Evidence for Stopping in Heavy-Ion Collisions from a Study of Hard-Photon Source Velocities

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(Received 25 October 1993)

We present data on hard-photon production in ^{36}Ar+^{197}Au and ^{36}Ar+^{12}C collisions at 95 MeV/nucleon. The photon source velocity β_S is investigated as a function of system size, photon energy, and impact parameter. In the heavy system, β_S is found to be sizably smaller than $\beta_{\text{beam}}/2$, except for very peripheral reactions. This unambiguously demonstrates that at intermediate bombarding energies photon emission is not solely dominated by first-chance p-n collisions, but carries also information on the later, stopping phase of the reaction.

PACS numbers: 25.70.−z

Hard-photon emission has proven to be one of the cleanest probes of intermediate-energy nucleus-nucleus collisions: High-energy photons are produced directly in the reaction zone and leave it virtually interaction free, offering thus an untainted view of the collision dynamics. Since the first measurements by Beard *et al.* [1], Grosse *et al.* [2], and Alamanos *et al.* [3] a large amount of mostly inclusive data has been accumulated, from which the following gross characteristics emerge [4,5]: (i) Above 30 MeV, i.e., the giant-resonance decay region, the hard-photon spectrum has an exponential shape, with an inverse slope parameter increasing with bombarding energy; (ii) its angular distribution is strongly forward peaked in the laboratory frame, but transformed into the nucleon-nucleon c.m. frame (with $\beta_{NN}=\beta_{\text{beam}}/2$), it is nearly isotropic, with a small dipole component; (iii) its intensity scales with the number of individual leading proton-neutron collisions. Recent exclusive measurements [4,6–9] have shown in addition that the photon multiplicity strongly increases with decreasing impact parameter, until maximum nuclear overlap, and that the energy spectra concomitantly tend to become harder.

This body of experimental evidence has often led to interpret hard photons as bremsstrahlung produced mainly in incoherent first-chance p-n collisions and probing therefore the very early, most violent stage of a nuclear reaction [4,5]. In this picture, subsequent N-N collisions, leading gradually to a complete damping of the relative motion, would contribute only little. On the other hand, in the extreme of complete thermalization, most properties of hard-photon emission can also be described reasonably well in statistical models [10]. A statistical or dissipative mechanism, however, implies more than one generation of N-N collisions and necessarily leads to some degree of stopping of the incoming projectile nucleons. For complete stopping the photons would appear to originate from the nucleus-nucleus c.m. system, rather than from the N-N c.m. system, the velocities of which differ only in reactions between mass-asymmetric partners. In this Letter we present clear evidence for strong deviations of the photon source velocity β_S from β_{NN}, observed in an exclusive study of hard-photon emission in the asymmetric reactions ^{36}Ar+^{197}Au and ^{36}Ar+^{12}C at 95 MeV/nucleon.

In a measurement performed at GANIL, gold targets of 20 mg/cm^2 and carbon targets of 15 mg/cm^2 were irradiated with a 95 MeV/nucleon ^{36}Ar beam of typically 0.5 particle nA. Photons were registered in 320 BaF_2 detectors from the two-arm photon spectrometer TAPS [11], arranged in 5 blocks of 64 scintillators each. The blocks were placed in the horizontal plane at a distance of 62 cm from the target, covering angles from 35° to 165° with respect to the beam axis. Furthermore, all BaF_2 crystals were equipped with individual plastic charged-particle veto (CPV) detectors. This setup yielded a detection efficiency of 12.3% for photons (with $E_\gamma \geq 30$ MeV) and of 1.6% for neutral pions. The BaF_2 signals were timed against the accelerator RF, yielding a FWHM time resolution of ≤ 550 ps. Light charged particles (LCP) were detected and identified in the KVI forward wall (FW) made of 60 plastic-scintillator phoswich detectors [12], covering an angular range of $\theta=3.5°$–24°. Finally, projectilelike fragments (PLF) were registered in the GANIL magnetic spectrograph SPEG [13] positioned at 0°, giving an angular acceptance of $\pm 2.0°$, both horizontally and vertically. With a magnetic field setting at 93.5% of the beam rigidity, we obtained PLF charge and mass resolutions of respectively 0.6 and 0.2

0031-9007/94/72(11)/1608(4)$06.00

units FWHM.

In the data analysis, a very clean separation of γ rays from charged particles and neutrons was achieved by requiring (i) the absence of a signal in the CPV modules in front of the hit BaF_2 modules, (ii) the proper time of flight and, (iii) the correct pulse shape of the BaF_2 signals. For each photon hit the energies of adjacent modules were summed to improve the overall energy resolution. High-energy background, produced by cosmic muons traversing a BaF_2 block and showing up as chance coincidences in the prompt time window, were eliminated by a cut on the lateral extension of the hit pattern in the block. This cut was optimized in Monte Carlo shower simulations, which yielded also the detector response and efficiency for high-energy photons, as well as neutral pions, identified in two-photon events through an invariant-mass analysis. The π^0 peak, with a FWHM mass resolution of 13%, allowed for a direct check of the BaF_2 energy calibration at photon energies up to about 200 MeV.

The response-corrected inclusive photon energy distribution measured for ^{36}Ar+^{197}Au and transformed into the N-N c.m. frame is shown in Fig. 1(a). Besides bremsstrahlung events, this spectrum also contains a sizable contamination from π^0 decay photons. To subtract this energy- and angle-dependent component, amounting to about 30% (50% above 100 MeV), a Monte Carlo simulation has been performed with a π^0 event generator carefully adapted to the simultaneously measured pion energy and angular distributions. The uncertainty on this correction, rising with energy, is estimated at 5%–10%. The resulting clean bremsstrahlung spectrum represented in Fig. 1(b) shows an exponential shape up to the highest measured energies, i.e., 300 MeV, with an inverse slope parameter of $E_0^{NN}=29.0\pm1.4$ MeV in the N-N c.m. frame; a comparable value is found for ^{36}Ar+^{12}C.

From the hard-photon double-differential cross sections the mean velocity of the γ source has been extracted with a two-dimensional moving-source fit. We use the expression proposed in Ref. [4], which contains both an isotropic and a dipole source term:

$$\left(\frac{d^2\sigma}{dEd\Omega}\right)_{\rm lab}=\frac{K}{X}\left(1-\alpha\frac{\alpha\sin^2\theta_{\rm lab}}{X^2}\right)\exp(-XE_\gamma/E_0^S)\,, \qquad (1)$$

with $X=(1-\beta_S\cos\theta_{\rm lab})/\sqrt{1-\beta_S^2}$, where β_S is the source velocity, α describes the dipole component, E_0^S is the energy slope in the source frame, and K is a normalization factor. From these four parameters, left free in the least-square fits, only α has a (rather large) sensitivity to the π^0 subtraction, which we have folded into the error bars. The fits, shown as solid lines in Fig. 2(a), yield values of $\alpha\simeq0.15$ and $E_0^S\simeq29$ MeV for both targets, but quite different source velocities, namely, $\beta_S=0.21\pm0.01$ for the C target and 0.15 ± 0.01 for the Au target. Whereas the photon source velocity found for Ar+C agrees indeed with the nucleon-nucleon c.m. velocity ($\beta_{NN}=0.22\simeq\beta_{\rm beam}/2$), in the Ar+Au system β_S is much lower, but still above $\beta_{\rm Ar+Au}=0.07$. Similar but smaller deviations from β_{NN} had previously been observed by

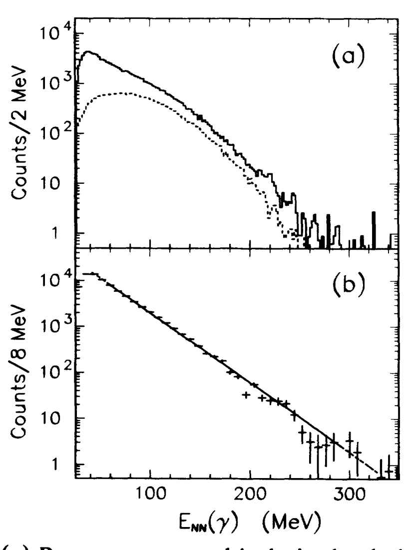

FIG. 1. (a) Response-corrected inclusive hard-photon energy spectrum measured for ^{36}Ar+^{197}Au at 95 MeV/nucleon. The dashed line represents the contribution from π^0 decay photons, as obtained from a GEANT Monte Carlo calculation based on measured π^0 spectra. The drop below 30 MeV is due to a trigger threshold. (b) Pion-subtracted photon spectrum in the N-N c.m. frame; error bars are statistical only; a systematic normalization error of 10% is not shown. The solid line is an exponential fit leading to an inverse slope $E_0^{NN}=29.0\pm1.4$ MeV.

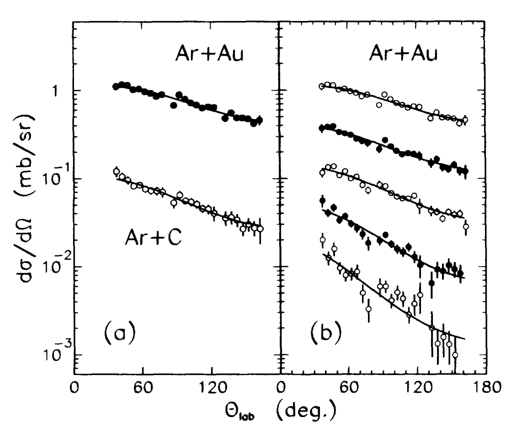

FIG. 2. (a) Bremsstrahlung ($E_\gamma^{\rm lab}\geq30$ MeV) inclusive angle-differential cross sections measured for ^{36}Ar+^{197}Au and ^{36}Ar+^{12}C at 95 MeV/nucleon. Error bars are statistical only; contributions from π^0 decay are subtracted. The solid lines are moving-source fits with Eq. (1), integrated over energy, yielding a bremsstrahlung production cross section of $\sigma_\gamma=9.5\pm1.0$ mb on ^{197}Au and $\sigma_\gamma=0.86\pm0.09$ mb on ^{12}C. (b) Same as (a), but with, from top to bottom, $E_\gamma^{\rm lab}\geq30$, 60, 90, 120, and 150 MeV.

Tam *et al.* [14] in the ^{7}Li+Pb and ^{40}Ar+Pb systems at 30 MeV/nucleon. We have checked that including an additional quadrupole term in Eq. (1) does not change β_S significantly.

We have investigated the behavior of the photon source velocity with increasing photon energy. From the fits shown in Fig. 2(b) for different cuts on E_γ, it appears that in Ar+Au, β_S has a nearly constant value, averaged at 0.15, with a gradual increase to 0.18 ± 0.02 above $E_{\rm cut}=120$ MeV. In parallel, E_0^S increases slightly to 31 MeV, while α decreases, to switch finally to negative values. We can, however, not fully exclude that the later result stems from imperfections at high energies in our subtraction of the π^0 contribution. The fits done for Ar+C display no significant variation with $E_{\rm cut}$.

We have furthermore studied the photon source velocities as a function of impact parameter b. In order to select events with different b, we have required photons with $E_\gamma \geq 30$ MeV in coincidence with light charged particles in the FW, selecting thus central to midperipheral collisions ($b=3$–9 fm), or in coincidence with a projectilelike fragment in the magnetic spectrometer, covering mostly peripheral collisions ($b=8$–11 fm). The FW multiplicity has been related to b through a statistical fragmentation calculation done with the code FREESCO [15] in conjunction with a realistic experimental filter, and the correspondence between the PLF charge and b has been obtained from an abrasion-ablation model [16]; the simulations yield a spread in b of 2.0–4.0 fm FWHM, from peripheral to central collisions. We think that this impact-parameter selection provides a useful measure of centrality, despite its limited selectivity and possible systematic errors [17]. Figure 3 shows a representative sample of bremsstrahlung angular distributions measured in Ar+Au for different selections (A–D); the corresponding moving-source fits are listed in Table I. It clearly appears that as one goes from central ($b\leq 5$ fm) to the most peripheral collisions ($b\geq 9$ fm), β_S increases from 0.14 to 0.21, i.e., approaches β_{NN}. In addition, the inverse slope parameter E_0 decreases slightly, i.e., by about 10%, going from small to large b. Again, in the Ar+C system, no significant changes of the photon spectra with b are observed.

The tendency of β_S to approach β_{NN} only for very large $E_{\rm cut}$ shows that in central Ar+Au collisions at most very high-energy photons can originate from the earliest phase of the reaction: Their energy would thus not be built up in a thermalization process spanning many successive generations of N-N collisions, but would directly stem from the intrinsic momentum distribution of the colliding nucleons. The bulk of the photons is evidently produced over a longer time span and therefore also probes the dissipative reaction phase which finally leads to the thermalization of the fireball. This picture is strongly supported by both the system-size and impact-parameter dependence of β_S: In the small Ar+C system, as well as in peripheral Ar+Au collisions, the resulting zone of participant nuclear matter apparently does not have the necessary volume and/or density to achieve sufficient stopping and consequent thermalization; hence first-chance N-N collisions dominate photon emission. This is in line with the results of Boltzmann-Uehling-Uhlenbeck [18] and time-dependent Hartree-Fock [19] calculations

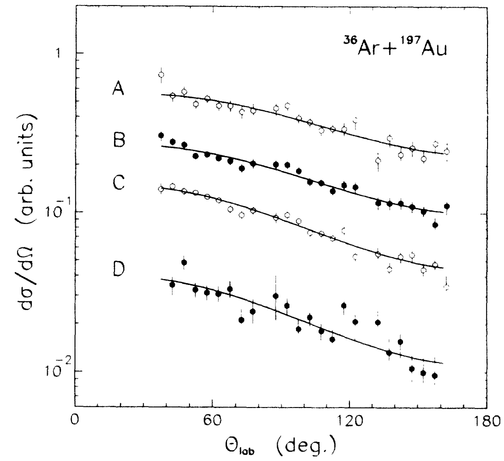

FIG. 3. Bremsstrahlung ($E_\gamma^{\rm lab}\geq 30$ MeV) laboratory angular distributions measured in ^{36}Ar+^{197}Au at 95 MeV/nucleon. Different mean impact parameters are selected through gates on the LCP multiplicity in the FW (selections A, B, C, corresponding to $M_{\rm LCP}=7$–8, 3–4, 1–2, i.e., $\langle b\rangle\simeq4.5$, 6.5, 8.0 fm) or on the PLF charge (selection D, corresponding to $Z_{\rm PLF}=14$–17, i.e., $\langle b\rangle\simeq9.5$ fm). Contributions from π^0 decay photons are subtracted. The solid lines are moving-source fits, with parameters listed in Table I. The four distributions are arbitrarily normalized to each other.

TABLE I. Parameters from moving-source fits to the hard-photon ($E_\gamma^{\rm lab}\geq 30$ MeV) angular distributions measured in Ar+Au collisions with different $M_{\rm LCP}$ and $Z_{\rm PLF}$ selections: A, B, C correspond to $M_{\rm LCP}=7$–8, 3–4, 1–2, and D corresponds to $Z_{\rm PLF}=14$–17 (for D, due to limited statistics, energy and angle projections had to be fitted separately). Inclusive results are also listed for both targets.

Selection	A	B	C	D	incl. Ar+Au	incl. Ar+C
E_0^S (MeV)	28.6 ± 2.0	29.4 ± 1.7	28.5 ± 1.7	25.9 ± 2.0	29.0 ± 1.4	30.3 ± 1.6
β_S	0.14 ± 0.02	0.16 ± 0.01	0.18 ± 0.02	0.21 ± 0.02	0.15 ± 0.01	0.21 ± 0.01
α	0.14 ± 0.05	0.15 ± 0.04	0.14 ± 0.05	0.1 ± 0.1	0.15 ± 0.03	0.14 ± 0.05

which indeed predict a large degree of stopping in central collisions of $\simeq 100$ MeV/nucleon heavy ions with $A_P + A_T > 200$. A comparison of our data with more specific calculations would, however, be necessary to extract quantitative information on nuclear stopping. Finally, the above arguments should apply even more stringently to the subthreshold production of massive particles, like pions, etas, and kaons, which require c.m. energies in excess of their rest mass, i.e., comparable to or larger than the highest photon energies observed here.

In summary we have measured inclusive and exclusive hard-photon emission in the reactions ^{36}Ar+^{197}Au and ^{36}Ar+^{12}C at 95 MeV/nucleon. Whereas the observed characteristics of the photon source are fully consistent with the picture of production in leading *p-n* collisions in the Ar+C system, a strong deviation of the source velocity from β_{NN} has been observed in the heavier Ar+Au system. There β_S is reaching β_{NN} only for very peripheral collisions. We conclude therefore that hard photons do not only probe the very first phase of heavy-ion reactions, but also carry information on the later, stopping stage of the collision.

We would like to thank the GANIL technical staff for very efficient support, the GANIL accelerator crew for delivering the stable ^{36}Ar beam, and the GSI target laboratory for producing the Au and C targets. Valuable assistance from J. Beene, P. Mueller, and R. Varner in the setting-up phase of the experiment is gratefully acknowledged. We thank W. Kühn for help with the data acquisition. This work was supported in part by BMFT under Contract No. 06 GI 464 I, by GSI Darmstadt under Contract Gi Met K, by the Deutsche Forschungsgemeinschaft (DFG), by the Stichting voor Fundamenteel Onderzoek der Materie (FOM), by CICYT under Contract No. PB90-0171, and by the Czech Academy of Sciences under Grant No. 14808.

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