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ROUND TABLE DISCUSSION
Elliptic flow in nuclear collisions

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This round table discussion followed the talk by J. Casalderrey-Solana on "Hydrodynamic Flow from Fast Particles", in which the appearance of Mach cones around high-energy jets were discussed.

H. Stöcker:
Di-Jet-Induced Mach Cones where first predicted in [1]. However, I would like to stress the importance of the underlying strong longitudinal, radial and elliptic matter flow due to the high Pressure PQCD of the QGP: This rapid explosion of the plasma (due to the flow) leads to

- Large deformations of the Mach Cone
- Deflection of it's axis in the flows' directions
- Away-side satellites being skewed and broadened.

These effects should be clearly visible in three particle correlations, of which two should be azimuthally far away from the trigger jet axis. This was shown in [2]. And basically there is no way out:
We have to prove that

– we do observe jet-induced Mach waves

if

– we want to claim that we do indeed produce
– a thermalized "state of matter"
– which behaves like a "perfect fluid".

M. Gorenstein:
How can the development of a Mach cone be considered a hydrodynamical phenomenon when it only contains, on average, about 1 particle?

H. Stöcker:
The bulk flow must be subtracted in order to see the effect. It will appear as a ripple on top of a strong v_2.

S. Mrowczynski:
How can we distinguish a Mach cone from Cherenkov radiation?

J. Casalderrey-Solana:
A mach cone can be distinguished because the p_T dependence of the associated particles are different. What we showed is that, due to the Cooper-Fry prescription to transform hydro fields into spectrum, the correlation function developes a peak that moves towards $\pi/2$ as you increase the p_T of the associated particles (although the amplitude decreases exponentially). On the contrary, in the Cherenkov picture, since it is radiation based, the correlation becomes more collinear with p_T associated, that is, closer to π. This was shown in the paper by Koch, Majumder and Wang[3]. So, they have a different $p_{T-associate}$ dependence.

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T. Trainor:
A question to Roy Lacey. Do you consider thermalization to be a necessary condition for elliptic flow? In the conventional hydro picture of HI collisions parton scattering in the first fm/c leads to a thermalized QGP and large pressure. That pressure is converted to transverse flow as a hydrodynamic process. In the case of finite impact parameter the flow field has a second-harmonic or quadrupole component: elliptic flow. Reversing the argument the presence of elliptic flow is taken to indicate the existence of the thermalized QGP. That is a central theme in the RHIC culture.

R. Lacey:
I would say that all results so far are consistent with thermalization.

T. Trainor:
While the pressure/thermalization scenario may be 'sufficient' to explain elliptic flow it has not been proven to be 'necessary.' If there is any alternative explanation the hydro scenario then has no special position relative to data and may be invalid. Alternatively, minijet production followed by parton rescattering (aka jet quenching) in an asymmetric medium may produce the elliptic flow field, not as a hydrodynamic response to early pressure but as a multiple-scattering process. I believe theoretical descriptions of such a process are currently unable to produce the correct flow amplitude, but a conventional pQCD $2 \to 2$ calculation is probably inappropriate. What is needed at large parton density is a molecular dynamics approach.

S. Mrowczynski:
I really think that the observation of elliptic flow and the translation of an asymmetry in configuration space to one in momentum space is a strong indication of thermalization, or, at least, of the importance of secondary processes.

The elliptic flow is essentially a translation of the coordinate space asymmetry (eccentricity) into the momentum space asymmetry. Such a translation naturally appears within the hydrodynamics where the flow is driven by the pressure gradients. Since the hydrodynamics requires, strictly speaking, that the system is in a local equilibrium, the presence of the elliptic flow means that the matter produced at the early stage of heavy-ion collisions achieved at least partial equilibrium with such a short time that the eccentricity is still present. According to the current estimates the time is even below 1 fm/c.

T. Trainor:
A new possibility arises from e^+e^- analysis. Reinhard Stock has made the point for several years that Francesco's statistical model results for e^+e^- (hadrons apparently thermalized at 170 MeV) suggest that hadrons are 'born' into chemical equilibrium in the hadronization process (following Fermi's golden rule). Our recent studies of fragmentation functions (Kettler's talk) indicate that fragments are also 'born' into kinetic equilibrium: the fragmentation function is a maximum-entropy distribution on hadron momentum. No thermalization by successive rescatterings is involved in either aspect of fragmentation.

One can then speculate that fragmentation, as a *quantum mechanical process*, involves a transition from an initial maximum-entropy state of partons in the parent nucleons to a final state which is also inherently maximum entropy (at least when averaged over an ensemble of transitions). It is possible to imagine therefore that the early stage of a HI collision is also a quantum mechanical transition, and the system is 'born' into a form of equilibrium including elliptic flow if nonzero impact parameter is a boundary condition.

V. Koch:
Let me give an example where thermalization is not necessary for elliptic flow. Enclose a set of electrons in an elliptic container and let them interact only through the Coulomb force.

R. Stock:
Instead of a pressure gradient you then have a force gradient, right?

V. Koch:
Yes, but equilibration is not necessary. Having long–range forces, however, is a requirement. I would like to point out that this hypothesis or toy model can actually be tested with D–mesons.

References

[1] H. Stöcker, Nucl. Phys. A **750** (2005) 121 [arXiv:nucl-th/0406018].

[2] L. M. Satarov, H. Stöcker and I. N. Mishustin, Phys. Lett. B **627** (2005) 64 [arXiv:hep-ph/0505245].

[3] V. Koch, A. Majumder and X. N. Wang, Phys. Rev. Lett. **96** (2006) 172302 [arXiv:nucl-th/0507063].