Towards laboratory detection of topological vortices in superfluid phases of QCD

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Topological defects arise in a variety of systems, e.g., vortices in superfluid helium to cosmic strings in the early universe. There is an indirect evidence of neutron superfluid vortices from glitches in pulsars. One also expects that topological defects may arise in various high baryon density phases of quantum chromodynamics (QCD), e.g., superfluid topological vortices in the color flavor locked (CFL) phase. Though vastly different in energy/length scales, there are universal features, e.g., in the formation of all these defects. Utilizing this universality, we investigate the possibility of detecting these topological superfluid vortices in laboratory experiments, namely heavy-ion collisions. Using hydrodynamic simulations, we show that vortices can qualitatively affect the power spectrum of flow fluctuations. This can give unambiguous signal for superfluid transition resulting in vortices, allowing for check of defect formation theories in a relativistic quantum field theory system, and the detection of superfluid phases of QCD. Detection of nucleonic superfluid vortices in low energy heavy-ion collisions will give opportunity for laboratory controlled study of their properties, providing crucial inputs for the physics of pulsars.

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I. INTRODUCTION

Topological defects are typically associated with symmetry breaking phase transitions. Due to their topological nature, they display various universal properties, especially in their formation mechanism and evolution. This has led to experimental studies of defect formation in a range of low energy condensed matter systems, e.g., superfluid helium, superconductors, liquid crystals etc.\cite{1,2} which have utilized this universality and have provided experimental checks on various aspects of the theory of cosmic defect formation, usually known as the Kibble mechanism \cite{3}. However, it is clearly desirable to experimentally test these theories also in a relativistic quantum field theory system for a more direct correspondence with the theory of cosmic strings and other cosmic defects.

We address this possibility in this paper and focus on heavy-ion collision (HIC) experiments. One of the main aims of these experiments is to probe the QCD phase diagram which shows very rich features, especially in the regime of high baryon density and low temperatures. FAIR and NICA are upcoming facilities for HIC, dedicated to the investigation of high baryon density phases of QCD. Exotic partonic phases e.g., two flavor color superconducting (2SC) phase, crystalline color superconducting phase, color flavor locked (CFL) phase, \cite{4} etc. are possible at very high baryon density. Transitions to these phases is associated with complex symmetry breaking patterns allowing for a very rich variety of topological defects in different phases. Even at moderately low baryon densities, nucleon superfluidity (neutron superfluidity and proton superconductivity) arises. The CFL phase occurs at very high baryon densities, with baryon densities at least an order of magnitude higher than the nuclear saturation density ($\rho_0$), and temperatures up to about 50 MeV, whereas nucleonic superfluidity occurs at much lower densities, of order $(10^{-3} - 1)\rho_0$, and temperatures as low as 0.3 MeV. Interestingly, this entire vast range of densities and temperatures may be accessible at the facilities such a FAIR and NICA. As we noted above, irrespective of the energy scale, universality of defect formation allows us to infer reasonably model independent predictions about qualitative effects arising from vortex formation from these different phase transitions.

In the present day universe, superfluid phases of nucleons are expected to exist inside neutron stars \cite{5} and resulting vortices are supposed to be responsible for the phenomenon of glitches \cite{6}. No such observational support exists yet for the high density phases of QCD (e.g., CFL phase) in any astrophysical object. In an earlier paper, some of us have proposed the detection of such phase transitions by studying density fluctuations arising from topological defect formation and its effects on pulsar timings and gravitational wave emission \cite{4,8}.

All of the HIC investigations in the literature probing the high baryon density regime of QCD have focused primarily on signals related to the quark-hadron transition. We propose a somewhat different line of focus at these experiments. Some of these exotic high baryon density partonic phases also have superfluidity. For example, the CFL phase corresponds to the spontaneous symmetry breaking pattern, $SU(3)_{\text{color}} \times SU(3)_L \times SU(3)_R \times U(1)_B \rightarrow SU(3)_{\text{color} + L + R} \times Z_2$. Superfluidity arises from spontaneous breaking of $U(1)_B$ to $Z_2$ as the diquark condensate for the CFL phase is not invariant under $U(1)_B$ baryon number transformations. This is also expected in
somewhat lower density phases (where effects of heavier strange quark become important) such as the CFL+$K^0$ phase [9]. In HIC, if any of these phases arise, a superfluid transition will inevitably lead to production of superfluid vortices via the Kibble mechanism [3].

Similarly, for relatively lower energy heavy-ion collisions, the hot nucleonic system formed in the collisions may undergo transition to nucleonic superfluid phase as it expands and cools. This will again lead to the formation of nucleonic superfluid vortices via the Kibble mechanism. Note, these are precisely the same vortices which are believed to play crucial role in pulsar glitches, though there they form due to rotation of the neutron star. As we will discuss later, universality of defect formation in the Kibble mechanism tells that defect density of order one will be produced per correlation domain [3]. (For a second order transition, critical slowing down can affect defect formation in important ways, and is described by the Kibble-Zurek mechanism[11].)

It is immediately obvious that the most dramatic effect of presence of any vortices will be on the resulting flow pattern. We carry out detailed simulations of development of flow in the presence of vortices and study qualitative changes in the flow pattern.

II. KIBBLE MECHANISM, VORTEX FORMATION AND LOCAL LINEAR MOMENTUM CONSERVATION

We briefly recall the basic physics of the Kibble mechanism which originates from the formation of a sort of domain structure during a phase transition. The order parameter field (superfluid condensate in this case) is correlated (hence can be approximately taken to be uniform) inside a domain while it varies randomly from one domain to another. Such a picture of domains is very natural for a first order transition via bubble nucleation with each bubble being an independent domain. Even for a second order transition, correlation length size regions correspond to such domains. For a superfluid transition, the phase of the order parameter varies randomly from one domain to another (the magnitude of the order parameter being fixed by the temperature). As the gradient of the phase directly correspond to superfluid velocity, spontaneous generation of flow is inevitable in a phase transition. Further, at the junction of several domains one can find non-zero circulation of flow if the order parameter phase winds non-trivially around the junction. These are superfluid vortices. This picture of formation of vortices is actually very general and applies to the formation of all types of topological defects in symmetry breaking transitions.

However, spontaneous formation of superfluid vortices via Kibble mechanism in a transition from normal to superfluid phase has certain non-trivial aspects which are not present in the formation of other types of topological defects. During phase transition, the spontaneous generation of flow of the superfluid, as mentioned above, is not allowed by local linear momentum conservation. Basically, some fraction of atoms (e.g. $^4$He atoms) form the superfluid condensate during the transition and develop momentum due to the non-zero gradient of the phase of the condensate. The only possibility is that the remaining fraction of atoms (which form the normal component of fluid in the two-fluid picture) develop opposite linear momentum so that the momentum is local conserved. This means that even though order parameter phase gradients are present across different domains generating superfluid flow across different domain junctions, there is no net momentum flow anywhere in the beginning. Note, this argument is somewhat different from the conventional argument of angular momentum conservation for Kibble superfluid vortices where one knows that spontaneous generation of net rotation of the superfluid has to be counter balanced by the opposite rotation of the vessel containing the superfluid. Here, we are arguing for local linear momentum conservation.

The immediate implication of this local linear momentum conservation is that the initial velocity profile for the normal fluid around each vortex formed via the Kibble mechanism should be exactly the same as the velocity profile of the superfluid velocity profile (as determined by the local momentum conservation at the time of vortex formation, depending on relative fraction of the normal fluid and the superfluid). The momentum balance is being achieved locally here, simply by the normal component of fluid recoiling to balance the local momentum generated for the superfluid component. So, basically, some particles fall into a quantum state with non-zero momentum, which, for an isolated system, is only possible when other particles in that part of the system develop equal and opposite momentum. The final picture is then that, spontaneous generation of vortex via the Kibble mechanism leading to superfluid circulation in such a system will be accompanied by opposite circulation being generated in the normal component of the fluid (to balance the momentum conservation).

We mention here an important implication of the above discussion. In standard application of the Kibble mechanism for superfluid $^4$He transition one expects a dense network of superfluid vortices which should be detectable in experiments. However, above arguments show that at the time of formation, superflow and normal flow have opposite flows, so experimental detection may become very complicated. As normal flow will be expected to change in time due to viscous effects one may expect easier detection at later times. However, the vortex network itself evolves and coarsens rapidly in time, thus complicating inference regarding Kibble estimate of vortex formation. In conclusion, counter balancing normal fluid flow which necessarily arises in Kibble mechanism must be accounted for when comparing theoretical predictions with data. We plan to carry out a detailed investigation of this issue in a future work.
III. HYDRODYNAMICAL SIMULATION OF FLOW FLUCTUATIONS WITH VORTICES

We will first focus on superfluid transitions in the high baryon density partonic phase of QCD and later comment on the possibility of low baryon density nucleonic superfluid phase transition. We carry out hydrodynamical simulations of the evolution of a partonic system in the presence of vortices using a two-fluid picture of superfluid. We also consider a range of values for the density fraction of superfluid to normal fluid and study its effect on the signals. The two fluids are evolved, as in our earlier simulations [10], with Woods-Saxon profile of energy density with and without additional density fluctuations (though it does not appear to have crucial effects on our results). It is known that various high baryon density partonic phases (QGP, 2SC, CFL etc.) do not differ much in energy density and pressure [4]. Thus, we evolve the superfluid component with the same equation of state as the normal fluid, which is taken simply to be an ideal gas of quarks and gluons at temperature $T$ and quark chemical potential $\mu_q$ with the energy density $\epsilon$ given as (for two light flavors) [11],

$$
\epsilon = \frac{6}{\pi^2} \left( \frac{7\pi^4}{60} T^4 + \frac{\pi^2}{2} T^2 \mu_q^2 + \frac{1}{4} \mu_q^4 \right) + \frac{8\pi^2}{15} T^4 \quad (1)
$$

with pressure $P = \epsilon/3$. Note, as our interest is only in discussing the hydrodynamics in the partonic phase (and not in the quark-hadron transition), we do not include the bag constant. The energy-momentum tensor is taken to have the perfect fluid form,

$$
T^{\mu\nu} = (\epsilon + P) u^\mu u^\nu - Pg^{\mu\nu} \quad (2)
$$

where $u^\mu$ is the fluid four-velocity. The hydrodynamical evolution is carried out using the equations, $\partial_\tau T^{\mu\nu} = 0$. Note that we do not need to use conservation equation for the baryon current as our interest is only in flow pattern requiring knowledge of $\epsilon$ and $P$ and the ideal gas equation of state relating $P$ and $\epsilon$ does not involve $\mu_q$. The simulation is carried out using a 3+1 dimensional code with leapfrog algorithm of 2nd order accuracy. For various simulation details we refer to the earlier work [10]. The initial energy density profile for both fluid components (normal fluid as well as superfluid) is taken as a Woods-Saxon background of radius 3.0 fm with skin width of 0.3 fm (with appropriate fractions of energy density). We take the initial central energy density $\epsilon_0$ with temperature $T_0 = 25$ MeV and $\mu_q = 500$ MeV as representative values [4]. Initial random fluctuations are incorporated in terms of 10 randomly placed Gaussian of half-width 0.8 fm, added to the background energy density, with central amplitude taken to be $0.4\epsilon_0$.

The initial velocity profile is determined by the fluid rotation around the vortices. For the superfluid part, The magnitude of the fluid rotational velocity at distance $r$ from the vortex center is taken as

$$
v(r) = \frac{v_0}{\xi} \quad (r \leq \xi); \quad v(r) = \frac{v_0}{2r} \quad (r > \xi) \quad (3)
$$

Here $\xi$ is the coherence length. For CFL vortex, estimates in ref. [5] give $v_0 = 1/(2\mu_q\xi)$ and the coherence length is given by

$$
\xi \simeq 0.26 \left( \frac{100 \text{MeV}}{T_c} \right) \left( 1 - \frac{T}{T_c} \right)^{-1/2} \text{ fm.} \quad (4)
$$

As we mentioned above, exactly at the time of formation of the vortex, the velocity profile of the normal component will be opposite, having exactly the same form as that of the superfluid vortex, but with a magnitude appropriate for the fraction of the normal fluid. So, for the normal fluid, the initial velocity profile is taken to be exactly the same as given by Eqn.(3), but with $v_0$ having opposite sign, and suitably scaled for local momentum conservation depending on superfluid density fraction. This will remain as correct profile if the normal fluid has very low viscosity (note, QGP at RHIC energies has low viscosity). However, if the viscosity is significant, then this velocity profile will not be sustained due to differential rotation, and will change in time. We have accounted for this possibility also by considering admixture of velocity profile for viscous fluid with a velocity profile $v(r) \propto r$ at different times (even though we use non-viscous hydrodynamics). We find that this does not affect the qualitative features of our results at all, except that with large fraction of this viscous velocity profile one also gets a non-zero directed flow in the presence of vortices.

We take value of superfluid transition temperature $T_c = 50$ MeV [5]. For the initial central temperature $T_0 = 25$ MeV, resulting values of $\xi = 0.7$ fm and $v_0 = 0.3$ (we take $c = 1$). (Note, even though we use 2-flavor equation of state, we use the estimates of the vortex velocity profile for the CFL phase for order of magnitude estimates.)

Formation of vortices in superfluid transition will be in accordance with the Kibble mechanism as we discussed above. We will not actually simulate the Kibble mechanism here as our interest is not in getting a statistical network of defects. Rather, we want to see effect of a couple of vortices on the resulting flow pattern. As we will see below, for the size of QGP region taken here, the number of superfluid vortices expected here is of order 1. We do not simulate coupled dynamics of normal and superfluid components. Instead, we evolve the two components using separate conservation equations for the two energy momentum tensors. This allows us to simulate a delayed superfluid transition. This models the situation when initial partonic system has too high a temperature (but with appropriate baryon density) to be in the superfluid phase, though it is still in the QGP phase, and subsequent expansion and cooling leads to crossing...
the phase boundary to the superfluid phase. Also, for the case of nucleon superfluidity (to be discussed below), initial high temperatures will lead to normal nucleonic phase, and only at late stages of expansion superfluid phase may arise. In a coupled fluid dynamics, this cannot be achieved as one always has a normal fluid as well as a superfluid component.

For observational signatures, we focus on the power spectrum of flow fluctuations. In a series of papers some of us have demonstrated that just like the power spectrum of CMBR, in HIC also the power spectrum of flow fluctuations has valuable information about the initial state fluctuations of the plasma \[12, 13\]. We will calculate the power spectrum of flow fluctuations and study the information contained in the power spectrum about the initial vortex induced velocity fields. We focus on the central rapidity region (focusing on a thin slab of width 2 fm in z direction at \(z = 0\)) and study the angular anisotropy of the fractional fluctuation in the transverse fluid momentum, \(\delta p(\phi)/p_{av}\), where \(\phi\) is the azimuthal angle, \(p_{av}\) is the angular average of the transverse fluid momentum, and \(\delta p(\phi) = p(\phi) - p_{av}\). This fluid momentum anisotropy is eventually observed as momentum anisotropy of the hadrons which are finally detected. The power spectrum of flow fluctuations is obtained by calculating the root mean square values \(v_{n}^{rms}\) of the \(n_{th}\) Fourier coefficient \(v_n\) of the momentum anisotropy \(\delta p(\phi)/p_{av}\). We use lab fixed coordinates, so event averaged value of \(v_n\) is zero.

We use standard Kibble mechanism, as described above, to estimate the probability of vortex formation. In the CFL phase, superfluidity corresponds to spontaneous breaking of \(U(1)\) symmetry (just like the case for superfluid \(^4\)He, though for \(^4\)He case \(U(1)\) is completely broken while for the CFL phase, \(U(1)\) breaks to \(Z_2\)). In two space dimensions, this leads to probability \(1/4\) for the formation of a vortex (V) or antivortex (AV) per correlation domain \[3\]. For the azimuthal momentum anisotropy in the central rapidity region, the relevant velocity field is essentially two-dimensional. With the correlation length of order 1 fm, and the plasma region which we are taking to have a radius of 3 fm, we expect number of superfluid vortices to be about 2. For definiteness, we will consider cases of 1 vortex, a V-V pair, and a V-AV pair. The locations of these are taken to be randomly distributed in the plasma region. To have clear signals, we have taken definite orientations for the vortices. We consider vortices either pointing along z axis (with random locations) or pointing along x axis (passing through the origin).

IV. RESULTS OF THE SIMULATION

We now present results of the simulations. Fig.1 shows the effect of vortices on the flow power spectrum for a central collision at \(\tau-\tau_0 = 1.68\) fm, (with \(\tau_0 = 1.0\) fm). We mention that with our numerical code, fluid evolution becomes unstable for large times, especially with complex flow pattern with high velocities, hence we show the results at relatively shorter times. However, these qualitative signals will be expected to survive even for longer times, though with possibly smaller magnitudes. As such these will apply to situations of early freezeout, e.g. for smaller nuclei, or for peripheral collisions. Fig.1 shows plots of \(v_{n}^{rms}\) for the cases of no vortex, one vortex, a V-V pair, and a V-AV pair. In all cases, vortices are taken along the z axis with random positions. Noteworthy is a large value of the elliptic flow for the V-AV case (even though this is a central collision). For all cases with vortices we find that the elliptic flow is very large initially (see, also, Fig.2). This is clearly seen in the inset of Fig.1 for the V-AV case which also shows the dependence of elliptic flow on superfluid fraction and its time evolution. This can be detected by its effects on photon or dilepton elliptic flow \[14\] which is sensitive to flow effects at very early stages.

Fig.2 shows the time evolution of the power spectrum for the case with a V-V pair (we find similar results for V-AV case as well). Note difference in the power for even and odd Fourier coefficients at earlier times. (Such a qualitatively different pattern in HIC has only been predicted in the presence of strong magnetic field, as reported in ref. \[15\]). This result also has interesting implications for the CMBR power spectrum. It is known that low \(l\) modes of CMBR power spectrum also show difference in even-odd modes \[16\]. It is possible that this feature may be indicative of the presence of a magnetic field, or presence of some vorticity during the very early stages of the inflation.

Fig.3 presents the case of non-central collisions. Here we consider an ellipsoidal shape for the plasma region as appropriate for a non-central collision with semi-minor axis along the x-axis, and initial spatial eccentricity =

![Graph](image-url)
0.6. Here we plot $v_2$ for a single event (not the rms value), for two cases, a V-AV pair pointing in z direction and located on the x-axis at $x = \pm 1.5 \text{fm}$ respectively, and the other case with a single vortex lying along the x-axis. Both cases show strongly negative elliptic flow at initial stages. Fig.3 also shows large (negative) values of $v_4$ for both these cases which arises from vortex induced elliptic flow being in the orthogonal direction to the shape induced elliptic flow. These large values of negative elliptic flow as well as $v_4$ may be observed if the freezeout occurs at early times (in smaller systems, or in peripheral collisions) and should also leave imprints on other observables such as on $v_2$ for photons [14]. Note that negative elliptic flow can arise in relatively low energy HIC due to squeeze-out effects [17]. However, for low energy collisions (as we discuss below for nucleonic superfluidity), a vortex induced negative elliptic flow is completely uncorrelated to the elliptic shape of the event (which can be inferred from independent observables), hence can be distinguished from the squeeze-out effect. Further, at higher energies (where CFL phase may be expected to arise), no squeeze-out is expected, so a negative elliptic flow can signal vortex formation.

We have also carried out all the simulations with a delay of up to 1 fm in the onset of superfluid transition (following our modeling of the two fluid picture as explained above). The results remain essentially unchanged with various plots showing changes of order only few percent.

V. NUCLEONIC SUPERFLUIDITY FOR LOW ENERGY COLLISIONS

We now discuss the possibility of detecting nucleonic superfluidity in HIC. Though neutron superfluid condensate is expected to exist inside several nuclei, these systems are typically too small to demonstrate bulk superfluid phase and its associated superfluid vortices, as are expected inside a neutron star. Calculations for neutron stars show that nucleonic superfluidity is expected in range of densities from $10^{-3} \rho_0$ (for $^1S_0$ pairing of neutrons) to few times $\rho_0$ (for $^3P_2 - ^3F_2$ pairing). The critical temperature can range from 0.2 MeV to 5 MeV (depending on the nuclear potential used [18, 19]). Temperatures and densities of this order are easily reached in HIC at relatively low energies. For example, at the FOPI-facility at GSI Darmstadt, temperatures of about 17 MeV (with $\rho \sim 0.4 \rho_0$) were reported in Au-Au collisions at 150 MeV/nucleon lab energy [20]. Temperatures of order 4-5 MeV were reported in Au-Au collisions at $E/A = 50$ MeV, at heavy-ion synchrotron SIS [21]. Thus temperatures/densities appropriate for the transition to the nucleonic superfluid phase can easily be reached in HIC. Universality of defect formation implies that the qualitative aspects of our results in this paper (for the CFL phase) will continue to hold even in this lower density regime. FAIR and NICA are ideal facilities for probing even this low energy regime with detectors suitable for measurements with which flow power spectrum analysis can be performed. Detection of signals as discussed in this paper can provide a clean detection of nucleonic superfluid vortices. It is worth emphasizing the importance of focused experiments for creating a nucleonic system of several fm size which can accommodate nucleonic superfluid vortices. Direct experimental evidence of these vortices and controlled studies of their properties can provide a firm basis for our understanding of neutron stars. This is all the more important in view of the fact that gravitational waves from rotating neutron stars and their collisions will be thoroughly probed by LIGO and upcoming gravitational wave detectors.
VI. CONCLUSIONS

We conclude by pointing out the importance of searching for the superfluid vortices during transition to high baryon density QCD phases, or to nucleonic superfluid phase, at FAIR and NICA. Due to universal features of vortex (topological defect) formation, these vortices directly probe the symmetry breaking pattern of the phase transition providing very useful information about the QCD phase diagram. Various high density phases of QCD such as CFL phase etc. are associated with definite symmetry breaking patterns leading to different topological defects. Detection of defects thus directly probes precise nature of symmetry breaking transition occurring in the system. In this sense, this technique has advantage over other observational signatures which depend on equation of state etc. as those quantities can be strongly model dependent (in contrast to the symmetry patterns which are the most universal features of any phase transition). In this context we mention that there has been study of stability of CFL vortices etc. and it is found that for certain parameter range these vortices may be unstable. Even for the unstable case, typical decay time for the vortices will be expected to be at least of order few fm which, though very short time for astrophysical relevance, should be long enough time for these vortices to leave their observational signature in heavy-ion collisions.

It is hard to overemphasize the importance of detecting nucleonic superfluid phase and associated vortices in these experiments which have capability of providing a controlled experimental investigation of the properties of these vortices and associated phases. Till date, there is no direct experimental observation of nucleonic superfluid vortices, though they provide probably the most accurate explanations of pulsar glitches. Thus detection of these in laboratory experiments will strengthen our understanding of pulsar dynamics. The signals we have discussed show qualitatively new features in flow anisotropies signaling the presence of vortices and the underlying superfluid phase in the evolving plasma. These qualitative features are expected to be almost model independent, solely arising from the vortex velocity fields. We mention that one has to properly account for the effects due to jets, resonance decays etc. to properly account for genuine hydrodynamic flow fluctuations. We hope to address these issues in a future work. Also, we have not included error bars in our plots to avoid overcrowding of the plots. The number of events was chosen suitably large (100 events) so that the main qualitative features of the plot are above any statistical fluctuations. (Our focus is mainly on the qualitative patterns of the plots, in the spirit of the universal features of topological vortices forming at varying energy scales, and not on precise numerical value.) As we mentioned, due to universality of defect formation, similar signals are expected from nucleonic superfluid vortices which can arise in low energy HIC providing direct experimental access to the physics of pulsars.

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