

On the Conversion of Ultracold Fermionic Atoms to Bosonic Molecules via Feshbach Resonances

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Recently amazing progress has been made in the achievement of increasingly degenerate regimes of trapped atomic Fermi gases. After reaching the degenerate regime, experiments have dealt with mixtures of two hyperfine levels. This allows quite conveniently to adjust the effective interaction between atoms, employing a Feshbach resonance. At low temperatures the scattering between atoms is characterized by their s-wave scattering length. By slowly varying the magnetic field one can sweep through the magnetic Feshbach resonance. Starting with a weak attractive interaction between atoms of different hyperfine levels, i.e., small negative scattering length, making it more and more negative, and finally have it jump to a positive value at the other side of the resonance, corresponding to a repulsive interaction between atoms leading to a formation of diatomic molecules. Utilizing such magnetically tuned scattering resonances between two-component Fermi gases experimentalists have been able to produce, Bose-Einstein condensates of molecules formed by Fermionic atoms of ${}^6\text{Li}$ and ${}^{40}\text{K}$ as well as to probe the, theoretically predicted crossover from a Bose-Einstein condensate (BEC) to a Bardeen-Cooper-Schrieffer (BCS) superfluid .

An interesting feature of a couple of such Feshbach sweep experiments [1,2] is that the experimental efficiency observed in the conversion of ultracold Fermi atomic gases of ${}^{40}\text{K}$ and ${}^6\text{Li}$ atoms into diatomic Bose gases was limited to 0.5. By constructing [3] the many-body state we show that the initial state preparation performed in such experiments involving two-component Fermi gases yields a mixture of even and odd parity pair-states, composed of two subsystems corresponding to two different spin states. Through the symmetry of the initial many-body state we are able to explain the 50% limited transfer efficiency in transforming atoms into molecules obtained in the above experiments as well as the fact that the Feshbach resonance sweep does not yield a swift heating of the remaining atomic Fermionic gas as was theoretically predicted [4].

In very low temperatures the Feshbach resonance is due to s-wave interactions, therefore the scattering atoms need to have a spatially symmetric wave function in order to create a molecule. In considering pairs of atoms in the initial state of the system, one from each spin state, half the atomic pairs are anti-symmetric spin-states and half are spin symmetric. More explicitly, the reduced two-particle density matrix obtained by tracing out all but one particle of one spin state and another particle of the other spin state contains 50% spin anti-symmetric spin-states, interacting via an s-wave (even parity spatial state), and 50% spin symmetric spin superposition which are effectively non-interacting at such low temperature. Thus when sweeping through the resonance sufficiently slow so that the Landau-Zener transition is traversed adiabatically it is clear that, since only even parity states can produce molecules through the Feshbach sweep, the conversion of ultracold Fermi gases into a diatomic Bose gas is limited to 0.5.

To obtain a transfer efficiency which is greater than 0.5, as is commonly achieved in current experiments, the odd parity spin-symmetric states must decorrelate before the constituent atoms can interact again via the Feshbach resonance. Therefore in achieving a higher efficiency the sweep rate was much slower, approaching "close to thermal equilibrium" conditions. Moreover in the relatively rapid sweep experiments [1,2] in which the Feshbach resonance sweep rate is sufficiently slow to pass adiabatically through the Landau Zener transition but faster than "the collision rate" in the gas, one expects a rapid heating of the Fermionic gas. However even though the Feshbach sweep produces holes in the Fermionic atomic sea, these holes can not be filled by the remaining atomic population, i.e., the population of atoms which have not been converted to molecules, since their composing atoms are non-interacting, due to their spatial symmetry which controls their interaction at ultra-low temperatures. This explains the experimental observation that the remaining atoms do not heat.

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