Van der Waals type PV diagrams of PNJL matter

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Study of the systems produced in high-energy heavy ion collision experiments are of immense interest for various reasons. Here we intend to take an attempt to discuss the presence of interactions in such systems and their effects to distinguish them from the ideal scenario under the framework of Polyakov–Nambu-Jona-Lasinio model. This model encapsulates two very important aspects of Quantum Chromo Dynamics(QCD), viz. the chiral and the confienement-deconfinement phase transitions.

With the help of T and μ dependent constituent quark mass $M(T,\mu)$, one can calculate net quark number density $n(T,\mu)$, pressure $P(T,\mu)$:

$$n(T,\mu) = g\int \frac{d^3p}{(2\pi)^3}(f_0^+ - f_0^-)$$
$$P(T,\mu) = g\int \frac{d^3p}{(2\pi)^3}\left(\frac{p^2}{3E}\right)(f_0^+ + f_0^-) \quad ,(1)$$

where $g = 3\times 3\times 2 = 18$ is degeneracy factor of quark or anti-quark with energy $E = \sqrt{p^2 + M^2(T,\mu)}$ and $f_0^{\pm} = 1/\left\{e^{\beta(E\mp\mu)} + 1\right\}$ for NJL model case and for PNJL model, we have to replace by modified distribution function, having effect from Polyakov loop [1].

Now let us go for rough estimation of number of hadrons or quarks, which can be produced in heavy ion collision experiments with large range of energy, $\sqrt{s} = 1-200$ GeV. Considering only pion production from this energy, one can get a rough number $\frac{(1-200)}{0.14} \approx 7-1,428$ pions and $14-2,856 \approx 10^{1-3}$??. Let us say that we want to restrict 100 net quark by varrying volume from $V = 1$ fm^3 to 100 fm^3 with number density $n = 100-1/\text{fm}^3$. Now for various characteristic temperatures, we can fix net quark number as,

$$N = n(T,\mu)\times V = 100$$
$$Vg\int \frac{d^3p}{(2\pi)^3}(f_0^+ - f_0^-) = 100\ , \quad (2)$$

Fig.(2) shows the dependence of Pressure, P on the volume, V of the system, where V is

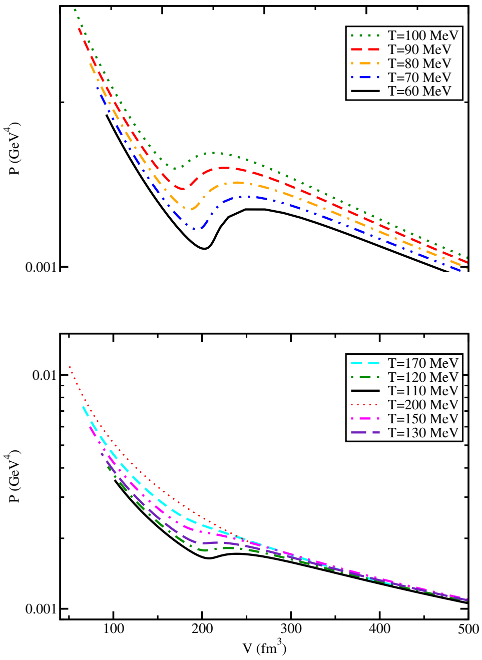

FIG. 1: Pressure as a function of volume at various characteristic temperatures

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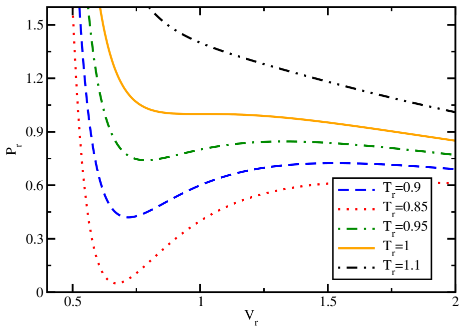

FIG. 2: Vander Waals type plots from PNJL model

obtained from Eqn.(2) as function of chemical potential, μ. Here, we are considering only quark chemical potential by assuming charge or strange chemical potential as zero. In order to obtain the constituent masses and thereby the volume, V from Eqn.(2) at various characteristic temperatures, we have varied μ_q keeping μ_Q and μ_S fixed at zero. The Pressure, P in Fig.(2) show non-monotonic behaviour with V. The results are portrayers of the quantum level interactions present in the system among the associated degrees of freedom. Also the modified potential in Polyakov loop part, mimicking to some extent the interactions present among gluonic degrees of freedom in Lattice QCD [2], also has a considerable effect. From any one isotherm below T=160 MeV, we can get the idea of the corresponding μ_q where a transition happens indicating a critical point on the phase diagram, using the V-μ relation. The transition point is signified by the minima present in the corresponding isotherms. For T>160 MeV, any such minima are absent as the system then resides entirely in the QGP region, no matter what the chemical potential is. This result is quite commensurate with the QCD phase diagram and hence T$\sim$160MeV can be considered as the cross-over transition temperature at $\mu_q = 0$, as extracted from the model study. This agrees quite satisfactorily with Lattice QCD results at continuum limit [3, 4] and as predicted by our earlier study[2, 5, 6].

The results appear simpler to explain if we look for isotherms with reduced Pressure, P_r and reduced Volume, V_r in Fig.(2) as was done by Van Der Waal.

The presence of non-monotonicities below T_r=1 signifies the interactions present causing transitions occuring in the system at particular chemical potential for one characteristic temperature. These critical temperatures and chemical potentials fall on the phase diagram shown in [2] for six-quark interactions. Below T_r=1, the isotherms therefore represent various states which could be unstable or metastable. Above T_r=1, the system comprises of quarks only and hence possibility of phase transition does not occur. Similar results had also been shown in [8], for normal nuclear matter with corrections from Quantum Statistical effects.

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