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Nuclear Physics A684 (2001) 641c–645c

NUCLEAR PHYSICS A

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High precision Feshbach spectroscopy of ultracold cesium collisions

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Abstract We report on the observation of multiple collision resonances in an ultracold cesium gas as an external magnetic field is tuned. These resonances, associated with the formation of quasibound Cs_2 molecules during atomic collisions, can be used to determine the energy structure of these molecules and the long-range binary atomic interaction parameters with high accuracy. In addition, we observe a set of much narrower collision resonances which may arise from higher-order binary scattering processes, or possibly even three-body Efimov states.

1. INTRODUCTION

Laser cooling and trapping opens the possibility to study atomic interactions with unprecedented resolution, since thermal fluctuations are dramatically reduced. Some examples of this are photoassociation spectroscopy [1], ultracold ground-state collision studies [1,2], and the observation of many-body effects in dilute-gas Bose-Einstein condensates (BECs) [3].

Among the most dramatic effects observed in these studies are Feshbach resonances [2], where a quasibound molecular state is tuned into near-degeneracy with the scattering energy of two free atoms, causing a resonant alteration of the cold-collision properties [2,4]. These collision properties, observed using laser-cooled atoms in the μK range, constitute a spectroscopic tool of extremely high resolution; resonance positions can be measured to $<$ h 10kHz, which is a part in 10^{10} of the Cs_2 molecular potential depth.

Cesium is of particular interest in this context, because its ground state hyperfine splitting, which defines the SI second, is strongly influenced by a cold-collision induced frequency shift [5]. In addition, its large mass makes relativistic effects much more important in cold collisions than for most other atomic species amenable to laser cooling [6]. This results in a strongly enhanced coupling of weakly-bound states of the cesium dimer to unbound states of the ultracold atoms, yielding much richer collision phenomena [7].

Finally, three-body processes may become important even in these relatively dilute samples when the two-body interaction is tuned to resonance. Efimov proposed in 1971 that a set of weakly bound three-body states should emerge under these conditions [8]. The many binary Feshbach resonances observed for cesium collisions therefore provide a promising system in which to observe these three-body phenomena.

PII S0375-9474(01)00461-4

2. COLD COLLISION PHENOMENON AND FESHBACH RESONANCE

At low temperatures where S-wave scattering dominates, collisions between bosonic cesium atoms can be described by a single complex parameter, the S-wave scattering length a. The cold collision properties including elastic and inelastic collision cross sections, as well as the mean field energy shift in a BEC, are determined by S-wave scattering length [9].

In our experiments we use an external magnetic field to produce Feshbach resonant scattering; since in general the molecular bound states we observe have different magnetic moments than that of two free atoms, their energies can be tuned into resonance simply by using the differential Zeeman shift [2], namely:

$$E_b(B=0) - \mu_b \cdot \mathbf{B}_{res} = E_f(B=0) - \mu_f \cdot \mathbf{B}_{res}$$

where the subscripts b and f denote the bound and free states of the atom pair, respectively. Around the resonance, the scattering length varies with B to leading order as $a = a_0 + \Delta/(B - \mathbf{B}_{res})$ [4], where Δ characterizes the resonance width, and a_0 is the background scattering length away from resonance. Elastic and inelastic cross sections change correspondingly, allowing us to observe the resonances experimentally; the results are shown in Figs. 1 and 2.

3. EXPERIMENTAL PROCEDURE AND RESULTS

All of our measurements are performed on a gas of Cs atoms loaded into a conservative optical trap [10]. The gas is cooled to 1~5 uK by 3D Raman-sideband cooling [11], and polarized into a given magnetic sublevel with ~95% efficiency. Various scattering

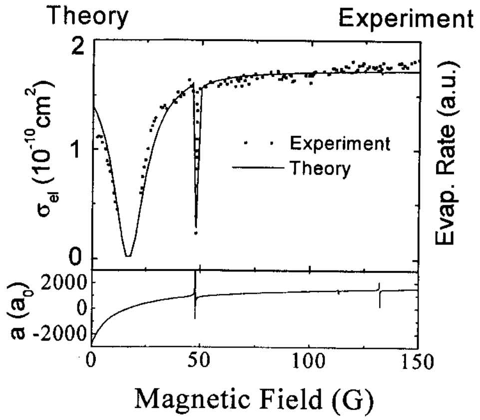

Figure 1. Elastic cross section of Cs atoms in |F=3, m$_F$=3> state

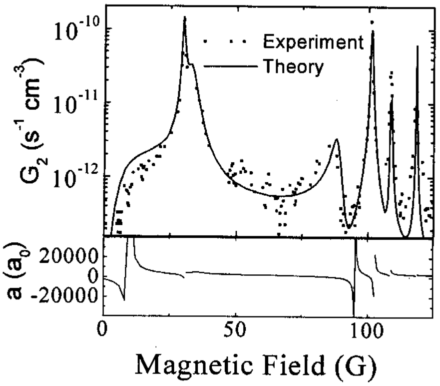

Figure 2. Binary loss coefficient of Cs atoms in |F=3, m$_F$=-3> state

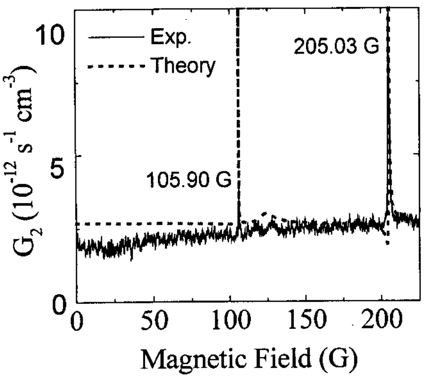

Figure 3. Binary Loss coeficient of Cs atoms in $|F=4,m_F=-4>$ state

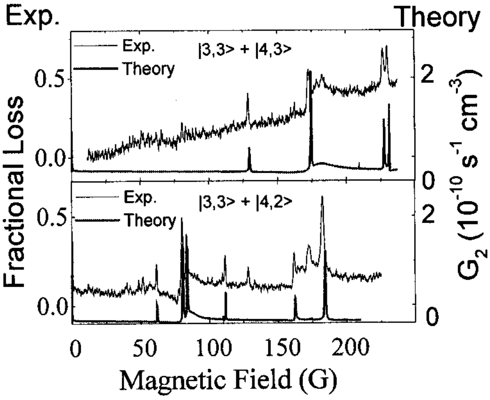

Figure 4. Atom loss of Cs atoms 90% in |3,3> and 10% in |4,m>

processes are then observed as a function of the external magnetic field. Samples are also prepared in mixtures of different sublevels using either Majorana transitions or state-selective microwave transitions.

The elastic collision cross section can be measured by producing a truncated thermal distribution of atoms in a very shallow trap and monitoring the relaxation of the sample to thermal equilibrium. The subsequent loss rate from the trap due to collision-induced evaporation is shown in Fig. 1 for atoms polarized in the |F=3,mf=3> state. This state has the lowest energy in a magnetic field, and therefore inelastic binary collisions are energetically forbidden. Higher energy states on the other hand can decay, converting magnetic or hyperfine potential energy into a kinetic energy sufficiently large to eject them from the trap. Thus, the inelastic cross section can be measured simply by observing the atomic loss rate from the trap. Measurements of this type are shown in Figs. 2, 3, and 4 for several higher-lying magnetic sublevels.

The formation of quasi-molecules during atomic collisions characteristic of a nearby Feshbach resonance can also be observed using a far-detuned probe laser beam. While free atoms remain virtually unaffected by this probe, which is typically detuned several nanometers above their resonance frequency, those atoms which penetrate to the very short interatomic distances characteristic of molecular formation experience a strong energy shift of their excited state due to the dipole-dipole interaction, and preferentially scatter photons. Atom pairs promoted to the excited state by absorption of a photon experience a large repulsive force due to this interaction, and are quickly expelled from our trap; this process is known as a "radiative collision" [1]. The radiative collision loss observed for trapped Cs atoms in the |F=3,mf=3> state is shown in Figs. 5 and 6 [12].

To obtain this high resolution and accuracy, the applied magnetic field must be extremely stable, and well-calibrated. In our experiment we stabilize the current driving the field coils to better than 10 ppm, and the absolute calibration of the field experienced by the atoms is accomplished using microwave spectroscopy, with a resolution of < 1mG.

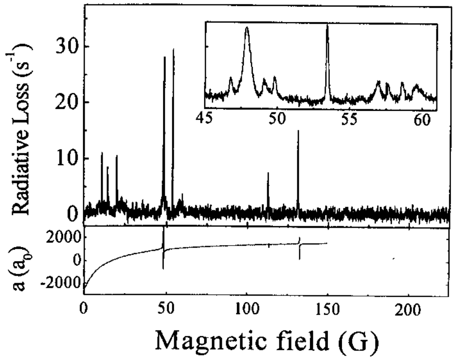

Figure 5. Radiative collision resonance spectra for a probe beam at 846nm, ~20W/cm^2

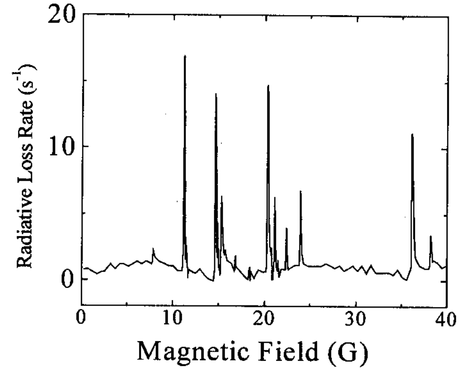

Figure 6. Detailed radiative collision spectra at low magnetic field for a probe beam at 844nm, ~20W/cm^2

4. DICUSSION

Based on the spectra in Figs. 1-3, the long-range binary interaction parameters for cesium atoms can be determined to high accuracy, using numerical coupled-channel calculations [13]. As shown in the figures, the results of these calculations reproduce our observed resonances. Based on the interaction parameters thus obtained, additional resonances were predicted in collisions between atoms in different magnetic sublevels, and Fig. 4 shows the agreement between this prediction and our subsequent experiments. Note that deviations from the predicted curve are mainly due to the additional interaction among |4,m> atoms and to the imperfection of the atomic polarization, neither of which were included in the calculation.

Figure 5 shows a comparison between the observed radiative loss spectrum for the |F=3,m=3> state, and the predicted variation of its scattering length. Note that the two very narrow resonances predicted at 113 and 131 Gauss, which were not observable in the thermalization spectrum of Fig. 1, are clearly observable here. These narrow resonances, as well as the strong feature at 48 G appearing in Figs 1 and 5, result from weak coupling to l=2 molecular states. The radiative loss measurement thus constitutes a sensitive probe of the scattering wavefunction at short range, and hence the molecular formation.

The inset to Fig. 5, as well as fig. 6, show detailed radiative loss spectra containing additional resonances which do not appear in the binary calculations. These extremely narrow resonances have an asymmetric lineshape determined by the atomic relative kinetic energy distribution, and an intrinsic linewidth as narrow as ~3mG. One possible explanation for these additional features is higher order binary processes, namely coupling to higher angular momentum molecular states with l=4,6,8, etc. Preliminary calculations suggest this may be a likely possibility [14]. A second, more intriguing explanation would involve three-body processes. By observing the density dependence of the loss rate on these narrow resonances, we have some evidence that more than two cesium atoms may be involved in the resonant scattering process. These resonances may be promising candidates for the long-sought Efimov states [9].

5. CONCLUSION

With laser cooled cesium atoms, we utilize Feshbach spectroscopy to probe the Cs_2 molecular energy structure near the dissociation limit. The long range binary interaction parameters are accurately extracted for the first time based on these spectra.

The loss induced by a radiative collision process is found to be sensitive to the formation of molecules in our trap. Several unexplained, extremely narrow radiative resonances are observed which may arise from high angular momentum molecular states or three-body bound states. Further studies of these resonances are currently ongoing.

REFERENCES

1. J. Weiner, V.S. Bagnato, S. Zilio and P.S. Julienne, Rev of Mod. Phys. **71**, 1 (1999) and references therein.
2. E. Tiesinga, A.J. Moerdijk, B.J. Verhaar, and H.T.C. Stoof, Phys. Rev. A **46**, R1167 (1992); E. Tiesinga, B.J. Verhaar, and H.T.C. Stoof, Phys. Rev. A **47**, 4114 (1993); S. Inouye, M.R. Andrews, J. Stenger, H.-J. Miesner, D.M. Stamper-Kurn, and W. Ketterle, Nature **392**, 151 (1998); J. L. Roberts, N. R. Claussen, James P. Burke, Jr., Chris H. Greene, E. A. Cornell, and C. E. Wieman, Phys. Rev. Lett **81**, 5109, (1998)
3. M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, and E.A. Cornell, Science **269**, 198 (1995); C.C. Bradley, C.A. Sackett, J.J. Tollett, and R.G. Hulet, Phys. Rev. Lett. **75**, 1687 (1995); K.B. Davis, M.-O. Mewes, M.R. Andrews, N.J van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle, Phys. Rev. Lett. **75**, 3969 (1995).
4. A.J. Moerdijk, B J. Verhaar, and A.Axelsson, Phys. Rev. A **51**, 4852 (1995)
5. K. Gibble and S. Chu, Phys. Rev. Lett. **70**, 1771 (1993).
6. F.H. Mies, C.J. Williams, P.S. Julienne, and M. Krauss, J. Res. Natl. Inst. Stand. Technol. **101**, 521 (1996); P. Leo, private communication.
7. M. Arndt, M. Ben Dahan, D. Guéry-Odelin, M.W. Reynolds, and J. Dalibard, Phys. Rev. Lett. **79**, 625 (1997); J. Söding, D. Guéry-Odelin, P. Desbiolles, G. Ferrari, and J. Dalibard, Phys. Rev. Lett. **80**, 1869 (1998); R. Monroe, E.A. Cornell, C.A. Sackett, C.J. Myatt, and C.E. Wieman, Phys. Rev. Lett. **70**, 414 (1993).
8. V.N. Efimov, Phys. Lett. **33B**, 563 (1970).
9. L.I. Schiff, Quantum Mechanics, (New York, McGraw-Hill, 1968); A.L. Fetter and J.D. Walecka, Quantum theory of Many-Particle System, (New York, McGraw-Hill, 1995)
10. V Vuletić, C. Chin, A.J. Kerman, and S. Chu, Phys. Rev. Lett. **81**, 5768 (1998).
11. A.J. Kerman, V. Vuletić, C. Chin, and S. Chu, Phys. Rev. Lett. **84**, 439 (2000).
12. V. Vuletić, C.Chin, A.J. Kerman, and S. Chu, Phys. Rev. Lett **83**, 943 (1999) .
13. P.J.Leo, C.J. Williams and P.S. Julienne, submitted to PRL.
14. P.J Leo, C.J. Williams and P.S. Julienne, private communication.