Subthreshold Pion Dynamics as a Source for Hard Photons beyond Proton-Neutron Bremsstrahlung in Heavy-Ion Collisions

K. K. Gudima,* T. Matulewicz,† H. Delagrange, F. M. Marqués,‡ G. Martínez, R. W. Ostendorf,§ M. Płoszajczak, Y. Schutz, V. D. Toneev,‖ and P. Bożek¶

Grand Accélérateur National d'Ions Lourds, F-14021 Caen, France

S. Hlaváč,** R. Holzmann, A. Schubert,†† R. S. Simon, and V. Wagner‡‡

Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany

H. Löhner, J. H. G. van Pol, R. H. Siemssen, and H. W. Wilschut

Kernfysisch Versneller Instituut, NL-9747 AA Groningen, The Netherlands

J. Díaz and A. Marín

Instituto de Física Corpuscular, E-46100 Burjassot, Spain

(Received 27 November 1995)

We report on the first measurement in heavy-ion collisions of hard photons of extremely high energies that extend the photon spectrum to 5 times the beam energy per nucleon. The photon spectrum was measured for the systems ^{86}Kr + $^{\mathrm{nat}}$Ni at 60*A* MeV and ^{181}Ta + ^{197}Au at 40*A* MeV. The data are interpreted using the Dubna cascade model. The radiative channel of pion-nucleon interaction $\pi + N \rightarrow N + \gamma$, involving subthreshold pions produced in the nuclear medium, dominates all other processes considered for the production of the very energetic photons. This channel was never considered so far at beam energies below the pion threshold.

PACS numbers: 25.70.–z, 13.75.Cs, 13.75.Gx

Extensive studies of hard photons ($E_\gamma > 30$ MeV) emitted in heavy-ion collisions at intermediate bombarding energies have demonstrated that they are a unique and sensitive probe of the reaction dynamics [1]. These photons have been found to mainly originate from the incoherent sum of the bremsstrahlung processes in first chance proton-neutron (*pn*) scattering. In a free *pn* collision the bremsstrahlung process generates a continuous photon spectrum up to a maximum energy given by

$$E_\gamma^{\max}(s) = \frac{s - 4m_N^2}{2\sqrt{s}} = \frac{T_L m_N}{\sqrt{2T_L m_N + 4m_N^2}} \approx \frac{T_L}{2}, \quad (1)$$

where $\sqrt{s}$ is the *pn* center-of-mass energy and m_N the nucleon mass. Up to approximately half the beam energy T_L may be converted into a photon. In heavy-ion collisions, the *pn* center-of-mass energy results from both the beam momentum per nucleon p_L and the intrinsic momenta due to the Fermi motion of nucleons. When the two intrinsic momenta are antiparallel and equal to the Fermi momentum p_F, the energy reaches a maximum value equal to

$$s_{\max} = 2\frac{[E_F(m_N + E_L) + p_F p_L]^2}{m_N(m_N + E_L)}, \quad (2)$$

where $E_F = \sqrt{m_N^2 + p_F^2}$ and $E_L = \sqrt{m_N^2 + p_L^2}$. Assuming an intrinsic momentum distribution with a sharp cutoff at $p_F = 270$ MeV$/c$, the maximum photon energy in a heavy-ion collision $E_\gamma^{\max}(s_{\max})$ is equal to 167 and 194 MeV at bombarding energies of 40*A* and 60*A* MeV, respectively. We define this maximum energy as the kinematical limit.

To overcome this kinematical limit in an individual *pn* collision, the nucleons must acquire more intrinsic momentum than available at saturation density. Several mechanisms supplying the extra energy may be considered: nucleon off-shell effects, three-body collisions which become important at high densities, dynamical fluctuations which can accumulate energy in one single *pn* collision [2,3], or multistep processes involving pions and deltas acting as a storage of energy.

In this Letter we report on the first measurement of the photon energy spectra in heavy-ion collisions in which the kinematical limit has been significantly exceeded. The highest energy data points of the experimental spectra are at the limit of the sensitivity of our measurement which in the present case was of the order of nb. Preliminary experimental results have been presented in [4]. At present a unique description, which takes into account all the possible mechanisms mentioned, does not exist. None of the processes alone mentioned in the previous paragraph can account for all the measured very energetic photons. However, with the photon-production process $\pi + N \rightarrow N + \gamma$, calculations performed with the Dubna cascade model (DCM) [5] can account for most of the photons produced above the kinematical limit once the pion dynamics is described correctly. This elementary process was never considered so far in the beam energy domain far below the threshold for pion production in free nucleon-nucleon (*NN*) collisions.

Photon energy spectra were measured for the systems ^{86}Kr + $^{\mathrm{nat}}$Ni at 60*A* MeV and ^{181}Ta + ^{197}Au at 40*A* MeV. The beams were provided by the cyclotron facility at GANIL, Caen. Photons were detected and identified by the photon multidetector TAPS [6]. Its 320 BaF_2 scintillation detectors, each one associated with a plastic scintillator acting as charged-particle veto (CPV), were arranged in 5 square blocks of 64 modules each. Completing the setup, the KVI hodoscope [7] for light charged particles (LCP) was located at forward angles inside the reaction chamber. The LCP multiplicity recorded in coincidence with photons detected by TAPS entered into the trigger definition, requiring that at least three detectors of the hodoscope have fired. It was checked [8] that this trigger condition reduces by at most 20% the total hard-photon production cross section and cuts out the most peripheral collisions. In the DCM calculation the selection of events with pion production will have the same effect as it corresponds to collisions with impact parameters less than about 6 fm. Energy and direction of incident photons were calculated by the reconstruction of the electromagnetic shower generated in the TAPS blocks. More details on the experimental setup and the data analysis are given elsewhere [9].

During the experiment hard photons were selected by requiring that at least one neutral hit (no energy recorded in the CPV and a deposited energy of at least 15 MeV in the BaF_2 scintillator) was registered. The most energetic photons were selected by the detection of at least two neutral hits in adjacent detector modules. In this way the detection of energetic photons, for which the electromagnetic shower spreads over more than one TAPS module, was favored. The two-photon decays of neutral pions were selected by requiring two neutral hits in two distinct blocks. We thus have exploited the decay kinematics in which the laboratory opening angle of the two photons is equal to 120° on average.

The efficiency of the detection system and of the offline photon identification was calculated for each trigger condition using Monte Carlo generated events obtained with GEANT [10]. Because of the extremely low cross sections cosmic-ray induced events, recorded in random coincidence with nuclear reactions and misidentified by the analysis as photons, have constituted an unavoidable background. To control their intensity and energy distribution, we had implemented an additional trigger allowing one to record events during the beam-off periods. In the offline analysis we have applied a cosmic-ray rejection algorithm based on the shower profile [11] on the in- and off-beam events. The resulting normalized in- and off-beam spectra were then subtracted, leading to background-free photon spectra for the Kr + Ni and the Ta + Au systems (Fig. 1). The photon energy E_γ was calculated in the frame of half beam rapidity, which is the center-of-mass system for the average *NN* collision. The spectra extend well above the kinematical limit, and reach up to 5 times

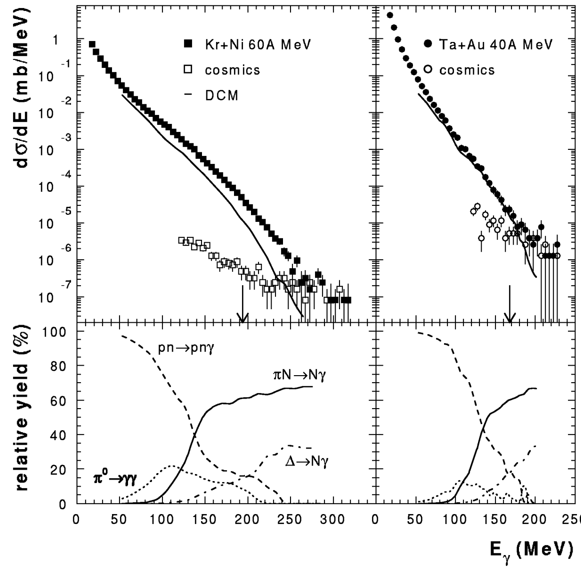

FIG. 1. Measured photon spectrum (full symbols) in the reaction ^{86}Kr + $^{\mathrm{nat}}$Ni at 60*A* MeV (left panel) and ^{181}Ta + ^{197}Au at 40*A* MeV (right panel) after subtraction of the cosmic-ray contribution. The level of cosmic-ray background is shown with open symbols. The solid line represents the DCM calculations. In the lower part the calculated spectrum is decomposed into fractions corresponding to the following elementary mechanisms: $p + n \to p + n + \gamma$, $\pi + N \to N + \gamma$, $\pi^0 \to \gamma\gamma$, and $\Delta \to N\gamma$. The arrows indicate the kinematical limits.

the beam energy per nucleon, i.e, 300 MeV and 200 MeV for the Kr + Ni and Ta + Au systems, respectively. In Fig. 2 we show the total energy ($m_{\pi^0} + T_{\pi^0}$) spectrum of neutral pions calculated in the *NN* center-of-mass frame. They were identified in the invariant-mass spectrum between 80 and 160 MeV. These limits were deduced from the GEANT simulation [9]. The mass resolution of the π^0 peak was 11% FWHM.

To trace the origin of the measured photons we have applied the Dubna cascade model, which was originally written for the description of particle and light fragment production in both $N + A$ and $A + A$ high energy reactions [5]. The model was extended to describe also the photon production. Pion and photon yields in DCM were evaluated in a perturbative approach. This approximation is justified by the very small particle production probabilities which do not influence the global dynamics of the heavy-ion collision. DCM is based on the Boltzmann-Uehling-Uhlenbeck (BUU) kinetic equations, but the mean-field evolution is treated in a simplified way. We have kept the scalar nuclear potential of the initial state, changing only the potential depth according to the number of knocked-out nucleons. This procedure allows one to take into account nuclear binding and the Pauli principle [12]. This frozen mean-field approximation is good enough for the description of yields of hard

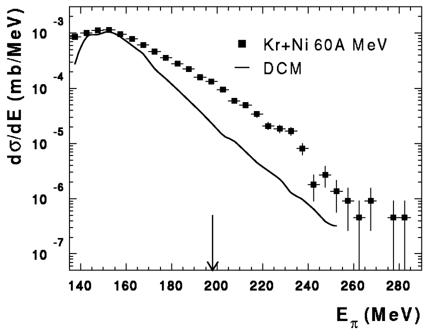

FIG. 2. Energy distribution of π^0 in the ^{86}Kr + $^{\mathrm{nat}}$Ni reaction at 60*A* MeV, compared with the DCM calculations (solid line). The arrow indicates the kinematical limit.

photons with energies above the kinematical limit, as these photons are produced only in the early stage of the collision. The Fermi motion in DCM was calculated in the local density approximation. The maximal value of the Fermi momentum is $p_F(r) = \hbar[3\pi^2\rho(r)/2]^{1/3}$, where the nuclear density $\rho(r)$ was approximated by a Woods-Saxon distribution with parameters extracted from electron-nucleus elastic scattering data [13].

First we have considered the *pn* bremsstrahlung process $p + n \rightarrow p + n + \gamma$. The relevant production cross section in the one-boson approximation was taken from the parametrization of Schäfer *et al.* [14]. In this approximation the photon emission from the external (proton) lines in the Feynmann diagram gives the main contribution. The *pp* bremsstrahlung is suppressed by destructive interference [14] and is omitted. The calculations strongly underpredict the measured cross section for the most energetic photons. Bremsstrahlung spectra in BUU [15] for $E_\gamma > 100$ MeV agree with those obtained in DCM and also have the same deficiency. At $E_\gamma < 50$ MeV, DCM spectra are significantly lower than seen experimentally. This is due to the existence of a second source producing thermal hard photons at a later stage of the reaction [15,16] which depends on the mean field dynamics and, in particular, on the compression properties of nuclear matter. The thermal hard photon yields can obviously not be reproduced by the DCM calculations.

The decay processes, $\pi^0 \rightarrow \gamma\gamma$ and $\Delta \rightarrow N\gamma$, which also give rise to hard photons, have been included in DCM calculations. In the latter process, the Δ isobars come exclusively from the reaction $N + N \rightarrow \Delta + N$. The γ decay of the Δ's happens with a branching ratio of 6×10^{-3}. As a next step, we have added in the DCM an additional source of hard photons, associated with the process $\pi + N \rightarrow N + \gamma$, which has been neglected so far in the description of photon production at intermediate energies.

Pions were produced in the DCM either directly, $N + N \rightarrow N + N + \pi$, or in two steps through Δ-resonance formation, $N + N \rightarrow \Delta + N$ and $\Delta \rightarrow N + \pi$. For the in-medium inelastic *NN* cross section, we have used the empirical fits of the free cross section [17] modified by Pauli blocking. Formation of Δ isobars was calculated so that the effective mass of the πN system follows the Δ mass distribution, its width being dependent on the pion momentum in the πN system. We have checked that the calculated pion spectra and the Δ production via the two-body channel closely reproduce the experimental data for free *NN* collisions [12]. One should emphasize that all of these pions are "subthreshold" in the considered T_L range.

The yield of primordial pions is subsequently modified by both absorption and rescattering processes in the nuclear matter. Pions can be absorbed either in the two-step process $\pi + N \rightarrow \Delta$ and $\Delta + N \rightarrow N + N$, or directly in the processes $\pi + (NN)_c \rightarrow N + N$ and $\pi + N \rightarrow N + \gamma$. The modified treatment of the inverse channel for short-lived resonances [18] was used to estimate the cross section of the $\Delta + N \rightarrow N + N$ process. The probability of the pion absorption on a correlated $(NN)_c$ pair was calculated from the inverse cross section for the reaction $p + p \rightarrow d + \pi^+$. This cross section could be enhanced by a factor 3 in the nuclear medium [19]. On the other hand, the probability of finding a deuteronlike pair has a relative weight of about $1/4$ [20]. Since the precise value of these factors is somewhat uncertain and since they have the tendency to cancel each other, we have used the free cross section for the pion absorption [21].

The cross section for the process $\pi + N \rightarrow N + \gamma$ was calculated from the pion photoproduction using the detailed balance principle and the Lorentzian parametrization of Prakash *et al.* [22]. To avoid double counting, Δ isobar γ decay in the intermediate state of the reaction $\pi + N \rightarrow N + \gamma$ was ignored since it is included implicitly in the inverse reaction parametrization.

To compare the calculations with our data, the calculated energy spectra have been folded with the TAPS response function and geometrical acceptance. The folding procedure also included the calculated angular distribution. In Fig. 2 we compare the calculated π^0 energy spectrum with the measured one for the reaction Kr + Ni at 60*A* MeV (for the Ta + Au reaction at 40*A* MeV, the number of detected pions is statistically insignificant for a spectral analysis). The calculated π^0 production cross section is 28 μb, lower than the experimental value of 42 ± 4 μb essentially because the pion energy spectrum in DCM is softer than that seen in the data. This difference can be explained by the fact that the popular Ver West–Arndt approximation of the pion production cross section [17], which is also used in the DCM, fails near the threshold. This is plausible in light of recent measurements [23]. The photon spectra including all the processes described earlier are compared to the data in Fig. 1. At energies of about $m_\pi/2$, the decay process $\pi^0 \rightarrow \gamma\gamma$ presents a maximum which is, however, significantly lower than the contribution of the bremsstrahlung $p + n \rightarrow p + n + \gamma$. At higher photon energies ($E_\gamma > 150$ MeV) these two contributions come close to each other. The role of π^0 decay as a photon source increases rapidly with bombarding energy and already at $E/A > 100$ MeV it will represent a main source of hard photons with $E_\gamma > m_\pi/2$. Here, for photon energies above the pion mass, the main contribution comes from the reaction $\pi + N \rightarrow N + \gamma$, which uses the primordial pions to create photons and dominates over both bremsstrahlung and Δ-decay processes. This process could be characterized by the positive correlation between γ and N energies, in contrast to bremsstrahlung where they are anticorrelated. The energy spectrum of the subthreshold pions is essential for the calculation of photons in the extreme high-energy tail of the spectrum in order to obtain a good quantitative agreement with the data. As mentioned above, DCM predicts too soft a pion spectrum in the Kr + Ni system (see Fig. 2). Consequently, the calculated photon spectra above the kinematical limit fall off too steeply.

In summary, we have measured hard photons emitted in the heavy-ion collisions, ^{86}Kr + $^{\mathrm{nat}}$Ni at 60*A* MeV and ^{181}Ta + ^{197}Au at 40*A* MeV. The photon spectra span an unprecedented wide dynamical range, extending up to 5 times the beam energy per nucleon. The high energy part of the spectra cannot be described in the standard approach based only on the incoherent sum of proton-neutron bremsstrahlung. In the analysis made with the Dubna cascade model, the process $\pi + N \rightarrow N + \gamma$, involving pions produced in the nuclear medium, dominates the production of very energetic photons. An improved quantitative description of photon production by this additional term, never considered so far in this beam energy range, requires a deeper understanding of the subthreshold pion production itself, as well as of the dynamics of pions in the nuclear medium.

We thank the members of the technical staff of the Grand Accélérateur National d'Ions Lourds (GANIL) for their help and delivery of high quality beams required for our measurements. One of us (M. P.) wishes to thank P. Danielewicz for helpful discussions. This work was in part supported by IN2P3 and CEA (France), the CICYT Research Project No. PB90-091 (Spain), FOM (The Netherlands), BMFT and DFG (Germany). K. K. G. and V. D. T. were supported by Grant No. 3405 from INTAS (International Association for promotion of cooperation with scientists from the independent states of the former Soviet Union).

*Permanent address: Institute of Applied Physics, Kishinev, Moldavie.

†Permanent address: Warsaw University, PL-00-681 Warszawa, Poland.

‡Present address: LPC Caen, F-14050 Caen, France.

§Present address: KVI, 9747 AA Groningen, The Netherlands.

‖Permanent address: Bogoliubov Laboratory of Theoretical Physics, JINR, 141980 Dubna, Russia.

¶Permanent address: Institute of Nuclear Physics, PL-31-342 Kraków, Poland.

**Permanent address: Slovak Academy of Sciences, Bratislava, Slovakia.

††Present address: Institute for Transuranium Elements, D-76125 Karlsruhe, Germany.

‡‡Permanent address: Nuclear Physics Institute, 250 68, Řež, Czech Republic.

[1] W. Cassing *et al.*, Phys. Rep. **188**, 363 (1990); H. Nifenecker and J. A. Pinston, Prog. Part. Nucl. Phys. **23**, 271 (1989).

[2] K. Niita, in *Proceedings of the Second IN2P3-RIKEN Symposium on Heavy-Ion Collisions, Obernai, France, 1990*, edited by B. Heusch and M. Ishihara (World Scientific, Singapore, 1990), p. 342; P. Bożek and M. Płoszajczak, in *Proceedings of the Second TAPS Workshop on Gamma Ray and Particle Production in Heavy Ion Reactions, Guardamar, Spain, 1993*, edited by J. Diaz, G. Martinez, and Y. Schutz (World Scientific, Singapore, 1994), p. 559.

[3] M. Belkacem *et al.*, Phys. Rev. C **47**, 47 (1993).

[4] T. Matulewicz, in *Proceedings of the XXIII Mazurian Lakes Summer School, Piaski, Poland, 1993* [Acta Phys. Pol. B **25**, 705 (1994)].

[5] K. K. Gudima and V. D. Toneev, Yad. Fiz. [Sov. J. Nucl. Phys.] **27**, 658 (1978); Nucl. Phys. **A400**, 173c (1983).

[6] R. Novotny, IEEE Trans. Nucl. Sci. **38**, 379 (1991).

[7] H. K. W. Leegte *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **313**, 26 (1992).

[8] G. Martínez, Ph.D. thesis, University of Valencia (Spain) (GANIL Report No. T94-06).

[9] F. M. Marqués *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **365**, 392 (1995).

[10] R. Brun *et al.*, CERN Report No. DD/EE/84-1, 1986.

[11] T. Matulewicz *et al.*, in *Proceedings of the Second TAPS Workshop on Gamma Ray and Particle Production in Heavy Ion Reactions, Guardamar, Spain, 1993*, edited by J. Diaz, G. Martinez, and Y. Schutz (World Scientific, Singapore, 1994), p. 590.

[12] V. D. Toneev, in *Proceedings of the Second TAPS Workshop on Gamma Ray and Particle Production in Heavy Ion Reactions* (Ref. [11]), p. 350.

[13] S. Frullani and J. Moguey, Adv. Nucl. Phys. **14**, 1 (1985).

[14] M. Schäfer *et al.*, Z. Phys. A **339**, 391 (1991).

[15] G. Martínez *et al.*, Phys. Lett. B **49**, 23 (1994).

[16] F. M. Marqués *et al.*, Phys. Lett. B **49**, 30 (1994).

[17] B. J. Ver West and R. A. Arndt, Phys. Rev. C **25**, 1979 (1982).

[18] P. Danielewicz and G. F. Bertsch, Nucl. Phys. **A533**, 712 (1991).

[19] J. Hüfner, Phys. Rep. C **21**, 1 (1975).

[20] I. N. Mishustin *et al.*, Phys. Rev. C **51**, 2099 (1995).

[21] B. G. Ritchie, Phys. Rev. C **28**, 926 (1983).

[22] M. Prakash *et al.*, Phys. Rev. C **37**, 1959 (1988).

[23] W. W. Doehnick *et al.*, Phys. Rev. Lett. **74**, 2913 (1995); A. Bondar *et al.*, Phys. Lett. B **356**, 8 (1995).