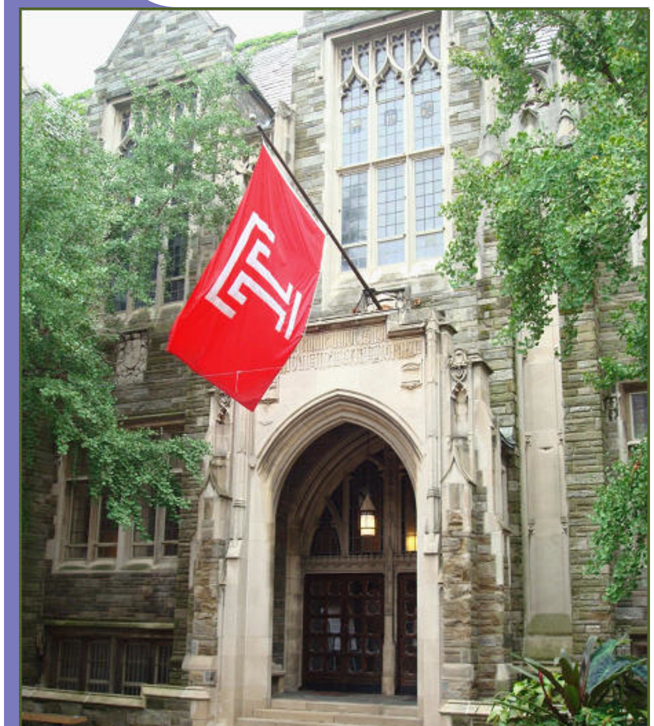
Three-Body Interactions with Magnetic Lanthanides



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Introduction

- There has been a lot of excitement in using confined ultra-cold atoms and molecules to simulate many-body physics.

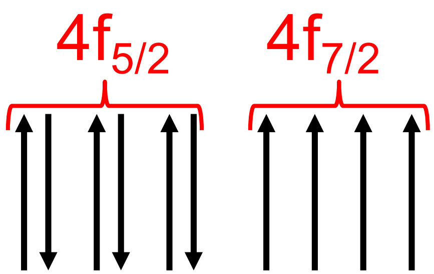
- Until recently, this type of study has *mainly* focused on alkali-metal atoms and their di-atomic molecules.

- Ultracold atomic physics is now poised to enter a new regime, where far-more complex atomic species can be cooled and studied.

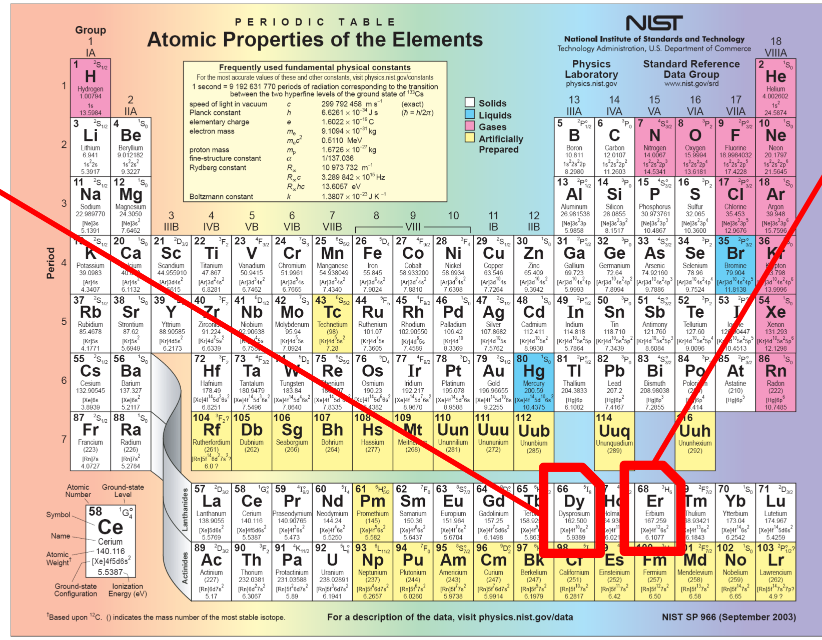
- Magnetic lanthanide atoms with their large magnetic moment and large orbital angular momentum are extreme examples of such species.

Dy and Er: submerged 4f-shell atoms

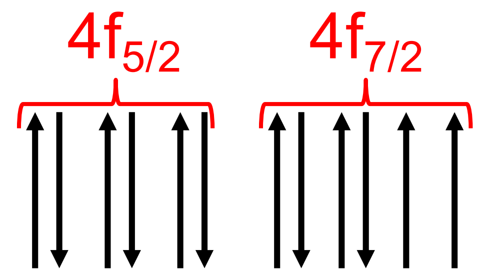
Dy ($4f^{10}$ $6s^2$ ($^5I_8$))



$\mu = 10\mu_B$



Er ($4f^{12}$ $6s^2$ ($^3H_6$))



$\mu = 7\mu_B$

Some of the electrons in the 4f shell are aligned in the same direction creating a large magnetic moment and a large spin.

First experiments with ultracold Dy and Er

The first realization of a quantum-degenerate gas of **Er** was achieved by F. Ferlaino's group.

*Aikawa et al. (PRL **108**, 210401 (2012))*

The Stanford group of B. Lev cooled **Dy** atoms to ultracold temperatures and also created BECs.

*Lu et al. (PRL **107**, 190401 (2011))*

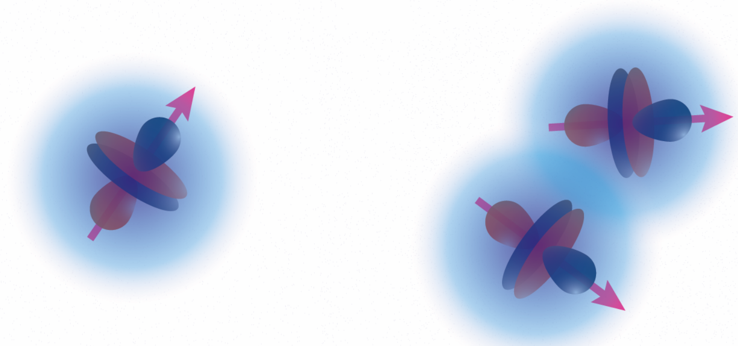
A growing number of other experimental groups started to work with these atoms.

Detection of resonances by three-body recombination

- Ultracold bosonic Er and Dy atoms are confined in an optical dipole trap and are in their energetically-lowest Zeeman sublevel.

- Inelastic three-body recombination causes atom loss from the trap.

Three colliding atoms form a weakly-bound dimer and atom



- At resonance, the recombination process is enhanced due to the coupling between the open and closed channel leading to a resonant increase of the atomic loss.

- We identify the magnetic field values with the maximum loss as the positions of Fano-Feshbach resonances.

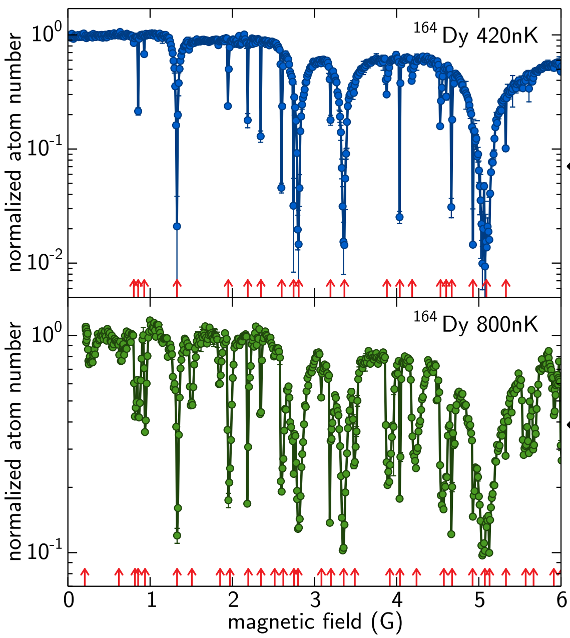
Extreme temperature sensitivity

We studed the extreme sensitivity of three-body recombination rate to the temperature of the atoms.

In magnetic lanthanides this phenomenon was first observed by Lev's group in Dy.

Phys. Rev. A 89, 020701 (2014)

Atom-loss spectrum for bosonic ^{164}Dy



3 res. per G at 420 nK

5 res. per G at 800 nK

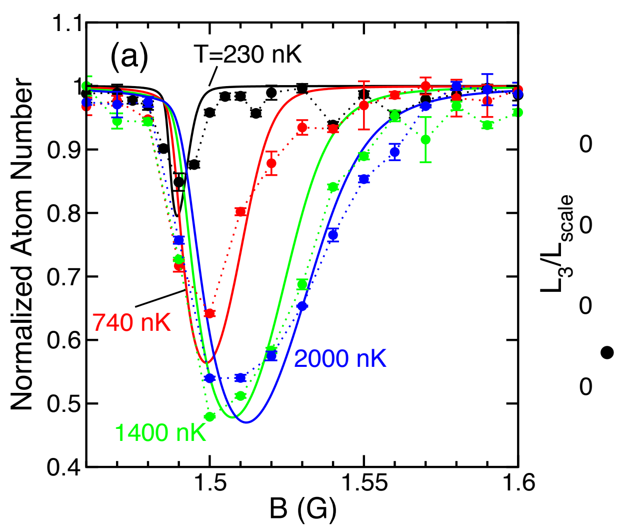
Number of resonances is increased by ~50 %

Trimer model

In atom-loss spectrum of ^{168}Er the increase of resonance number with temperature was only 25%.

In addition, the new atom-loss features show a dramatic broadening and a shift of maximum loss to larger B fields with increasing T.

Resonances that already exist at the lowest T do not show these behaviors.

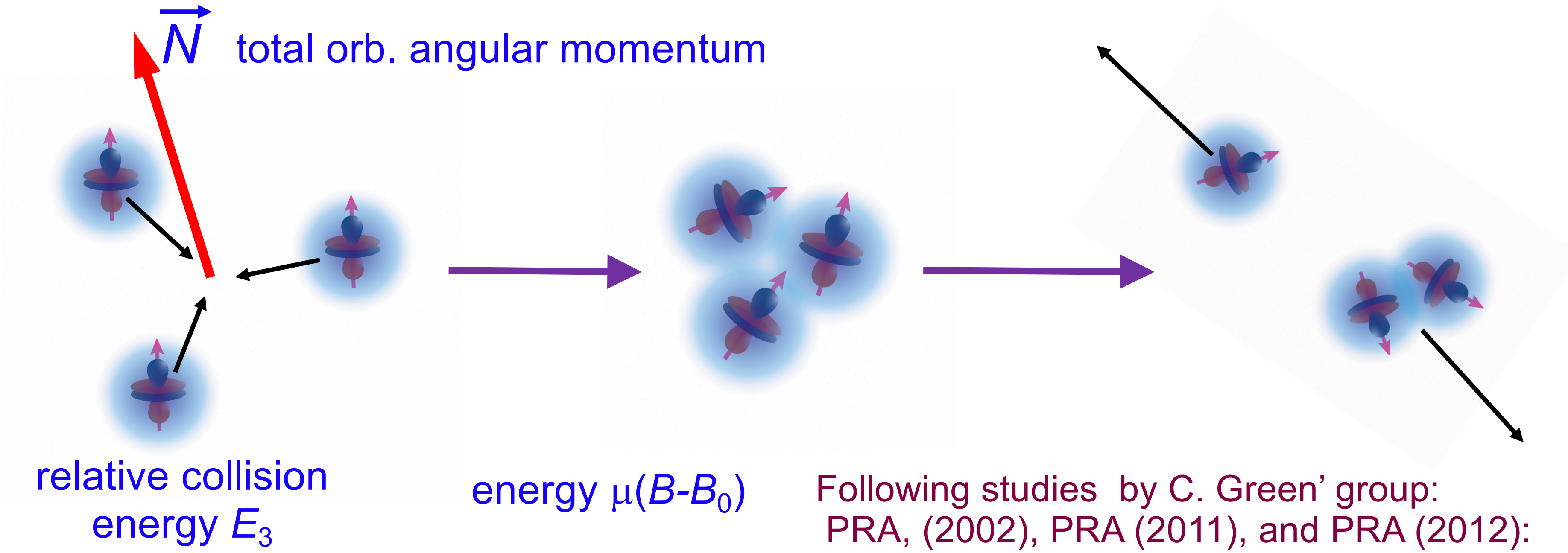


- We describe "trimer" model that suggests that this T dependence is due to scattering processes in the d-wave entrance channel of the trimer. (total orbital angular momentum *N*=2 of the trimer)

- This is despite of the fact that the two-body d-wave centrifugal barrier (250 μK) is a 100x larger than our highest T.

d-wave Feshbach resonances were detected in loss spectrum of Cr.
Laburthe-Tolra group (PRA 79, 032706 (2009))

Trimer model



Following studies by C. Green' group: PRA, (2002), PRA (2011), and PRA (2012):

$$\Gamma(E_3) \propto E_3^{N+2}$$

$\Gamma_{\rm br}$ constant for small E_3

- Lineshape of the resonance

$$|S(E_3, B)|^2 = \frac{\Gamma(E_3)\Gamma_{\rm br}}{(E_3 - \mu(B - B_0))^2 + (\Gamma_{\rm tot}(E_3)/2)^2}$$

Trimer model

- Three-body recombination rate coefficient is

$$L_3(E_3, B) \propto v_3 \frac{\pi^2}{k_3^5} |S(E_3, B)|^2 \quad (\text{cm}^6/\text{s})$$

relative velocity → v_3; relative wavenumber → k_3

- Thermal averaging of rate coefficients leads to additional broadening

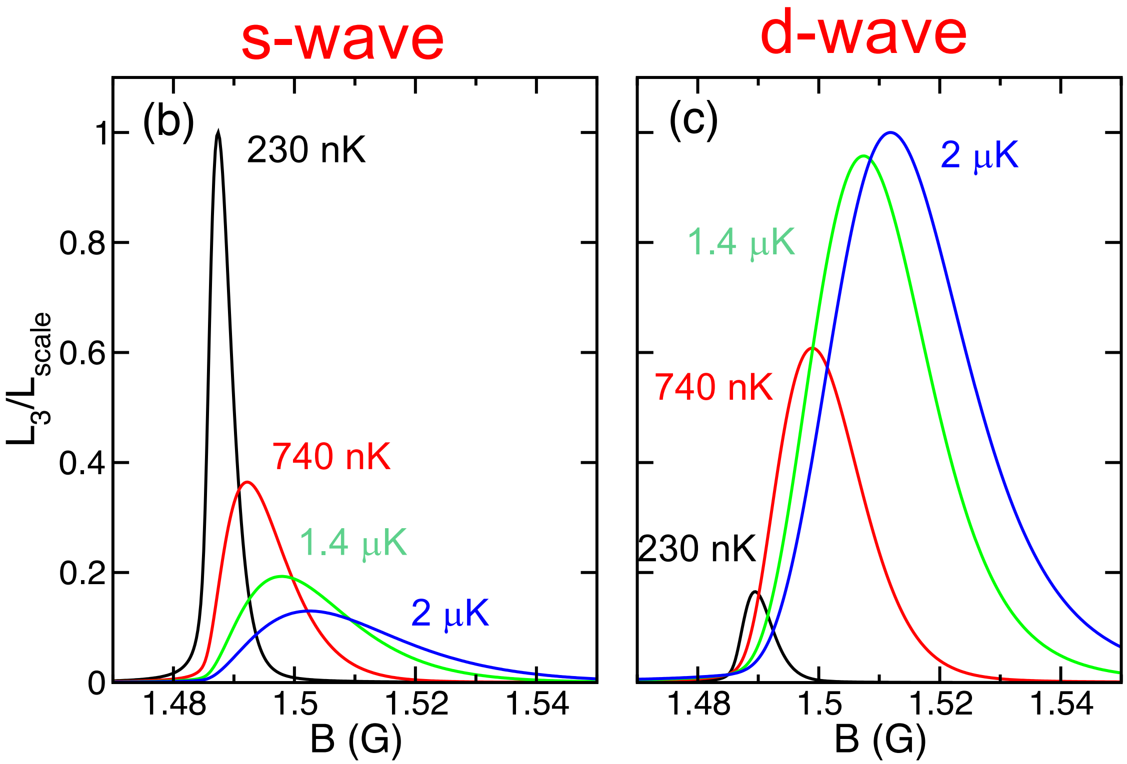
$$L_3(T, B) = \frac{1}{Z} \int_0^\infty E^2 dE \, L_3(E, B) \, e^{-E/kT}$$

- For kT >> $\Gamma(E_3)$, Γ_{br} we derive $L_3(T, B) \propto (kT)^{N-1}$

Trimer simulation

- Loss rate coeff. L_3 for the N=0 (s-) and N=2 (d-) wave entrance channel for several temperatures.

scaled in relative units



Γ_{br}/k=250 nK

$\Gamma(E_3)/k=0.2\ (E_3/1000\ nK)^2$ nK for s-wave

$\Gamma(E_3)/k=0.1\ (E_3/1000\ nK)^4$ nK for d-wave

- A striking difference is the temperature-dependence of the s- and d-wave entrance-channel resonances. The d-wave case agrees with experiment.

Conclusion

- I described the extreme sensitivity to the temperature of the atom-loss spectra and three-body recombination in scattering of magnetic lanthanides.
- Here, I shown that entrance channels with zero and non-zero relative orbital angular momentum N lead to line shapes with different temperature behavior.
- Those with N=0 (s-wave) entrance channels have sharply decreasing recombination rates with T, whereas those with N=2 (d-wave) entrance channels have an increasing recombination rate.

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Eite Tiesinga
NIST, JQI, and QuICS