Sun-Earth-Moon, the Helium atom, the proton: at all length scales, three-body systems are ubiquitous in physics, yet they challenge our understanding in many ways. Their complexity conspicuously exceeds the two-body counterparts. A peculiar class of three-body systems defying our intuition arises when the constituents feature resonant pair-wise interactions, such that the scattering length is much larger than the effective range of the pair potential. In a few seminal papers, V. Efimov advanced our understanding of such three-body systems and demonstrated the existence of a large number of weakly bound three-body states, thereafter known as the Efimov effect \cite{1,2}. What makes Efimov states truly remarkable is their universality, i.e., the fact that their main properties are independent from the details of the pair potential, be it the strong interaction between two nucleons or the van der Waals force between two neutral atoms.

For over 35 years, the Efimov effect sparked an intense theoretical research \cite{3}, while eluding experimental observation. The first experimental evidence of Efimov states was only recently reached with ultracold $^{133}$Cs \cite{4} and $^{39}$K \cite{5} atoms, thanks to the possibility to adjust at will the scattering length by means of Feshbach resonances. In nuclear physics, the original context studied by V. Efimov, the Efimov effect is hampered by the strong long-range Coulomb interactions and therefore confined to triads where at least two constituents are neutral. Among these, halo nuclei, i.e., nuclei like $^{6}$He, $^{11}$Li, $^{14}$Be, $^{20}$C composed of a smaller core nucleus plus two loosely bound neutrons, have been identified as possible examples of Efimov physics \cite{6} and there is an ongoing debate about the prospects of observing nuclear Efimov states \cite{7}. To this goal, it is crucial to study Efimov physics in systems composed of distinguishable particles with different masses.

In this work, we report the first experimental evidence of Efimov physics with particles of different masses, i.e., Efimov resonances in the three-body collisions of a mixture of ultracold $^{41}$K and $^{87}$Rb atoms. Our experiment demonstrates that two resonantly interacting pairs are sufficient to grant the existence of Efimov states \cite{8} and, thanks to universality, suggests that they could be observed also in other asymmetric triads, like the halo nuclei.

In ultracold atomic gases, Efimov states fragile and unstable to decay toward deeply bound two-body molecular levels. While direct observation has never been achieved, the presence of Efimov states is revealed by measuring the atomic losses, since it bears a dramatic impact in the three-body recombination (3BR) collisions \cite{3, 4}.

The energy of Efimov states depends on the resonant scattering length, as depicted in Fig. 1. For a certain negative value of the two body scattering length $a = a_{-}$, the binding energy of an Efimov state vanishes, i.e., the energy of the trimer coincides with that of three free atoms. At this scattering length $a_{-}$, the 3BR collisions are resonantly enhanced. For positive values of the scattering length, the Efimov sc-
ber decays due to 3BR losses. Then, we switch off the trap and hold the optical trap at constant depth while the atom number is suppressed. The 3BR rate displays an oscillatory behavior with broad maxima and minima. In addition, at a scattering length value $a = a_\ast$, the Efimov trimers energy hits the atom-dimer threshold: here, a resonant enhancement occurs for the atom-dimer collisions, both elastic and inelastic. In the limit of infinite $|a|$, the above features repeat for each state of the Efimov spectrum as the scattering length is multiplied by integer powers of a scaling factor, usually denoted with $e^{\pi/\lambda}$. While the values of the resonant scattering lengths $a_\ast$ and $a_-$ depend on the details of the atomic potential and are so far unpredictable, theoretical predictions are available for their ratios $a_\ast/a_-$, at least in systems of identical particles [3, 8].

With the mixture of $^{41}$K and $^{87}$Rb, we have two distinct three-body loss channels enhanced by the proximity of the interspecies Feshbach resonance, namely KKRb and KRbRb collisions, as shown in Fig. 1. Correspondingly, there exist two Efimov series, whose relative location is so far unpredictable, with different scaling factors $e^{\pi/\lambda} = 3.51 \times 10^5$ for KKRb and 131 for KRbRb [9].

We now briefly describe our experimental procedure. We prepare the ultracold atomic mixture by sympathetic cooling [10], first in a magnetic trap and then in a crossed dipole trap, far off-resonant with respect to both K and Rb atomic transitions ($\lambda = 1064$ nm). We cool the mixture to temperatures as low as 300 nK, while trapping it in a harmonic potential ($\omega = 2\pi \times 70$ Hz, $\omega_K = \omega_{Rb} \sqrt{m_{Rb}/m_K}$). Both species are prepared in the $|F = 1, m_F = 1\rangle$ states, featuring a broad interspecies Feshbach resonance at 38.4 G [11], which allows to adjust the interspecies scattering length $a$. Since the $|1, 1\rangle$ state is the absolute ground state, inelastic two body collisions are suppressed.

We apply a uniform magnetic field (Feshbach field) and hold the optical trap at constant depth while the atom number decays due to 3BR losses. Then, we switch off the trap and separately image the falling K and Rb clouds. An example of atom decay during the hold time is shown in Fig. 2. We record the atom losses as we scan the interspecies scattering length varying the Feshbach field. For the best signal-to-noise ratio, we use the total atom number $N(\tau) = N_K(\tau) + N_{Rb}(\tau)$ after a fixed hold time $\tau$ as our main observable, while the atom numbers of individual species, $N_K$ and $N_{Rb}$, are used to ascertain the dominant channel of three-body losses at the resonance peaks. We point out that, since our losses are due to 3BR collisions, our observable $N(\tau)$ yields the same information as the 3BR rate, as far as the position and the width of the Efimov resonances are concerned.

On the side of negative scattering length, i.e., for magnetic fields above 38.4 G, we observe two peaks of three-body losses above a smooth increase with the scattering length (see Fig. 3). The broadest peak, strong and visible up to temperatures of approximately 0.8 ± 0.1 μK, is centered at a magnetic field of 57.7(5) G. The second peak, weaker and visible only at our lowest possible temperature of 0.3 ± 0.1 μK, lies at 38.8(1) G. Conversion of these magnetic field values into scattering length is done with the aid of the numerical results of the collisional model of the Rb potential [12], based on extensive studies of Feshbach spectroscopy [13, 14] combined with our recent spectroscopy measurements of the weakly bound molecular state [15].

To make sure that the peaks are genuine interspecies 3-body features, we have taken the following steps. First, we verified that both loss peaks are absent if we prepare samples with only a single species. Second, according to the collisional model, at the corresponding magnetic field values no sufficiently broad Feshbach resonances occur, even considering molecular levels with angular momentum $\ell = 1, 2$. Indeed, we do observe predicted narrow Feshbach $d$-wave resonances, that further confirms the validity of the collisional model [14]. We also checked that the frequency offset between the crossed trap beams is sufficiently far detuned with respect to any bound state, in order to avoid Raman transition to molecular levels.

Finally, at 56.8 G we verified that the ratio of lost Rb to K atoms is 1.7(3), which unambiguously proves that to the stronger resonance peak is due to 3BR and it is dominated by the KRbRb channel. This is shown by the time evolution of individual species atom number, see Fig. 3. For the weaker peak at 38.8 G, for best signal-to-noise we analyze the individual species atom number at fixed hold time. From our dataset we calculate the linear combination $2N_K - N_{Rb}$, that is expected to be constant for KRbRb collisions and to display a negative peak for KKRb collisions. In the inset of Fig. 3 we show that such a peak is indeed observed and that experimental data for $2N_K - N_{Rb}$ nicely agree with our numerical results. As a consequence we assign the loss peak to the KKRb channel.

To derive the 3BR rates, we model the loss process by a set of differential rate equations. We start from the local rate equations for the atom densities $n_K$ and $n_{Rb}$, i.e., $\dot{n}_K = -2\alpha_{KKRb} n_K^2 n_{Rb} - \alpha_{KRbRb} n_K n_{Rb}^2$ and $\dot{n}_{Rb} = -2\alpha_{KRbRb} n_K n_{Rb}^2 - 2\alpha_{KKRb} n_K^2 n_{Rb}$, where $\alpha_{KKRb}$ and $\alpha_{KRbRb}$ denote the event col-
collision rates in the KKRb and KRbRb 3B channels. By integration upon coordinates, we obtain the rate equations for the atom numbers $N_K, N_{Rb}$. In addition, we also consider recombination heating and evaporation, taking into account the displacement between the two species due to the differential gravity sag. The set of (four) differential equations, for atom number and total energy of each species, is numerically integrated. In analogy with the case of identical particles, the rate $\alpha$ is constrained by unitarity below the theoretical upper limit

$$\alpha_{\text{KrRRb}} = \frac{C}{N_K/N_{Rb}} \frac{\sin 2\eta}{\sin^2(s_0(\delta) \log(a/a_\ast)) + \sin^2\eta/\mu_\delta} \frac{\hbar a_\delta^2}{\delta}$$

with $\delta = m_K/m_{Rb}$, $a_\delta = a \sqrt{\delta(\delta+2)}/\sqrt{\delta+1}$ and $\mu_\delta = m_K/\sqrt{\delta(\delta+2)}$. Likewise, we assume the equivalent expression for $\alpha_{\text{KrRb}}$, with independent $C$, $a_\ast$, $\eta$ parameters. The mass-dependent scaling parameter $s_0(\delta)$ equals 0.644 for KRbRb and 0.246 for KKRb. The positions, widths and multiplicative factors $(a_\ast, \eta, C)$ are adjusted to match the numerical results of the above rate equations with the measured number of atoms. For the weaker peak at 38.8 G, it is crucial to introduce the unitary limit. Indeed for each channel the 3BR rate is constrained by unitarity below the theoretical upper limit

$$\alpha_{\text{KrRRb}} = \frac{192\pi^2h}{(\mu_\delta k^4)}$$

that depends on temperature through $(hk)^2 = 2\mu_\delta k^B T$. However, following the numerical results of [18] we use as upper limit a value which is a factor of 20 lower than the above expression. In practice, for each channel we replace the appropriate $\alpha$, with an effective $\alpha_{\text{eff}} = 0.05\alpha_{\text{max}} + \alpha$ approximately equal to the minimum between $\alpha$ and 0.05$\alpha_{\text{max}}$.

The output of numerical integration, shown in Fig. 3, agree nicely with data, once we adjust the parameters to the following values: $a_\ast = -246(14) a_0$, $\eta = 0.12(1)$ and $C = 28(5) \times 10^3$ for $\alpha_{\text{KRbRb}}$ and $a_\ast = -22(4) \times 10^3 a_0$, $\eta = 0.02(1)$ and $C = 23(5) \times 10^{-4}$ for $\alpha_{\text{KRbRb}}$. The uncertainties on the positions reflect the estimated uncertainty on the magnetic field values.

We find that the KRbRb channel dominate 3BR collisions at nearly all magnetic fields, with the exception of a narrow region next to Feshbach resonance where we detect the Efimov peak of the KKRb channel (see dashed lines in Fig. 3). It is important to note that this peak is observable because, at these magnetic fields, the dominant KRbRb channel is limited by unitarity, while the much weaker KKRb channel is not.

For positive scattering length, the three-body inelastic collision rate is expected to display an oscillatory behavior with no sharp peaks. However, we observe a peak of atomic losses at $B = 4.25(0.10)$ G, corresponding to $a = 667(1) a_0$. Loss peaks at positive values of the scattering length have been recently reported in $^{39}$K and attributed to resonantly enhanced secondary collisions between atoms and dimers created in 3BR processes [5]. The atom-dimer collisions are enhanced for values of the scattering length, $a = a_\ast$, where the Efimov state intercepts the atom-dimer threshold: at this values, a resonance occurs in the atom-dimer scattering [19], similar to a Feshbach resonance. In analogy with [5], the narrow peak of losses at 4.2 G, shown in Fig. 3, could be due to an atom-dimer resonance. With the same arguments as above, we can exclude inelastic two body collisions to be the cause of this peak.

Assuming the presence of an atom-dimer resonance, we modified the rate equations to include the atom-dimer collisions using the following formulas for the elastic cross-section $\sigma_{\text{AD}} = C' \times 20.3(\hbar a_\delta/\mu_\delta) \sin(2\eta)/D$ and inelastic collision rate $\beta_{\text{AD}} = C' \times 20.3(\hbar a_\delta/\mu_\delta) \sin(2\eta)/D$ where $D = \sin^2(s_0(\log(a/a_\ast)) + \sin^2\eta_\ast$ and $(C', \eta_\ast, a_\ast)$ are free parameters. Since for this...
peak we lose more Rb than K atoms, the resonance is assumed for the KRbRb channel only.

The fit results are: $C' = 1.2(0.3) \times 10^{-5}$, $\eta_s = 2(1) \times 10^{-3}$ and $a_s = 667(1) \times 10^{-3}$. We notice that both the elastic cross section and the inelastic collision rate are approximately five orders of magnitude lower than the theoretical results for identical particles at zero temperature. Lower than predicted values of the inelastic atom-dimer collision rate $\beta_{AD}$ have also been observed in Cs [19]. We remark, however, that a meaningful comparison of our data with theoretical predictions will require, on one hand, the extension of the homonuclear results to the heteronuclear case [8], on the other hand, the extension to finite temperature. If confirmed, the atom-dimer resonance would allow to assess the energy of the Efimov state, that, as shown in the picture of Fig. 1, is approximately equal to the dimer energy at 4.2 G, i.e., $\sim h \times 0.2$ MHz [15].

In summary, we have observed three distinct peaks of the inelastic collision rate of the mixture $^{41}\text{K}^{87}\text{Rb}$ near an interspecies Feshbach resonance. These peaks represent Efimov resonances, of both the KKRb and KRbRb channel, occurring at values of the interspecies scattering length $a$ such that the binding energy of Efimov trimers vanishes. Our data represent the first unambiguous observation of Efimov physics in systems composed of distinguishable particles with different masses and the first experimental demonstration that two resonant interactions are sufficient for Efimov physics to take place. These findings have a direct impact on the search of Efimov physics in a broad domain of physical systems, in primis nuclear physics.

We foresee that in the future more Efimov physics will emerge especially with very asymmetric systems composed of one particle which is much lighter than the other two: for such systems, the scaling factor approaches 1 and several consecutive Efimov states could be detected. With ultracold atoms, very promising combinations are LiYbYb ($e^{\pi/30} \approx 4.5$), LiCsCs ($e^{\pi/30} \approx 5.5$), as well as LiRbRb ($e^{\pi/30} \approx 7.9$) where an interspecies Feshbach resonance has already been observed [20].

Recently an unexpected loss feature, perhaps an Efimov resonance, has been observed in a system composed of fermionic atoms in three spin states where all the scattering lengths are large [21].

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