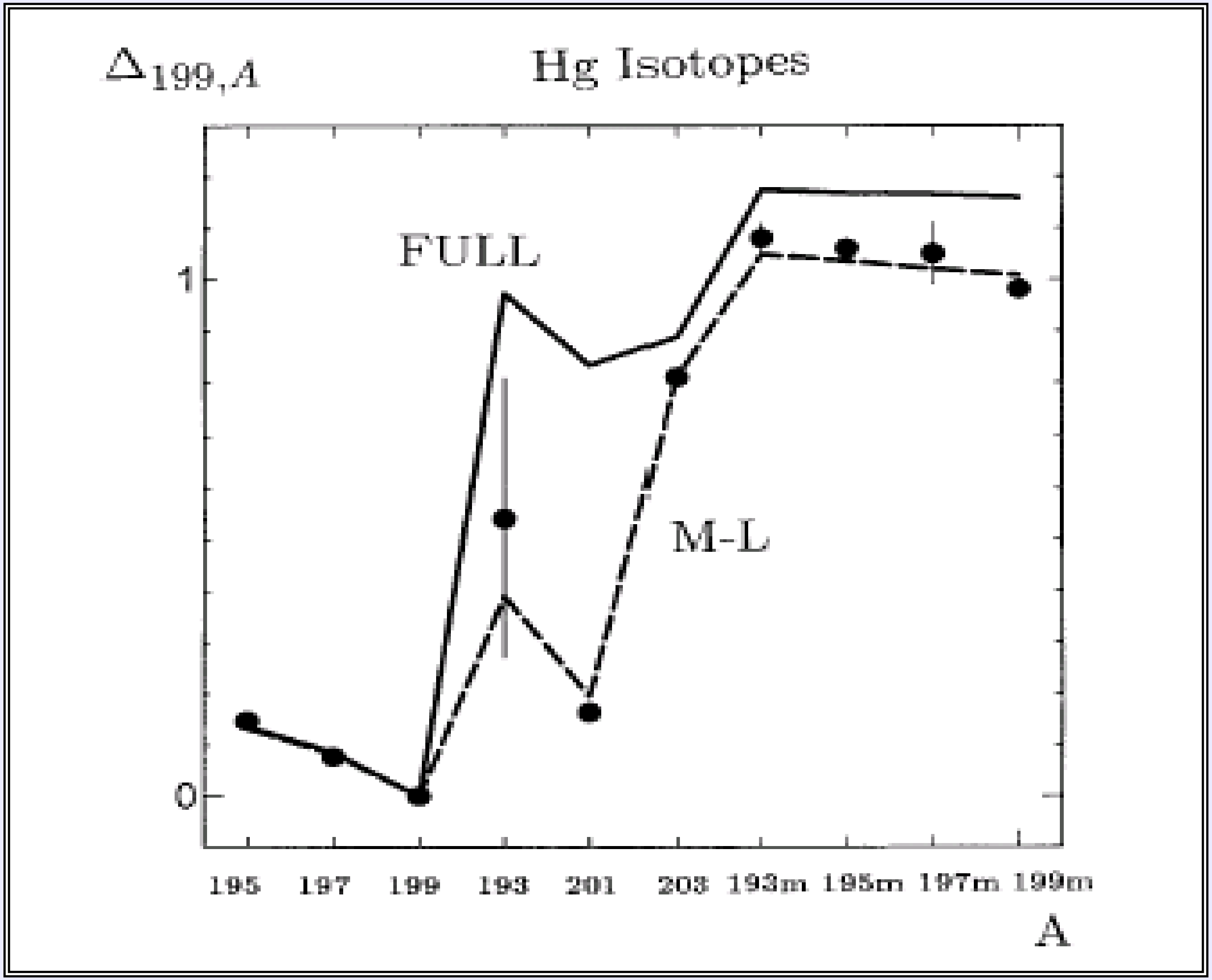
Moskowitz-Lombardi rule

- Empirical relation for the hyperfine anomaly:

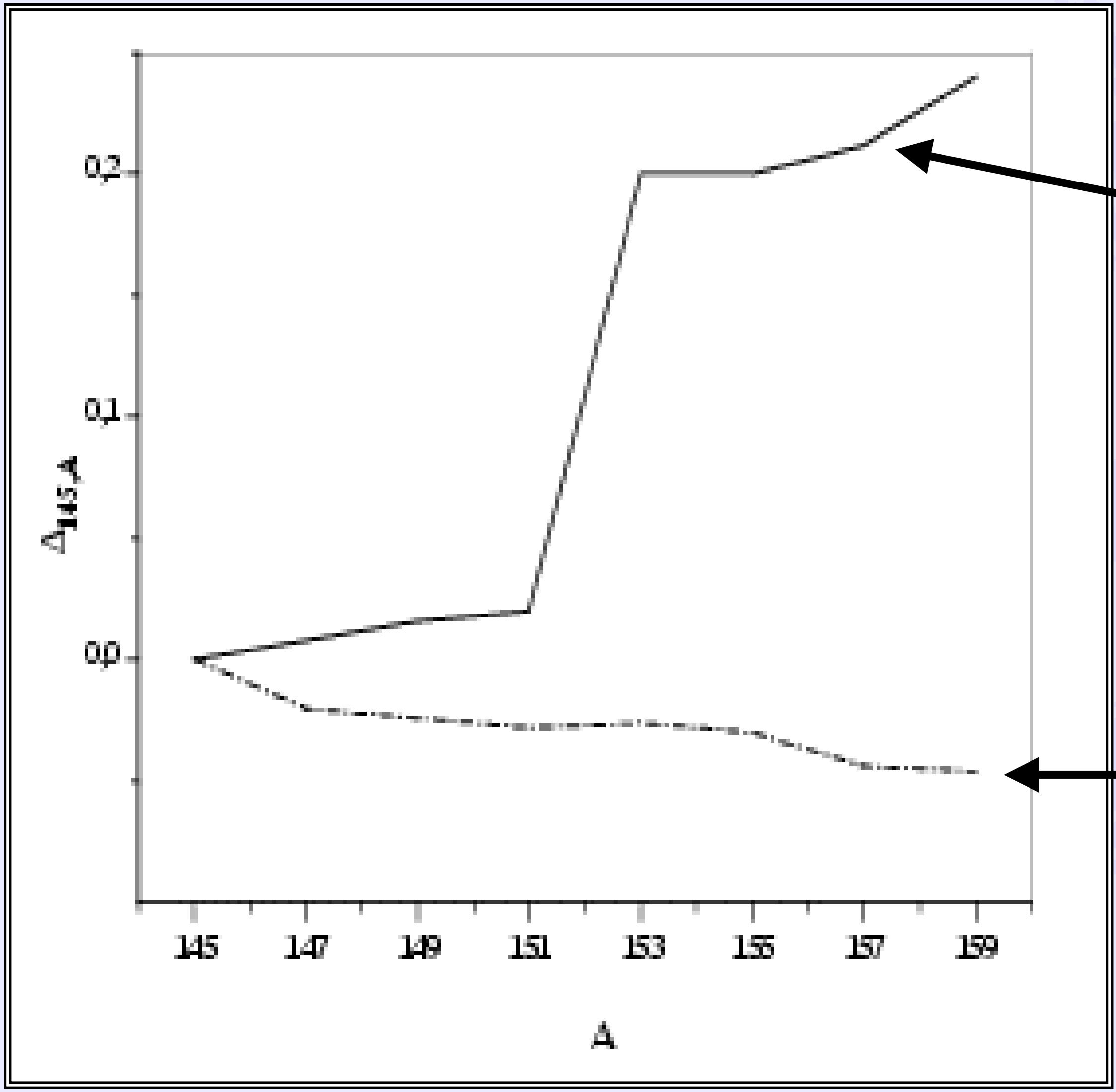
$$\varepsilon_{BW} = \frac{\alpha}{\mu_I}$$

- Works well for Hg isotopes
- Applicability requires a check with a different chain of isotopes

Hyperfine anomalies in Hg isotopes



Comparison of hyperfine anomalies for Eu isotopes



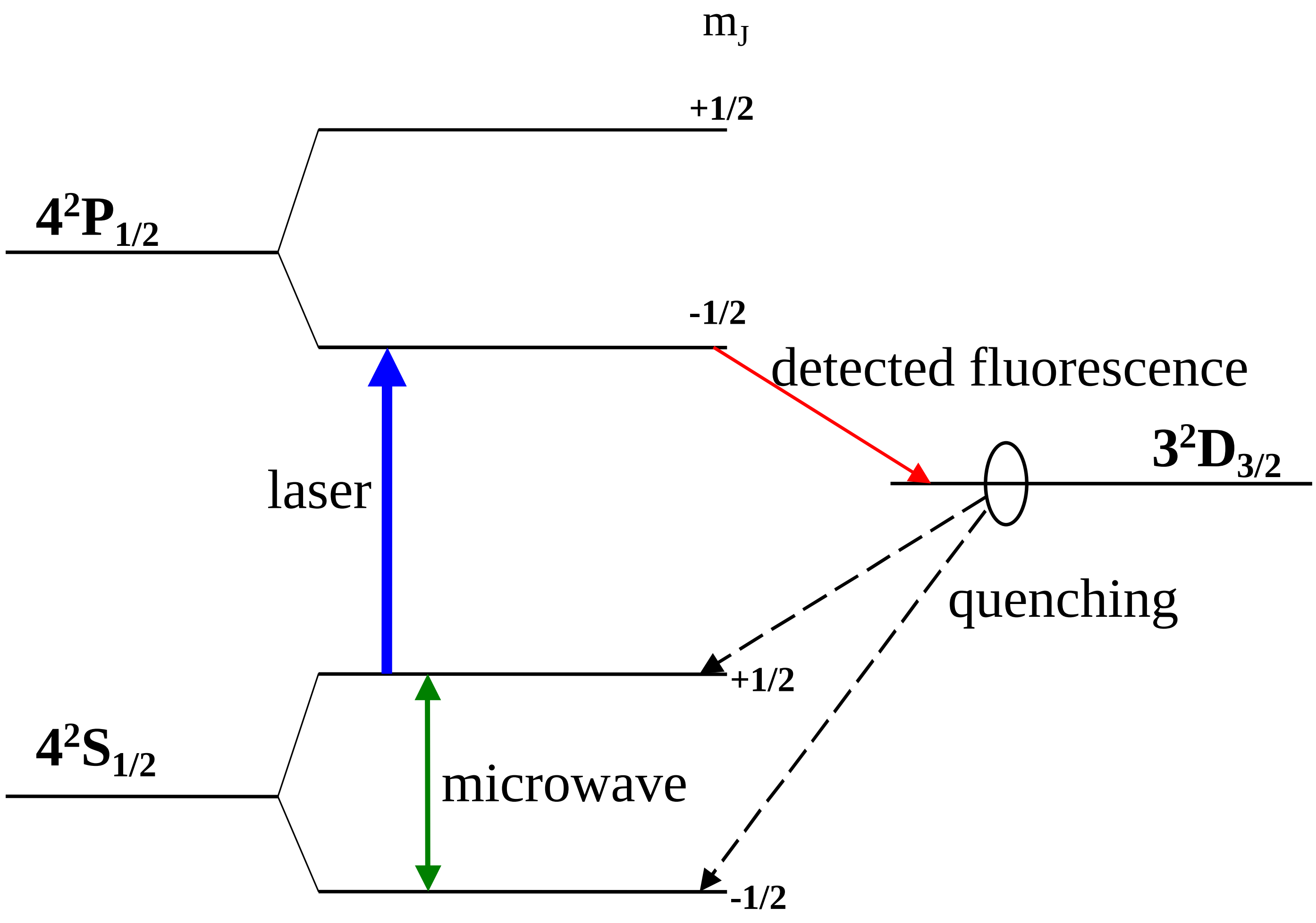
expectation from
Moskowitz-Lombardi rule

Shell model calculation
T. Asaga et al.,
Z. Phys. A359, 327 (97)

Measurement method

- Trapping of selected ions from outside source
- Selective laser excitation of ground state Zeeman sublevel (optical pumping)
- Induction of (rf) transitions between Zeeman sublevels
- RF resonance will result in state repopulation – thus change in fluorescence
- Calibration of magnetic field by cyclotron frequency of stored electrons in the same trap

Ba$^+$ level diagram (I=0)



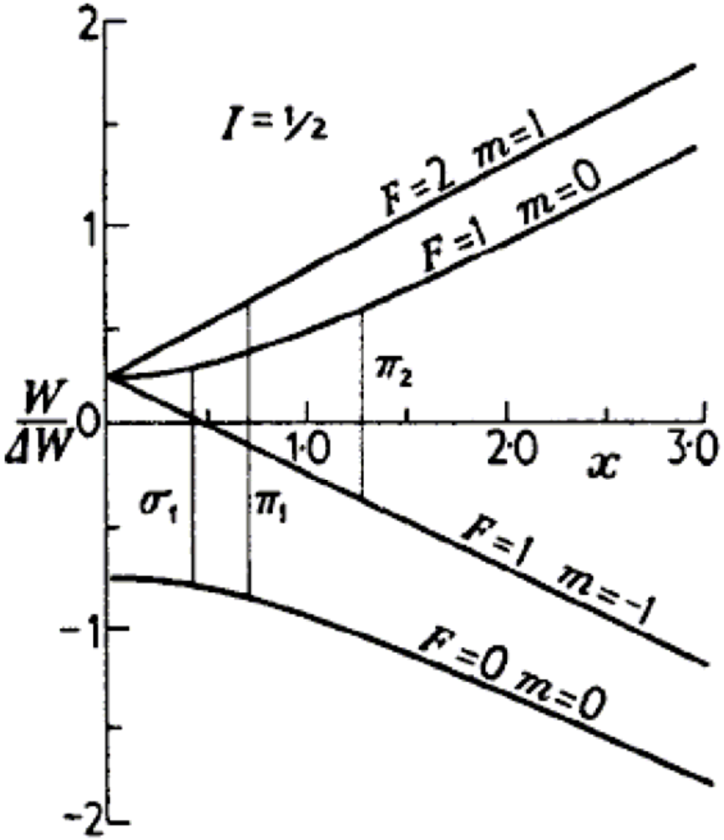
Zeeman splitting in the magnetic field (I=1/2)

$$\nu(B, I\pm 1/2) = -\frac{\Delta W}{2(2I+1)} + g_I \mu_B m_F B \pm \frac{\Delta E_0}{2}\sqrt{1+\frac{4m_F}{2I+1}x + x^2}$$

$$x(B) = \frac{g_J \mu_0 - g_I \mu_B}{\Delta E_0} B$$

$$\Delta E_0 = \Delta W\left(I + 1/2\right)$$

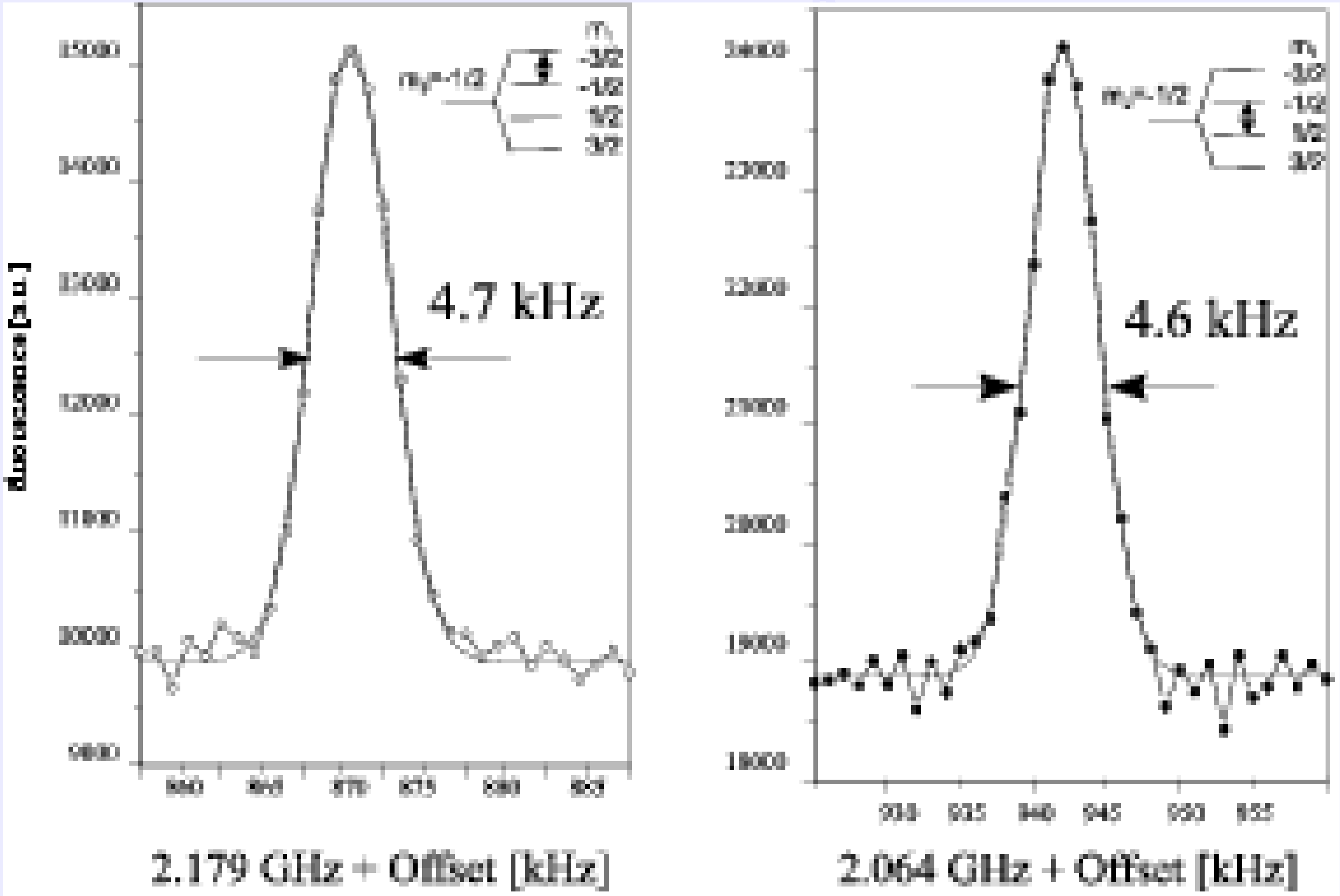
Breit-Rabi formula result for $S_{1/2}$ ground state



Given the transition data

- 3 unknown quantities:
  - Hyperfine constant A
  - g_I
  - g_J
- g_J can be determined from even isotope (known for Ba^+)
- **Then 2 Zeeman transitions are required to determine A and g_I**

Example: $^{135}Ba^{+}$ (I=3/2)

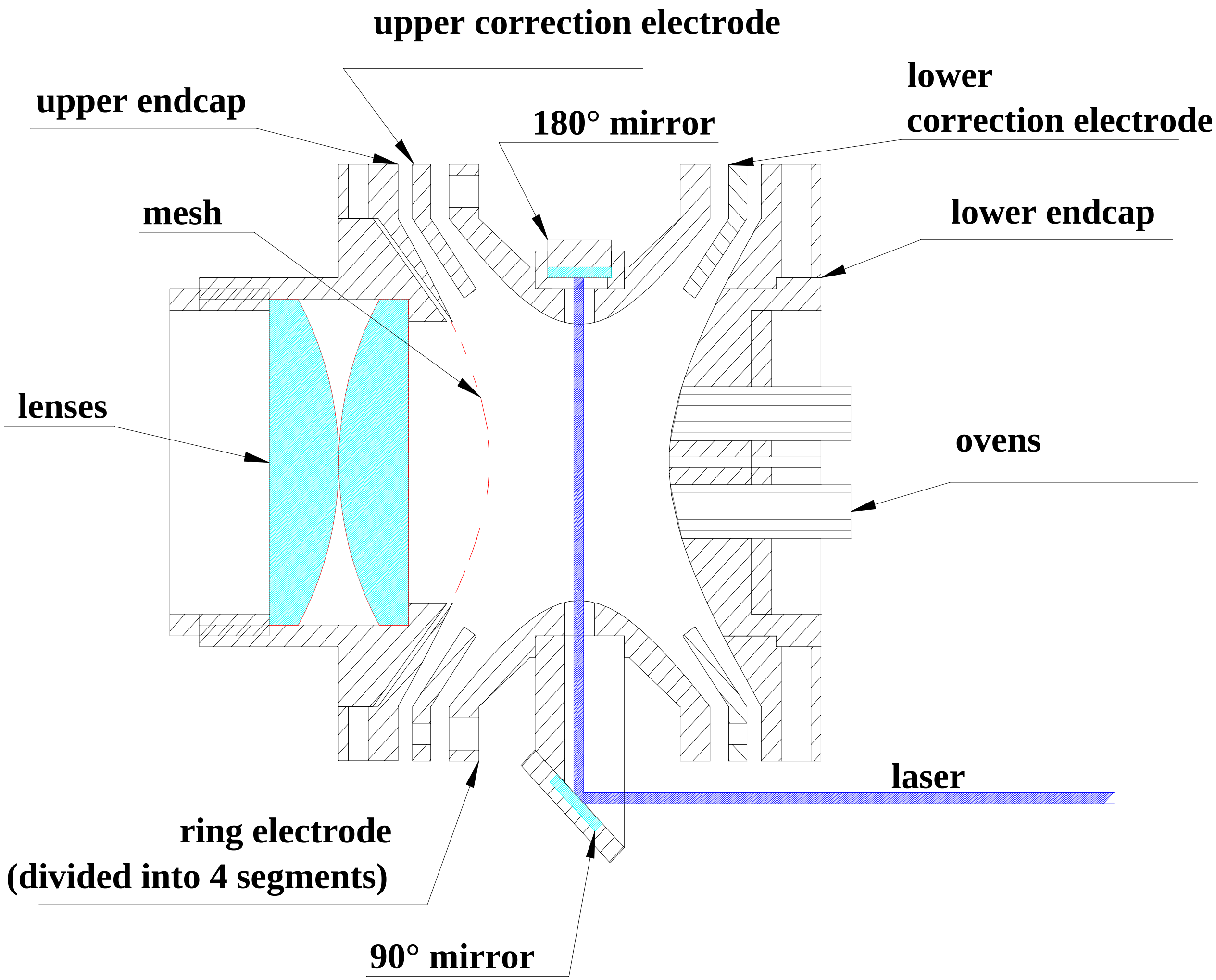


Ba isotopes

123	**125**	**127**	**129**	**131**	**133**	**135**	**137**	**129**	**141**
5/2	1/2	1/2	1/2	1/2	1/2	3/2	7/2	7/2	3/2
2.7 m	3.5 m	13 m	2.2 h	12 d	11 a			14 h	18 m

From Marik Dombsky webpage: ^{140}Ba yield is $7x10^{9}$ s^{-1} with 10μa proton beam.

Trap for spectroscopy



Estimate for the yield needed

- Ba^+ represents a 3-level scheme with a long lived metastable state ($D_{3/2}$). The number of fluorescence photons is limited by the lifetime of this state (lifetime: 40 s). Reduced lifetime by collisions with buffer gas (N_2, 10^{-4} mbar): **10 ms**
- **100 fluorescence photons per second from a single ion**
- Detection efficiency: 10^{-3}
  - 10% multiplier quantum efficiency
  - 10% solid angle
  - 10% filter and transmission losses

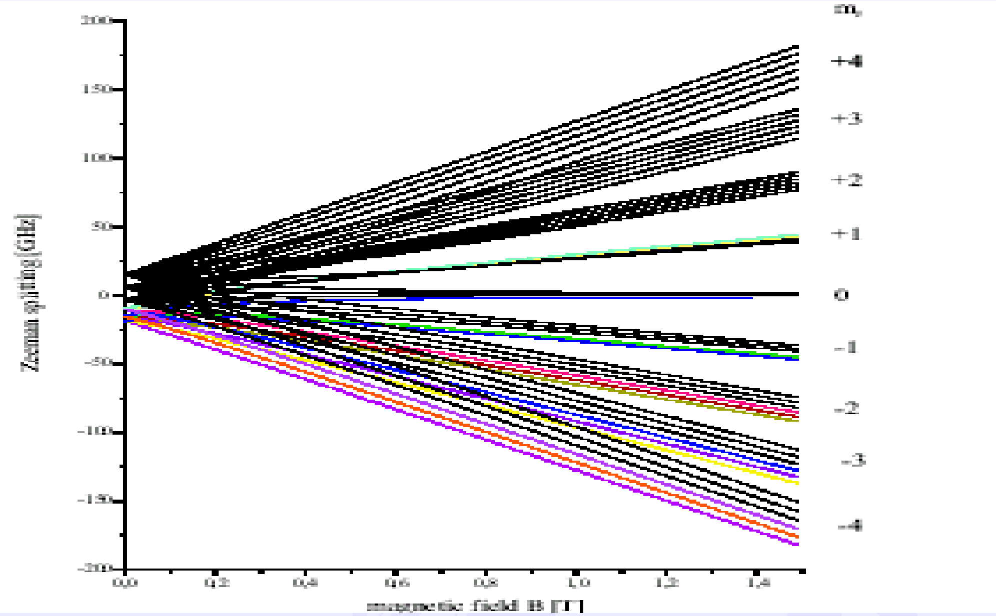
From 10^4 ions in the trap on gets 10^3 counts/s
Photomultipler dark current: 10 counts /s

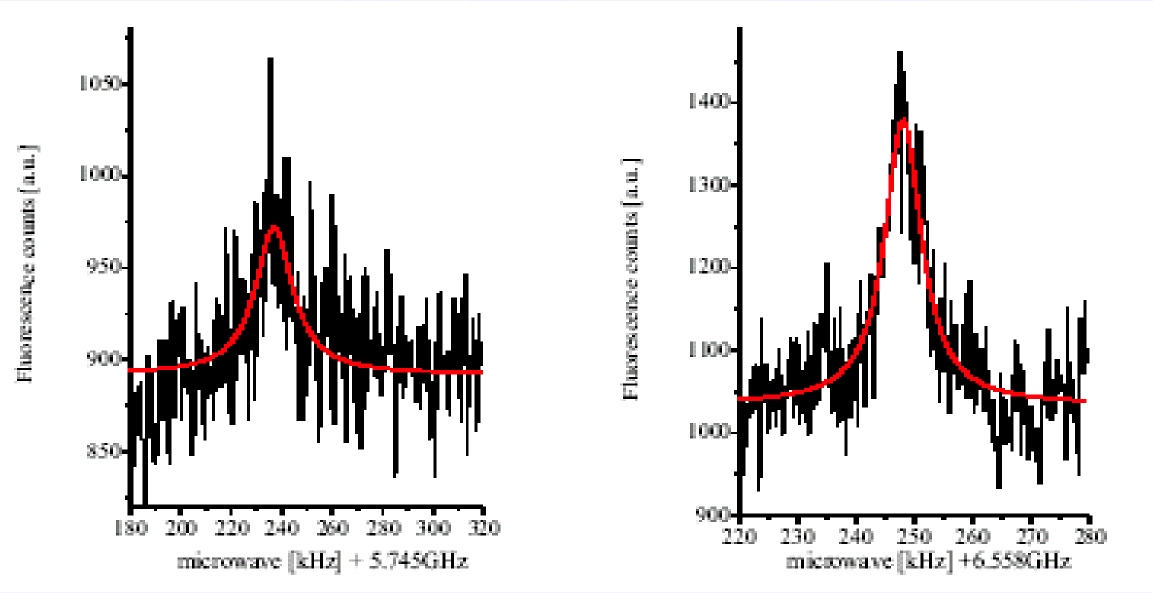
For ~1 min lifetime we need 10^2 - 10^3 ions/s yield with no more than 90% isobaric contamination (assume 10^5 trap capacity). Also, this is a Penning trap, purification is possible!

Equipment needed

- ✓ Helholtz coil magnet with the field of up to 3T (we have 7T Belle magnet)
- ✓ Laser suitable for optical pumping of the Ba transition (from Mainz)
- ✓ Microwave generator of up to 100GHz (from Mainz)
- ✓ Penning trap (Mainz trap is available, but it is a bit too large for our magnet. Not a big deal)
- ✓ Low noise PMT with good quantum efficiency at 650nm

Other (more difficult!) possibilities





^{153}Eu+

Conclusion

- Very feasible experiment with solid motivation
- Equipment for Ba experiment would be mostly available
- If additional construction on the TITAN platform is undesirable, can be done off-line collecting isotopes on a foil