CAN CP-VIOLATION BE OBSERVED IN HEAVY-ION COLLISIONS?

I.B. Khriplovich and A.S. Rudenko

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

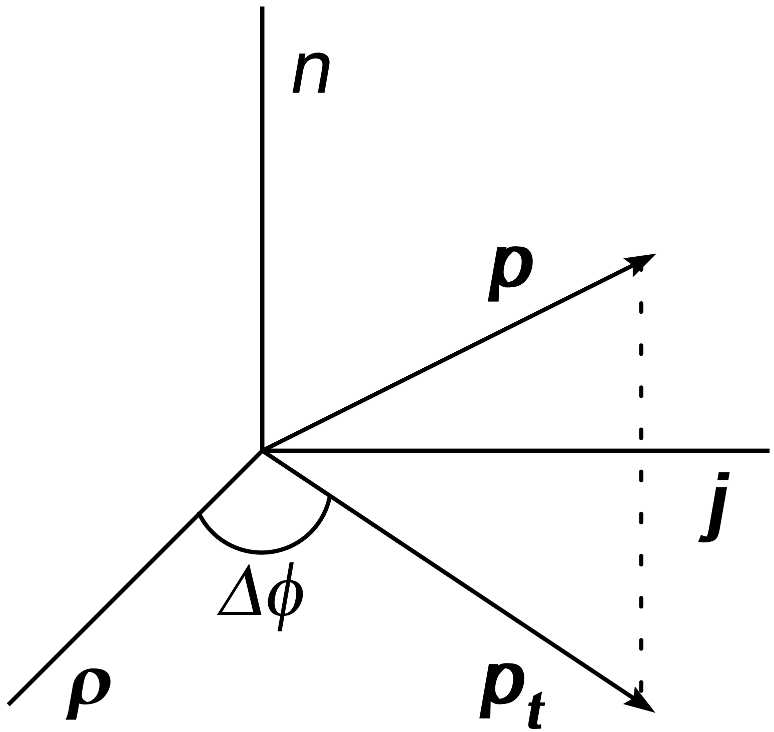
A few years ago it was predicted that in the hot and dense matter created in the collisions of ultrarelativistic heavy nuclei, metastable regions may form with nonvanishing values of the θ-term $\theta \widetilde{F} F$, locally violating CP-invariance (Kharzeev et al).

To search for the effect, few P- and T-odd correlations of momenta of the pions produced in the collisions have been proposed, for instance,

$$\left(\sum_{\pi^+ \pi^-} \frac{\mathbf{p}_+}{|\mathbf{p}_+|} \times \frac{\mathbf{p}_-}{|\mathbf{p}_-|} \right) \left(\sum_{\pi^+} \mathbf{p}_+ - \sum_{\pi^-} \mathbf{p}_- \right) . \qquad (1)$$

$\mathbf{p}_\pm$ are the momenta of $\pi_\pm$-mesons, respectively.

Numerical simulations (Finch et al) demonstrate that to observe such momenta correlations too high statistics is required.



Another correlation, $< \cos(\Delta\phi_a + \Delta\phi_b) >$, was considered by S. Voloshin. Here, cosine is averaged over all particles in each event, and over all events; $\Delta\phi_{a,b}$ are the azimuthal angles of the particles a and b counted off the reaction plane $(n\rho)$ (see Figure); therein n is the beam axis, ρ is the impact parameter of colliding nuclei, $\mathbf{j}$ is the unit vector of the total angular momentum, $\mathbf{p}$ is the particle momentum, $\mathbf{p_t}$ is its projection onto the plane orthogonal to n.

This correlator is widely discussed, sometimes however with the claims that its nonvanishing value is the evidence of $\boldsymbol{P}$- and $\boldsymbol{CP}$-violation.

The correlation has been investigated experimentally by STAR Collaboration. If particles $\boldsymbol{a}$ and $\boldsymbol{b}$ have opposite charges, the experimental results are reasonably well reproduced by model simulations. However, there is no such agreement when particles $\boldsymbol{a}$ and $\boldsymbol{b}$ have same charges. In fact, the analogous disagreement takes place for some other, quite common, correlations. Most probably, the reason of the disagreements is some shortcomings of the model simulations themselves.

The discussed correlator is conveniently rewritten as follows:

$$\langle [\mathbf{p}_a \mathbf{p}_b - (\mathbf{p}_a \mathbf{n})(\mathbf{p}_b \mathbf{n})] - 2(\mathbf{j}\mathbf{p}_a)(\mathbf{j}\mathbf{p}_b) \rangle \, . \tag{2}$$

Here $\mathbf{j}$ and $\mathbf{v}$ are unit vectors directed along the total angular momentum of the system and along the velocity of one of the beams, respectively; $\mathbf{p}_{a,\,b}$ are the particle momenta.

Obviously, this correlator is P-even and CP-even !

However, correlator (2), being dependent on $(j_m j_n + j_n j_m)$, allows one to find axis along which $\mathbf{j}$ in given event is oriented.

Nobody knows how to measure direction of vector $\mathbf{j}$ and of impact parameter $\boldsymbol{\rho}$. Indeed, let us consider particle distribution in azimuthal angle $\Delta\phi$

$$\frac{dN}{d\phi} \sim 1 + 2v_1 \cos(\Delta\phi) + 2v_2 \cos(2\Delta\phi) + ...$$

$$+2a_1 \sin(\Delta\phi) + 2a_2 \sin(2\Delta\phi) + ..., \tag{3}$$

or

$$\frac{dN}{d\phi} \sim 1 + 2v_1(\boldsymbol{\rho}\,\mathbf{p})/(\rho p) + ... + 2a_1(\mathbf{j}\,\mathbf{p})/p + ... \tag{4}$$

In fact, the $\boldsymbol{P}$-odd correlator $a_1(\mathbf{j}\,\mathbf{p})$ (and those of higher odd orders in $(\mathbf{j}\,\mathbf{p})$) is in principle measurable in the discussed experiments.

Still, with certainly measurable particle momentum $\mathbf{p}$, one can fix in this way the direction of the product $a_1\mathbf{j}$ only, but not the direction of $\mathbf{j}$ itself: to this end, one should know the sign of a_1. The same situation takes place with the vector $\boldsymbol{\rho}$. The P-even correlator $v_1(\boldsymbol{\rho}\,\mathbf{p})$ is also measurable. But here as well one can fix the direction of the product $v_1\boldsymbol{\rho}$ only, but not the direction of $\boldsymbol{\rho}$ itself.

At last, the analogous line of reasoning applies to the idea (STAR Collaboration) of measuring the global polarization of Λ-hyperons created in the heavy-ion collisions. It consists in looking for correlation of the Λ-hyperons polarization $\boldsymbol{\zeta}$ with the direction of the system angular momentum $\mathbf{j}$: the sign of the corresponding "coupling constant" α in the correlation $\alpha(\boldsymbol{\zeta}\mathbf{j})$ cannot be found independently.

Coming back to the $\boldsymbol{P}$- and $\boldsymbol{T}$-odd correlations, even their detection on the level $\lesssim \mathbf{10^{-3}}$ in the heavy-ion collisions would not mean by itself that $\boldsymbol{CP}$-violation takes place. Indeed, at the discussed energies $\sim \mathbf{100}$ GeV/nucleon, the effects of parity violation, due to the exchange by the $\boldsymbol{W}$- and $\boldsymbol{Z}$-bosons, can be on the relative level of $\mathbf{10^{-3}}$. Then, the rescattering of produced hadrons due to the strong interactions among them, in particular the final-state interaction, transforms these $\boldsymbol{P}$-odd correlations into $\boldsymbol{P}$- and $\boldsymbol{T}$-odd ones (Zhitnitsky et al, Finch et al), roughly on the same level of $\mathbf{10^{-3}}$.

On the other hand, irrespective of the idea of the spontaneous $\boldsymbol{CP}$-violation, one should expect that the $\boldsymbol{P}$-odd correlation $\boldsymbol{a_1}(\mathbf{j\,p})$ will be regularly present, roughly on the mentioned level of $\mathbf{10^{-3}}$.

One more signature of possible CP-violation in heavy ion collisions could be CP-forbidden decays $\eta, \eta' \to \pi\pi$.
(Kharzeev et al, Zhitnitsky et al, Millo and Shuryak)

It is far from being clear whether one can reconcile demands arising here:

1) Discussed decays should occur in a sufficiently hot and dense medium where nonvanishing values of the θ-term $\theta\widetilde{F}F$, locally violating CP-invariance, do exist outside and/or inside η-, η'-mesons.

2) Medium should be sufficiently rarefied, so that one could talk sensibly about distinct mesons such as η, η', and π.

In addition, the peaks in the invariant mass of the produced pions should be strongly smoothed out due to the rescattering in the hadronic medium.

We note also that there are strong disagreements among quantitative predictions for the magnitude of this effect made in different models: the estimates for the fraction of η's decaying via forbidden channels vary from $\sim 10^{-1}$ (Zhitnitsky) to $\sim 10^{-3}$ (Millo and Shuryak).

At least, at present there is no convincing way to detect CP-violation in heavy-ion collisions.