

Dipolar Bose-Bose mixture of dysprosium isotopes with controllable interspecies interactions

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We report on the realization of a quantum-degenerate Bose-Bose mixture of ^{162}Dy and ^{164}Dy . Owing to the near-identical mass and polarizability of the two isotopes, the mixture thermalizes efficiently, with evaporation trajectories closely following those of the single-isotope case. Using a broad interspecies Feshbach resonance, we explore a miscible-immiscible transition between the two Bose-Einstein condensates. The tunability of the interspecies interaction, combined with the large magnetic dipole moment of Dy, makes this platform well suited for exploring dipolar effects in ultracold mixtures, including multicomponent supersolidity.

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Introduction. Ultracold gases of highly magnetic lanthanide atoms, such as dysprosium (Dy) and erbium (Er), have recently emerged as an ideal system for the investigation of quantum gases with long-range and anisotropic dipole-dipole interactions. The large magnetic dipole moment in Dy and Er stems from the large orbital angular momentum of their electronic ground state. In Dy, the ground state has a total angular momentum $J = 8$, which results in a magnetic dipole moment of $10 \mu_B$, where μ_B is the Bohr magneton. The control over large magnetic dipole-dipole interactions in lanthanide quantum gases has recently enabled the observation of dipolar supersolids, a phase of matter characterized by the simultaneous presence of phase-coherence and density modulation [1–4]. More exotic regimes of supersolidity have been predicted in multicomponent dipolar condensates [5–10]. However, spinor mixtures of lanthanides suffer from strong inelastic losses due to dipolar relaxation [11–14]. In this work, we realize a stable quantum degenerate mixture of dipolar atoms consisting of the isotopes ^{162}Dy and ^{164}Dy , the two most abundant bosonic isotopes of Dy. Since both isotopes are trapped in their lowest spin state, dipolar relaxation is naturally suppressed. This allows us to realize a mixture with good collisional properties that can be further controlled via convenient interspecies Feshbach resonances. Moreover, their combination constitutes the most dipolar mixture realized to date, establishing Dy isotope mixtures as an ideal platform for investigating multicomponent dipolar gases and new regimes of dipolar superfluids and supersolids. Together with the near-identical trap parameters and masses

of the two isotopes, which minimize gravitational sag, our system is particularly well suited to study mediated effects in dipolar mixtures. The interspecies Feshbach resonance and the resulting control over the miscible-immiscible transition established here directly target this regime, providing the tunable interspecies coupling required to realize binary supersolids in this platform.

Experimental sequence. The starting point of our experiment is a dual-isotope magneto-optical trap (DI-MOT) of ^{162}Dy and ^{164}Dy , as described in Ref. [15]. We create spatially overlapping MOTs of ^{162}Dy and ^{164}Dy , without the need of additional laser systems or optical storage times. This is achieved by using first order sidebands imprinted through phase modulation onto the 421-nm slowing light and the 626-nm trapping light. After an initial loading phase of 5 s, the DI-MOT is compressed in 500 ms by reducing the detuning and the optical power of the MOT beams, while increasing the magnetic-field gradient. The combination of radiation pressure and gravity in the narrow-line DI-MOT leads to a spontaneous polarization of the trapped Dy isotopes [16]. As a result, both isotopes are prepared in their lowest absolute Zeeman sublevel $m_J = -8$ [16,17], with very similar phase-space density (PSD) conditions. At the end of the compression phase we typically trap around 3×10^7 atoms at 10 μK for each isotope. Atoms are then transferred into a crossed-beam optical dipole trap (ODT) for forced evaporative cooling. The trap is formed by two beams derived from a 50-W fiber laser at 1064 nm, crossing at an angle of 45° at the DI-MOT position, each with a circular waist of 22 μm . To increase the trapping volume, each ODT beam is spatially modulated to widen its effective horizontal waist to approximately 55 μm . With these settings, we typically transfer around 10% of the atoms from the DI-MOT into the crossed ODTs. After the loading phase, the mixture is evaporatively cooled by lowering the optical trap power through a series of exponential ramps. A key advantage of the Dy-isotope mixture is the almost identical electronic polarizability of the two isotopes at the trapping wavelength, which ensures almost equal trapping potential throughout the evaporation sequence.

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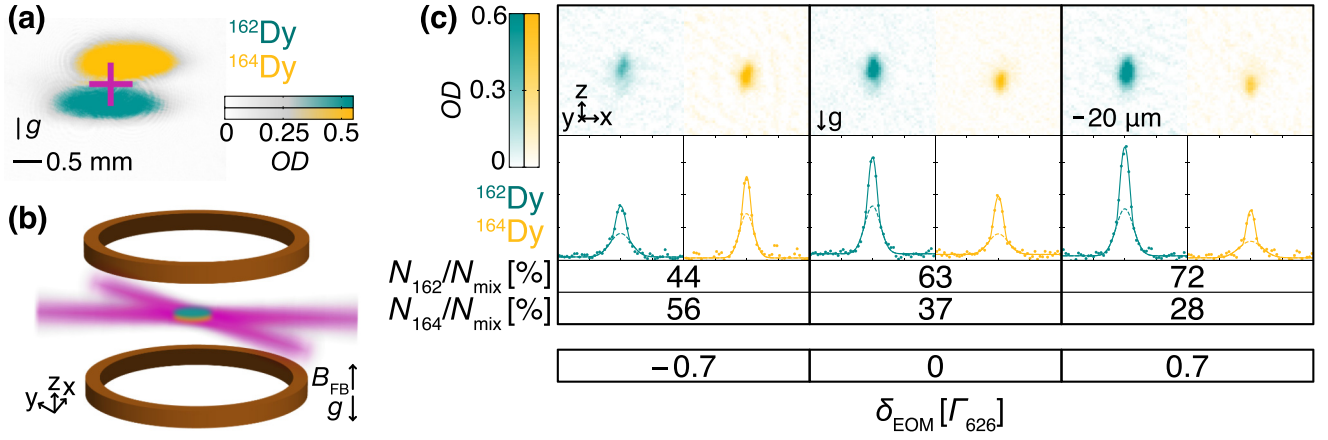


FIG. 1. (a) *In situ* absorption images of ^{162}Dy and ^{164}Dy in the DI-MOT at $\delta_{\text{EOM}} = -3.0 \Gamma_{626}$, with $\Gamma_{626}/2\pi = 135 \text{ kHz}$ being the natural linewidth of the 626-nm transition. The vertical displacement allows us to control the population imbalance in the crossed ODT, whose position is marked by a purple cross. (b) Sketch of the experimental apparatus showing the atoms being loaded from the DI-MOT into the crossed ODT. (c) Absorption images of the dual-isotope BECs after a TOF = 18 ms for different population ratios, with clear aspect ratio inversion and bi-modal fit as evidence of condensation. Left: At negative detuning $\delta_{\text{EOM}} = -0.7 \Gamma_{626}$, the loading of ^{164}Dy into the ODT is favored over ^{162}Dy . Here, we realize a BEC of ^{162}Dy and ^{164}Dy consisting of $N_{162} = 1.4 \times 10^4$ and $N_{164} = 1.8 \times 10^4$, with a condensed fraction of around 25% and 40% respectively. N_{162} and N_{164} are the atom numbers of ^{162}Dy and ^{164}Dy respectively. Center: For $\delta_{\text{EOM}} = 0$ the mixture is composed of a BEC of $N_{162} = 2.2 \times 10^4$ and $N_{164} = 1.3 \times 10^4$, with a condensed fraction of around 50% and 20%, respectively. Right: For $\delta_{\text{EOM}} = 0.7 \Gamma_{626}$, we favorably load ^{162}Dy into the ODT and realize a mixture of $N_{162} = 2.6 \times 10^4$ and $N_{164} = 1.0 \times 10^4$, with a condensed fraction of around 55% and 10%, respectively. Additionally, we report the population fraction of each isotope, where $N_{\text{mix}} = N_{162} + N_{164}$ refers to the total atom number of the mixture.

We find that the mixture is stable at a magnetic field around 9.7 G. In this region, we optimize the evaporation sequence by imaging each isotope independently via resonant absorption imaging. We find that evaporation ramps of similar duration to the single-isotope case are sufficient to reach quantum degeneracy. Below the critical temperature for Bose-Einstein condensation, both isotopes develop the characteristic bimodal momentum distribution. Time-of-flight images of the two Bose-Einstein condensates (BECs) expanding from the same crossed-beam ODT are shown in Fig. 1(c). We can tune the population imbalance between the two isotopes via the radio-frequency drive of the electrooptic modulator (EOM) that generates the 626-nm DI-MOT trapping light. As detailed in Ref. [15], detuning this drive by δ_{EOM} from half the isotope shift of the 626-nm transition makes the two isotopes experience different radiation pressure. This difference shifts the equilibrium position of each laser-cooled cloud [Fig. 1(a)] and makes the transfer efficiency into the ODT isotope dependent. We exploit this effect to control the population imbalance in the mixture. We can arbitrarily prefer one isotope over the other, however, it seems easier to realize larger clouds of ^{162}Dy than ^{164}Dy . Our analysis suggests that ^{162}Dy displays lower three-body losses in the magnetic field region around 9.7 G, which results in larger degenerate ^{162}Dy gases at the end of the sequence. For simplicity, we focus for the remainder of the paper on the condition $\delta_{\text{EOM}} = 0$, which corresponds to a similar initial loading into the ODT. Nevertheless, this tool may be useful in the future to investigate impurity physics in dipolar mixtures [18,19]. At $\delta_{\text{EOM}} = 0$, we typically realize a Bose-Bose mixture consisting of $N = 2.2 \times 10^4$ ^{162}Dy atoms and $N = 1.3 \times 10^4$ ^{164}Dy atoms, with a condensed fraction around 50% and 20%, respectively, at an equilibrium temperature around 20 nK. Here, we measure trap

frequencies of $(\nu_x, \nu_y, \nu_z) = [68(2), 30(1), 168(2)] \text{ Hz}$ along the three trap axes. The tightest confinement is along the vertical axis, parallel to both gravity and the bias magnetic field [see Fig. 1(b)]. Cooling even further, we can realize condensates with no measurable thermal fraction consisting of around 1.2×10^4 ^{162}Dy atoms and 5×10^3 ^{164}Dy atoms. To better characterize the evaporation efficiency of our dipolar mixture, we track the peak PSD ρ_0 as a function of the atom number N throughout the evaporation sequence for both the single-isotope case and the mixture. The peak PSD ρ_0 is defined as $\rho_0 = n\lambda_T^3$ with λ_T the thermal de Broglie wavelength for an atom of mass m at temperature T [20]. From the data shown in Fig. 2, we extract the evaporation efficiency $\gamma = -\frac{\partial \ln \rho_0}{\partial \ln N}$. We find almost identical values of γ in all cases, with 2.6(5) for ^{162}Dy and 2.7(8) for ^{164}Dy . Importantly, in the mixture both isotopes show a comparable evaporation efficiency, $\gamma = 2.4(1.0)$, indicating efficient thermalization between the two species with neither acting preferentially as a coolant for the other [21,22]. While the mixture reaches the onset of condensation with nearly equal atom numbers in the two isotopes, ^{164}Dy seems to suffer from stronger inelastic losses once the condensate has formed. At the end of evaporation, the ^{164}Dy BEC shows a significantly lower lifetime with respect to a ^{162}Dy BEC. The lifetime of both isotopes at the magnetic field $B_{\text{BEC}} = 9.7 \text{ G}$ is shown in Fig. 2(b). The rapid loss of ^{164}Dy at short times points towards some isotope-specific three-body-loss mechanism. We note that, at $B_{\text{BEC}} = 9.7 \text{ G}$, the relative ordering is opposite to that reported for single-isotope supersolids, where ^{164}Dy exhibits a longer lifetime than ^{162}Dy [4]. In other magnetic-field regions, our single-isotope lifetime measurements are consistent with already-published experiments, indicating that the reduced ^{164}Dy lifetime observed here is specific to this

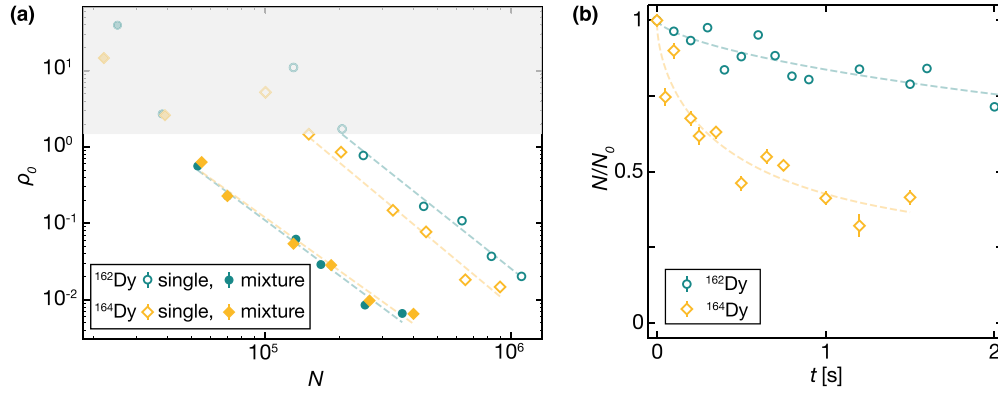


FIG. 2. Evaporative cooling trajectories for single-species and dual-species operation at a magnetic field of 9.7 G. (a) Peak PSD ρ_0 as a function of atom number N during forced evaporation of ^{162}Dy (green) and ^{164}Dy (orange) in single-species (hollow) and mixture (solid) experiments. We extract γ as the slope of the respective linear fits (dashed lines). The gray band marks the threshold PSD for the onset of condensation ($\text{PSD} \sim 1$). The near-identical slopes in the single-isotope and mixture configurations indicate that the interspecies interactions do not greatly affect the evaporation efficiency at a magnetic field of 9.7 G. (b) Lifetime measurements of ^{162}Dy BEC [$\tau_{162} = 14(1)\text{s}$] and ^{164}Dy BEC [$\tau_{164} = 0.6(3)\text{s}$] at a magnetic field of 9.7 G. We normalize the atom number N to the atom number N_0 at zero hold time. For this measurement, $N_0 = 1.2 \times 10^4$ for ^{162}Dy and $N_0 = 5 \times 10^3$ ^{164}Dy .

field region and warrants further investigation. We point out that this mechanism may also affect the evaporation efficiency in the single-isotope case. When we evaporatively cool single isotopes at B_{BEC} , we can produce pure condensates of more than 1.3×10^5 ^{162}Dy atoms, while BECs of ^{164}Dy are limited to 8.0×10^4 atoms. The lower atom number in the degenerate mixture compared to the single-isotope cases originates from the smaller initial loading of the DI-MOT, which is limited by the available laser-cooling power [15]. When the population is balanced, the isotopes reach quantum degeneracy at the same point of the evaporation, confirming that the optical potentials experienced by ^{162}Dy and ^{164}Dy at 1064 nm are nearly identical. At the end of evaporation, we estimate a rather small difference in gravitational sag on the order of 100 nm.

Interspecies Feshbach resonances. Lanthanide quantum gases are well known to show a dense spectrum of Feshbach resonances [1,23–25]. To assess the presence of interspecies Feshbach resonances in our isotopic mixture, we perform atom-loss spectroscopy as a function of magnetic field. We prepare mixtures at temperatures ranging from 300 nK to 1 μK , with atom numbers ranging from 10^5 to 3×10^5 for each isotope. To enhance the interspecies Feshbach signal, we balance the isotope populations during the scan. The atom-number difference is kept below 10% of the more abundant species, typically ^{162}Dy . We then linearly ramp the magnetic field from the evaporation field $B_{\text{BEC}} = 9.7\text{ G}$ to a target field B_{FB} in 20 ms, hold for 500 ms, and measure the remaining trapped atoms N via absorption imaging. For each target field B_{FB} , we normalize N to a reference value N_0 obtained by holding at B_{BEC} for the same duration. We calibrate the magnetic field via radio-frequency spectroscopy using an antenna inspired by the design of Ref. [26]. The magnetic field shows a shot-to-shot stability of around 10 mG. To identify an interspecies Feshbach resonance, we compare the atom-loss spectra of the mixture [Fig. 3(b)] to similar atom-loss spectra of each individual isotope [Figs. 3(a) to 3(c)]. Features appearing in the mixture spectrum but absent from

both single-species spectra are attributed to the presence of an interspecies Feshbach resonance. In the low-field region ($B_{\text{FB}} < 7\text{ G}$), where the individual isotopes have convenient Feshbach resonances that allow the realization of BECs and of dipolar supersolids [1], we detect different interspecies Feshbach resonances with a width around 100 mG, as shown in Fig. 3. The realization of quantum degenerate Bose-Bose mixture in this magnetic-field region will be explored in future investigations. At magnetic fields larger than the $B_{\text{BEC}} = 9.7\text{ G}$, we can identify a broad interspecies resonance (see Fig. 3). This resonance is centered around $B_0 = 10.8(3)\text{ G}$, extending from approximately 10.1 G to 11.95 G. This is a relatively broad Feshbach resonance by the standards of lanthanide systems and, in combination with the possibility to create a degenerate mixture in its surroundings, it may turn into a convenient resource for easily controlling the interspecies scattering length a_{12} and explore new regimes of dipolar superfluidity. We point out that in Ref. [24], a rather similar broad Feshbach resonance was found in a Dy-Er mixture. Going back to our isotopic mixture, an additional, narrower interspecies resonance is identified at $B_0 = 9.05(5)\text{ G}$, just below B_{BEC} . The BEC production field $B_{\text{BEC}} = 9.7\text{ G}$ lies in the center of a 0.3 G plateau where the individual isotopes do not show any single-isotope Feshbach resonance. This condition might restrict the exploration of the mixture phase-diagram since only the interspecies scattering length can be widely controlled.

Controlling interspecies interactions and the miscible-immiscible transition. In this section, we exploit the broad Feshbach resonance at $B_0 = 10.8(3)\text{ G}$ to tune the interspecies scattering length a_{12} and provide first evidence of a miscible-immiscible transition in our dipolar Bose-Bose mixture. As described above, we produce a mixture of nearly pure BECs containing 1.2×10^4 ^{162}Dy atoms and 5×10^3 ^{164}Dy atoms. After evaporating at B_{BEC} , we let the mixture equilibrate for 30 ms, ramp the magnetic field to a target value B_z between 9.55 G and 9.9 G in 5 ms, and hold for a further 10 ms. We then release the mixture and measure the center-of-mass

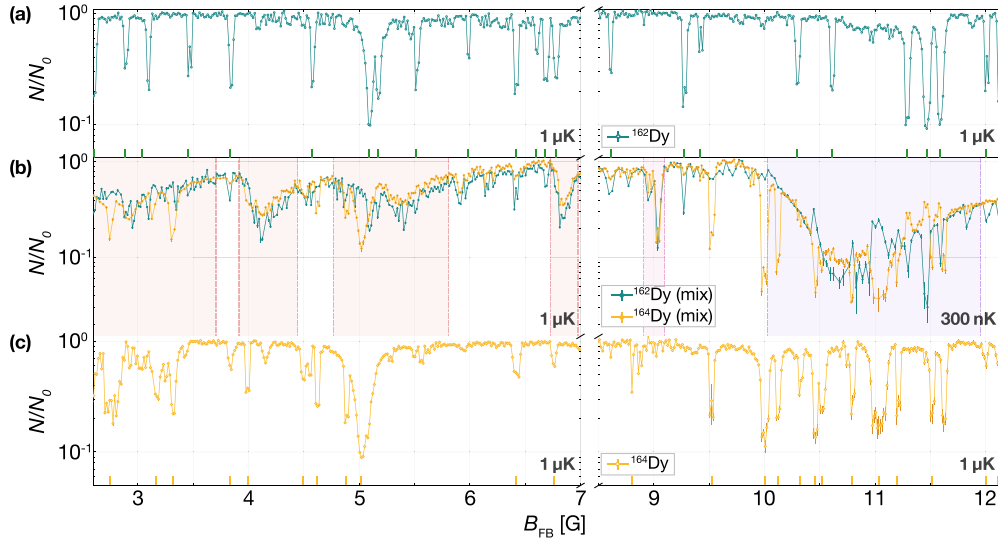


FIG. 3. Interspecies Feshbach resonances between ^{162}Dy and ^{164}Dy . Panels (a), (c) show the single-isotope atom-loss spectra over 2.6–7 G and 8.5–12.1 G for ^{162}Dy (green) and ^{164}Dy (orange), recorded at 1 μK with a 1 s hold time. Panel (b) shows the atom-loss spectra of the ^{162}Dy – ^{164}Dy mixture over the same field range. The lower-field range ($B < 7$ G, left side) is recorded at 1 μK , for a higher signal-to-noise ratio in an area with large interspecies losses. The higher-field region ($B > 8.5$ G, right side) is recorded at 300 nK, for a reduced thermal broadening. Both spectra were recorded with a 500 ms hold time. Shaded regions highlight interspecies resonances. A broad resonance, extending from approximately 10.1 to 11.95 G, is centered at $B_0 = 10.8(3)$ G, offering the opportunity to easily control the interspecies scattering length a_{12} in the Bose-Bose mixture.

separation of the two clouds after 20 ms of time-of-flight at the target field. As shown in Fig. 4, the two centers of mass overlap only below B_{BEC} and separate increasingly above it, with the heavier species ^{164}Dy always sitting lower. The field-dependent center-of-mass separation provides a direct probe of the interplay between the inter- and intraspecies scattering lengths. Owing to the broad interspecies scattering lengths. Owing to the broad interspecies resonance, we assume that the change in magnetic field translates predominantly into a change in the interspecies scattering length a_{12} , though a more detailed investigation remains for future work, including, for instance, the effects of the narrow ^{164}Dy resonance at 9.52 G. As a_{12} is tuned across the broad Feshbach resonance, the balance between inter- and intraspecies contact

interactions shifts, and the resulting center-of-mass displacement tracks the approach toward the miscibility threshold. A similar qualitatively field-dependent center-of-mass separation has been used in nondipolar dual-species condensates as a continuous probe of the miscibility parameter [27–32], where full phase separation manifests as a strong deviation of the density distribution from the symmetry of the trapping potential [28,30]. In our experiment, the smooth and monotonic variation of the center-of-mass separation with magnetic field is consistent with tuning the mixture across or near the miscibility crossover. This constitutes the first evidence of interaction-driven spatial reorganization in a mixture of Dy BECs. A definitive demonstration of full phase

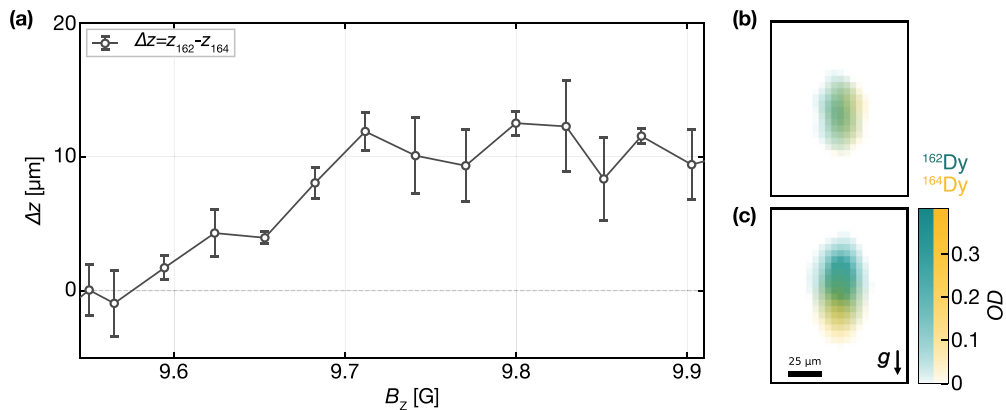


FIG. 4. Evidence of miscible-immiscible transition in a Dy mixture. (a) Relative vertical displacement Δz defined as $\Delta z = z_{162} - z_{164}$, where z_{162} and z_{164} are the centers of mass of the ^{162}Dy and ^{164}Dy BECs, respectively, after 20-ms time-of-flight expansion for different magnetic field regions. (b) At a magnetic field of 9.58 G, the two clouds are overlapped, consistent with the miscible phase. (c) At a magnetic field of 9.675 G we move close to the resonance at 10.8(3) G, a_{12} increases and the two clouds repel each other, consistent with an immiscible phase, where ^{162}Dy (green) sits on top of ^{164}Dy (orange). Our analysis suggests that at B_{BEC} the mixture is produced in the immiscible regime.

separation would require in-trap density profiles resolving the spatial segregation of the two components, which we leave to future work. In the immiscible regime, we do not observe the sharp cloud edges seen in alkali mixtures [30,31]. This is likely limited by the resolution of our current imaging system. Additionally, the strongly attractive dipole-dipole interaction along the z axis may further soften the edges in time of flight (TOF) through magnetostriction [1,5]. Nevertheless, the broad Feshbach resonance at 10.8 G gives direct control of a_{12} over a wide range. This makes the ^{162}Dy - ^{164}Dy mixture a promising platform for studying density-modulated transitions in multicomponent dipolar gases. For such mixtures, the anisotropic dipole-dipole interaction is expected to reshape both the phase boundary and the structure of the phase-separated state [33,34].

Conclusion. In summary, we reported a realization of a quantum degenerate Bose-Bose mixture of ^{162}Dy and ^{164}Dy , and started to characterize its collisional properties. We located many interspecies Feshbach resonances in this system, most notably a broad resonance at $B_0 = 10.8(3)$ G that provided a wide and experimentally convenient tuning

range for a_{12} . Exploiting this resonance, we demonstrated field-dependent control of the interspecies interactions and presented evidence of a miscible-immiscible transition between two Dy BECs. The ^{162}Dy - ^{164}Dy mixture combined the large magnetic dipole moment of Dy with the tunability of a dual-species system. The tools demonstrated here lay the groundwork for future studies of dipolar supersolidity, droplet physics, and exotic density-modulated phases in multicomponent quantum gases [6,7,10,35–37].

Note added. After submission of the paper, we became aware of a similar result in Ref. [38].

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Data availability. There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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