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

I.B. Khriplovich$^1$ and A.S. Rudenko$^2$
Budker Institute of Nuclear Physics
630090 Novosibirsk, Russia

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 nonvanishing values of the $\theta$-term $\theta \tilde{F}F$ locally violating $CP$-invariance [1]. Certainly, the experimental observation of this local $CP$-violation would be extremely interesting. Recently, an extended workshop [2] was dedicated to the problem.

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, [3]:

$$\left( \sum_{\pi^+, \pi^-} \frac{p_+}{|p_+|} \times \frac{p_-}{|p_-|} \right) \left( \sum_{\pi^+} p_+ - \sum_{\pi^-} p_- \right) ; \quad (1)$$

here $p_\pm$ are the momenta of $\pi^{\pm}$-mesons, respectively.

However, numerical simulations [4] 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, $\langle \cos(\Delta \phi_a + \Delta \phi_b) \rangle$, was proposed and considered in [5]. Here, the cosine is averaged over all charged particles ($a$, $b$ denote electric charge + or −) 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 $q_a$, $q_b$ of momenta $p_a$, $p_b$ of particles $a$ and $b$, respectively, onto the plane formed by the impact parameter $\rho$ and the angular momentum $j$; this plane is orthogonal to the collision axis $n$ (see the figure). This correlator is widely discussed, sometimes however with the claim that its nonvanishing value is evidence of $P$- and $CP$-violation.

This correlation has been investigated experimentally [6]. In the case when particles $a$ and $b$ have opposite charges, the experimental results for the correlation $\langle \cos(\Delta \phi_a + \Delta \phi_b) \rangle$ 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.

$^1$khriplovich@inp.nsk.su
$^2$a.s.rudenko@inp.nsk.su
But let us come back to the correlator $\langle \cos(\Delta \phi_a + \Delta \phi_b) \rangle$. It can be conveniently rewritten as follows:

$$\langle \cos(\Delta \phi_a \cos \Delta \phi_b + \sin \Delta \phi_a \sin \Delta \phi_b) - 2 \sin \Delta \phi_a \sin \Delta \phi_b \rangle.$$ 

In this expression, the term in brackets is proportional to the scalar product of the two-dimensional projections $q_{a,b}$ of the particle momenta onto the plane $(\rho j)$, 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

$$\langle \left[ (p_a \cdot p_b) - (p_a \cdot v)(p_b \cdot v) \right] - 2 (j p_a)(j p_b) \rangle. \quad (2)$$

Here, $j$ and $v$ are unit vectors directed along the total angular momentum of the system and along the velocity of one of the beams, respectively; $p_{a,b}$ 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 $j$, as well as that of the impact parameter $\rho$. To demonstrate it, let us consider the particle distribution in the azimuthal angle $\Delta \phi$ (see the figure) [7]:

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

For our purpose it can be conveniently rewritten as

$$\frac{dN}{d\phi} \sim 1 + 2 v_1 (\rho p)/(\rho q) + ... + 2 a_1 (j p)/q + ... \quad (4)$$

In fact, the $P$-odd correlator $a_1(j p)$ (and those of higher odd orders in $(j p)$) is in principle measurable in the discussed experiments [6]. Still, with certainly measurable particle momentum $p$, one can fix in this way the direction of the product $a_1 j$ only, but not the direction of $j$ itself: to this end, one should know the sign of $a_1$. The same situation takes place with the vector $\rho$. The $P$-even correlator $v_1(\rho p)$ is also measurable. But here as well one can fix the direction of the product $v_1 \rho$ only, but not the direction of $\rho$ itself.

And finally, the analogous line of reasoning applies to the idea [8, 9] of measuring the global polarization of $\Lambda$ hyperons created in the heavy-ion collisions. It consists in looking for correlation of the $\Lambda$ hyperons polarization $\zeta$ with the direction of the system angular momentum $j$: the sign of the corresponding “coupling constant” $\alpha$ in the correlation $\alpha(\zeta j)$ 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 estimated as $\alpha/\pi \sim 10^{-3}$. 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 [10, 11]), 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 $a_1(j p)$ 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 \cite{1,10,11,12}. 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 nonvanishing values of the \( \theta \)-term \( \theta \bar{F} F \), locally violating \( CP \)-invariance, do exist outside and/or inside \( \eta, \eta' \)-mesons. On the other hand, the medium should be sufficiently rarefied, so that one could talk sensibly about distinct mesons such as \( \eta, \eta' \), and \( \pi \). 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 \( \eta \)'s decaying via forbidden channels vary from \( \sim 10^{-1} \) \cite{10} to \( \sim 10^{-3} \) \cite{12}.

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We are grateful to A.E. Bondar, D.E. Kharzeev, V.A. Novikov, L.B. Okun, E.V. Shuryak, S.A. Voloshin, M.I. Vysotsky, and W.A. Zajc for their interest to our work and useful discussions. The work was supported in part by the Russian Foundation for Basic Research through Grant no. 08-02-00960-a and by Dmitry Zimin’s Dynasty Foundation.

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