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Can CP-violation be observed in heavy-ion collisions?

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Abstract

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

A few years ago the idea was put forward according to which in the hot and dense matter created in the collisions of ultrarelativistic heavy nuclei, metastable regions may form with non-vanishing values of the θ-term $\theta F\tilde{F}$ locally violating CP-invariance [1].

Certainly, the experimental observation of this local CP-violation would be extremely interesting. To search for the effect, a few P- and T-odd correlations of momenta of the pions produced in the collisions have been proposed, for instance, [2]

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

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

However, numerical simulations [3] have demonstrated that to observe momenta correlations on the level predicted by the model of local CP-violation, too high statistics is required. We will come back to such correlations below.

One more correlation, $< \cos(\Delta\phi_a + \Delta\phi_b) >$, was proposed and considered in [4]. Here, the cosine is averaged over all particles in each event, as well as over all events themselves. In this expression, $\Delta\phi_a$, $\Delta\phi_b$ are the azimuthal angles of the two-dimensional projections $\mathbf{p}_a$, $\mathbf{p}_b$ of momenta $\mathbf{P}_a$, $\mathbf{P}_b$ of particles a and b, respectively, onto the plane formed by the impact parameter $\boldsymbol{\rho}$ and the angular momentum $\mathbf{j}$; this plane is orthogonal to the collision axis n (see Fig. 1). This correlator is widely discussed, sometimes however with the claims that its non-vanishing value is evidence of P- and CP-violation.

This correlation has been investigated experimentally [5]. In the case when particles a and b have opposite charges, the experimental results for the correlation $< \cos(\Delta\phi_a + \Delta\phi_b) >$ are reasonably well reproduced by model simulations. However, there is no such agreement at all when particles a and 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.

But let us come back to the correlator $< \cos(\Delta\phi_a + \Delta\phi_b) >$. It can be conveniently rewritten as follows:

$$< (\cos\Delta\phi_a \cos\Delta\phi_b + \sin\Delta\phi_a \sin\Delta\phi_b) - 2\sin\Delta\phi_a \sin\Delta\phi_b > \ .$$

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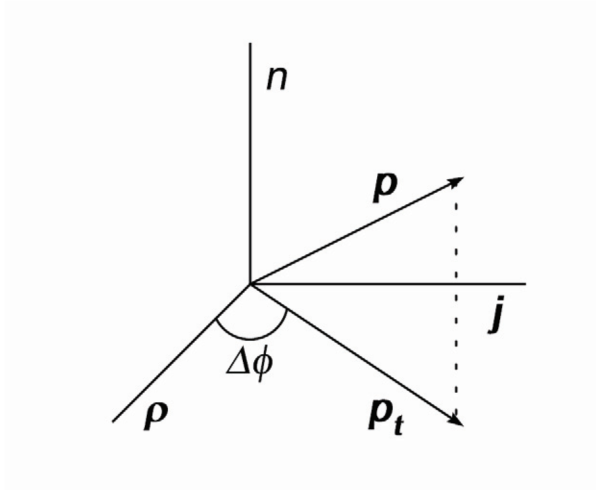

Figure 1: Coordinate system of relevant parameters: ρ .... impact parameter,
j ... angular momentum, n .... collision axis, $\Delta\Phi$ ... azimuthal angle.

In this expression, the term in brackets is proportional to the scalar product of the two-dimensional projections $\mathbf{p}_{a,b}$ of the particle momenta onto the plane (ρj), and the last term is proportional to the product of the projections of the particle momenta onto the j axis. Thus, this correlator can be conveniently presented as

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

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, the discussed correlator is both P- and T-even, and therefore it has by itself no direct relation to the problem of possible P- and CP-violation in heavy-ion collisions.

On the other hand, correlator (2), being dependent on $(j_m j_n + j_n j_m)$, allows one to find the axis along which the total angular momentum in a given event is oriented.

However, nobody knows (at least, at present) how to measure the direction of the vector $\mathbf{j}$, as well as that of the impact parameter $\boldsymbol{\rho}$. To demonstrate it, let us consider the particle distribution in the azimuthal angle $\Delta\phi$ (see Fig. 1) [6]

$$\frac{dN}{d\phi} \sim 1 + 2v_1\cos(\Delta\phi) + 2v_2\cos(2\Delta\phi) + ...$$
$$+2a_1\sin(\Delta\phi) + 2a_2\sin(2\Delta\phi) + ... \tag{3}$$

For our purpose it can be conveniently rewritten as

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

In fact, the 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 [5]. 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.

And finally, the analogous line of reasoning applies to the idea [7] 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 P- and T-odd correlations, even their detection on the level $\lesssim 10^{-3}$ in the heavy-ion collisions would not mean by itself that CP-violation takes place. Indeed, at the discussed energies $\sim$ 100 GeV/nucleon, the effects of parity violation, due to the exchange by the W- and Z-bosons, can be on the relative level of 10^{-3}. Then, the rescattering of produced hadrons due to the strong interactions among them, in particular the final-state interaction, transforms these P-odd correlations into P- and T-odd ones (see in this connection Refs. [3, 8, 9]), roughly on the same level of 10^{-3}.

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

At last, as one more signature of possible CP-violation in heavy ion collisions, the CP-forbidden decays $\eta, \eta' \to \pi\pi$ were discussed in [1, 8, 9, 10]. However, it is far from being clear whether one can reconcile the demands arising here. On the one hand, the discussed decays should occur in a sufficiently hot and dense medium where non-vanishing values of the θ-term $\theta\widetilde{F}F$, locally violating CP-invariance, do exist outside and/or inside η-, η'-mesons. On the other hand, the medium should be sufficiently verified, 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 $\sim 10^{-1}$ [8] to $\sim 10^{-3}$ [10].

Thus, the only positive point about my presentation at the workshop is that I did not exceed the time allotted to it.

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