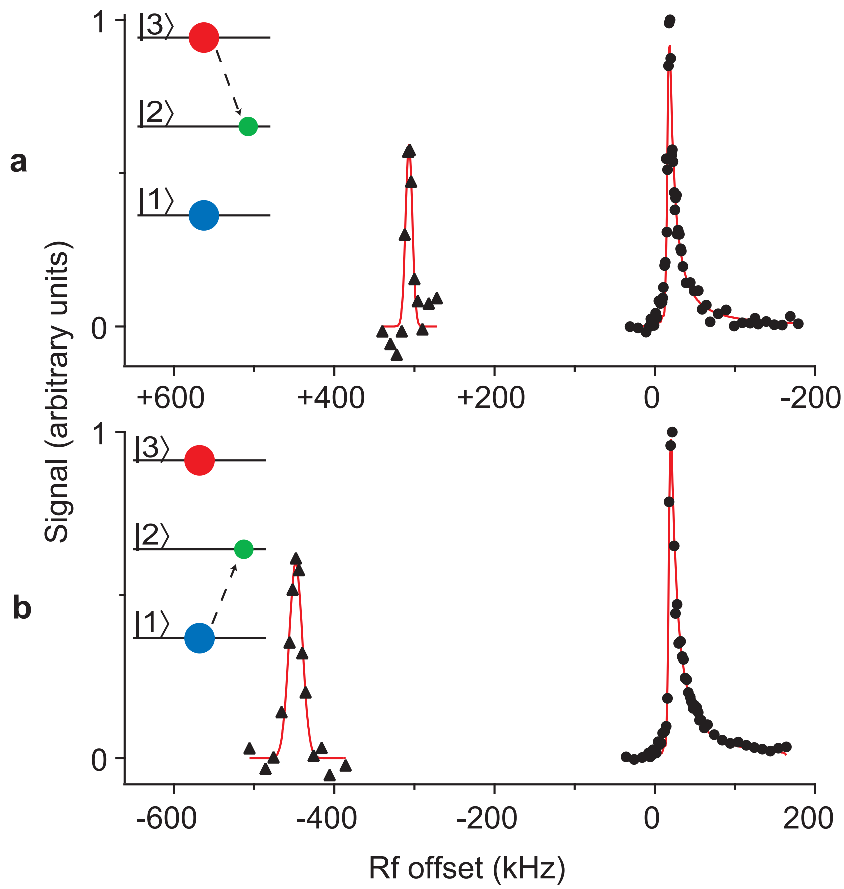
doi: 10.1038/nature07176

Determination of the fermion pair size in a resonantly interacting superfluid

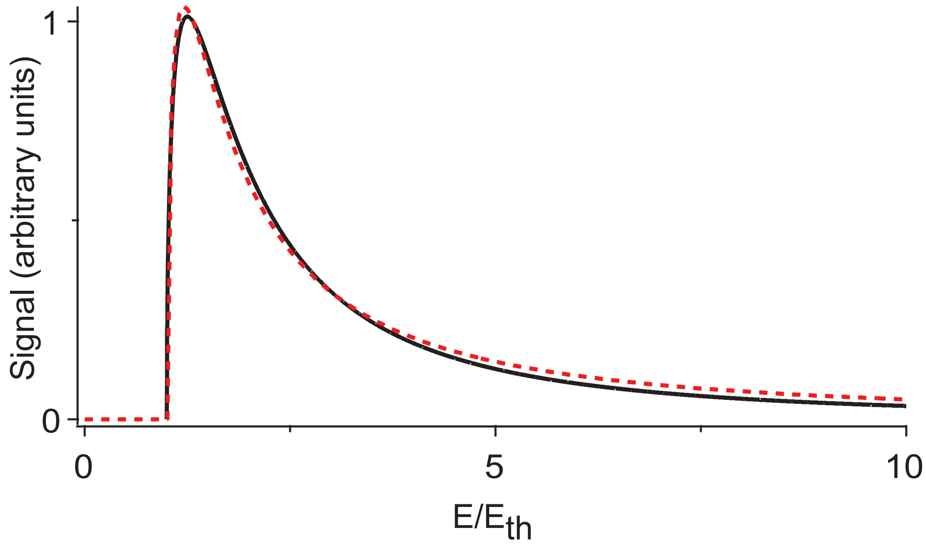
Christian H. Schunck, Yong-il Shin, André Schirotzek & Wolfgang Ketterle

Supplementary Information

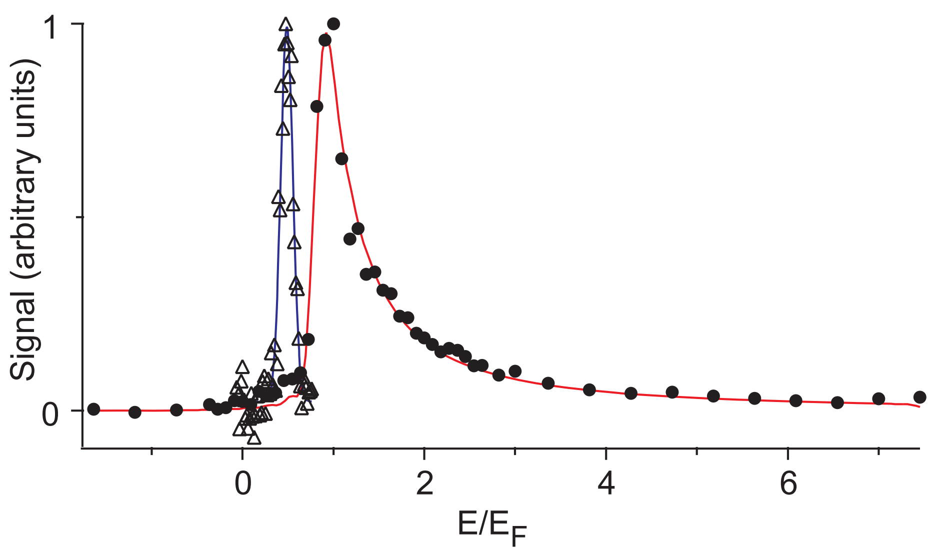
Supplementary Figures



Supplementary Figure 1: Radio-frequency spectra at unitarity for the (1,3) mixture at 691 G. For all spectra the number of atoms transferred to state |2⟩ has been recorded. In the (1,3) mixture radio-frequency transitions to the final state |2⟩ are possible from both states |1⟩ and |3⟩. The final states can therefore be either a bound (2,3) or, respectively, a (1,2) molecule or a dissociated free atom in state |2⟩. Note that the bound-free spectra are very similar for both |3⟩ to |2⟩ (**a**) and |1⟩ to |2⟩ (**b**) transitions. The bound-bound spectra, however, show different shifts indicating that the final (2,3) molecule is more strongly bound than the (1,2) molecule. This is a consequence of the smaller width of the (2,3) Feshbach resonance at 811 G compared to the width of the (1,2) resonance at 834 G[1]. **a,** |3⟩ to |2⟩ transition, ε_F = 21 kHz, T/T_F =0.1; **b,** |1⟩ to |2⟩ transition, ε_F = 22 kHz, T/T_F = 0.14.



Supplementary Figure 2: Generic pair dissociation line shape. A simulated radio-frequency dissociation spectrum in the BCS limit[5] (black solid line) is fit with I_{generic} (red dashed line) which is the molecular line shape I_{m} with an additional offset parameter E_{offset} (see Methods).



Supplementary Figure 3: Comparison of the radio-frequency spectra of the (1,2) and (1,3) superfluids at unitarity, showing dramatic final-state effects for the (1,2) mixture. Open circles: same radio-frequency dissociation data as in Supplementary Fig. 1b. Solid diamonds: radio-frequency spectrum at unitarity for the (1,2) mixture at 833 G from ref. 2. The frequency axis has been normalized by the local Fermi energies. In the (1,2) mixture final-state effects lead to a strong suppression of the asymmetric "tails" of the radio-frequency spectrum and a shift of the peak to lower energies.

Supplementary Discussion

Final-state interactions in the radio-frequency spectroscopy experiments with the (1,2) and (1,3) mixtures.

Supplementary Figure 3 shows the dramatic effect of final-state interactions in the (1,2) mixture at unitarity. The narrow and symmetric line shape observed in the (1,2) to (1,3) radio-frequency spectrum suggests that this spectral peak is dominated by a bound-bound transition from (1,2) pairs to a (1,3) correlated state.

In the molecular case final-state interactions can be included in an analytical model[3]. The final states for molecular dissociation are two atoms with momentum $\hbar k$ in an *s*-wave scattering state with scattering length a_f. For a large and positive $a_i \approx b$ and an increasing a_f ($0 < a_f < a_i \approx b$) the dissociation spectrum looses in weight and narrows as $(1 - a_f / a_i)/(1 + k^2 a_f^2)$ until it disappears when a_f/a_i approaches one. At this point the spectrum consists of a delta function for the bound-bound transition between molecular states of equal size.

A very similar behaviour of the bound-bound and bound-free parts of the spectrum is expected for a superfluid with resonant interactions[4]: for $|a_f|,|a_i| >> 1/k_F$ the spectrum is reduced to a delta function. Here, the initial state is a fermion pair condensate described by the BCS-BEC crossover wavefunction[4,5]. In contrast to the molecular case, the spectrum of the superfluid at resonance shows a bound-bound peak even for small negative values of $1/k_F a_f$ i.e. in a regime where binding is only due to many-body effects[4]. The spectra in Fig. 4 of our paper show that bound-bound transitions dominate when $|1/(k_F a_i) - 1/(k_F a_f)| \leq 1.5$ (a region that is about a factor of two larger than obtained in ref. 4). We also infer from ref. 4 that for a system in the unitarity limit it is much more difficult to spectrally resolve bound-bound and bound-free transitions if $a_f < 0$. When one approaches resonance for the (1,2) system from the BEC side the bound-free spectrum narrows and smoothly turns into a bound-bound dominated spectrum.

Compared to the (1,2) superfluid, a_f in the (1,3) system is up to three times smaller and positive. This leads, both in the molecular model (due to the quadratic dependence on $k_F a_f$) and in the resonant case[23], to a dramatic change in the dissociation spectrum towards the limit of negligible final-state interactions. Fits to the (1,3) dissociation spectrum both with and without a correction factor for final-state effects (see Methods)[3] show negligible differences, indicating the small influence of final-state interactions. In fact, the (1,3) spectra in Fig. 4(a-c) of the paper show the absence of final-state effects without any detailed analysis. The splitting between bound-bound and bound-free parts given by $\hbar^2 / m a_f^2$ is considerably larger than the width of the bound-free spectrum (which is approximately $\hbar^2/mb^2$). Therefore the condition $a_f<b$ is fulfilled, implying that final-state interactions do not strongly affect the dissociation spectrum.

Supplementary Notes

1. Bartenstein, M. *et al.* Precise determination of ^{6}Li cold collision parameters by radio-frequency spectroscopy on weakly bound molecules. *Phys. Rev. Lett.* **94**, 103201 (2004).

2. Shin, Y., Schunck, C. H., Schirotzek, A. & Ketterle, W. Tomographic rf spectroscopy of a trapped Fermi gas at unitarity. *Phys. Rev. Lett.* **99**, 090403 (2007).

3. Chin, C. & Julienne, P. S. Radio-frequency transitions on weakly bound ultracold molecules. *Phys. Rev. A* **71**, 012713 (2005).

4. Basu, S. & Mueller, E. J. Final-state effects in the radio frequency spectrum of strongly interacting fermions. Preprint at ⟨http://xxx.tau.ac.il/abs/0712.1007v2⟩ & private communication.

5. Ketterle, W. & Zwierlein, M. W. *Ultracold Fermi Gases* (eds Inguscio, M., Ketterle, W. & Salomon, C.) 95-287 (Proc. International School of Physics Enrico Fermi, Course CLXIV, IOS Press, Amsterdam, SIF Bologna, 2008).