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Proton Superfluidity in Neutron-Star Matter

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The observed long relaxation times after the sudden speed-ups of the Crab and Vela pulsars indicate that there exist the proton superfluid as well as the neutron one in these neutron stars.[1] In this note we study, as a series of investigation, the possible realization of the proton superfluidity in neutron-star matter.

The protons begin to mix for $\rho \gtrsim \rho_2 = (0.5 \sim 2.4) \times 10^{14}\text{gcm}^{-3}$ (ρ: total density, ρ_2: proton-drip density)[2] in neutron-star matter. But the density of the mixed protons is very low because of the small contamination (several %) compared with neutrons, and hence the proton Fermi energy $E_F^{(p)}$ is small. This means that the interaction between proton pairs is the strongly attractive $^1S_0$ interaction. Therefore we can expect that the protons admixed at these higher densities are in the $^1S_0$-superfluid state just as the neutrons at lower densities $\rho \lesssim 1.5 \times 10^{14}\text{gcm}^{-3}$.[3] However the situation is different: The proton single particle potentials $V_p(k)$ which reproduce the potential values calculated by Ikeuchi et al.[4] and tend to zero as k becomes infinity, are presented in Table I for typical $E_F^{(p)}$, where the effective mass parameters m^* are shown ($\equiv M^*/M$: the ratio of the proton effective mass to its normal one). It should be noted that the effective mass of a proton is much smaller than that of a neutron, reflecting the strong dispersive effect. For example, m^* for a proton is ~ 0.6 at $E_F^{(p)} \cong 9.4$ MeV whereas the one for a neutron is ~ 1.0 at the same Fermi energy.[3] This important difference in m^* brings much smaller $^1S_0$-gap for protons compared with that for neutrons.

Using the OPEG potential[5] and $V_p(k)$ on Table I, the $^1S_0$-gap equation is solved by the same method as adopted in Ref. 3). The calculated results are given in Fig. 1 where the density-dependence of m^* is indicated by arrows. The proton $^1S_0$-gap is found to be smaller by a factor $\sim 1/5$ than the neutron $^1S_0$-gap[3] and its maximum value is about 0.5 MeV at $E_F^{(p)} \cong 10$ MeV. The proton $^1S_0$-gap exists up to $E_F^{(p)} \cong 25$ MeV corresponding to $\rho \cong 8 \times 10^{14}\text{gcm}^{-3}$. Although the proton-drip density is not

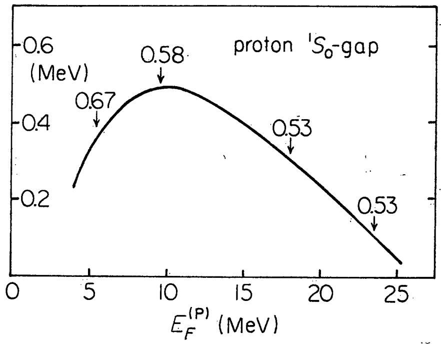

Fig. 1. Proton $^1S_0$-gap versus $E_F^{(p)}$. The density-dependence of m^* is also shown by arrows.

Table I. The proton single particle potential $V_p(k)$ and the corresponding effective mass parameter m^* for typical $E_F^{(p)}$.

$E_F^{(p)}$ (MeV)	ρ (10^{14} gcm^{-3})	$V_p(k)$ (MeV) (k in fm^{-1})	m^* ($\equiv M^*/M$)
5.4	2.4	$-82.80\exp(-0.13k^2)$	0.67
9.4	4.0	$-100.0\exp(-0.15k^2)-11.5\exp(-0.12k^2)$	0.58
18.0	6.5	$-104.0\exp(-0.15k^2)-30.0\exp(-0.20k^2)$	0.53
23.5	7.9	$-125.0\exp(-0.15k^2)-17.3\exp(-0.20k^2)$	0.53

sharply determined, if $\rho_2 \gtrsim 1.0 \times 10^{14}$gcm^{-3} is adopted, protons in neutron-star medium can be regarded as in the $^1S_0$-superfluid state as soon as they drip (nuclei disappear), because the proton $^1S_0$-gap is still sizeable even for $E_F^{(p)} \cong 2$ MeV ($\rho \cong 1.0 \times 10^{14}$gcm^{-3}). The proton $^1S_0$-gap obtained by Chao et al.[5] using the correlation function of Jastrow type has the maximum value 0.6∼0.9 MeV at $E_F^{(p)} \cong 7.5$ MeV which is about 1/3 of the neutron one and it exists for $E_F^{(p)} \lesssim 20$ MeV ($\rho \lesssim 7 \times 10^{14}$gcm^{-3}). These results are approximately equal to our results. The small discrepancy reduces to the calculational method, the two-nucleon potential and m^* used. The proton-neutron pairing is neglected although they coexist for $\rho \gtrsim \rho_2$ because of the large difference in proton and neutron Fermi energies. It is of interest that the proton $^1S_0$- and the neutron $^3P_2$-superfluids[3] coexist in the region $\rho \cong (2\sim 8) \times 10^{14}$gcm^{-3}.

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1) G. Baym, C. Pethick, D. Pines and M. Ruderman, Nature **224** (1969), 872.
2) A. G. W. Cameron, Ann. Rev. Astron. Astrophys. **8** (1970), 179.
H. A. Bethe, G. Börner and K. Sato, Astron. and Astrophys. **7** (1970), 279.
G. Baym, H. A. Bethe and C. J. Pethick, Nucl. Phys. **A175** (1971), 225.
3) T. Takatsuka, Prog. Theor. Phys. **48** (1972), 1517.
4) S. Ikeuchi, S. Nagata, T. Mizutani and K. Nakazawa, Prog. Theor. Phys. **46** (1971), 95.
5) R. Tamagaki, Prog. Theor. Phys. **39** (1968), 91.
6) N. C. Chao, J. W. Clark and C. H. Yang, Nucl. Phys. **A179** (1972), 320.