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MagLiF workshop: Measuring magnetic fields and flux compression
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Zeeman Spectroscopy

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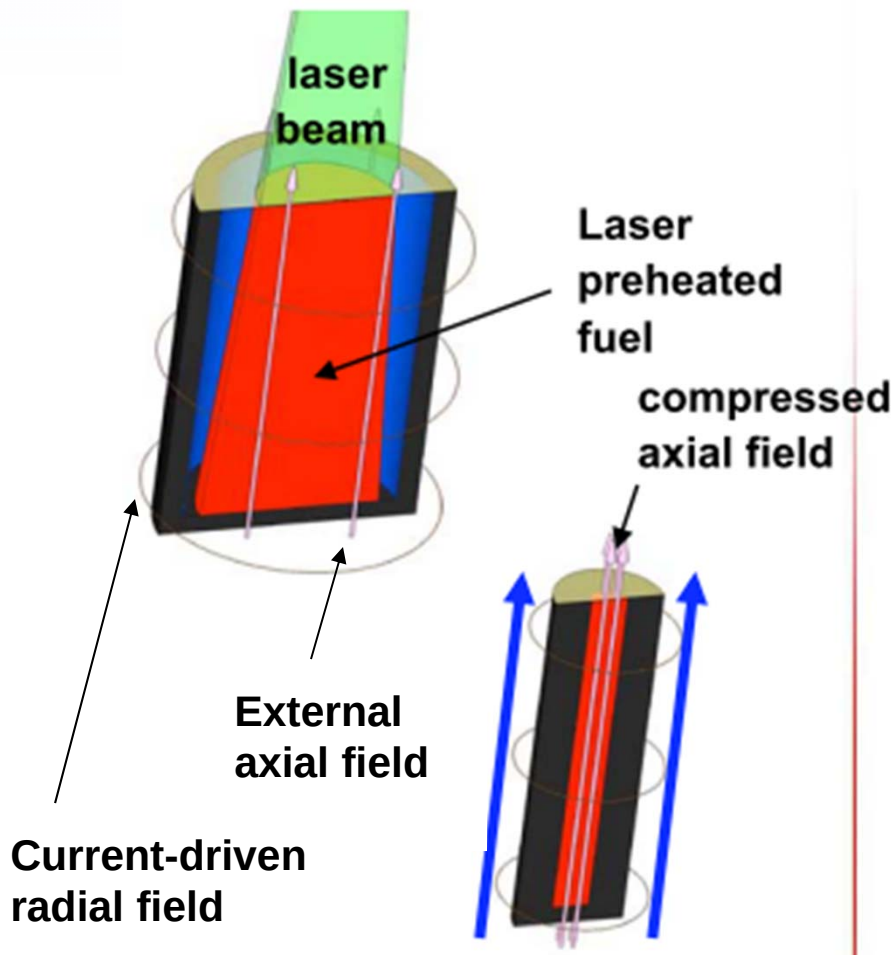
Magnetic field measurements in MagLiF targets are challenging – and critical

- **Challenges**
  - Fields from ~10T to ~100 kT
  - External Bz and intrinsic B_θ
  - Liner may block side-on emission
- **Benefits**
  - Verify flux compression
  - Test current delivery to small radii
  - Critically test simulations

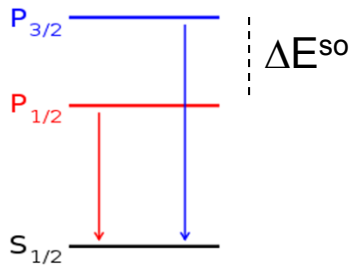


Optical and x-ray Zeeman spectroscopy offer powerful tools for investigating MagLiF targets

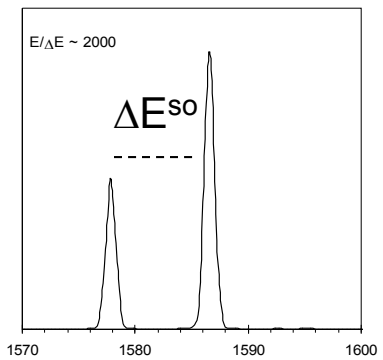
Zeeman splitting arises from the interaction of bound electrons with an external magnetic field

The orbital motion of electrons in bound states drives an internal magnetic field, which leads to fine structure effects like spin-orbit splitting

e.g.
ns-n'p splitting:

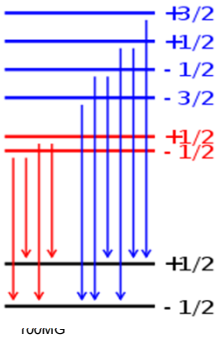


→ a simple doublet:

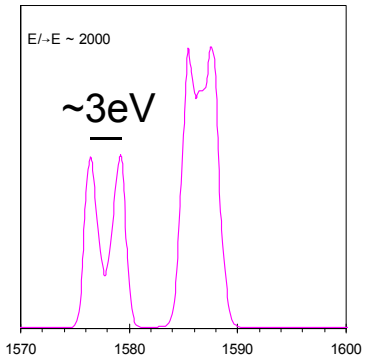


Spectrometers on hand:
> 600 eV (x-ray) & ~1.5 - 3 eV (optical)
(~ 3 – 100 kT) (~1 – 300 T)

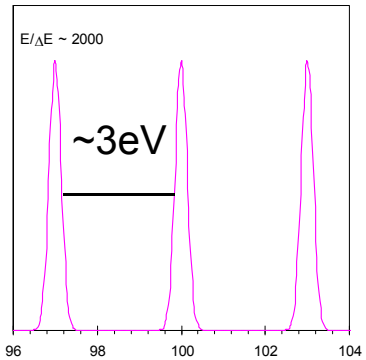
Additional magnetic fields break the degeneracy of magnetic sublevels:
$\Delta E^Z \sim \mu_0\, g_J\, m\, B$



ΔE^Z is the same for any photon energy, optical to x-ray!
(~ 3eV for ~10kT)



10 kT is a weak field ($\Delta E^z < \Delta E^{SO}$) for hν~1 keV



…but a strong field for hν~0.1 keV!

Differential splitting may help overcome limitations of instrumental spectral resolution ~ 1000

- Zeeman splitting is larger in the $np_{1/2} – n's_{1/2}$ line than the more intense $np_{1/2} – n's_{1/2}$ line
- Since Stark*, thermal, instrumental, and motional broadening are all the same for the two lines, B fields are the only thing that preferentially broaden the smaller line
- Opacity effects would act in the opposite direction
- Fields of ~ 1 30 T have been measured at the Weizmann Institute using optical (~2 eV) 4p – 4s lines.

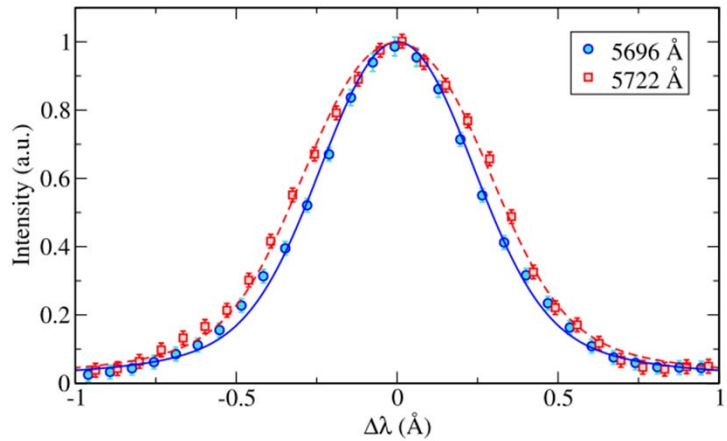
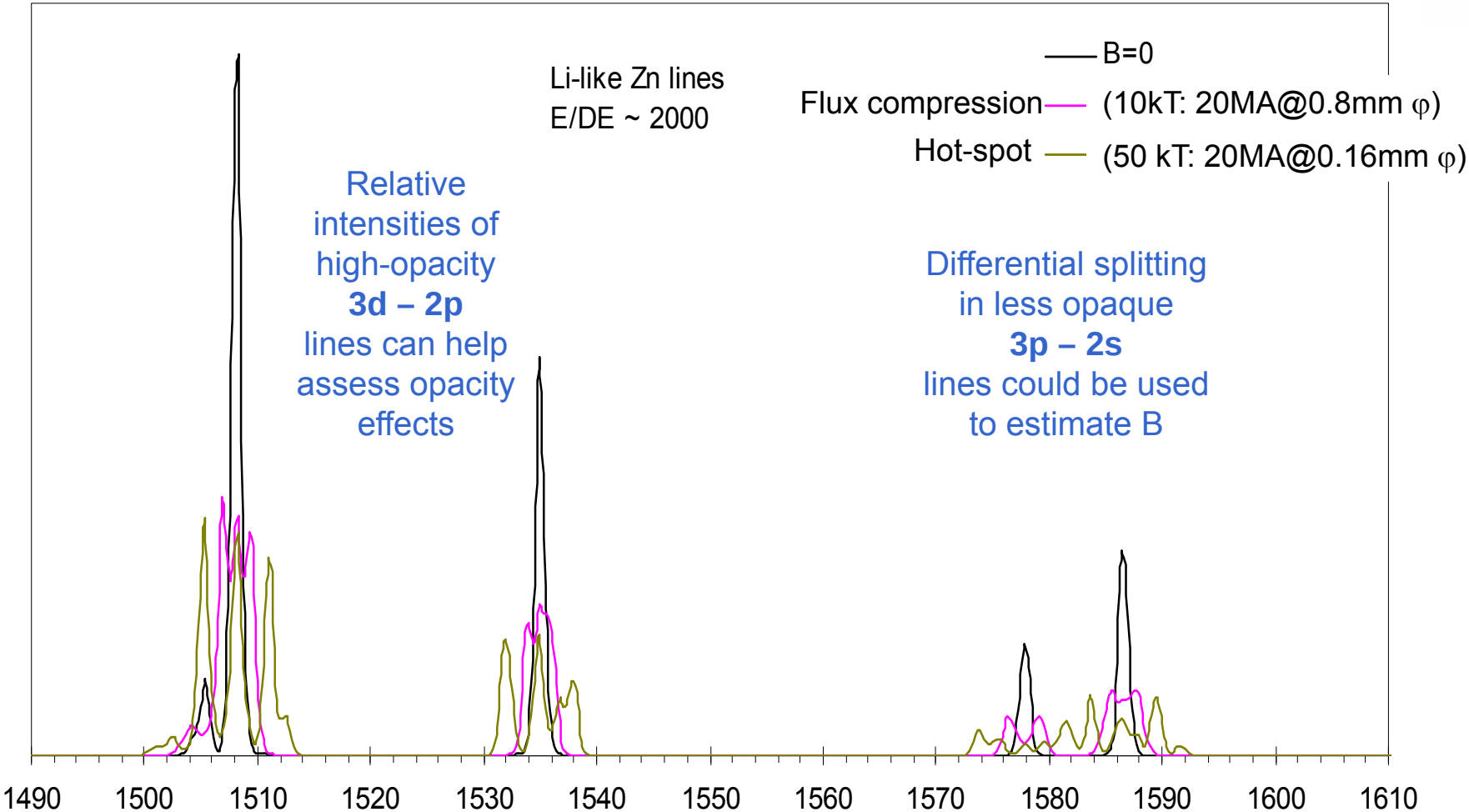


FIG. 5 (color online). The AlIII $4p$-$4s$ (5696 & 5722 Å) doublet. The line shapes of the two components are peak-normalized and shifted to a common spectral center. The smooth lines represent best-fit calculations for $B = 0.9$ T, $N_e = 2 \times 10^{16}$ cm^{-3}, and $T_e = 10$ eV.

Stambulchik, Tsigutken, and Maron, *Phys. Rev. Lett*. **98**, 225001 (2007).

*As long as total broadening $\Delta Ez < \Delta E^{SO}$ (line separation)

For higher fields, x-ray Li-like lines in transition metals might give B at moderate spectral resolution



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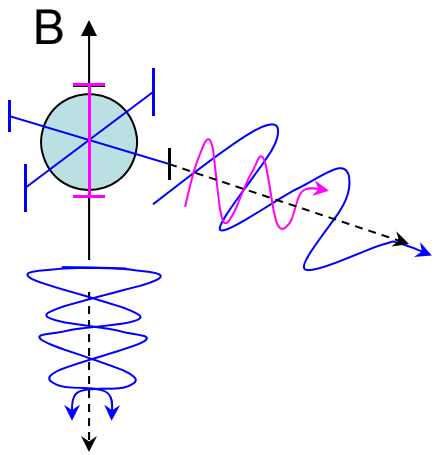
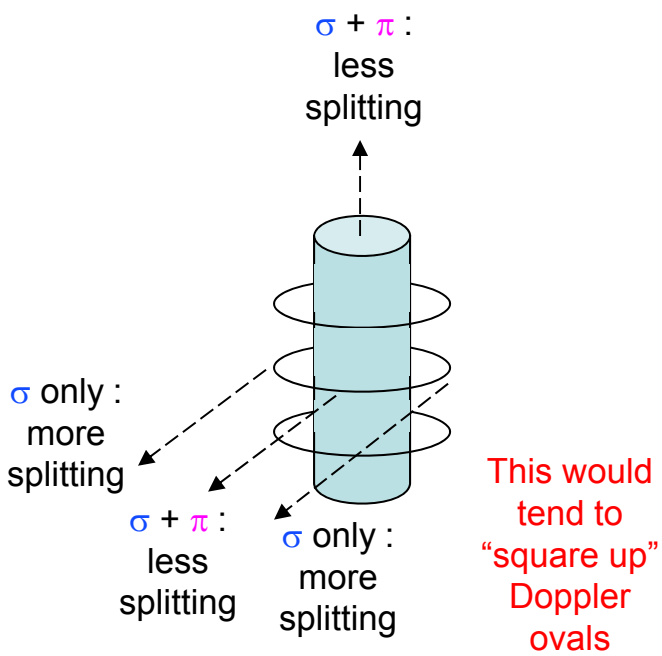
Zeeman splitting also offers information about the direction of the field

Magnetic fields change the spatial characteristics of the atom; the splitting is greatest in directions perpendicular to B: ΔE for $\Delta m = +/-1$ (σ) > ΔE for $\Delta m = 0$ (π)



Since splitting for $\sigma > \pi$, larger splitting is observed along lines of sight parallel to B



We can, in principle, observe these effects in radially resolving side-on measurements and between side-on and end-on measurements. And we may be able to distinguish between radial and axial fields.

Spatial resolution might be as important as spectral resolution.

Practical Zeeman spectroscopy on Z will have to balance multiple considerations

- **Optical:**
  - Zeeman effect will be large
  - Lines may be optically thick (even continuum κ gets large for $h\nu$ < 100 eV)
  - For diagnosing flux compression in MagLiF side-on, they will not escape liner
  - Stark broadening may be very large at the densities we care most about
  - Photons from hot emission regions might overwhelm the transitions of interest
  - Most useful for measurements in initial stages of compression

- **X-rays:**
  - May be the only way to asses fields in hot plasmas
  - Zeeman splitting may be near instrument resolution
  - Differential splitting may help us overcome resolution requirements (E/DE ~ 5000 for direct measurements)
  - Li-like 3p – 2s transitions are promising candidates:
    - Emitted from plasma regions with T ~ 0.3 – 3 keV from transition metals up to Kr
    - Nearby 3d – 2p transitions can help asses opacity effects
    - relatively large ΔE^{so} (~10x larger than ΔE^{so} of Lyα at similar energies) – so we could use Weizman differential splitting analysis
  - X-rays may escape Be liner, so we are not restricted to end-on lines of sight

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