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We discuss cooling efficiency for different-species Fermi-Bose mixtures in magnetic traps. A better heat capacity matching between the two atomic species is achieved by a proper choice of the Bose cooler and the magnetically trappable hyperfine states of the mixture. When a partial spatial overlap between the two species is also taken into account, the deepest Fermi degeneracy is obtained for an optimal value of the trapping frequency ratio between the two species. This can be achieved by assisting the magnetic trap with a deconfining light beam, as shown in the case of fermionic ^{6}Li mixed with ^{23}Na, ^{87}Rb, and ^{133}Cs, with optimal conditions found for the not yet explored ^{6}Li-^{87}Rb mixture.

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The availability of different cooling techniques in the nanokelvin range has recently opened up a field of study of condensed matter systems at low densities. Mean-field theory can be reliably used in the low-density limit to understand many-body quantum phenomena involving dilute Bose gases, in particular superfluidity [1]. In the case of trapped Fermi gases, which maps the physics of interacting electrons in a metal, impressive progress has been made in the last few years. Following an observation of quantum degeneracy for an atomic Fermi gas [2], both ideal behavior—the effect of the Fermi pressure [3,4]—and the interacting features in Fermi-Bose mixtures [5] and in two-component Fermi gases [6], have been reported. More recently, Bose-Einstein condensation (BEC) of tightly confined Fermi pairs have been observed by various groups [7–11], including the spectroscopic results [12] that have been interpreted as the first evidence for a pairing gap in a fermionic superfluid [13]. These latest results are based upon the manipulation of the fermions scattering length through Feshbach resonances, in a strong coupling regime for the interacting atoms, also named *resonant* superfluidity [14]. While this evidence is a major breakthrough towards understanding the BCS-BEC crossover, it is also important to observe such a transition in a system with moderate scattering length, as this will mimic, in a different context, the situation of BCS Cooper pairs with the large correlation distance typical of low-T_c superconductors [15]. According to theoretical predictions, this requires reaching much lower temperatures than the ones at which resonant superfluidity is expected, implying more challenges from the experimental viewpoint. In this paper we discuss the efficiency for sympathetically cooling different-mass Fermi-Bose species in a magnetic trap. We identify an optimal range of parameters where heat capacity matching between the two species in the mixture is obtained while optimizing their spatial overlap. It turns out that, by using a light-assisted magnetic trap (a feasible addition to many experimental setups already available for Fermi cooling) degeneracy parameters T/T_F in the 10^{-3} range could be achieved.

In order to assess more quantitatively the cooling strategies, we consider magnetically trapped Fermi-Bose mixtures made of fermionic ^{6}Li, a promising candidate for observing superfluidity features [15], and bosonic ^{23}Na, ^{87}Rb, and ^{133}Cs. Our discussion is elicited by a recent result obtained at Massachusetts Institute of Technology (MIT) [16], where a value of $T/T_F \simeq 0.05$ has been achieved by using a ^{6}Li-^{23}Na mixture in a magnetic trap. Other groups using same species Fermi-Bose mixtures like ^{6}Li-^{7}Li have instead obtained higher T/T_F [3,4]. The MIT result can be simply explained, as discussed in [17], by considering the heat capacities of ideal Bose and Fermi that can be approximated in the degenerate regime respectively as

$$C_B \simeq 10.8\, k_B N_B \left(\frac{T}{T_c}\right)^3, \quad C_F \simeq \pi^2 k_B N_F \frac{T}{T_F}, \tag{1}$$

where T is the temperature, T_c and T_F the critical temperature for the Bose-Einstein phase transition and the Fermi temperature, respectively, N_B and N_F the corresponding number of trapped atoms, and k_B the Boltzmann constant. By considering the heat capacity ratio C_B/C_F, supposing that there is complete spatial overlap between the two species, and expressing T_c and T_F in terms of the trapping frequencies ω_B and ω_F, the T/T_F ratio can be written as

$$\frac{T}{T_F} \simeq 0.35 \left(\frac{\omega_B}{\omega_F}\right)^{3/2} \left(\frac{C_B}{C_F}\right)^{1/2}. \tag{2}$$

Since the MIT experiment involves a relatively large mass ratio between the two species, $m_B/m_F \simeq 4$, and the trapping strengths are similar in a magnetic trap, the trapping frequency ratio $\omega_B/\omega_F \simeq (m_F/m_B)^{1/2}$ implies a lower T/T_F degeneracy parameter with respect to the case of ^{6}Li sympathetically cooled with ^{7}Li. By assuming that sympathetic cooling stops completely when $C_B/C_F \simeq 0.1$, an hypothesis which should be close to reality for experiments with complete evaporation of the Bose component as in [16], we obtain $T/T_F \simeq 0.11$ for a ^{6}Li-^{7}Li mixture, while $T/T_F \simeq 0.04$ for a ^{6}Li-^{23}Na mixture, estimates not dissimilar from the actual experimental values.

The fact that a large mass ratio between the Bose and the Fermi species is beneficial for reaching lower temperatures is due to basic quantum statistical laws. As seen from Eq. (1),

TABLE I. Magnetically trappable Fermi-Bose mixtures in the ground state with ^{6}Li as the fermionic component. For each mixture we report the hyperfine state (F,m_F), the ratio between the $m_F g_F$ factors of the Fermi and the Bose hyperfine states, $\alpha = (m_F g_F)_{\mathrm{fermion}}/(m_F g_F)_{\mathrm{boson}}$, and the corresponding trapping frequency ratio.

Fermi-Bose mixture	Hyperfine states	α	ω_F/ω_B
^{6}Li-^{23}Na	Li(1/2,−1/2)-Na(1,−1)	2/3	1.599
	Li(1/2,−1/2)-Na(2,2)	1/3	1.130
	Li(3/2,3/2)-Na(1,−1)	2	2.769
	Li(3/2,3/2)-Na(2,2)	1	1.958
^{6}Li-^{87}Rb	Li(1/2,−1/2)-Rb(1,−1)	2/3	3.109
	Li(1/2,−1/2)-Rb(2,2)	1/3	2.198
	Li(3/2,3/2)-Rb(1,−1)	2	5.385
	Li(3/2,3/2)-Rb(2,2)	1	3.808
^{6}Li-^{133}Cs	Li(1/2,−1/2)-Cs(3,−3)	4/9	3.138
	Li(1/2,−1/2)-Cs(4,4)	1/3	2.718
	Li(3/2,−3/2)-Cs(3,−3)	4/3	5.436
	Li(3/2,3/2)-Cs(4,4)	1	4.707

the specific heat of a Bose gas in the degenerate regime decreases with the temperature as T^3, while a Fermi gas has a milder, linear temperature dependence. In order to preserve a large heat capacity it is therefore important to maintain the Bose gas as close as possible to the classical regime. More classicality for the Bose gas can be easily achieved by using more massive species or, equivalently, in an inhomogeneous situation such as the one of harmonic trapping, by having smaller vibrational quanta $\hbar\omega_B$ [18]. A purely optical trapping solution has been proposed in [19], by selectively trapping the two species in different potentials via different detunings in a bichromatic optical trap. In the context of magnetic trapping this can be instead obtained by using larger mass ratios m_B/m_F, for instance, using ^{87}Rb or ^{133}Cs as Bose coolers, and by properly choosing the combination of trapped hyperfine states. Different hyperfine states have different magnetic moments, and in Table I we show possible hyperfine states for various combinations of mixtures which are trappable with weak magnetic fields, including their trapping frequency ratio. It is evident that trapping frequency ratios ω_F/ω_B up to almost 5.5 can be obtained by using particular hyperfine states in the case of rubidium and cesium. However, there are two issues to be taken into account in the analysis when realistic losses of particles unavoidably occurring in the trap are taken into account. First, some mixtures are not optimal in terms of spin-exchange losses, and this favors some stretched states which have a natural protection against such a kind of losses. Second, very large mass ratios imply diminished spatial overlap between the trapped clouds, and also larger relative sagging due to the gravitational field. The consequent lack of complete overlap between the two species will affect the cooling efficiency. In the extreme case of a very large mass ratio for the two species, the two atomic clouds, due to gravity sagging, could end up with no overlap at all, therefore completely inhibiting any cooling. In the presence of losses inducing heating, as theoretically discussed in [20–22], the final temperature of the mixture will depend upon the balance between cooling and heating rates, and the partial overlap will diminish the former, shifting the equilibrium temperature to higher values than those estimated in Eq. (2).

The degree of spatial overlap between the Fermi and the Bose clouds in the inhomogeneous case can be quantified by considering a dimensionless figure of merit defined as [23]

$$\eta = \int \rho_F^{1/2}(r)\rho_B^{1/2}(r)d^3r, \tag{3}$$

where ρ_F and ρ_B are the densities of the Fermi and the Bose gases. From a quantum mechanical viewpoint η represents the scalar product between the amplitudes of the macroscopic wave functions associated with the two gases. The quantity η^2 is proportional to the number of atoms which share the same region of space and therefore the cooling rate in the presence of a partial overlap will be decreased by the geometric factor η with respect to ideal overlap as $\dot{Q}_{\mathrm{cool}} \to \eta^2 \dot{Q}_{\mathrm{cool}}$. Accordingly, the minimum attainable degeneracy parameter T/T_F in the presence of a partial overlap will be increased as $T/T_F \to \eta^{-2} T/T_F$, since the balance between heating rate and cooling rate is now shifted towards higher equilibrium temperatures. The key point is that by choosing different trapping frequencies for the Bose and the Fermi gases, one can match their spatial sizes in spite of a large mass ratio between the two species. In particular, since the Bose gas is more massive and therefore more confined in a purely magnetic trap, its confinement should be made less stiff in order to match the size of the more delocalized, lighter Fermi gas.

A simple analysis can be developed in the Thomas-Fermi approximation, as in this case the density profiles of the two species can be obtained from the knowledge of the local chemical potentials. In a zero-temperature homogeneous Fermi-Bose mixture the chemical potentials μ_F, μ_B are written in terms of the densities ρ_F, ρ_B as [24,25]

$$\mu_B = \lambda_B \rho_B + \lambda_{FB}\rho_F,$$

$$\mu_F = (6\pi^2)^{2/3}\frac{\hbar^2}{2m_F}\rho_F^{2/3} + \lambda_{FB}\rho_B, \tag{4}$$

where the parameters λ_B, λ_{FB} have been introduced, with $\lambda_B = 4\pi\hbar^2 a_B/m$, $\lambda_{FB} = 2\pi\hbar^2 a_{FB}/m_{FB}$, a_i ($i=B$ or FB) being the s-wave elastic scattering length, and $m_{FB} = m_F m_B/(m_F + m_B)$ the reduced mass. In the inhomogeneous case corresponding to trapping with potentials $V_B(r)$, $V_F(r)$, we have $\mu_B \to \mu_B - V_B(r)$, $\mu_F \to \mu_F - V_F(r)$, and then

$$\rho_B(r) = \frac{\mu_B - V_B(r)}{\lambda_B} - \frac{\lambda_{FB}}{\lambda_B}\rho_F(r),$$

$$\rho_F(r) = \frac{1}{6\pi^2\hbar^3}\{2m_F[\mu_F - V_F(r)] - 2m_F\lambda_{FB}\rho_B\}^{3/2}, \tag{5}$$

where the density dependence in the case of null interspecies interaction is easily recovered for $\lambda_{FB}=0$. An iterative technique in which the trial initial densities are the ones corre-

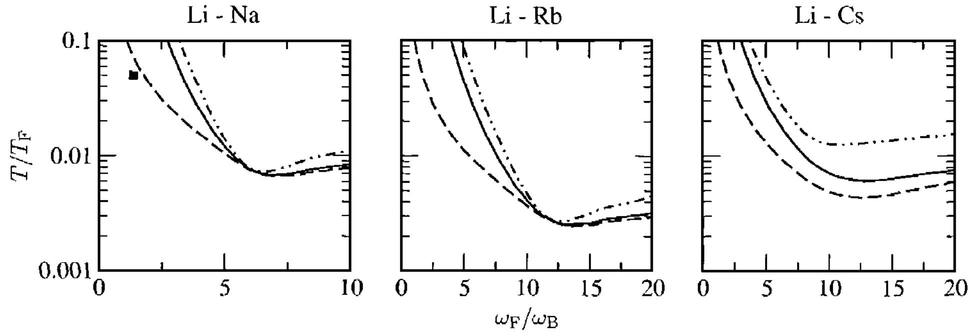

FIG. 1. Optimal sympathetic cooling of ^{6}Li with different Bose coolers. The degeneracy parameter T/T_F is shown the trapping frequency ratio ω_F/ω_B for the cases of fermionic ^{6}Li mixed with bosonic ^{23}Na (left), ^{87}Rb (center), and ^{133}Cs (right). The various curves within each mixture refer to various possible values for the interspecies scattering length, $a_{FB}=-0.5$ nm (dashed line), $a_{FB}=0.0$ nm (continuous), $a_{FB}=1.0$ nm (dot-dashed), while the known intraspecies scattering lengths for the Bose components have been assumed. The square corresponds to the MIT result obtained for the $(3/3,3/2)-(2,2)$ combination of the ^{6}Li-^{23}Na mixture [16].

sponding to noninteracting species allows us to evaluate numerically the density profiles in a three-dimensional situation also taking into account the presence of gravity. In Fig. 1 we report the degeneracy parameter T/T_F versus the ω_F/ω_B ratio for the stretched states of the mixtures, corresponding to the bottom row for each mixture in Table I. Initially, the degeneracy parameter has an inverse dependence upon ω_F/ω_B, as expected on the basis of Eq. (2) and the fact that the size of the heavier Bose gas is approaching that of the lighter Fermi counterpart. When the trapping frequency ratio is such that the Bose gas size exceeds the size of the Fermi gas, and the relative sagging is starting to play a role due to the weakened trapping frequency for the Bose gas, the overlap factor decreases significantly and the T/T_F ratio increases. An optimal ω_F/ω_B is then obtained for each mixture, with the lowest values obtained for the ^{6}Li-^{87}Rb mixture as a compromise betweeen a larger ratio m_B/m_F with respect to the ^{6}Li-^{23}Na mixture, and a smaller relative sagging with respect to the ^{6}Li-^{133}Cs mixture. In the latter mixture, unlike the former two mixtures, the effect of sagging is quite substantial, as it can be seen in Fig. 2 where the degeneracy parameter is shown versus the ω_F/ω_B ratio in presence or absence of gravity, for various values of the absolute trapping frequency of the Bose species. Indeed, gravity sagging introduces an absolute scale for the frequencies in such a way that the cooling curves depend not only on the ω_F/ω_B ratio, but on the absolute values of the frequencies. Analogous curves for the other two mixtures show a much milder dependence on gravity sagging. The various curves for each Fermi-Bose mixture in Fig. 1 correspond to different values for the interspecies scattering length, including the case without interspecies interactions. It is worth pointing out that the interspecies scattering lengths have not yet been measured, and that our analysis reproduces the observed value for the degeneracy parameter obtained by the MIT group if a negative value $a_{FB}\simeq-(0.5–1)$ nm is assumed, at variance with the theoretical estimate reported in [26], and compatible with the discussion reported in [25] where a window on the values of the interspecies scattering length was estabilished based on issues of stability and lack of phase separation for the Fermi-Bose mixture. The presence of attractive interspecies interactions $(a_{FB}<0)$, naturally present or momentarily induced by a Feshbach resonance, could allow to increase for some time the overlap between the species enhancing the cooling speed, as demonstrated in the case of the ^{40}K-^{87}Rb mixture [27].

This analysis is limited by the static picture implicit in Eq. (2), which in a more detailed study should be superseded by a simulation of the master equation for the Fermi-Bose mixture during cooling, also including the dependence of the density profiles upon the temperature [28]. Despite these limitations, from Fig. 1 it is evident that the magnetic trap alone is far from being optimized for cooling, and that more selective confinement of the Fermi and the Bose species is necessary to achieve the highest degeneracy.

One way to move the trapping frequency ratio in the region where T/T_F is minimized is to use a focused laser beam as in usual optical dipole traps. The different detunings of the light with respect to the atomic transitions can be exploited to achieve a weaker confinement for the Bose species. Su-

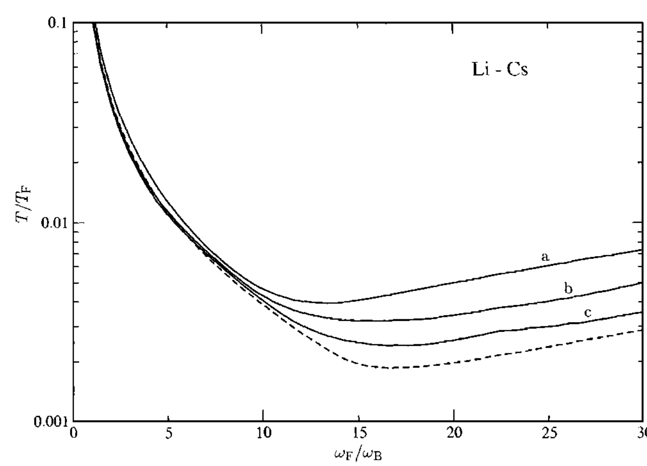

FIG. 2. Optimal sympathetic cooling for a ^{6}Li ^{133}Cs in presence of gravity. The degeneracy parameter T/T_F is shown vs the trapping frequency ratio ω_F/ω_B for various values of the absolute frequency of the Bose species, in absence of (dashed), and in presence of, gravity [continuous curves, with $\omega_B/2\pi=50$ Hz (a), $\omega_B/2\pi=100$ Hz (b), $\omega_B/2\pi=150$ Hz (c)], for an interspecies scattering length of $a_{FB}=-0.5$ nm. The influence of gravity sagging in the cooling efficiency is particularly evident for weak confinement.

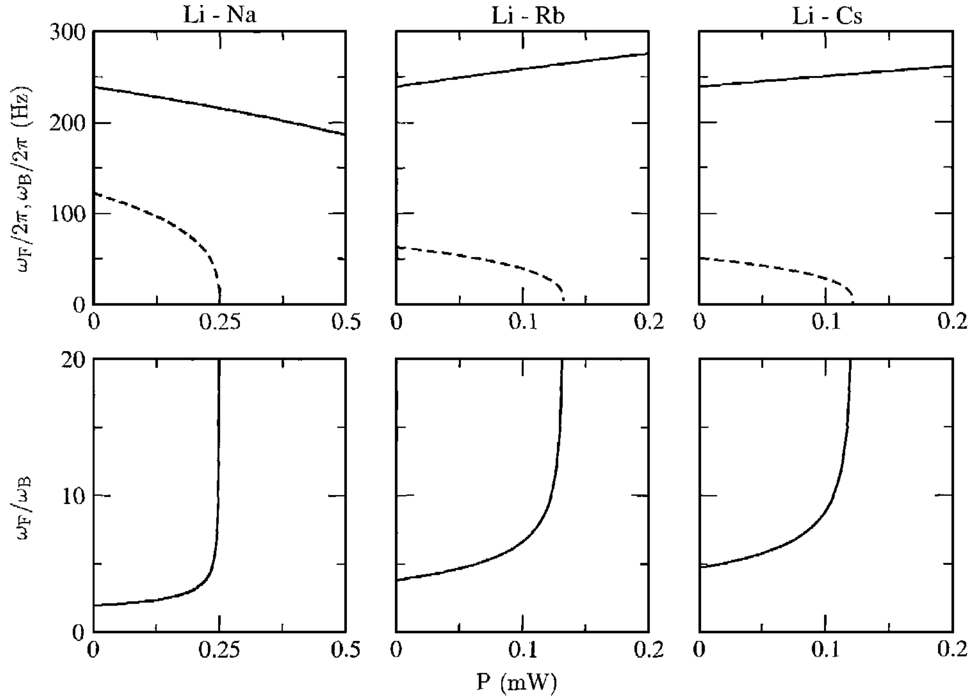

FIG. 3. Trapping Fermi-Bose mixtures in light-assisted magnetic traps. The trapping frequencies (top panels, Bose species, dashed line) and their ratio (bottom panels) are depicted vs the laser power of the deconfining beam for the Bose species, for the cases of ^{6}Li-^{23}Na (left), ^{6}Li-^{87}Rb (center), and ^{6}Li-^{133}Cs (right). We discuss the case of a Ioffe-Pritchard magnetic trap with radial gradient $B_r' = 170$ G/cm, axial curvature $B_{ax}'' = 125$ G/cm^2, and bias field $B_0 = 1$ G. The optical antitrap is assumed to have a focused laser beam with waist $w = 8$ μm, and a wavelength $\Lambda = 560$, 741, and 808 nm in the three cases, respectively. These wavelengths are blue detuned by 5% with respect to the corresponding atomic transition for the Bose species, enough to ensure small residual scattering rates.

perimposed with the trapping magnetic potential, generated for instance through a Ioffe-Pritchard magnetic trap, a laser beam propagates along the axial direction of the magnetic trap. The trapping angular frequencies in the presence of the laser beam can be written as ($\alpha = \mathrm{B}, \mathrm{F}$)

$$\omega_\alpha = [(\omega_\alpha^{ax\,2} + \xi_\alpha^{ax\,2})^{1/2}(\omega_\alpha^{r\,2} + \xi_\alpha^{r\,2})]^{1/3}, \tag{6}$$

where ω_α^{ax} (ω_α^r) is the intrinsic trapping angular frequency of the magnetic trap for the species α in the axial (radial) direction and ξ_α^{ax} (ξ_α^r) is the angular frequency due to the focused laser beam in the axial (radial) direction. The latter are derived by the trapping potential due to the laser beam, which we assume to propagate along the direction x,

$$U_\alpha(x,r) = -\frac{\hbar\Gamma_\alpha^2 T^\alpha P}{4\pi I_\alpha^{sat} w^2}\frac{\exp\left(\dfrac{-2r^2}{w^2(1+x^2/R^2)}\right)}{1+x^2/R^2}, \tag{7}$$

where $r^2 = y^2 + z^2$ in the radial direction, $T^\alpha = 1/(\Omega_\alpha - \Omega) + 1/(\Omega_\alpha + \Omega)$ is a parameter related to the detuning between the atomic transition angular frequencies $\Omega_\alpha = 2\pi c/\Lambda_\alpha$, and the laser angular frequency $\Omega = 2\pi c/\Lambda$ (Λ_α, Λ being the atomic transition and laser beam wavelengths, respectively), P and w power and waist of the laser beam, $R = \pi w^2/\Lambda$ its Rayleigh range, Γ_α the atomic transition linewidth, and $I_\alpha^{sat} = \hbar\Omega_\alpha^3\Gamma_\alpha/12\pi c^2$ is the saturation intensity for the atomic transition. By setting $\hbar\Gamma_\alpha^2 T^\alpha/4\pi I_\alpha^{sat} w^2 = \delta_\alpha$ we get contributions to the angular trapping frequencies due to the deconfining beam as

$$\xi_\alpha^{ax} = \sqrt{\frac{1}{m_\alpha}\frac{\partial^2 U}{\partial x^2}} = \sqrt{\frac{2\delta_\alpha P}{m_\alpha R^2}},$$

$$\xi_\alpha^{r} = \sqrt{\frac{1}{m_\alpha}\frac{\partial^2 U}{\partial y^2}} = \sqrt{\frac{1}{m_\alpha}\frac{\partial^2 U}{\partial z^2}} = \sqrt{\frac{4\delta_\alpha P}{m_\alpha w^2}}. \tag{8}$$

If the laser wavelength Λ is blue detuned with respect to the atomic transition wavelength of the Bose species the contribution of the focused laser beam will decrease the curvature of the overall trapping, corresponding to imaginary values for $\xi_\alpha^{ax}, \xi_\alpha^r$ in Eq. (8). In Fig. 3 we present the dependence of the frequencies and their ratio versus the laser power for a fixed relative detuning of the laser beam with respect to the atomic transition wavelength of the Bose species. Due to the smaller atomic transition wavelength for ^{6}Li versus ^{23}Rb and ^{133}Cs, the trapping strength of the Fermi species is also increased, while for the case of ^{23}Na there is a slight decrease. It is evident that for moderate values of the power of the laser beam, it is possible to bring the ω_F/ω_B ratio to the value minimizing the degeneracy parameter T/T_F for the three mixtures. Although we have focused on a particular example, the possibility to deconfine in a selective way a magnetically trapped species by means of a focused blue-detuned beam is quite general, and relies on well-explored techniques which have been implemented for other purposes,

namely the suppression of Majorana spin-flip losses during evaporative cooling of Bose species [29] (see also [30] for related recent work).

In summary, we have discussed Fermi-Bose cooling in a magnetic trap and how it can be optimized by using a laser beam. The result of this analysis can be summarized as showing that the ^{6}Li-^{87}Rb mixture is the more promising for achieving degeneracy parameters in the 10^{-3} range, provided that the interspecies scattering length is large enough and possibly negative. This also leads to the need for determining the interspecies scattering lengths, as this is crucial to identify configurations manifesting efficient sympathetic cooling, possibly also exploiting Feshbach resonances at low or moderate values of magnetic field. With respect to the ^{6}Li-^{23}Na mixture, ^{6}Li-^{87}Rb allows for significantly larger ω_F/ω_B ratios, and consequently smaller values of T/T_F, could be achieved. Over the ^{6}Li-^{133}Cs, ^{87}Rb has the advantage that the relative gravitational sagging is less pronounced, and it is easier to bring it close to Bose condensation. Moreover, on the practical side, both lithium and rubidium can take advantage of the same diode laser technology. The achievement of $T/T_F \simeq 10^{-3}$ is considered crucial to obtain fermion superfluidity in the widest range of the relevant parameter space and to study Fermi-Bose quantum fluids [31].

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