强磁场中弱相互作用费米气体的热力学性质*

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基于赝势法和局域密度近似研究了强磁场中弱相互作用费米气体的热力学性质,得出化学势、总能和热容量的解析式,同时分析了磁场及相互作用对系统热力学性质的影响. 研究表明,无论是高温情况还是低温情况下,磁场都能调节相互作用的影响. 低温下,与无磁场的系统相比,磁场降低系统的化学势、总能和热容量;与无相互作用系统相比,排斥作用增加化学势而降低总能及热容量. 高温下,磁场和排斥作用均可降低系统的总能而增加热容量,强磁场可以改变相互作用对总能及热容量的影响.

关键词: 强磁场, 弱相互作用, 费米气体, 热力学性质

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1. 引 言

近年来,超冷费米气体的研究已成为一个热门领域,并取得了许多重要的成果[1—11]. 在实验上,Duke 大学的 Thomas 小组最先研究了强关联费米气体的集体激发[8],随后 Grimm 小组也独立地观测到了低温超流—玻色-爱因斯坦凝聚(BEC)渡越区域中系统的集体激发以及能隙的存在[9]. Thomas 小组还对共振磁场附近系统的热力学性质进行了细致的实验研究,实验结果清晰地反映了相变的存在[10]. 文献[11]对超冷费米原子气体具有超流动性作出了实验论证,并报道^{6}Li 原子气体形成 BEC 时会出现持久的无摩擦的涡流运动. 在理论上,文献[7]研究了强磁场中无相互作用费米气体在低温下的统计性质,并且给出了统计特征量的解析表达式. 文献[2]在理论上研究了 Feshbach 共振附近梯度磁场作用下的超冷两组分费米气体,该文率先提出在 Feshbach 共振附近施加梯度磁场后,将可以实现分子 BEC、原子库珀对的凝聚体以及强相互作用费米气体这三种物态同时并存的理论预言,为进一步研究超冷费米气体的基本性质提供了一个新的窗口. 有关超冷费米气体的实验及理论研究表明,粒子之间的相互作用对费米对以及低温超流相变有重要的影响. 本文基于赝势法和局域密度近似研究强磁场中弱相互作用费米气体的热力学性质,分析磁场及粒子间的相互作用对热力学性质的影响,探讨强磁场对相互作用影响的调节机制. 虽然粒子之间的相互作用较弱,但其影响特别是对具有超精细结构的^{6}Li 原子系统是至关重要的.

2. 低温性质

在本文研究中,强磁场条件为 $T \leqslant \mu_{\mathrm{B}} B \ll |\mu|$;弱相互作用条件为 $a/\lambda \ll 1, an^{1/3} \ll 1$, 其中 B 为磁感应强度, a 为 s 波散射长度, μ_{B} 为玻尔磁子, T 为系统的温度, μ 为化学势, $\lambda = h/\sqrt{2\pi m T}$ 为热波长, n 为粒子数密度,同时令玻尔兹曼常数 $k_{\mathrm{B}} = 1$.

据文献[12],外势中弱相互作用费米气体的粒子数密度 n 和能量密度 u 分别表示为

$$n \approx \frac{2}{\lambda^3} f_{3/2}(z') \left[1 - \frac{2a}{\lambda} f_{1/2}(z')\right], \tag{1}$$

$$u \approx \frac{T}{\lambda^3} \Big\{ 3 f_{5/2}(z') + \frac{2}{T} V(r) f_{3/2}(z') - \frac{4a}{\lambda}\Big[f_{3/2}^2(z') + \frac{V(r)}{T} f_{3/2}(z') f_{1/2}(z')\Big]\Big\}, \tag{2}$$

其中

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$$z' = \exp((\mu - V(r))/T).$$

对沿 z 轴正向的均匀磁场,可令势

$$V(r) = -By.$$

在 $T \ll T_F$ 下,有

$$n \approx \frac{8\pi}{3h^3}(2m)^{3/2}(\mu + By)^{3/2}\left[1 + \frac{\pi^2}{8}\left(\frac{T}{\mu + By}\right)^2 - \frac{4a}{h}(2m)^{1/2}(\mu + By)^{1/2}\right], \tag{3}$$

$$u \approx \frac{8\pi}{3h^3}(2m)^{3/2}\left\{\frac{3}{5}(\mu + By)^{5/2}\left[1 + \frac{5\pi^2}{8}\left(\frac{T}{\mu + By}\right)^2\right] - By(\mu + By)^{3/2}\left[1 + \frac{\pi^2}{8}\left(\frac{T}{\mu + By}\right)^2\right]\right.$$
$$\left. - \frac{4a}{h}(2m)^{1/2}\left[\frac{2}{3}(\mu + By)^3 - By(\mu + By)^2\right]\right\}. \tag{4}$$

系统的总粒子数

$$N = \int n\mathrm{d}y = \frac{16\pi(2m)^{3/2}}{15h^3B}\left\{(\mu + BV)^{5/2} - \mu^{5/2} + \frac{5}{8}\pi^2T^2[(\mu + BV)^{1/2} - \mu^{1/2}] - \frac{10\sqrt{2m}}{3h}a[(\mu + BV)^3 - \mu^3]\right\}. \tag{5}$$

当 $B \neq 0$ 及 $a = 0$ 时,(5)式表示为

$$N = \frac{16\pi(2m)^{3/2}}{15h^3B}\{(\mu_0 + BV)^{5/2} - \mu_0 + \frac{5}{8}\pi^2T^2[(\mu_0 + BV)^{1/2} - \mu_0^{1/2}]\}. \tag{6}$$

当 $B = 0$ 及 $a = 0$ 时, 根据文献[13],有

$$N = \frac{(2m)^{3/2}}{3\pi^2\hbar^3}V\mu_0^{03/2}. \tag{7}$$

这里 μ_0^0 为无磁场和无相互作用系统即理想系统的化学势,

$$\mu_0^0 = \varepsilon_F\left[1 - \frac{\pi^2}{12}\left(\frac{T}{T_F}\right)^2\right];$$

其中 ε_F 为理想系统的费米能, T_F 为 ε_F 所对应的费米温度; μ_0 为有磁场而无相互作用系统的化学势.

(6)式可近似表示为

$$(\mu + BV)^{5/2} - \mu^{5/2} + \frac{5}{8}\pi^2T^2[(\mu + BV)^{1/2} - \mu^{1/2}] = \frac{15h^3BN}{16\pi(2m)^{3/2}}\left\{1 + \frac{32\pi\sqrt{2m}a}{9h^4BN}[(\mu_0 + BV)^3 - \mu_0^3]\right\}. \tag{8}$$

系统的总能

$$U = \int u\mathrm{d}y = \frac{32\pi(2m)^2}{105h^3B}\left\{\mu^{7/2} - (\mu + BV)^{7/2} + \frac{7}{2}\mu[(\mu + BV)^{5/2} - \mu^{5/2}] + \frac{35}{24}\pi^2T^2[(\mu + BV)^{3/2} - \mu^{3/2}]\right.$$
$$\left. + \frac{35}{16}\pi^2T^2\mu[(\mu + BV)^{1/2} - \mu^{1/2}] - 4\frac{(2m)^{1/2}}{h}a\left[\frac{35}{48}\mu^4 - \frac{35}{48}(\mu + BV)^4 + \frac{35}{12}\mu(\mu + BV)^3\right]\right\}. \tag{9}$$

系统的热容量

$$C = \frac{\pi(2m)^{3/2}}{3h^3B}\left\{8\mu(\mu + BV)^{3/2} - 8\mu^{5/2} + 4\pi^2T^2\left[(\mu + BV)^{1/2} - \frac{5}{4}\mu^{1/2}\right] + \pi^2T^2\mu(\mu + BV)^{-1/2}\right.$$
$$\left. - \frac{32(2m)^{1/2}}{3h}a[3\mu(\mu + BV)^2 + \mu^3]\right\}\frac{\partial\mu}{\partial T} + \frac{8\pi^3(2m)^{3/2}}{9h^3B}T\left[(\mu + BV)^{3/2} + \frac{3}{2}\mu(\mu + BV)^{1/2} - \frac{5}{2}\mu^{3/2}\right]. \tag{10}$$

考虑 $BV \ll \mu$ 及 $BV \ll \mu_0$, $T \ll \mu$ 及 $T \ll \mu_0$ 的条件,根据(6),(7)式,可近似有

$$\mu_0^{03/2} = \mu_0^{3/2}\left[1 + \frac{3}{4}\frac{BV}{\mu_0}\right], \tag{11}$$

即

$$\mu_0 = \mu_0^0 - \frac{1}{2}BV$$
$$= \varepsilon_F\left[1 - \frac{\pi^2}{12}\frac{T^2}{T_F^2} - \frac{1}{2}\frac{BV}{\varepsilon_F}\right]. \tag{12}$$

在此条件下,系统的化学势可表示为

$$\mu \approx \varepsilon_{\mathrm{F}} \left\{ \left[1 - \frac{1}{2} \frac{BV}{\varepsilon_{\mathrm{F}}} + \frac{64}{9} \frac{\pi (2m)^2}{h^4 n_0} \varepsilon_{\mathrm{F}}^2 a \left(1 - \frac{3}{2} \frac{BV}{\varepsilon_{\mathrm{F}}} \right) \right] - \frac{\pi^2}{12} \left(\frac{T}{T_{\mathrm{F}}} \right)^2 \left[1 + \frac{3}{2} \frac{BV}{\varepsilon_{\mathrm{F}}} + \frac{64}{3} \frac{\pi (2m)^2}{h^4 n_0} \varepsilon_{\mathrm{F}}^2 a \left(1 - \frac{1}{2} \frac{BV}{\varepsilon_{\mathrm{F}}} \right) \right] \right\}$$

$$= \mu_0^0 - \frac{1}{2} BV + \frac{64}{9} \frac{\pi (2m)^2}{h^4 n_0} \varepsilon_{\mathrm{F}}^3 a \left(1 - \frac{3}{2} \frac{BV}{\varepsilon_{\mathrm{F}}} \right) - \frac{\pi^2}{12} \left(\frac{T}{T_{\mathrm{F}}} \right)^2 \left[\frac{3}{2} BV + \frac{64}{3} \frac{\pi (2m)^2}{h^4 n_0} \varepsilon_{\mathrm{F}}^3 a \left(1 - \frac{1}{2} \frac{BV}{\varepsilon_{\mathrm{F}}} \right) \right], \tag{13}$$

并有

$$\left. \frac{\partial \mu}{\partial T} \right|_{N,V} \approx - \frac{\pi^2}{6} \frac{T}{T_{\mathrm{F}}} \left[1 + \frac{3}{2} \frac{BV}{\varepsilon_{\mathrm{F}}} + \frac{64}{3} \frac{\pi (2m)^2}{h^4 n_0} \varepsilon_{\mathrm{F}}^2 a \left(1 - \frac{1}{2} \frac{BV}{\varepsilon_{\mathrm{F}}} \right) \right]. \tag{14}$$

所以,系统的总能可表示为

$$U \approx \frac{8(2m)^{3/2} V}{5h^3} \left[\mu^{5/2} + \frac{5}{8} \pi^2 T^2 \mu^{1/2} - \frac{35 (2m)^{3/2}}{3h} a \mu^4 \left(1 + \frac{2BV}{\mu} \right) \right]$$

$$\approx \frac{8(2m)^{3/2} V}{5h^3} \varepsilon_{\mathrm{F}}^{5/2} \left\{ 1 - \frac{5BV}{4\varepsilon_{\mathrm{F}}} + \frac{5\pi^2 T}{8\varepsilon_{\mathrm{F}}^2} \left[1 - \frac{BV}{4\varepsilon_{\mathrm{F}}} \right] - \frac{35\pi (2m)^{1/2}}{3h} \varepsilon_{\mathrm{F}}^{3/2} a \left(1 - \frac{3BV}{2\varepsilon_{\mathrm{F}}} \right) \right\}$$

$$= U_0^0 - \frac{8(2m)^{3/2} V}{5h^3} \varepsilon_{\mathrm{F}}^{5/2} \left[\frac{5BV}{32\varepsilon_{\mathrm{F}}} (8 + \pi^2 T^2) + \frac{35\pi (2m)^{1/2}}{3h} \varepsilon_{\mathrm{F}}^{3/2} a \left(1 - \frac{3BV}{2\varepsilon_{\mathrm{F}}} \right) \right]. \tag{15}$$

系统的热容量可表示为

$$C \approx \frac{4\pi (2m)^{3/2} V}{h^3} \mu^{3/2} \frac{\partial \mu}{\partial T} + \frac{2\pi^3 (2m)^{3/2} TV}{h^3} \mu^{1/2}$$

$$\approx \frac{4\pi^3 (2m)^{3/2} TV}{3h^3} \varepsilon_{\mathrm{F}}^{1/2} \left\{ 1 - \left[\frac{3BV}{4\varepsilon_{\mathrm{F}}} + \frac{32\pi (2m)^2}{h^4 n_0} \varepsilon_{\mathrm{F}}^2 a \right] \right\}$$

$$= C_0^0 - \frac{4\pi^3 (2m)^{3/2} TV}{3h^3} \varepsilon_{\mathrm{F}}^{1/2} \left[\frac{3BV}{4\varepsilon_{\mathrm{F}}} + \frac{32\pi (2m)^2}{h^4 n_0} \varepsilon_{\mathrm{F}}^2 a \right]. \tag{16}$$

由(13),(15)式还可得到系统的费米能及基态能分别为

$$E_{\mathrm{F}} \approx \varepsilon_{\mathrm{F}} \left\{ \left[1 - \frac{1}{2} \frac{BV}{\varepsilon_{\mathrm{F}}} + \frac{64}{9} \frac{\pi (2m)^2}{h^4 n_0} \times \varepsilon_{\mathrm{F}}^2 a \left(1 - \frac{3}{2} \frac{BV}{\varepsilon_{\mathrm{F}}} \right) \right] \right\}, \tag{17}$$

$$U^0 = \frac{8(2m)^{3/2} V}{5h^3} \varepsilon_{\mathrm{F}}^{5/2} \left[1 - \frac{5BV}{4\varepsilon_{\mathrm{F}}} - \frac{35\pi (2m)^{1/2}}{3h} \times \varepsilon_{\mathrm{F}}^{3/2} a \left(1 - \frac{3BV}{2\varepsilon_{\mathrm{F}}} \right) \right]. \tag{18}$$

3. 高温性质

在高温条件下,即 $T \gg T_{\mathrm{F}}$ 时,粒子数密度

$$n \approx \frac{2}{\lambda^3} z' \left[1 - \frac{2a}{\lambda} z' \right]$$

$$= \frac{2}{\lambda^3} \exp\left(\frac{\mu + By}{T} \right) \left[1 - \frac{2a}{\lambda} \exp\left(\frac{\mu + By}{T} \right) \right], \tag{19}$$

总粒子数

$$N = \int n \mathrm{d}y = \frac{2}{\lambda^3} \frac{T}{B} \exp\left(\frac{\mu}{T} \right) \left(\exp\left(\frac{BV}{T} \right) - 1 \right) \times \left[1 - \frac{a}{\lambda} \exp\left(\frac{\mu}{T} \right) \frac{\exp\left(\frac{2BV}{T} \right) - 1}{\exp\left(\frac{BV}{T} \right) - 1} \right]. \tag{20}$$

由该式确定的化学势为

$$\mu \approx T \ln \frac{BN\lambda^3}{2T \left(\exp\left(\frac{BV}{T} \right) - 1 \right)} + \frac{a}{\lambda} \frac{BN\lambda^3}{2 \left(\exp\left(\frac{BV}{T} \right) - 1 \right)^2} \times \left(\exp\left(\frac{2BV}{T} \right) - 1 \right). \tag{21}$$

当 $B = 0$ 时,(21)式应为

$$\mu_0 = T \ln \frac{\bar{n} \lambda^3}{2} + \frac{a}{\lambda} \bar{n} \lambda^3 T, \tag{22}$$

其中 $\bar{n}$ 为平均粒子数密度. 当 $B = 0$ 及 $a = 0$ 时,由(21)式得化学势

$$\mu_0^0 = T \ln \frac{\bar{n} \lambda^3}{2}. \tag{23}$$

这正是我们所熟知的. 由此,系统的化学势可表示为

$$\mu = \mu_0^0 + T \ln \frac{BV}{T \left(\exp\left(\frac{BV}{T} \right) - 1 \right)} + \frac{a}{\lambda} \frac{BN\lambda^3}{2 \left(\exp\left(\frac{BV}{T} \right) - 1 \right)^2} \left(\exp\left(\frac{2BV}{T} \right) - 1 \right). \tag{24}$$

系统的能量密度为

$$u \approx \frac{T}{\lambda^3} \left\{ 3z' - \frac{2}{T} Byz' - \frac{4a}{\lambda} \left[z'^2 - \frac{By}{T} z'^2 \right] \right\}$$

$$= \frac{1}{\lambda^3} \exp\left(\frac{\mu + By}{T} \right) \left[(3T - 2By) - \frac{4a}{\lambda} \exp\left(\frac{\mu + By}{T} \right) (T - By) \right]. \tag{25}$$

系统的总能及热容量分别为

$$U=\int u\mathrm{d}y=\frac{T}{\lambda^{3}}\exp\left(\frac{\mu}{T}\right)\left\{\frac{5T}{B}\left(\exp\left(\frac{BV}{T}\right)-1\right)-2V\exp\left(\frac{BV}{T}\right)-\frac{4a}{\lambda}\exp\left(\frac{\mu}{T}\right)\left[\frac{3T}{4B}\left(\exp\left(\frac{2BV}{T}\right)-1\right)-\frac{V}{2}\exp\left(\frac{2BV}{T}\right)\right]\right\}$$

$$\approx\frac{5}{2}NT-NV\exp\left(\frac{BV}{T}\right)\frac{B}{\exp\left(\frac{BV}{T}\right)-1}+\frac{a}{\lambda}\frac{N^{2}\lambda^{3}}{T}\left(\exp\left(\frac{BV}{T}\right)+1\right)\frac{B^{2}}{\left(\exp\left(\frac{BV}{T}\right)-1\right)^{2}}\left(\frac{5T}{4}\frac{\exp\left(\frac{BV}{T}\right)-1}{B}-\frac{V}{2}\exp\left(\frac{BV}{T}\right)\right),\tag{26}$$

$$C\approx\frac{5}{2}N-NB^{2}\frac{V^{2}}{T^{2}}\frac{\exp\left(\frac{BV}{T}\right)}{\left(\exp\left(\frac{BV}{T}\right)-1\right)^{2}}+\frac{a}{\lambda}\frac{N^{2}\lambda^{3}}{T^{2}}\left(\exp\left(\frac{BV}{T}\right)+1\right)\frac{B^{2}}{\left(\exp\left(\frac{BV}{T}\right)-1\right)^{2}}$$
$$\times\left[-\frac{5T}{4B}\left(\exp\left(\frac{BV}{T}\right)+1\right)+V\exp\left(\frac{BV}{T}\right)-\frac{3}{2}\frac{BV^{2}}{T}\right].\tag{27}$$

当 $B=0$ 时,(26),(27)式变为

$$U_0=\frac{3}{2}NT\left[1+\frac{a}{2\lambda}\bar{n}\lambda^{3}\right],\tag{28}$$

$$C_0=\frac{3}{2}N\left[1-\frac{a}{3\lambda}\bar{n}\lambda^{3}\right].\tag{29}$$

当 $B=0$ 及 $a=0$ 时,(26),(27)式写为

$$U_0^0=\frac{3}{2}NT,\tag{30}$$

$$C_0^0=\frac{3}{2}N.\tag{31}$$

4. 结果讨论与分析

在低温情况下,由(17)及(18)式可知,与理想系统(无外势和无相互作用系统)相比,当满足 $BV\ll\varepsilon_{\mathrm{F}}$ 条件时,磁场降低系统的费米能及基态能,排斥(吸引)作用增加(降低)系统的费米能而降低(增加)基态能.但磁场对相互作用的影响有一定的调节作用,即磁场以因子 $\left(1-\frac{3BV}{\varepsilon_{\mathrm{F}}}\right)$ 降低相互作用的影响.类似地,由(13)式可以看出,磁场降低系统的化学势,排斥作用增加系统的化学势,而且随着温度升高,磁场和相互作用对化学势的影响也随之增大.(15)及(16)式则表明,磁场和排斥作用均降低系统的总能及热容量,温度越高,磁场和排斥作用的影响就越明显.在相互作用对化学势、总能及热容量的影响中,磁场有明显的调节作用.从排斥作用对系统总能的影响性质看,强磁场与弱磁场情况完全不同[14].

在高温情况下,(24)式显示,与理想系统相比,排斥作用始终增加化学势.若 $BV>T(\exp(BV/T)-1)$,磁场会增加系统的化学势,反之,磁场会降低系统的化学势.而温度、粒子数和磁场都可调节相互作用对化学势的影响.(26)及(27)式则表明,当满足 $BV>k_{\mathrm{B}}T$ 条件时,磁场、粒子间的排斥作用均可降低系统的总能而增加热容量.而对于无外势的系统,与理想系统相比,粒子间的排斥作用增加系统的总能降低热容量.这表明强磁场不仅能调节相互作用对总能及热容量影响的大小,而且可以改变相互作用对其影响的性质.高温下粒子间的排斥作用对系统总能的影响同样体现了强磁场与弱磁场的差异.另外,温度和粒子数也参与调节相互作用对总能及热容量的影响.

5. 结　论

本文基于赝势法和局域密度近似研究了强磁场中弱相互作用费米气体的热力学性质,推导了化学势、总能、热容量的解析表达式,分析了磁场及相互作用对系统热力学性质的影响.研究表明,无论是高温情况下还是低温情况下,磁场都能调节相互作用的影响.在低温情况下,磁场降低系统的化学势、总能和热容量,排斥作用增加系统的化学势而降低总能及热容量.在高温情况下,磁场和粒子间的排斥作用可以降低系统的总能而增加热容量.强磁场不仅能调节相互作用对总能及热容量影响的大小,而且可以改变相互作用对其影响的性质.无论高温情况下还是低温情况下,从排斥作用对系统总能影响的性质看,强磁场与弱磁场完全不同.

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Thermodynamic properties of a weakly interacting Fermi gas in a strong magnetic field*

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Abstract

Based on the "pseudopotential" method and the local-density approximation, the thermodynamic properties of a weakly interacting Fermi gas in a strong magnetic filed are studied, the integrated analytical expressions of thermodynamic quantities of the system are derived, and the effects of magnetic field as well as interparticle interactions on the thermodynamic properties of the system are analyzed. It is shown that at both high and low temperatures, magnetic field may adjust the effects of interacting. At low temperatures, magnetic field can lower the chemical potential, total energy and heat capacity of the system compared with the situation of Fermi gas in the absence of the magnetic field. The repulsive interactions may increase the chemical potential, but reduce the total energy and heat capacity of the system compared with the situation of non-interacting Fermi gas. At high temperatures, magnetic field as well as repulsive interactions can reduce the total energy and increase heat capacity of the system, moreover, strong magnetic field may change the effects of interaction on the total energy and the heat capacity of the system.

Keywords: strong magnetic field, weakly interacting, Fermi gas, thermodynamic property

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