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Density oscillations of nuclear matter probed via bremsstrahlung photons

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From the extended experimental data on hard-photon ($E_\gamma > 30$ MeV) production at intermediate energies obtained during the last decade and from dynamic phase-space simulations of heavy-ion collisions, the dominant source of hard-photons has been attributed to the bremsstrahlung radiation emitted in first-chance proton-neutron (pn) collisions. Therefore, hard photons probe the phase-space distribution of the nucleons in the collision zone and convey information on the dynamics of the collision in its early stage.

Aside of the aforementioned dominant source which produces *direct* hard-photons, at intermediate energies BUU calculations predict the existence of a second source of pn bremsstrahlung photons occurring at a later stage of the heavy-ion collision when the system is almost fully thermalyzed, *thermal* hard-photons. A dense system is formed in the first stage of the collision, which then slowly expands until the attractive part of the nuclear force is strong enough to drive a second compression of the system. It subsequently undergoes oscillations around the saturation density. The strength of the restoring force (attractive below ρ_0 and repulsive above) depends on the incompressibility of nuclear matter K_∞: for large values the restoring force is larger than for small ones, so the second compression produces higher densities for larger K_∞.

Therefore there are two distinct hard-photon sources clearly separated in time because of the absence of photon production during the expansion phase. The second source is characterized by a softer energy spectrum, since in the later stage of the collision the energy available in the center-of-mass of pn collisions is, on average, smaller than that at the beginning of the collision. At higher bombarding energies the expansion is sufficiently violent to breakup the system into many fragments and no thermal hard-photons are produced.

Experimentally we have searched for the existence of this second photon source by analysing the energy spectra of inclusive and exclusive hard-photons and the photon-photon correlation function for three different systems.

The exclusive spectra were measured in coincidence with light-charged particles and projectile-like fragments enabling a selection on impact parameter. The slope parameters and the production rates follow the predicted behaviour: the thermal component is softer than the direct one and the production rate of thermal photons is largest for the heaviest system and the lowest bombarding energy. Because direct photons are produced in *first-chance* pn collisions their production rate does not depend on K_∞. In contrast, thermal photons are very sensitive to the amplitude of the density oscillation and thus to K_∞. It should be emphasized that K_∞ is deduced from the relative yield of thermal to direct hard-photons, thus making this method almost independent of the choice of the nucleon-nucleon cross-section. Comparing the measured relative rates of the hard-photon production to the ones calculated with BUU we obtain the value $K_\infty = (290 \pm 50)$. The exclusive spectra show clearly that the thermal-photon relative intensity and slope are lower for peripheral collisions, as one should expect since the compression effects are less important in these. We thus conclude that the two components observed in the experimental hard-photon spectrum confirm the predicted existence of a thermal hard-photon source in addition to the dominant hard-photon production in first-chance nucleon-nucleon collisions.

A more powerful tool to characterize the properties of the photon source is provided by the technique of Bose-Einstein correlations (or intensity interferometry) between independent hard-photons, which allow to determine directly the collision geometry. The two-photon correlation function provides a direct mapping of the Fourier transform $\varrho(q)$ of the space-time photon-source distribution $\rho(r)$:

$$C_{12}(q) = 1 + \lambda|\varrho(q)|^2 , \tag{1}$$

and therefore gives access to information on the medium from which they are emitted.

To study the effect of a secondary photon-source displaced in space-time by the four-vector Δr, we have assumed that both sources have the same distribution $\rho(r)$ and we have called A_D the relative intensity of direct hard-photons and $A_T = 1 - A_D$ the one of thermal hard-photons. The interference term is then modulated by a factor depending on the relative intensities of the two sources and on their space-time separation:

$$C_{12}(q) = 1 + \lambda|\varrho(q)|^2\{A_D^2 + A_T^2 + 2A_DA_T\cos(q\Delta r)\} . \tag{2}$$

In the case of no density oscillation, i.e. one source, as would happen at bombarding energies high enough to break the system into fragments, $A_T = 0$, and Eq. (2) reduces to Eq. (1).

This analysis has been applied to the data measured for two of the three systems studied in order to demonstrate the high sensitivity of the correlation technique to the characteristics of the photon source. The study of the projection of the experimental correlation functions onto the Lorentz-invariant relative four-momentum $Q = (\mathrm{q}^2 - q_0^2)^{1/2}$ shows that in the case of the lighter system the correlation function exhibits at small Q a clear Gaussian-like pattern, which analysed in terms of Eq. (1) corresponds to a large photon-source, while in the case of the heavier system no Gaussian-like pattern is observed. We therefore conclude that Eq. (1) that assumes one space-time source cannot represent the experimental correlation functions.

We have then analysed the correlation functions in terms of Eq. (2) and found that the assumption that hard photons are emitted from two distinct sources leads to an excellent agreement with the data. The effect of the second source is to attenuate for the light system the Gaussian pattern expected in the correlation function and to completely wash out the pattern for the heavy system where the intensities of both sources are equal. The values deduced for the source size follow the size of the compound system, demonstrating that the observed effect is related to the size of the colliding heavy-ions; the values deduced for the relative intensity of direct hard-photons are in excellent agreement with the relative intensity A_D predicted by BUU calculations.

In conclusion, we have shown that the hard-photon energy spectra and correlation functions measured for several systems different in size and bombarding energy cannot be interpreted with the assumption of a single photon-source. By introducing a second photon-source we obtain a good description of the data. This observation is in agreement with the reaction mechanism expected for heavy-ion collisions at low-intermediate bombarding energies leading to the formation of a hot nucleus oscillating in a monopole mode. It confirms also the prediction of the BUU calculation that bremsstrahlung photons are emitted during each compression phase. We have therefore at hand with hard photons a probe emitted at two very different stages of the collision, the initial one when nuclear matter is formed at high densities and the second one when nuclear matter reaches again high densities but is already thermalized. This result opens new opportunities to study the properties of hot and dense nuclear matter.

References

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