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# Bremsstrahlung photons as a probe of hot nuclei ★

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**Abstract**

Aside from the dominant production of hard photons in first-chance p–n collisions, a significant hard-photon production in a later stage of heavy-ion reactions is predicted by the BUU theory. These *thermal hard photons* are emitted from a nearly thermalized source and still originate from bremsstrahlung produced in individual p–n collisions. The calculations predict that the production of the thermal hard photons is strongly correlated with the incompressibility of nuclear matter. Tentative experimental evidence for their production is found in the hard-photon energy spectra measured in the systems $^{86}$Kr +$^{nat}$Ni at 60.0*A* MeV, $^{181}$Ta+$^{197}$Au at 39.5*A* MeV and $^{208}$Pb+$^{197}$Au at 29.5*A* MeV.

Heavy-ion collisions in the energy domain from a few tens of *A* MeV up to about 2*A* GeV offer a unique possibility to study hot and dense nuclear matter far away from its equilibrium state. However, the exploration of the phase diagram of nuclear matter by heavy-ion collisions is dynamical, since the extreme conditions in temperature and density are formed transiently during the reaction. Therefore, to understand the underlying physics and to link it to the nuclear equation of state (EOS) specific reaction probes sensitive to the dynamics of the reaction and a reliance on models are required.

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Collective observables like the transverse flow have been proposed as a sensitive probe for the EOS. However, the flow pattern results from a subtle mixture of several effects: the EOS, the medium effects on the nucleon–nucleon interaction and the momentum dependence of the nucleon–nucleon interaction [1–4]. Aside from collective variables such as flow, the emission of particles like nucleons, mesons, photons and dileptons may yield complementary information on the EOS. Among these, the photons are of particular interest because they are not subject to final-state interactions. However, the bombarding energy domain in which hard photons can be used as probes is restricted to intermediate energies below roughly 100*A* MeV in which the contribution of photons from neutral pion decay is still weak.

From the extended experimental data on hard-photon production at intermediate energies obtained during the last decade (see, e.g., [5,6]) and from dynamic phase-space simulations of heavy-ion collisions [5] the dominant source of hard photons, i.e., photons with energies larger than 30 MeV, has been attributed to the bremsstrahlung radiation emitted in first-chance p–n collisions. Since the relative velocities of the colliding nucleons result from a superposition of the projectile velocity and the Fermi motion of the nucleons in projectile and target, at intermediate energies, at which the projectile velocity is comparable to the velocity associated with the Fermi momentum, 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 [7].

Aside from the aforementioned dominant source which produces what we shall call *direct* hard photons, BUU calculations [8] have predicted the existence of a second source of n–p bremsstrahlung photons occurring at a later stage of the heavy-ion collision when the system is almost fully thermalized, as can be deduced from the quadrupole moment in momentum space [8]. The photons originating from this source we call *thermal* hard photons and are distinct from the statistical photons emitted by a compound nucleus [9]. Using the CASCADE code [10] we have verified that the photon emission from the compound nucleus is negligible. Less than 5% of the statistical photons contribute to the photon spectrum at 30 MeV when the compound nucleus excitation energy is 100 MeV, a value deduced from a fit of the CASCADE calculation to the photon spectrum between 5 and 20 MeV. We present in this and in the following Letter [14] the first experimental evidence for the thermal hard photons. In addition we have performed BUU calculations which show the sensitivity of the relative yield of these thermal hard photons to the incompressibility of the EOS. To simulate the hard-photon production we have used transport equations of the Boltzmann-Uehling-Uhlenbeck type [11,12]. For the interaction between particles we employed a Skyrme-type mean-field potential, the Coulomb force for charged particles and a Yukawa force to get the proper surface properties [5]. The momentum dependence plays in the present case a negligible role because of the low relative velocities of the nucleons. The model used for the calculations, of which a detailed description is given in [5,11,12], successfully describes the ground state of nuclei and the particle production in the energy regime under consideration [5].

Calculations predict that at intermediate energies, typically below 50*A* MeV, the dominant reaction mechanism for a symmetric system in central heavy-ion collisions is incomplete fusion. In the first stage of the collision a dense system is formed ($\rho \sim 1.4\ \rho_0$) which then slowly expands until the attractive part of the nuclear force is strong enough to drive a second compression of the system. The system subsequently undergoes oscillations around the saturation density and a hot nucleus is formed. The strength of the restoring force (attractive below $\rho_0$ and repulsive above) depends on the incompressibility of nuclear matter $K_\infty$: for large $K_\infty$ the restoring force is larger than for small $K_\infty$, so the second compression produces higher densities for larger $K_\infty$. Direct hard photons are produced in the first stage in which they probe dense but relatively cold nuclear matter, while thermal hard photons are produced in the later stage when dense and hot nuclear matter is formed. For simplicity and because of the diminishing rate with time of thermal hard-photon production, we shall consider only one oscillation as depicted in Fig. 1, which shows the spatial evolution of a central $^{181}$Ta+$^{197}$Au collision at 40*A* MeV as obtained from the model calculation. At higher bombarding energies (approximately larger than 100*A* MeV) the expansion is sufficiently violent to breakup the system into many fragments and no thermal hard photons are produced.

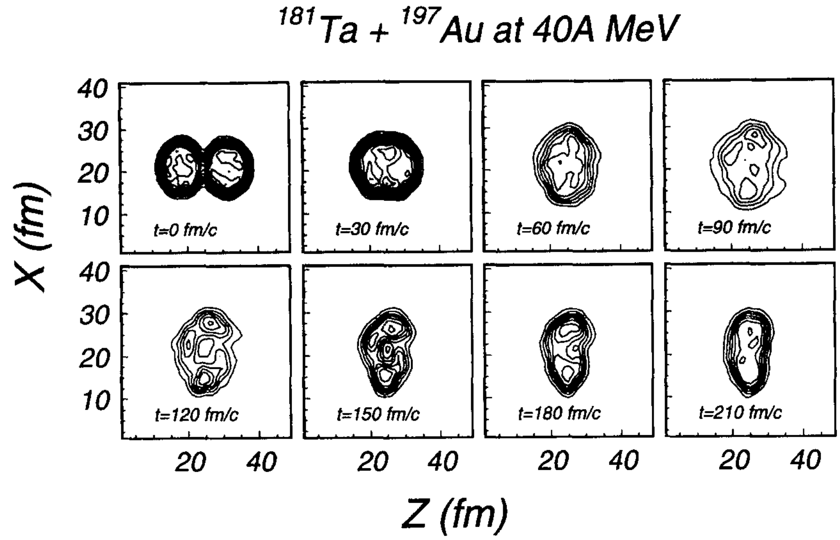


Fig. 1. Spatial evolution of a central collision in the nucleus–nucleus center of mass frame obtained with BUU calculations for the system $^{181}$Ta+$^{197}$Au at 40$A$ MeV.

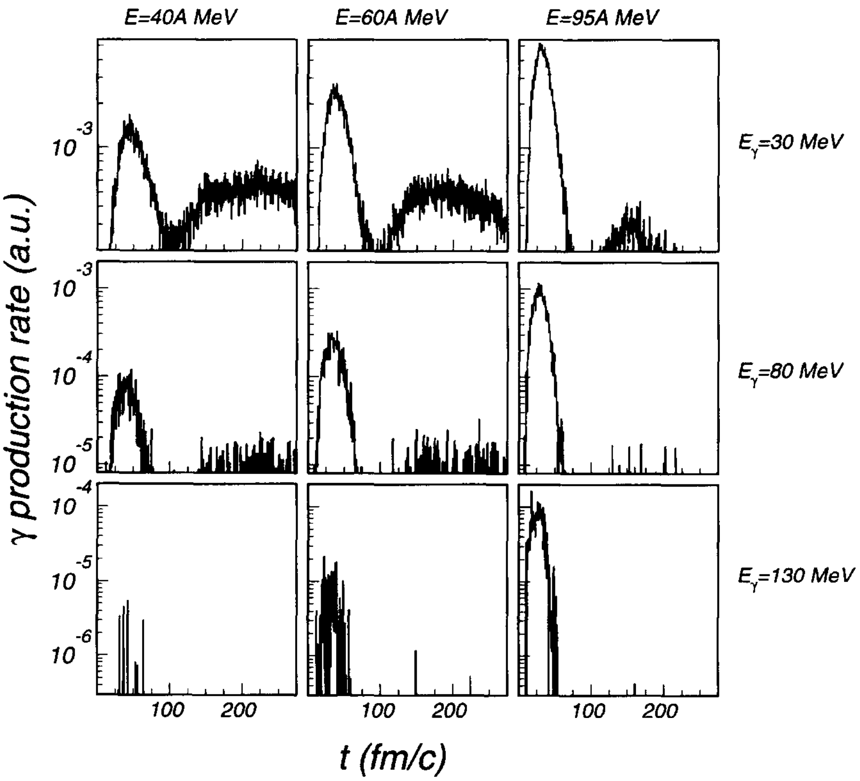


Fig. 2. Production rate of photons with energies of 30, 80 and 130 MeV obtained with BUU for the system $^{181}$Ta+$^{197}$Au at 40, 60 and 95$A$ MeV. The impact parameter was $b = 5$ fm.

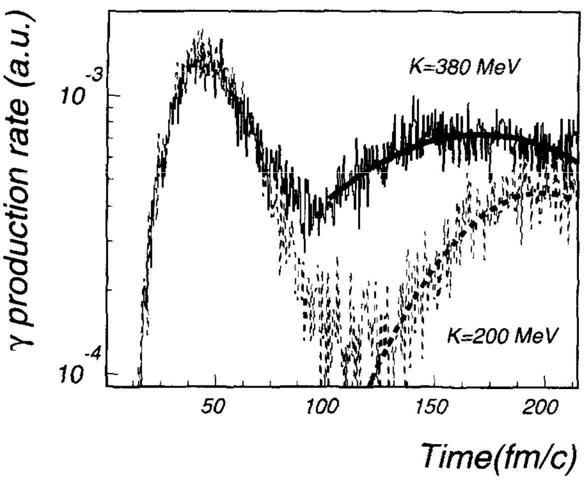


Fig. 3. Production rate of photons with an energy of 30 MeV as a function of the incompressibility $K_\infty$ of nuclear matter obtained with BUU for the system $^{181}$Ta+$^{197}$Au at 40$A$ MeV and $b = 5$ fm.

The computed production rates of hard photons with energies of 30, 80 and 130 MeV are shown as a function of the collision time in Fig. 2. They were calculated for the system $^{181}$Ta+$^{197}$Au at 40, 60 and 95$A$ MeV bombarding energies and at an impact parameter of $b = 5$ fm. There are two distinct hard-photon sources clearly separated in time because of the absence of photon production during the expansion phase. As expected the thermal hard-photon production decreases with increasing beam energy and it almost disappears at 95$A$ MeV as the system has fragmented. The figure indicates also a radical difference in the energy spectra of photons from the two sources, thermal hard photons having a softer spectrum than direct ones. This reflects the fact that in the later stage of the collision the energy available in the center-of-mass of p–n collisions is, on average, smaller than that at the beginning of the collision. Most importantly the calculations predict that the production rate of the thermal hard photons is very sensitive to the incompressibility modulus $K_\infty$ of infinite nuclear matter since the density oscillations themselves are sensitive to $K_\infty$. This is demonstrated in Fig. 3 where the production rate of hard photons is shown as a function of the collision time for two values of $K_\infty$ (200 and 380 MeV) for the system $^{181}$Ta+$^{197}$Au at 40$A$ MeV and $b = 5$ fm. Because direct hard photons are produced in *first-chance* p–n collisions their production rate does not depend on $K_\infty$. In contrast, thermal hard photons are very sensitive to the amplitude of the density oscillation and thus to $K_\infty$. Their production rate therefore varies strongly with $K_\infty$ by up to a modulus 3 between the two extreme values of $K_\infty$ that we have selected. Such a strong variation implies that the measurement of thermal hard photons provides a new and sensitive method to determine the incompressibility modulus of nuclear matter. It should be emphasized that $K_\infty$ 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. Moreover, here the uncertainty corresponding to the unknown momentum-dependent force and the parameterization of the mean-field potential (which is also unknown above $\rho_0$) do not play any role.

Experimentally we have searched for the existence of thermal hard photons by analyzing the energy spectra of inclusive and exclusive hard photons on one hand and the photon–photon correlation function on the other. The latter analysis in terms of two distinct sources in space and time is presented in the following Letter [14]. First indications for hard-photon production beyond first-chance collisions have already been seen in photon moving-source fits in the asymmetric system Ar+Au at 95 MeV/u [13].

The hard-photon energy spectra have been measured for the systems $^{86}$Kr+$^{\mathrm{nat}}$Ni at 60.0$A$ MeV, $^{181}$Ta+$^{197}$Au at 39.5$A$ MeV and $^{208}$Pb+$^{197}$Au at 29.5$A$ MeV. Photons were detected and identified with the photon spectrometer TAPS [15]. The experimental conditions and the identification methods are described in Refs. [7,16]. The exclusive spectra were measured in coincidence with light-charged particles and projectile-like-fragments enabling a selection on impact parameter [7]. To reduce the Doppler effect we have analyzed the inclusive spectra measured at $\theta_{\mathrm{lab}} = 90°$, while the exclusive spectra were measured over the whole angular range to provide enough statistics. In Fig. 4 we show the inclusive spectra measured for the systems Kr+Ni and Pb+Au and the exclusive spectra measured in central ($b < 5$ fm) and peripheral ($b > 5$ fm) collisions for the system Kr+Ni. The following distribution has been fitted to the data between 30 and 200 MeV for the Kr+Ni system and between 30 and 100 MeV for the Pb+Au system [7]:

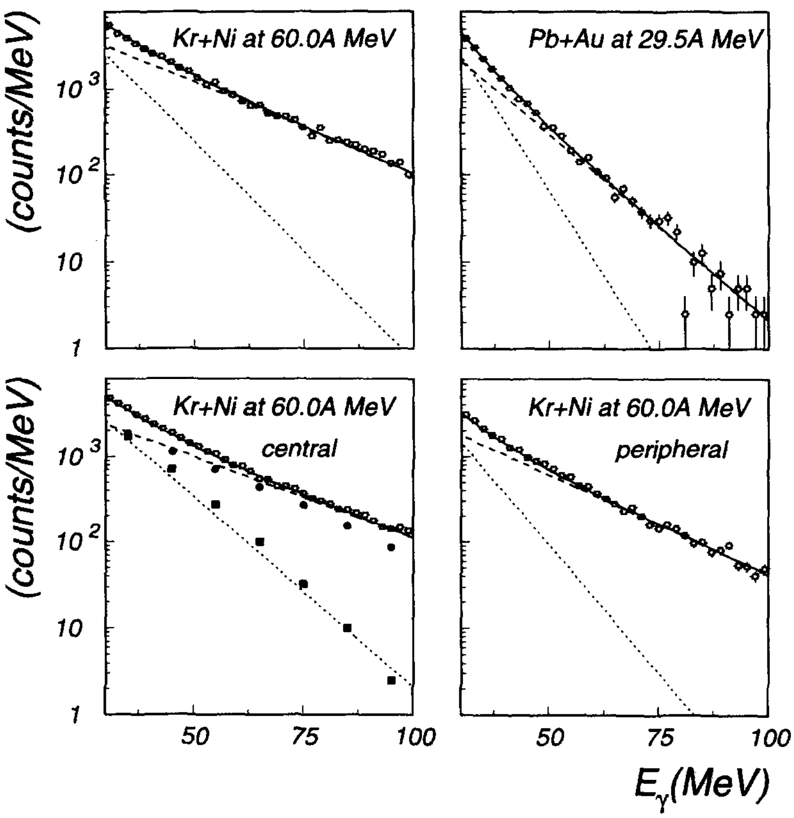


Fig. 4. Experimental spectra of hard photons (inclusive measured at $\theta_{\mathrm{lab}} = 90^\circ$). The full line represents the fit to Eq. (1). Dashed and dotted lines represent the direct and thermal contribution, respectively. For the central collision spectra, we have added the energy spectra predicted by the BUU calculations performed at $b = 0$ fm, scaled by a factor 2. Thermal (solid squares) and direct (solid circles) components are plotted separately.

$$\frac{d\sigma}{dE_\gamma} = \frac{P_0^{\mathrm{thermal}} \exp(30/E_0^{\mathrm{thermal}})}{E_0^{\mathrm{thermal}} \exp(-E_\gamma/E_0^{\mathrm{thermal}})} + \frac{P_0^{\mathrm{direct}} \exp(30/E_0^{\mathrm{direct}})}{E_0^{\mathrm{direct}} \exp(-E_\gamma/E_0^{\mathrm{direct}})}. \quad (1)$$

All parameters were allowed to vary freely and their values are reported in Table 1 for each system. The slope parameters and the production rates follow the predicted behavior: the thermal hard-photon spectrum is softer than that of the direct hard photons and the production rate of thermal photons is largest for the heaviest system and the lowest bombarding energy. The values for $P_0$ were also calculated from the BUU results after the spurious photon production from the ground state [8] has been removed. However since BUU fails to reproduce the high energy part of the photon spectrum (see Fig. 4), the values for $P_0$ were calculated from the time distribution of the photon production rate. Comparing the measured relative rates of the hard-photon production to the calculated ones, we deduce the values for $K_\infty$ reported in Table 1. The errors reflect only the statistical errors on the measured intensity ratios. Taking an average of the three measured values, based on the BUU calculations with a Skyrme type force, we obtain the value $K_\infty = (293 \pm 50)$.

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. On top of the spectra we have added the energy spectra predicted by the BUU calculations performed at $b = 0$, thermal and direct components are plotted separately. The calculation have been scaled down by a factor 2.

Table 1
Parameters characterizing the inclusive and exclusive hard-photon spectra ($E_\gamma > 30$ MeV) in the reactions $^{86}$Kr+$^{nat}$Ni at 60.0*A* MeV, $^{181}$Ta+$^{197}$Au at 39.5*A* MeV and $^{208}$Pb+$^{197}$Au at 29.5*A* MeV, assuming two exponential components (Eq. (1))

| System | $b$ [fm] | $P_0^{direct}/P_0^{thermal}$ | $E_0^{direct}$ [MeV] | $E_0^{thermal}$ | $K$ [MeV] |
|---|---|---|---|---|---|
| Kr+Ni (60.0*A* MeV) | incl. | $3.0 \pm 0.5$ | $20.2 \pm 0.4$ | $8.5 \pm 0.8$ | $314 \pm 50$ |
| | <5 | $2.1 \pm 0.5$ | $22.7 \pm 0.9$ | $9.8 \pm 1.0$ | - |
| | >5 | $3.1 \pm 0.6$ | $18.7 \pm 0.9$ | $7.3 \pm 1.5$ | - |
| Ta+Au (39.5*A* MeV) | incl. | $2.0 \pm 0.6$ | $13.4 \pm 0.8$ | $6.9 \pm 0.6$ | $294 \pm 80$ |
| Pb+Au (29.5*A* MeV) | incl. | $1.6 \pm 0.5$ | $10.1 \pm 0.4$ | $5.5 \pm 0.6$ | $270 \pm 80$ |

We observe an overall agreement between the data and calculations as far as the shape is concerned. At the highest energies ($E_\gamma > 100$ MeV) we observe an increasing discrepancy as the calculation underpredicts the data. This is due to the fact that the calculated photon production rate is cut off when the photon energy reaches the kinematical limit whereas the data indicate no deviation from the exponential distribution up to the highest measured energies [17]. 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.

In summary, we have shown that BUU calculations predict in the energy range where incomplete fusion is the dominant mechanism, a significant production of thermal hard photons which are emitted in a later stage of the collision from a nearly thermal source. We have suggested a novel method, independent of the choice of the nucleon–nucleon cross section, to measure the incompressibility modulus of infinite nuclear matter using the production rate of thermal hard photons. Experimentally, we have measured the production of these photons by analyzing the inclusive and exclusive energy spectra for the systems $^{86}$Kr +$^{nat}$Ni at 60.0*A* MeV, $^{181}$Ta+$^{197}$Au at 39.5*A* MeV and $^{208}$Pb+$^{197}$Au at 29.5*A* MeV, and we have demonstrated the existence of thermal hard photon in as much that their spectrum follows the predicted trend: it is softer than that of hard photons produced in first chance nucleon–nucleon collisions and the production rate increases when the mass of the system is increased, when the bombarding energy is decreased, or when the collision becomes more central. As we show, the measurement of the thermal hard photons offers a promising and novel methode to determine the nuclear compressibility.

From the foregoing we conclude that hard photons convey information on both the states of nuclear matter formed in a heavy-ion collision and the dynamics of the collision which is essential to link the observation to the nuclear matter EOS.

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