Thermal bremsstrahlung probing the thermodynamical state of multifragmenting systems

D.G. d’Enterria\textsuperscript{a,g}\textsuperscript{*}, L. Aphecetche\textsuperscript{a,*}, A. Chbihi\textsuperscript{a}, H. Delagrange\textsuperscript{a,*}, J. Díaz\textsuperscript{d}, M.J. van Goethem\textsuperscript{b}, M. Hoefman\textsuperscript{b}, H. Huisman\textsuperscript{b}, A. Kugler\textsuperscript{e}, H. Loehner\textsuperscript{b}, G. Martínez\textsuperscript{a,*}, R. Ortega\textsuperscript{g}, R. Ostendorf\textsuperscript{b}, S. Schadmand\textsuperscript{f}, Y. Schutz\textsuperscript{a,*}, R. Siemssen\textsuperscript{b}, D. Stracener\textsuperscript{e}, P. Tlustý\textsuperscript{c}, R. Turrisi\textsuperscript{a†}, M. Volkerts\textsuperscript{b}, V. Wagner\textsuperscript{c}, H. Wilschut\textsuperscript{b}, and N. Yahlali\textsuperscript{d}.

\textsuperscript{a} GANIL, BP 5027, 14076 Caen Cedex 5, France
\textsuperscript{b} Kernfysisch Versneller Instituut, 9747 AA Groningen, The Netherlands
\textsuperscript{c} Institute of Nuclear Physics, 250 68 Rež, Czech Republic
\textsuperscript{d} IFIC, Universitat de València-CSIC, Dr. Moliner 50, 46100 Burjassot, Spain
\textsuperscript{e} Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
\textsuperscript{f} II. Physikalisches Institut, Universität Gießen, 35392 Gießen, Germany
\textsuperscript{g} Grup de Física Radiacions, Universitat Autònoma de Barcelona, 08193 Bellaterra, Catalonia

Inclusive and exclusive hard-photon (E_{\gamma} > 30 \text{ MeV}) production in five different heavy-ion reactions (\textsuperscript{36}Ar+\textsuperscript{197}Au, \textsuperscript{107}Ag, \textsuperscript{58}Ni, \textsuperscript{12}C at 60A MeV and \textsuperscript{129}Xe+\textsuperscript{120}Sn at 50A MeV) has been studied coupling the TAPS photon spectrometer with several charged-particle multidetectors covering more than 80% of 4\pi. The measured spectra, slope parameters and source velocities as well as their target-dependence, confirm the existence of thermal bremsstrahlung emission from secondary nucleon-nucleon collisions that accounts for roughly 20% of the total hard-photon yield. The thermal slopes are a direct measure of the temperature of the excited nuclear systems produced during the reaction.

Nucleus-nucleus collisions constitute the only mean to study in the laboratory the thermodynamical properties of hot and dense nuclear matter and, consequently, to determine the nuclear equation-of-state [1]. Heavy-ion (HI) reactions at bombarding energies between 20A MeV and 100A MeV lead to the formation of chunks of nuclear matter at subnuclear densities and moderate excitation energies in the vicinity of the predicted transition from the Fermi liquid phase to the nucleon gas phase [2]. HI collisions are however dynamical processes involving finite and transient systems. This fact renders difficult the extraction of the thermostastistical properties of infinite nuclear matter at equilibrium. As a matter of fact, several key questions still remain open: Is thermodynamical equilibrium attained? If so, what is the temperature of the excited nuclear systems produced? What is the time-scale of nuclear break-up? Is multifragmentation a signal of the liquid-gas phase transition and/or of the passage through the spinodal region of the phase diagram? To answer these questions, precise experimental probes of the phase-space evolution of the HI collision are needed. This is the primary motivation for the investigation of “el-
elementary” particle production (hard photons, dileptons or mesons) \[3\]. Despite their very small production cross-sections, such energetic particles convey valuable information about the stages of the reaction in which they are created. Among them, photons are very clean probes since, due to their weak electromagnetic coupling to nucleons, they have a small probability of interacting with the surrounding medium and provide a faithful image of the emission source. Hard-photons with \(E_\gamma > 30\text{ MeV}\) have been consistently interpreted as issuing from the bremsstrahlung scattering of protons against neutrons, \(pn \rightarrow pn\gamma\), within the first 50 fm/c of the reaction \[3\][4]. Such prompt photons provide thus valuable information about the two-body dissipation mechanism in the compressed and pre-equilibrium phase of the reaction. During the last 5 years, however, it has been experimentally proven that the production of hard-photons exclusively through first-chance \(NN\) collisions needed to be reconsidered as the existence of a bremsstrahlung emission component of thermal origin emerged \[5–7\]. To confirm the existence of this second-chance bremsstrahlung emission and to exploit its characteristics to extract the thermodynamical properties (temperature, density) of the hot nuclear source(s), two campaigns of the TAPS collaboration were carried out in 1997 and 1998 at the KVI and GANIL facilities. These experiments coupled the TAPS photon spectrometer with several charged-particle multidetectors for \(\gamma\)-particle coincident detection. The heavy-ion reactions studied were \(^{36}\text{Ar}^+^{197}\text{Au}, ^{107}\text{Ag}, ^{58}\text{Ni}, ^{12}\text{C}\) at 60\(A\) MeV and \(^{129}\text{Xe}^+^{120}\text{Sn}\) at 50\(A\) MeV.

1. EXPERIMENTAL RESULTS

The inclusive photon energy spectra in the \(NN\) CM frame have been obtained after correction for the detector response function and subtraction of the cosmic and radiative \(\pi^0\)-decay contributions (Fig. 1). The spectrum of the \(^{36}\text{Ar}^+^{197}\text{Au}\) system\[3\] features two distinct exponential distributions with different slopes, and can be described by \[5\]:

\[
\frac{d\sigma}{dE_{\gamma}} = K_d e^{-E_{\gamma}/E^d_0} + K_t e^{-E_{\gamma}/E^t_0} \tag{1}
\]

For the four heavier targets the slope parameters of the “direct” component \((E^d_0 \approx 15 - 20\text{ MeV})\) are two to three times larger than the “thermal” ones \((E^t_0 \approx 6 - 9\text{ MeV})\) and the contribution of thermal hard-photons represents a 15% - 25% of the total hard-photon yield \[5\][7]. No thermal component is apparent in the photon spectrum of the small \(^{36}\text{Ar}^+^{12}\text{C}\) projectile-target combination and pure direct bremsstrahlung clearly accounts for the whole photon emission above \(E_{\gamma} = 20\text{ MeV}\) (Fig. 1, right).

The slopes of the direct component, \(E^d_0\), follow the known linear dependence with the projectile energy per nucleon in the laboratory \[8\] as expected for pre-equilibrium emission in prompt \(NN\gamma\) collisions \[4\] (the large values of the slope reflect the coupling of the beam energy with the intrinsic Fermi momentum of the colliding nucleons). The thermal hard-photon slopes, \(E^t_0\), at variance, scale with the total energy in the nucleus-nucleus center-of-mass (Fig. 2). This property points to a thermal process taking place during later stages of the reaction after dissipation of the incident kinetic energy among internal degrees of freedom over the whole system in the \(AA\) center-of-mass (the lower slope values reflecting the less energy available in secondary \(NN\gamma\) collisions).

\[^3\text{As well as that of the } ^{36}\text{Ar}^+^{107}\text{Ag}, ^{58}\text{Ni} \text{ and } ^{129}\text{Xe}^+^{120}\text{Sn}\text{ reactions, not shown in Fig. 1}\]
Figure 1. Hard-photon ($E_\gamma > 30$ MeV) spectra measured for the heaviest ($^{36}\text{Ar}+^{197}\text{Au}$, left) and lightest ($^{36}\text{Ar}+^{12}\text{C}$, right) systems and fitted, according to Eq. (1), to the sum of two exponential distributions: a direct (solid line) and a thermal one (dashed line).

Figure 2. Thermal hard-photon slopes as a function of the (Coulomb-corrected) nucleus-nucleus center-of-mass energy for the reactions studied at KVI in 1997 [8], and at GANIL in 1998 [9] and 1992 [7]. The solid line is a linear fit to the data.
The interpretation of the second component of the hard-photon spectrum as being emitted during later stages of the reaction in a thermal process is also confirmed by the study of the (Doppler-shifted) laboratory angular distributions [8]. The hard-photon angular distributions can be well interpreted assuming an emission from a source with slope parameter $E_0^d$ moving with $\beta_S^d \approx \beta_{NN}$ plus an isotropic source with slope parameter $E_0^i$ and $\beta_S^i \approx \beta_{AA}$, with the ratios of thermal to direct intensities being fixed by the energy spectra. This result is consistent with direct hard-photons being emitted from the $NN$ center-of-mass, and thermal hard-photons being emitted isotropically from a slowed-down source moving with the $AA$ center-of-mass velocity.

2. THERMODYNAMICAL PROPERTIES OF THE NUCLEAR SOURCES

The existence of a thermal mechanism accounting for part of the total hard-photon yield, justifies the use of a thermal bremsstrahlung model [10] to extract the thermodynamical properties of the radiating nuclear systems. Such a model predicts thermal photon spectra basically exponential in the region $E_\gamma = 30 - 80$ MeV in agreement with our data. The slopes $E_0^i$ of such exponential spectra are linearly correlated with the local temperature $T$ of the nuclear source according to:

$$T(\text{MeV}) = a \cdot E_0^i(\text{MeV}) - b \quad \text{with } a = 0.75 \pm 0.05 \text{ and } b = -0.65 \pm 0.05 \text{ MeV}(2)$$

The correlation of the temperatures obtained using eq. (2), in the range $T = 4 - 6$ MeV, with the excitation energies attained in each reaction ($\epsilon^* = 4A - 10A$ MeV) yields a “caloric curve” which shows a slightly increasing “plateau” [11]. Such a trend, observed by the ALADIN collaboration, was interpreted as a signal of the nuclear liquid-gas phase transition [4]. This observation disagrees with the higher apparent temperatures obtained using the slopes of the (Maxwell-Boltzmann) kinetic energy distributions of different light-particles ($p$, $n$ or $\alpha$) [12]. However, at variance with ALADIN data, we measure temperatures for nuclear systems around the saturation density ($NN\gamma$ collisions only take place with sizeable cross-sections around or above $\rho_0$). We conclude that the hot radiating nuclear residues are more likely in a liquid-gas coexistence phase in an “evaporation”-like scenario, than undergoing a simultaneous breakup in a dilute state.

REFERENCES

1. G. Peilert, H. Stöcker and W. Greiner, Rep. Prog. Phys. 57 (1994) 533.
2. J. Pochodzalla, Prog. Part. Nucl. Phys. 39 (1997) 443.
3. W. Cassing, V. Metag, U. Mosel and K. Niita, Phys. Rep. 188 (1990) 363.
4. H. Nifenecker and J. Pinston, Ann. Rev. Nucl. Part. Sci. 40 (1990) 113.
5. G. Martínez et al., Phys. Lett. B349 (1995) 23.
6. F.M. Marqués et al., Phys. Lett. B349 (1995) 30.
7. Y. Schutz et al., Nucl. Phys. A622 (1997) 405.
8. D.G. d’Enterria, Proc. V TAPS Workshop, Řež, Sept. 1999, nucl-ex/0007003.
9. R. Ortega, Proc. V TAPS Workshop, Řež, Sept. 1999, Czech Jour. Phys.
10. D. Neuhauser and S.E. Koonin, Nucl. Phys. A462 (1987) 163.
11. D.G. d’Enterria, PhD thesis, U.A. Barcelona and U. Caen, Mars 2000.
12. Y.-G. Ma et al., Phys. Lett. B390 (1997) 41.