Outline – Second Part

• Two-component Fermi gases
• How to create a 3-component mixture
• First experiments
• Probing a strongly interacting system
• Conclusion and outlook
Three hyperfine states with Feshbach resonances for each combination:

Transitions between the states can be driven via radio-frequency (RF)-fields!
Evaporation at $B = 760 \text{G}$:

$\Rightarrow a_0$ large and positive:

$\Rightarrow$ Molecule formation when $T \sim E_b$

$$E_b = \frac{\hbar}{ma^2} \quad (\sim 3 \mu K \text{ at } 760 \text{ G})$$

Close to resonance the molecules are stable and can form a BEC!

Molecules can easily be transformed into Cooper pairs by ramping across the Feshbach resonance (BEC-BCS crossover)
Creating 3-component Fermi gases

Basic Idea:

- Create degenerate 2-component Fermi gas
- Drive RF-transitions to populate the third state

Unfortunately, it is not that easy:

Ultracold gases are metastable objects…
Stability of ultracold gases

• Formation of molecules from free atoms is energetically favorable
• This is a three-body process
• Therefore ultracold gases are stable if they are dilute and weakly interacting

But the crossover is in the strongly interacting regime (\( a \to \infty \))? Those are Fermions!

⇒ Pauli blocking strongly suppresses three-body losses:

Strongly interacting systems with 3 non-identical Fermions decay within milliseconds

⇒ It is impossible to create a thermalized three-component sample close to resonance
Creating stable 3-component mixtures

Solution: Create mixture where all scattering lengths are small...

...But the problem is how to get there:

Result: Balanced 123 mixtures with long lifetimes
Creating stable 3-component mixtures

1. Evaporative cooling of a $|1>-|2>$ mixture to $T \sim 10 \, \mu \text{K}$ at $B = 755 \, \text{G}$
2. Finish evaporation at $B = 300 \, \text{G}$ to avoid molecule formation
3. Ramp to $B = 532 \, \text{G}$ (zero-crossing of $a_{12}$)
4. Simultaneously apply 200 ms RF pulse on both transition frequencies

Result: Balanced 123 mixtures with long lifetimes
First experiments

Holding the mixture for 250 ms at different magnetic fields:

- Mixture is stable if all two-particle scattering lengths are small
- Rapid decay close to the two-particle Feshbach resonances
- Decay is the same for all components
- Three-body process
Probing strongly interacting systems

- Prepare a thermalized 3-component gas with small interactions
- Go to the strongly interacting regime
- Observe the system and try to deduce information about the equation of state
Signatures for pairing and/or superfluidity

- Energy gap
- Phase separation
- Oscillation Frequencies of collective modes
- Vortices
Signatures for pairing and/or superfluidity

- Quantitative measurement of the pairing energy
- Can be done on short timescales

RF-Spectroscopy:
Signatures for pairing and/or superfluidity

Phase separation:

- Directly observable via in-situ imaging
- Qualitative knowledge of what to expect
- System has to form equilibrium

Phase Separation in an imbalanced two-component system, MIT 2005
Signatures for pairing and/or superfluidity

Collective Oscillations:

- Easy to excite and observe
- Can be done on relatively short timescales
- Effects might be small
- No quantitative expectations

Quadrupole mode for hydrodynamic and collisionless two-component gas (Innsbruck 2007)
Signatures for pairing and/or superfluidity

Vortices:

• Definite proof of superfluidity
• Rotation can already be introduced into the weakly interacting gas
• Only local density changes necessary to form vortex lattice
• Impressive pictures
• **Very** difficult to observe

Vortices in a two-component Fermi gas (MIT 2005)
Signatures for trimer formation

- Trimers Cannot be observed directly

Indirect methods:

- Analyzing trap loss
- RF spectroscopy
- Adiabatic ramping
Conclusion

So far there has been only very little work on three-component Fermi systems...

...But this is about to change