Feshbach resonances of large mass-imbalance Er-Li mixtures

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(Dated: November 17, 2021)

We report on the experimental observation of Feshbach resonances in large mass-imbalance mixtures of Erbium (Er) and Lithium (Li). All combinations between 166Er, 168Er and 7Li, 6Li are cooled to temperatures of a few microkelvin, partially by means of sympathetic cooling together with Ytterbium (Yb) as a third mixture component. The Er-Li inelastic interspecies collisional properties are studied for magnetic fields up to 680 G. In all cases resonant interspecies loss features, indicative of Feshbach resonances, have been observed. While most resonances have sub-Gauss widths, a few of them are broad and feature widths of several Gauss. Those broad resonances are a key to the realization of ultracold Er-Li quantum gas mixtures with tunable interactions.

I. INTRODUCTION

Ultracold quantum gases are by now an established and indispensable means to manipulate, probe and study the intricate behavior of quantum matter as for example impressively demonstrated in the realization of strongly correlated quantum many-body systems [1] as well as few-body systems [2]. In many cases experiments are facilitated by use of Feshbach resonances that give rise to the necessary fine-tuned control of atomic interactions [3]. Landmark experiments demonstrating the crossover from Bardeen-Cooper-Schrieffer (BCS) pairing to a Bose-Einstein condensate (BEC) [4] and Efimov trimer-state series [5] are due to that minute interaction control mechanism. Finally, going from single-component to dual-species experiments the realm of accessible physics is further broadened and allows as a direct application the simulation of impurity problems [6, 7] and the study of polaron physics [8] but also more intricate applications such as the production of ultracold heteronuclear molecules [3], mixed-species Efimov trimer physics with reduced scaling constants [2] and chiral p-wave superfluids [9, 10]. It is important to note that in the preceding last two examples the effects, while rendered possible already by the presence of two different species, can be crucially enhanced by use of large mass-imbalance mixtures. There, a large mass ratio is the driving force in the reduction of Efimov scaling constants and a deciding factor in bringing the superfluid critical temperature into experimentally accessible realms.

We here present our first results of the experimental realization of a large mass-imbalance mixture of heavy Erbium (Er) and light Lithium (Li) atoms and the discovery of interspecies Feshbach resonances. In previous experiments much effort was spent on similar investigations in ultracold mixtures of heavy Ytterbium (Yb) and light Li [11–13]. While these works scanned a large range of isotope combinations, electronic configurations and magnetic field strengths, only a few traces of Feshbach resonances could be detected with limited applicability towards an efficient control of interspecies interactions. In that respect Er seems a formidable candidate to remedy these shortcomings of Yb-Li mixtures. While generally being comparable in mass to the heavy lanthanide Yb, it has the distinct properties of a very large magnetic moment giving rise to strong dipole-dipole interactions and the existence of non-zero orbital angular momentum states. As such successful efforts to create quantum degenerate gases of Er already reach ten years back [14] and lead to the unveiling of dense Er-Er Feshbach spectra akin to chaotic behavior [15]. Further theoretical work revealed the strong possibility of a rich Feshbach physics in Er-Li mixtures [16] which is the subject of the present experimental work. Starting with the bosonic isotopes of either 168Er or 166Er and either bosonic 7Li or fermionic 6Li we are now able to indeed identify a variety of resonantly enhanced inelastic scattering losses between Er and Li at microkelvin temperatures. The purpose of the present work is, after summarizing the experimental method in Sec. II and apart from generally reporting on the observation of Er-Li interspecies Feshbach resonances, to give a succinct overview of the accessible parameters and the range of observable resonances (Sec. III). We conclude in Sec. IV by discussing the range of possible applications of such a large mass-imbalance mixture with tunable interspecies interactions.

II. EXPERIMENT

The experiment is based on our Yb-Li machine described previously [17, 18]. In an upgrade of the experiment a high-temperature oven for Er has additionally been added to the setup, giving us the freedom to work with either single species or with arbitrary combinations of Er, Yb and Li in dual- or triple-species mixtures. The Er part of the setup and experimental sequence largely follows the established techniques [14]. From the Er source heated to about 1050°C a hot atomic beam is formed. A transversal cooling stage operating on the
broad $4f^{12}6s^2(3^2\text{D}_\text{g})$ to $4f^{12}6s6p(1^2\text{P}_1)$ transition at 401 nm limits the initial transverse spread to the thermal Er beam. A subsequent Zeeman slowing stage operating on the same transition reduces the longitudinal velocity of the Er atoms. A magneto-optical trap (MOT) operating on the narrow $4f^{12}6s^2(3^2\text{D}_\text{g})$ to $4f^{12}6s6p(3^2\text{P}_1)$ intercombination line at 583 nm forms the initial trapping stage. From there the atoms are transferred into a far-off-resonant optical trap (FORT) of crossed, focused beams at 1064 nm and 1070 nm. It is known that due to the narrow linewidth of the transition at 583 nm of 186 kHz and the resulting displacement of the heavy Er atoms from the center of the MOT by gravitational pull the atomic state is automatically polarized in the lowest angular momentum sublevel [14], $m_J = -6$ in the case at hand. By maintaining a sufficiently strong magnetic field for a well defined quantization axis during the following forced evaporation period this polarized state is maintained throughout the experiment. Evaporation typically starts at 1.2 G to prevent depolarization by thermal excitation and the field is lowered to 0.4 G once the sample is sufficiently cold for more favorable collisional properties and better evaporation efficiency. Following the technique outlined in [19] the polarization state has been confirmed via absorption imaging on the narrow 583 nm line which at moderate magnetic bias fields of about 20 G and low imaging light intensities is selective to a single spin state only. Trapping and cooling of either $^7\text{Li}$ or $^6\text{Li}$ is performed as previously reported [17, 20] including optical pumping of Li during the initial stage of the evaporation process to a spin-stretched ground state. Successful spin polarization is confirmed by a Stern-Gerlach technique, that is standard absorption imaging after short application of a magnetic field gradient to spatially separate the $m_F$ hyperfine magnetic sublevels. The accessible stretched states are $F = 1/2, m_F = \pm 1/2$ for $^6\text{Li}$ and $F = 1, m_F = \pm 1$ for $^7\text{Li}$. Additionally, when investigating $^{168}\text{Er}-^7\text{Li}$ a third loading stage of $^{174}\text{Yb}$ has been added to the experiment. Due to the very efficient evaporation of $^{174}\text{Yb}$ and by virtue of sympathetic cooling of both $^{168}\text{Er}$ and $^7\text{Li}$ larger and colder mixtures can be achieved. The remaining Yb atoms are then removed before the actual Feshbach resonance measurement by a short pulse of light resonant to the $^1\text{S}_0-^1\text{P}_1$ transition of $^{174}\text{Yb}$.

Forced evaporation of the two- or three-species mixture is done by suitably lowering the intensities of the FORT lasers within 8 s (10 s when sympathetically cooled by Yb). After that time we typically obtain an Er-Li mixture with $2 \times 10^4$ to $5 \times 10^4$ Er atoms and $5 \times 10^3$ to $15 \times 10^3$ Li atoms. The actual atom number depends on the chosen isotope combination, the desired final temperatures and also on the day-to-day performance details of the experiment. The sample is non-degenerate and in the absence of sympathetic cooling with Yb its temperature is found between 2 and 5 μK with Er typically being about 1 μK colder than Li. This demonstrates both that Er sympathetically cools down Li and that during the last stages of the evaporation the transfer of thermal energy between the species becomes less efficient which is similar to former experience in Yb-Li mixtures [21], whereas in Yb-assisted sympathetic cooling of $^{168}\text{Er}$-Li temperatures as low as 0.5 μK are observed. The expected trap frequencies are about $\omega_x, \omega_y, \omega_z = 2\pi \times (420, 100, 50)$ Hz for Er and $2\pi \times (2640, 610, 300)$ Hz for Li with the $z$-axis being in the vertical direction. In that condition the difference in the trap centers due to gravitational sag is about 1.4 μm which is sufficiently less than typical atom cloud dimensions in vertical direction of about 6 μm and is thus negligible for the purposes of the present work.

The main part of the experimental sequence is to detect magnetic-field-dependent changes in the interspecies inelastic collision rates in a trap-loss sequence. For this, after the initial preparation of the desired cold mixture sample a homogeneous magnetic field is linearly ramped up to the target value within 10 ms. The system is then kept in this condition for 500 ms. During this time inelastic collisions between the atoms lead to a reduction of the number of atoms in the optical trap. The magnetic field value is stabilized via a feedback signal from a current sensor on the magnetic coil that acts on an insulated-gate bipolar transistor (IGBT). The absolute magnetic field value is found by characterizing the narrow s-wave Feshbach resonance [22] of $^6\text{Li}$ at 543.28(8) G and we assume linearity of the setup for other field values. Comparing our data for $^{168}\text{Er}$-$^{168}\text{Er}$ Feshbach resonances at low magnetic fields to those presented in [15] we find agreement in the observed resonance positions to within 0.3 G. This systematic uncertainty is the major contribution to our measurement error and outweighs the high frequency noise of our magnetic field which is estimated to be about 0.02 G. The magnetic field resolution is limited by the setpoint resolution of the employed 16 bit digital-to-analog control frontend to about 0.03 G. After the holding time at the target magnetic field the current in the magnetic coils is ramped down to zero in 10 ms and the system is kept there for another 10 ms to allow for eventual residual fields due to Eddy-currents to decay. In standard time-of-flight absorption imaging we then image the remaining Er atoms after 2 ms and the Li atoms after 0.3 ms of free expansion. Additionally, for every magnetic field setting of this main sequence we interleave additional control measurements in which either of the two species is removed from the optical trap by a short pulse of resonant 583 nm (Er) or 671 nm (Li) light before starting the magnetic field sequence. These measurements serve as reference points to distinguish losses due to inter-species collisions from those caused by single-species only interactions. Finally, while these data are obtained every 60 or 180 mG, typically every 1 G additional data of the mixture is taken where the magnetic field is kept constantly low. This is to better detect possible drifts of the overall atom numbers or general changes in the performance of the experimental setup.
FIG. 1. Magnetic field dependence of Li atom losses for various Er-Li mixtures. The four different panels show the fraction of remaining Li atoms for four Er-Li isotope combinations after 500 ms interaction time at magnetic fields between 50 and 680 G. (Note that the magnetic field axis is not continuous as some magnetic field ranges without data are omitted.) In each case Li has been optically pumped to one of the two stretched state configurations (see panel labels) and Er is always spin polarized into the \( m_J = -6 \) ground state. Each data point is the averaged ratio of typically three measurements with and without Er. Many narrow and some broad resonant loss features are observed.

III. RESULTS

In the following we give an overview of the data obtained in the experiment. This is to demonstrate the range of typically observed resonance shapes, their densities and dependence on isotope- and spin-combinations.

We first take a look at the general isotope and hyperfine spin-state dependence of the Feshbach spectra. Figure 1 shows for the magnetic field range 50 to 680 G trap-loss spectra of all isotope and spin combinations that could be investigated in the present work. The spectra are taken at a magnetic field resolution between 60 and 180 mG. In each case we report the fractional loss of Li atoms expressed as the ratio of atoms remaining in the trap after the interaction time for the Er-Li mixture case compared to the case of Li atoms only in the trap. Note that for brevity we will in the following suppress \( m_J = -6 \) in the quantum state description of Er and \( F = 1/2 \) \((F = 1)\) for \(^6\text{Li} (^7\text{Li})\), they are to be understood implicitly. We further need to point out that for \(^{168}\text{Er}^7\text{Li} \) (top panel) we were not able to create a cold mixture of \(^{168}\text{Er}^7\text{Li} \(m_F = 1\)). Even though at the beginning of the evaporation ramp such a mixture could be produced, the \(^7\text{Li}(m_F = 1)\) atoms are rapidly lost during the evaporation sequence. Also no magnetic field could be found that allows for both efficient evaporation and collisional stability of the mixture, indicating the existence of a broad resonance at only a few Gauss for this isotope and hyperfine spin-state combination. This is especially interesting as the energetically lowest state in \(^7\text{Li}\) is the \( m_F = 1 \) state and naively one would expect this state to be most stable towards possible inelastic processes. Instead it is the energetically higher \( m_F = -1 \) state that can be prepared in the experiment. The data in the top panel of Fig. 1 therefore only shows the \(^{168}\text{Er}^7\text{Li}(m_F = -1)\) mixture. The other isotope combinations (remaining panels) do not suffer from such a limitation. The available data do not cover the complete magnetic field range (note the omission marks in the magnetic field scale in Fig. 1) and only a total range of between roughly 150 G \(^7\text{Li}\) and 250 G \(^6\text{Li}\) was scanned for each mixture. As such, with a continuous measurement time of about a week per isotope and hyperfine spin combination, a good overview of the spectral properties has been obtained. Each mixture features a distinct resonance structure of numerous narrow and several broader resonances. A detailed list of all observed resonance positions and their widths is provided in Tab. I. While the broader Feshbach resonances can be induced by ordinary s-wave coupling, the numerous...
TABLE I. List of identified Er-Li interspecies Feshbach resonances. The resonance positions $B_0$ and their widths $\Delta B$ are given as determined by fits of squared Breit-Wigner lineshapes to the Li loss data shown in Fig. 1. Within the present experiments no reliable width determination is possible for very narrow resonances and those resonances with widths below 100 mG are here indicated by $< 100$. Further, only resonances that are either reasonably broad or that cause a loss of Li atoms by at least one third are listed. Where imperfect optical pumping causes seemingly simultaneous losses in both Li spin states the resonance is attributed to the dominant spin component only. Resonances that are marginal for the identification are also included but put in brackets. Note that for $B > 50$ G only resonances within the investigated magnetic field ranges (cf. Fig. 1) are listed that due to the finite magnetic field step size some very narrow resonances might not have been detected. Below 50 G some additional resonances are included that have been found in separate measurements.

| $B_0$ (G) | $\Delta B$ (mG) | $B_0$ (G) | $\Delta B$ (mG) | $B_0$ (G) | $\Delta B$ (mG) |
|-----------|----------------|-----------|----------------|-----------|----------------|
| $^{168}$Er$^7$Li($m_F = -1$) | | | | | |
| 1.7 | $< 100$ | 23.6 | 130 | 231.7 | 100 |
| 7.5 | $< 100$ | 233.8 | 500 | 245.5 | $< 100$ |
| 15.8 | 100 | 234.3 | 200 | 248.9 | $< 100$ |
| 177.5 | $< 100$ | 238.3 | 200 | 254.1 | $< 100$ |
| 237.6 | 300 | 260.8 | 900 | 263.2 | $< 100$ |
| 246.8 | 300 | 300.7 | $< 100$ | 291.3 | $< 100$ |
| 248.8 | 1600 | 302.7 | $< 100$ | 303.6 | $< 100$ |
| 261.6 | 500 | 306.3 | $< 100$ | (305.9) | (< 100) |
| 306.8 | 200 | 308.5 | 4900 | 316.7 | 200 |
| 311.1 | 1400 | 308.9 | 100 | 517.9 | $< 100$ |
| 507.3 | 4000 | 319.8 | 100 | 518.4 | 100 |
| 511.4 | $< 100$ | 319.9 | 3200 | 561.7 | $< 100$ |
| 566.0 | 200 | 500.1 | $< 100$ | 564.8 | 100 |
| 566.1 | 200 | 503.6 | 300 | (570.4) | (100) |
| 675.9 | 300 | (512.4) | (1700) | 579.6 | 200 |
| $^{168}$Er$^5$Li($m_F = 1$) | | | | | |
| 13.1 | 400 | 563.3 | $< 100$ | 20.9 | $< 100$ |
| 16.8 | $< 100$ | 565.3 | $< 100$ | 24.0 | $< 100$ |
| 164.2 | 100 | 568.4 | 1800 | 26.7 | 100 |
| 169.8 | 100 | 658.4 | 100 | 32.7 | $< 100$ |
| 170.6 | 100 | 663.7 | 500 | 57.0 | 1700 |
| 178.4 | 200 | (672.4) | (4000) | 212.5 | 300 |
| 231.7 | $< 100$ | 677.0 | $< 100$ | 225.2 | $< 100$ |
| 233.6 | 700 | | | | |
| $^{166}$Er$^7$Li($m_F = 1/2$) | | | | | |
| 247.0 | $< 100$ | 18.9 | $< 100$ | 232.4 | 400 |
| 300.2 | 100 | 22.1 | $< 100$ | 240.4 | $< 100$ |
| 309.6 | $< 100$ | 25.6 | $< 100$ | 242.4 | $< 100$ |
| 311.6 | $< 100$ | 26.3 | $< 100$ | 247.0 | 4200 |
| 316.0 | 100 | 37.8 | $< 100$ | 256.2 | 100 |
| 507.8 | 100 | 64.6 | 200 | 259.0 | 1300 |
| 509.9 | $< 100$ | 68.6 | $< 100$ | 274.5 | $< 100$ |
| (512.4) | (2500) | 87.7 | $< 100$ | 283.0 | 200 |
| 560.8 | 100 | 98.2 | $< 100$ | 297.5 | $< 100$ |
| 566.4 | $< 100$ | 200.8 | $< 100$ | 314.1 | 100 |
| 658.5 | $< 100$ | 211.9 | 100 | 575.8 | 200 |
| 659.8 | 300 | 219.1 | 100 | 578.3 | 100 |
| 663.7 | 300 | 223.7 | $< 100$ | 666.2 | $< 100$ |
| (672.4) | (3200) | 228.8 | 100 | (42.5) | (< 100) |
| 667.6 | 300 | 228.8 | $< 100$ | 46.4 | 100 |
| (672.4) | (3200) | 230.8 | $< 100$ | 53.1 | $< 100$ |

observed narrow resonances may be understood as a result of anisotropy-induced Feshbach resonances where the anisotropy originates form the electrostatic interaction between Er and Li [16, 23]. It seems further worth mentioning that there is an apparent lack of broad Feshbach resonances with Li in the energetically lowest magnetic sublevel ($^7$Li($m_F = +1$) and $^6$Li($m_F = +1/2$)) which is not reflected in current calculations [16]. Further experimental efforts will be necessary, however, to further corroborate such observations.

We now turn to a discussion of the structures of individual resonances. The panels of Fig. 2 display in the
The additional losses in the complicated structure of $^{168}$Er are not fully attributed to a drift of the general performance of the experiment, the data of the mixture clearly display a broad resonant loss. In contrast to the data at 15.8 G, the interspecies loss is this time only weakly reflected in the Er data. This is partially due to a reduced visibility caused by the dense Er-Er Feshbach resonance structure but is expected to also be induced by the large mass imbalance between the two species. The resonance shape is asymmetric and we extract an approximate resonance position and FWHM by a Lorentzian fit to the $^{7}$Li data. We find a resonance position of 507.3 G and a FWHM of 4.0 G. This broad resonance is accompanied by a very narrow one at 511.4 G that has a width well below 0.1 G at the limit of our experimental resolution.

IV. DISCUSSION AND CONCLUSION

With the present set of experimental results we demonstrate the realization of large mass-imbalance mixtures of Er and Li in various isotopic combinations. While not seamlessly exploring the complete magnetic field range up to 680 G we focus on a more detailed investigation of the Er-Li interspecies Feshbach resonance structure in multiple field locations. This approach is chosen to obtain a general idea of the expected spectra and to better support theoretical efforts in the modeling and understanding of the Feshbach spectra by providing data samples over a possibly large range of magnetic fields, isotope and spin combinations. As expected we find a wealth of interspecies Feshbach resonances at a density of about one resonance per ten Gauss, most of them quite narrow, some of them with widths beyond 1 G. This encourag-
ing overall consistency between the observed Feshbach resonance spectra and current theory predictions [16] is contrasted by the lack of a detailed understanding of the exact resonance structures. Joint efforts of both experiment and theory will be necessary for a better grasp of this complicated system. Additionally, the present work reveals mixture lifetimes on the order of up to 1 s even at resonance. This is, e.g., about two orders of magnitude longer than inelastic collision rate limited lifetimes found in the large mass-imbalance system of Yb\(^{3}\)P\(_{2}\)-Li [12] and an encouraging starting point for further research of Er-Li mixtures in the strongly interacting regime.

To our knowledge this mixture system currently represents the largest experimentally realized mass-imbalanced mixture with tunable interactions. Additional measurements are in preparation to precisely determine the binding energies of the corresponding Feshbach molecules. Considering in particular a similar kind of mixture of heavy \(^{167}\)Er fermions and light \(^{7}\)Li bosons this opens the road to three-body Efimov states with both reduced scaling constants and non-vanishing angular momenta [2], and chiral p-wave superfluids in mixed dimensions. Additionally, ultracold mixtures of Yb and Er should allow for a detailed study of mass-scaling effects in Yb-Er Feshbach resonances [24]. Ultracold triple-species quantum gas mixtures of Ytterbium, Erbium and Lithium are also within reach.

ACKNOWLEDGMENTS

We thank Y. Takasu for early experimental assistance and useful discussions, K. Aikawa for helpful advice in early stages of the experiment and P. \.{Z}uchowski for fruitful discussions of the Feshbach spectra and for sharing his theoretical insight with us. NM acknowledges support from the JSPS (KAKENHI Grant No. 21J20153). This work was supported by the Grant-in-Aid for Scientific Research of JSPS Grants No. JP17H06138, No. 18H05405, and No. 18H05228, JST CREST Grant No. JPMJCR1673 and the Impulsing Paradigm Change through Disruptive Technologies (ImpACT) program by the Cabinet Office, Government of Japan, and MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant No. JPMXS0118069021.

[1] I. Bloch, J. Dalibard, and W. Zwerger, Rev. Mod. Phys. 80, 885 (2008).
[2] P. Naidon and S. Endo, Rep. Prog. Phys. 80, 056001 (2017).
[3] C. Chin, R. Grimm, P. Julienne, and E. Tiesinga, Rev. Mod. Phys. 82, 1225 (2010).
[4] M. Randeria and E. Taylor, Annu. Rev. Condens. Matter Phys. 5, 209 (2014).
[5] M. Zaccanti, B. Deissler, C. D’Errico, M. Fattori, M. Jona-Lasinio, S. Müller, G. Roati, M. Inguscio, and G. Modugno, Nat. Phys. 5, 586 (2009).
[6] P. W. Anderson, Phys. Rev. 109, 1492 (1958).
[7] J. Kondo, Prog. Theor. Phys. 52, 37 (1964).
[8] C. Kobrall, M. Zaccanti, M. Jag, A. Trenkwalder, P. Massignan, G. M. Bruun, F. Schreck, and R. Grimm, Nature 485, 615 (2012).
[9] Y. Nishida, Ann. Phys. 324, 897 (2009).
[10] Y.-J. Wu, J. He, C.-L. Zang, and S.-P. Kou, Phys. Rev. B 86, 085128 (2012).
[11] W. Dowd, R. J. Roy, R. K. Shrestha, A. Petrov, C. Makrides, S. Kotochigova, and S. Gupta, New J. Phys. 17, 055007 (2015).
[12] F. Schäfer, H. Konishi, A. Bouscal, T. Yagami, and Y. Takahashi, Phys. Rev. A 98, 051602(R) (2018).
[13] A. Green, H. Li, J. H. See Toh, X. Tang, K. C. McCormick, M. Li, E. Tiesinga, S. Kotochigova, and S. Gupta, Phys. Rev. X 10, 031037 (2020).
[14] K. Aikawa, A. Frisch, M. Mark, S. Baier, A. Rietzler, R. Grimm, and F. Ferlaino, Phys. Rev. Lett. 108, 210401 (2012).
[15] A. Frisch, M. Mark, K. Aikawa, F. Ferlaino, J. L. Bohn, C. Makrides, A. Petrov, and S. Kotochigova, Nature 507, 475 (2014).
[16] M. L. González-Martínez and P. S. \.{Z}uchowski, Phys. Rev. A 92, 022708 (2015).
[17] H. Hara, Y. Takasu, Y. Yamaoka, J. M. Doyle, and Y. Takahashi, Phys. Rev. Lett. 106, 205304 (2011).
[18] F. Schäfer, H. Konishi, A. Bouscal, T. Yagami, and Y. Takahashi, New J. Phys. 19, 103039 (2017).
[19] F. Leroux, K. Pandey, R. Rehbi, F. Chevy, C. Miniatura, B. Grémaud, and D. Wilkowski, Nat. Comm. 9, 3580 (2018).
[20] F. Schäfer, N. Mizukami, P. Yu, S. Koibuchi, A. Bouscal, and Y. Takahashi, Phys. Rev. A 98, 051602(R) (2018).
[21] A. H. Hansen, A. Krhamov, W. H. Dowd, A. O. Jamison, V. V. Ivanov, and S. Gupta, Phys. Rev. A 84, 011606(R) (2011).
[22] C. H. Schunck, M. W. Zwierlein, C. A. Stan, S. M. F. Raupach, W. Ketterle, A. Simoni, E. Tiesinga, C. J. Williams, and P. S. Julienne, Phys. Rev. A 71, 045601 (2005).
[23] S. Kotochigova, Rep. Prog. Phys. 77, 096901 (2014).
[24] M. B. Kosicki, M. Borkowski, and P. S. \.{Z}uchowski, New J. Phys. 22, 023024 (2020).