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Measurement of S-Wave Scattering Length between ^{6}Li and ^{88}Sr Atoms Using Interspecies Thermalization in an Optical Dipole Trap *

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We report the creation of the first mixture of ^{6}Li and ^{88}Sr atoms in an optical dipole trap. Using this mixture, a measurement of the interspecies thermalization process is carried out and the previously unknown interspecies s-wave scattering length between ^{6}Li and ^{88}Sr atoms is extracted to be $|a_{^6\mathrm{Li}-^{88}\mathrm{Sr}}| = (380^{+160}_{-100})a_0$ with a_0 being the Bohr radius from the rate of interspecies thermalization.

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Quantum gas mixtures composed of different chemical elements or isotopes of the same elements add many exciting possibilities to the study of various physics phenomena, e.g., heteronuclear Efimov resonance,[1,2] impurity in superfluids,[3–5] and ultracold chemical reactions.[6] Of particular interest, these mixtures constitute the starting point of forming heteronuclear ground-state molecules, which can possess large electric dipole moments and thus can exhibit long-range and anisotropic interactions,[7–9] facilitating rich applications ranging from precision measurements,[10,11] simulation of many-body quantum systems,[10,12] to quantum computation processing.[13]

However, most quantum-gas-mixture experiments involve two alkali-metal species, research in this field has also extended to richer combinations[14–23] along with the development of cooling techniques for atoms beyond alkali elements.[24–30] Among them, mixtures of alkali and alkaline-earth(-like) atoms highlight a unique advantage for their possibilities of creating open-shell ground-state molecules with an electric dipole moment and an electron spin, which make them promising candidates for testing fundamental symmetries[31] and for simulating lattice-spin models.[32] To date, intensive efforts have been carried out in investigating mixtures of Li-Yb,[15,16] Rb-Sr,[17,18,33] Rb-Yb,[19,20] and Cs-Yb[21] atoms. The work we report here focuses on Li-Sr atom mixtures. Although a number of theoretical predictions on the properties of Li-Sr mixture have been reported[34–37] in recent years, few direct experimental measurements have been carried out.

In this Letter, we report the first production of an optically trapped mixture of ^{6}Li and ^{88}Sr atoms based on a sequential cooling and trapping strategy for the two species. Using this system, we study thermalization between the two atomic species in the same optical dipole trap, and extract the previously unknown interspecies scattering length from the rate of thermalization.

Given the low vapor pressure of Li and Sr atoms at room temperatures, we load both ^{6}Li and ^{88}Sr atoms into a magneto-optical trap (MOT) from decelerated atomic beams. Figure 1(a) illustrates the design of our vacuum setup, which is made up of a dual-species oven, a spin-flip Zeeman slower (ZS), and an octagonal glass science chamber. Typically, the Li and Sr ovens are heated to 450 ℃. The divergence angle of the atomic beam emitted from the oven is limited by an array of microtubes with an inner diameter of 200 μm and length of 10 mm. In our design, the two species share the same Zeeman slower, which features a capture velocity of 974 m/s (669 m/s) and deceleration coefficient of 0.43 (0.40) for ^{6}Li (^{88}Sr) atoms.[38] The customized glass cell made by synthetic quartz plates with double-sided anti-reflection coating offers excellent optical access and allows for precise and fast magnetic-field control.

To cool ^{6}Li atoms, we adopt the standard MOT procedure using the $^2S_{1/2} \rightarrow {}^2P_{3/2}$ (D2) transition at 671 nm with subsequent gray molasses (GM) cooling stage using the $^2S_{1/2} \rightarrow {}^2P_{1/2}$ (D1) transition.[39,40] For ^{88}Sr atoms, the presence of singlet and triplet states enables an intriguing two-stage cooling process, which starts with a blue MOT (bMOT) operating on the broad $^1S_0 \rightarrow {}^1P_1$ transition at 461 nm (linewidth $\Gamma/2\pi = 30.5$ MHz) to capture atoms from the slowed atomic beam, and ends with a red MOT (rMOT) on the narrow $^1S_0 \rightarrow {}^3P_1$ transition at 689 nm ($\Gamma/2\pi = 7.5$ kHz) to cool atoms to μK-regime. During the blue MOT stage, we use a pair of repumping lasers at 679 nm and 707 nm wavelengths for recycling atoms falling into the $5s5p^3P_2$ dark states back into

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the MOT.

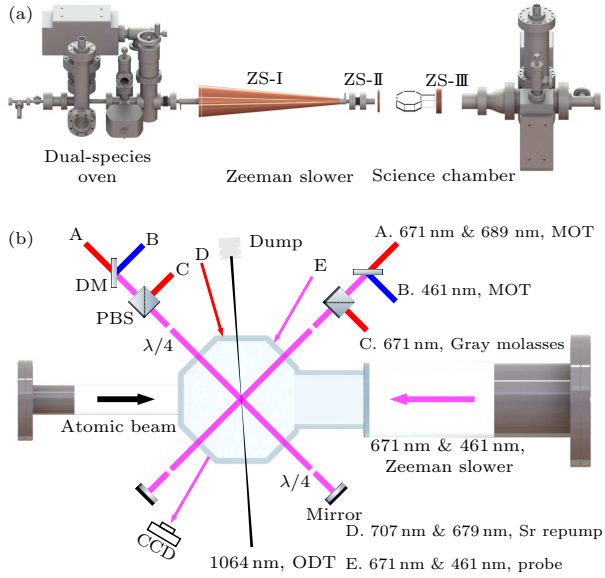

Fig. 1. Li-Sr mixture setup. (a) Three-dimensional illustration of the main vacuum system, consisting of three major parts: a dual-species oven, a common spin-flip Zeeman slower, and an octagonal glass science chamber. (b) Top view of the optical layout near the science chamber. To provide better optical access, fiber couplers (not shown), dichroic mirrors (DM), and polarization beam splitters (PBS) are used extensively to combine various light beams. Some optical elements are omitted for clarity.

As the optimal magnetic field gradients for loading the Li and Sr atoms, and for performing the gray molasses and rMOT are very different, we employ a sequential cooling and trapping strategy to prepare a mixture of ^{6}Li and ^{88}Sr atoms in an optical dipole trap (ODT), which is formed by a horizontal 1064-nm light beam with a waist of 28 μm. Figure 1(b) depicts the top view of the optical layout near the science chamber, which shows various light beams needed for cooling and trapping the atoms. Figure 2 illustrates the simplified experimental sequence we adopt for preparing the ^{6}Li-^{88}Sr mixture in the ODT. Our experiment starts with accumulating ^{88}Sr atoms in the blue MOT for 500 ms, followed by a 250-ms rMOT cooling stage as described in detail in Ref. [38]. By adjusting the magnetic bias field at the end of the rMOT stage, we optimize the overlap between the ODT and the rMOT, and transfer about 1.2×10^7 ^{88}Sr atoms into the ODT with a typical trap depth of k_B (82.4 μK) (k_B being the Boltzmann constant). Then, we turn on the D2-line MOT for ^{6}Li for a variable time. At the end of the D2-line MOT, a 1-ms D1-line GM is set up to further cool ^{6}Li atoms to 38 μK. The ^{6}Li atoms are optically pumped to the lowest hyperfine manifold $F = 1/2$ at the end of the GM. As the GM calls for essentially zero external magnetic field, bias fields could no longer be used to adjust the position of the cooled ^{6}Li atomic cloud. Therefore, the ODT is pre-adjusted to a position that provides optimal loading efficiency for ^{6}Li atoms. To load ^{6}Li atoms into the ODT, we adiabatically (for the Sr atoms in the trap) ramp up the ODT power to 26.4 W in 50 ms shortly before the gray molasses stage, raising the trap depth to k_B (1.33 mK). At the end, we obtain optically trapped ^{6}Li atoms with a temperature of 163 μK. At this point, a ^{6}Li-^{88}Sr mixture in an ODT is created with ^{6}Li atoms distributed equally in the two Zeeman sub-states $|F = 1/2, M_F = \pm 1/2\rangle$ and ^{88}Sr atoms in the $^1S_0$ ground state. The number and temperature of atoms are measured via the standard absorption imaging technique using the $^2S_{1/2} \rightarrow {}^2P_{3/2}$ transition at 671 nm for Li and $^1S_0 \rightarrow {}^1P_1$ transition at 461 nm for Sr.

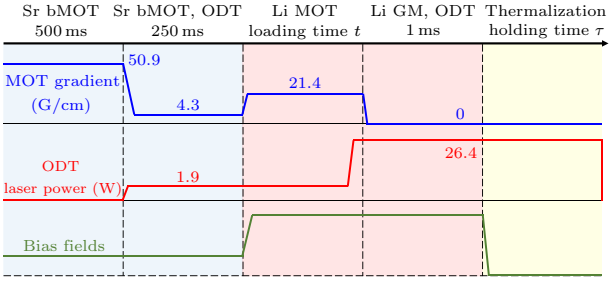

Fig. 2. The adopted experimental sequence for preparing ^{6}Li-^{88}Sr mixtures and for measuring interspecies thermalization in an ODT. Here ^{88}Sr and ^{6}Li atoms are cooled and transferred to the ODT in sequence. The MOT magnetic field gradient, optical dipole trap laser power, and magnetic bias fields are varied over time to optimize for loading of atoms into the ODT. Interspecies thermalization is observed over a variable mixture holding time at a constant ODT depth.

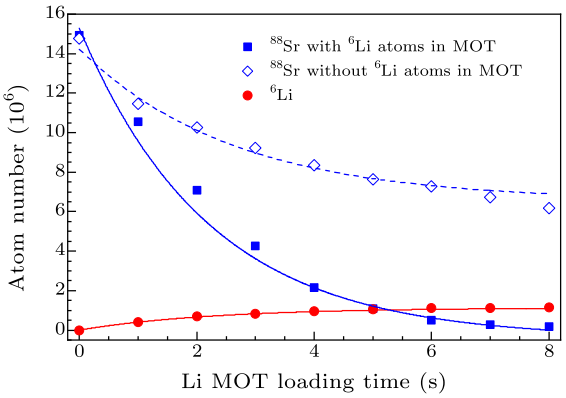

Fig. 3. Atom numbers of ^{88}Sr (blue squares) and ^{6}Li (red circles) in the ODT as a function of ^{6}Li MOT loading time. For comparison, ^{88}Sr atom number in the same MOT loading process but without ^{6}Li atoms is also shown (open blue diamonds). The blue solid (dashed) line is an exponential-decay fit to ^{88}Sr atom number, yielding a $1/e$ lifetime of 2.2 s (9.7 s) with (without) ^{6}Li atoms in MOT. The error bars are smaller than the size of the symbols.

The ^{88}Sr atoms in the ODT are observed to be influenced by the ^{6}Li MOT. Figure 3 compares the loss of ^{88}Sr atoms from the ODT as a function of the Li-MOT loading time with and without ^{6}Li atoms. The latter is achieved by either switching off the cooling or the repumping light, or the magnetic gradient field, all end up with the same results. It is apparent that the existence of ^{6}Li atoms in the MOT re-

sults in a dramatic reduction of the trapping lifetime for ^{88}Sr atoms (2.2 s) compared to that without ^{6}Li atoms (9.7 s). The latter is presumably due to collision with residual gases in the vacuum chamber and also to the plain evaporation of ^{88}Sr atoms in the ODT. The dominant loss mechanism behind the former may be attributed to light assisted collisions between ^{88}Sr atoms with electronically excited ^{6}Li atoms.[41] During the process of increasing the ODT laser power for loading Li atoms, ^{88}Sr atoms are heated from 23 μK to 98 μK, presumably due to adiabatic compression of the ^{88}Sr atomic cloud. We control the ratio of the two species in the ODT, $N_{\rm Li}/N_{\rm Sr}$, by varying the loading time of the ^{6}Li MOT.

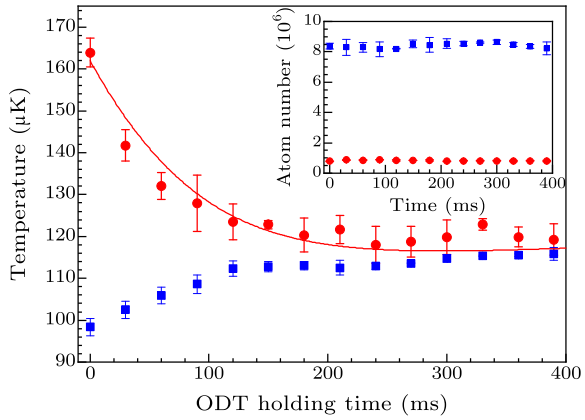

Fig. 4. Interspecies thermalization. Temperature evolutions of ^{6}Li (red circles) and ^{88}Sr (blue squares) atoms are shown as a function of holding time in the ODT. The red solid line shows the fitted result of a numerical model (see text). The inset shows the atom number of the two species as a function of the holding time. Both species experience negligible loss in 400 ms.

To give a first estimate of the scattering cross section between the two species, we study the interspecies thermalization by monitoring the evolution of the atom numbers and temperatures of both ^{6}Li and ^{88}Sr atoms after they become mixed in the ODT. The results are shown in Fig. 4. The initial atom number and temperature of ^{6}Li (^{88}Sr) atoms are $N = 8.3\times10^5$ (8.4×10^6) and $T = 163\,\mu$K (98 μK), respectively, with an associated peak density of $1.7\times10^{10}\,{\rm cm}^{-3}$ ($2.8\times10^{11}\,{\rm cm}^{-3}$). The hotter ^{6}Li atoms get cooled down and reach thermal equilibrium with the colder ^{88}Sr atoms in approximately 250 ms, while ^{88}Sr atoms are only slightly heated due to their much larger abundance. Note that the fermionic ^{6}Li atoms in the $F = 1/2$ hyperfine ground state experience essentially no intrastate scattering and a negligible interstate scattering at zero magnetic field.[42] Also, the ^{88}Sr atoms exhibit a very small intrastate s-wave scattering length of $-2a_0$. We can, therefore, conclude that the intra-species and interspecies thermalization of the Li and Sr atoms in such a short duration must arise from the interspecies scattering between Li and Sr atoms. As for atom numbers, neither ^{6}Li nor ^{88}Sr atoms suffer from significant losses during the thermalization process, which indicates that inelastic collisions between the two species are negligible under our experimental conditions.

We extract the ^{6}Li-^{88}Sr s-wave scattering length from the thermalization process shown in Fig. 4, assuming that the elastic collisions in our measurements ($T_{\rm Li(Sr)}$ <170 μK) are dominated by s-wave interactions. This assumption is reasonable given that the p-wave barrier threshold is ∼2.3 mK, according to the C_6 coefficient for LiSr.[43] The thermalization can be modeled by connecting the rate of interspecies thermalization to the interspecies s-wave scattering cross section σ through the equation[44–47]

$$-\frac{1}{\Delta T}\frac{d(\Delta T)}{dt} = \frac{\xi}{\alpha}\bar{n}\sigma\bar{v}, \tag{1}$$

where $\Delta T = T_1 - T_2$ is the temperature difference of the two species, $\alpha = 2.7$ is the average times of collisions needed for thermalization between colliding pairs with equal mass,[48] and between nonequal mass partners it should be corrected by the factor $\xi = \frac{4m_1m_2}{(m_1+m_2)^2}$ ($\xi = 0.24$ for ^{6}Li-^{88}Sr mixture). The mean relative velocity is $\bar{v} = \sqrt{\frac{8k_{\rm B}}{\pi}(\frac{T_1}{m_1}+\frac{T_2}{m_2})}$, and the overlap density is defined by $\bar{n} = (\frac{1}{N_1}+\frac{1}{N_2})\int n_1(\boldsymbol{r})n_2(\boldsymbol{r})d^3r$ with

$$\int n_1(\boldsymbol{r})n_2(\boldsymbol{r})d^3r = \frac{N_1N_2(m_1m_2\bar{\omega}_1^2\bar{\omega}_2^2)^{3/2}}{[2\pi k_{\rm B}(m_1\bar{\omega}_1^2T_2+m_2\bar{\omega}_2^2T_1)]^{3/2}}, \tag{2}$$

where $\bar{\omega}_i = (\omega_{xi}\omega_{yi}\omega_{zi})^{1/3}$ is the mean trap frequency for atom species i.

To obtain the interspecies scattering cross section σ, we first perform an exponential fit to the temperature evolution of the ^{88}Sr atoms. With this information, Eq. (1) can be solved numerically for the temperature evolution of the Li atoms at a given scattering cross section σ since all other initial conditions are known. We obtain the interspecies cross section by varying σ to give a minimum variance between the simulated Li temperatures and the measured results. The cross section σ is related to the s-wave scattering length a by the expression[49] $\sigma = 4\pi a^2/(1+k^2a^2)$ with $\hbar k$ being the relative collision momentum. Considering the lack of spin for ^{88}Sr atoms, we expect $a_{^6{\rm Li}-^{88}{\rm Sr}}$ to be the same for the two states of ^{6}Li atoms. Our best fitted results give an s-wave scattering length amplitude of $|a_{^6{\rm Li}-^{88}{\rm Sr}}| = (380^{+160}_{-100})a_0$. Under the model we employed, the main uncertainty in the measured scattering length comes from the systematic uncertainties in the trap frequencies at the level of about 10%.

In conclusion, we have produced the first optically trapped mixture of ^{6}Li and ^{88}Sr atoms, and have investigated their interspecies thermalization experimentally. We extract the previously unknown scattering length between ^{6}Li and ^{88}Sr atoms to be $|a_{^6{\rm Li}-^{88}{\rm Sr}}| = (380^{+160}_{-100})a_0$ by numerically modeling the thermalization process. Our results show that efficient sympathetic cooling between Li and Sr atoms is pos-

sible and pave the way for possible double degenerate mixture of Li and Sr atoms.

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