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Photon production in heavy-ion collisions close to the pion threshold

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Abstract

We report on a measurement of hard photons ($E_\gamma > 30$ MeV) in the reaction Ar + Ca at 180A MeV at an energy in which photons from the decay of π° mesons are dominating. Simultaneous measurement with the TAPS spectrometer of the photon spectrum and photon-photon coincidences used for the identification of π° enabled the subtraction of π° contribution. The resulting photon spectrum exhibits an exponential shape with an inverse slope of $E_0 = (53 \pm 2_{(\mathrm{stat})}{}^{-5}_{+8}{}_{(\mathrm{syst})})$

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MeV. The photon multiplicity equal to $(1.21 \pm 0.03_{(\mathrm{stat})}{}^{+0.3}_{-0.2}{}_{(\mathrm{syst})}) \cdot 10^{-2}$ is roughly one order of magnitude larger than the value extrapolated from existing systematics. This enhancement of the hard photon production is attributed to a strong increase in the contribution of secondary *np* collisions to the total photon yield. We conclude that, on average, the number of *np* collisions which contribute to the hard photon production is 7 times larger than the number of first chance *np* collisions in the reaction Ar + Ca at 180A MeV.

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Hard photons ($E_\gamma > 30$ MeV) produced in heavy-ion collisions have been proposed and since extensively exploited [1–3] as probes of excited nuclear matter formed in the early stages of nucleus-nucleus reactions. In contrast to hadronic probes photons interact only weakly with the surrounding nuclear medium and therefore convey unperturbed information of the photon-creation phases of the reaction. Insight on the dynamical evolution of nuclear reactions leading to the formation of a hot and dense nuclear system could be gained by studying the hard photon production in inclusive as well as exclusive measurements [3]. Such measurements were up to now limited to bombarding energies below 125A MeV [4] because of the fast increase of the pion production cross-section, resulting in a strong background of photons from the dominant electromagnetic π° decay ($\pi^\circ \to \gamma\gamma$).

The apparent saturation of the photon production cross-section with bombarding energy, as deduced from the commonly adopted extrapolation of hard photon systematics [2,5] together with the overabundant photon yield from the neutral meson decay seemed to place the hard photon detection at higher bombarding energies beyond experimental reach. Investigation of hard photon production at relativistic energies would, however, provide a new insight to phenomena such as the formation phase of resonant matter excited in central collisions [6] or the thermalization process of highly excited projectile- and target-like fragments created in semi-peripheral reactions [7]. To explore this direction, we have investigated the production of hard photons in the reaction ^{40}Ar + ^{40}Ca at 180A MeV using the TAPS photon spectrometer. The hard-photon spectrum was obtained after careful subtraction of the π°-decay contribution from the inclusive photon spectrum. We find that the photon multiplicity is noticeably larger than the value extrapolated from the hard photon systematics [2,5]. This enhancement of the hard photon yield is ascribed to the increasing importance of secondary *np* collisions to the production of hard photons [8,9].

The ^{40}Ar beam was delivered by the heavy-ion synchrotron SIS at GSI, Darmstadt, with an average intensity of 5×10^8 particles in spills of about 9 s. The total number of accumulated beam particles was 4×10^{13}. The natural calcium target was 320 mg/cm^2 thick. A Start Detector (SD) [10] consisting of 32 NE102 plastic-scintillators surrounding the target at a distance of 101 mm signaled the occurrence of a reaction and delivered the start signal for time-of-flight measurements. The SD efficiency averaged over the impact parameter, $\langle \epsilon_s \rangle_b = 0.56$, was estimated from GEANT simulations [11] using the FREESCO event generator [12]. The average SD efficiency when a hard photon is produced was calculated by weighting the impact-parameter distribution with the distribution of the number of participant nucleons $A_{\mathrm{part}}(b)$ [13]. We found $\langle \epsilon_s \rangle_{A_{\mathrm{part}}(b)} = 0.90$. As one can expect, $\langle \epsilon_s \rangle_{A_{\mathrm{part}}(b)}$ slightly increases when the impact-parameter distribution is weighted by $[A_{\mathrm{part}}(b)]^\alpha$ ($\alpha > 1$), being the induced systematic error lower than 10%. The reaction rate measured with the SD was $p_s = 6.9 \times 10^{-3}$ per beam particle. The TAPS multidetector [14] was used for photon detection. The 384 TAPS modules (a BaF$_2$ crystal associated with a plastic veto scintillator) were assembled in six blocks of 8×8 detectors and mounted in two symmetric towers of three blocks each [15]. The towers were positioned at $\theta = \pm 70°$, 80 cm away from the target, on each side of the beam direction. The photon trigger was defined by requiring a neutral hit in the TAPS multidetector, with a deposited energy of at least 10 MeV in the BaF$_2$ crystals without a coincident hit in the corre-

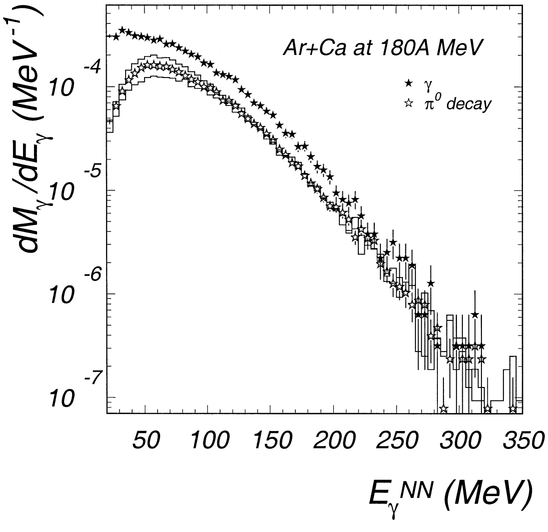

Fig. 1. Inclusive photon *spectrum* measured in the *NN* center-of-mass (full symbols) for the reaction Ar + Ca at 180 *A* MeV. The contribution from the two-photon decay of π° mesons has been deduced by extrapolating the measured π° yield to the full solid angle assuming the measured transverse mass distribution with an anisotropy value $b_{\mathrm{ani}} = 1.0$ (open symbols). Solid lines delimit the range of systematic errors induced by the uncertainty on this extrapolation.

sponding veto detector, validated with a reaction trigger given by the SD.

Photons were discriminated against hadrons through time of flight, BaF_2 pulse-shape analysis, and by requiring an anti-coincidence with the corresponding charged-particle veto detector [15]. The energy calibration of the BaF_2 crystals was based on the energy loss of minimum ionizing cosmic-ray muons. Photon momenta were reconstructed from the electromagnetic shower using a clustering algorithm [16]. The photon ($E_\gamma >$ 30 MeV) efficiency of the detection system, $\epsilon_\gamma = 12.3\%$, was calculated with the GEANT package assuming that photons are emitted from a moving source at the velocity of the nucleon-nucleon (*NN*) center-of-mass. The angular distribution was taken as the sum of an isotropic and a dipolar term [1]. The uncertainty on the dipolar contribution induces a systematic error in the photon efficiency of 5%. The measured photon spectrum at mid-rapidity (Fig. 1) exhibits a convex shape due to the contribution of the π° electromagnetic decay. Contributions from heavier mesons or baryonic resonances can be safely neglected below the pion threshold energy. The total measured photon multiplicity for energies larger than 30 MeV is (0.025 ± 0.003).

To calculate the π° contribution to the measured photon spectrum (Fig. 1), the m_t distribution of π° (where m_t is the transverse mass, $m_t = \sqrt{p_t^2 + m^2}$) was measured at mid-rapidity by invariant mass reconstruction of photon pairs (Fig. 2). The m_t distribution exhibits an exponential shape in the m_t range 180 to 400 MeV$/c^2$ with an inverse slope $T = (24 \pm 1)$ MeV and deviates from the exponential behaviour at m_t values below 180 MeV$/c^2$ due to the energy-dependent absorption [17] and π° rescattering [18]. However, because of the limited π° rapidity acceptance of TAPS, one needs to extrapolate the measured π° distribution, dM_{π°/dm_t, to the full solid angle. An anisotropic pion emission in the *NN* center-of-mass was assumed and the TAPS response was calculated from GEANT simulations. The anisotropy of the π° angular distribution is parameterized as $(1 + b_{\mathrm{ani}}\cos^2\theta_{CM})$. For light systems, the anisotropy b_{ani} has been found to be close to 1.0 at intermediate and relativistic bombarding energies [19,20]. In the only existing measurement at 200 *A* MeV [21] performed with a heavy system, a flat angular distribution was found for charged pions.

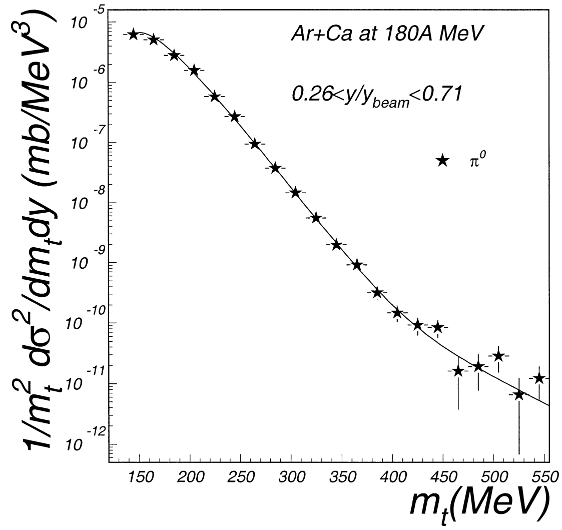

Fig. 2. Transverse mass distribution of π° measured at mid-rapidity for the reaction Ar + Ca at 180A MeV.

Since the anisotropy cannot be determined from our data, we have considered, as suggested by the systematics [19–21], $b_{\mathrm{ani}} = 1.0$ for the determination of the π° contribution to the photon spectrum (Fig. 1). Systematic errors due to the uncertainty on the anisotropy were estimated by setting $b_{\mathrm{ani}} = 0.0$ and $b_{\mathrm{ani}} = 2.0$, respectively, and these are shown in Fig. 1 as well. The systematic error also includes the uncertainties on SD and photon efficiencies.

After subtraction of the π° contribution to the photon yield, the inclusive hard photon spectrum (Fig. 3) exhibits the usual exponential shape which can be parametrized as:

$$\frac{dM_\gamma}{dE_\gamma} = \frac{M_\gamma}{E_0}\exp\left(\frac{E_s - E_\gamma}{E_0}\right), \tag{1}$$

where $E_s = 30$ MeV is the threshold energy of measured photons. The fitted inverse slope in the energy range from $E_\gamma = 30$ to 150 MeV is $E_0 = (53 \pm 2_{(\mathrm{stat})}{}^{-5}_{+8}{}_{(\mathrm{syst})})$ MeV. The experimental photon multiplicity per nuclear reaction ($E_\gamma \geq 30$ MeV) amounts to $M_\gamma = (1.21 \pm 0.03_{(\mathrm{stat})}{}^{+0.3}_{-0.2}{}_{(\mathrm{syst})}) \cdot 10^{-2}$.

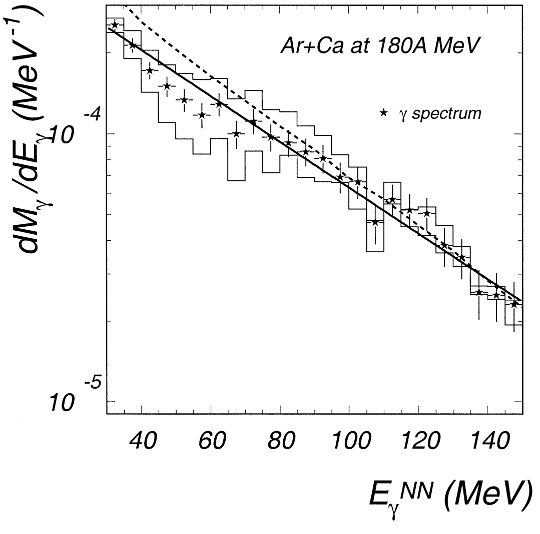

Fig. 3. Hard-photon *spectrum* for the reaction Ar + Ca at 180 *A* MeV obtained after subtraction of the π° contribution from the inclusive photon spectrum (Fig. 1). Histograms represent the systematic error induced by the uncertainty on the anisotropy value of the π° decay contribution. Solid line represents an exponential fit the measured photon spectrum in the energy range from 30 to 150 MeV. The dashed line represents a semiclassical transport calculation described in Ref. [25] for the studied system.

The systematics of hard photon production ($E_\gamma > E_s = 30$ MeV) [2,5] at intermediate energies points to individual first chance *np* bremsstrahlung as the main mechanism behind their production, although secondary contributions to the photon production beyond first chance *np* bremsstrahlung have also been found [8,9,22]. The hard photon multiplicity is found to scale as $M_\gamma = \langle N_{np}^{\text{1st-chance}} \rangle P_\gamma^{1,np}$, where $\langle N_{np}^{\text{1st-chance}} \rangle$ is the number of first chance *np* collisions averaged over the impact parameter [2] and $P_\gamma^{1,np}$ is the hard photon probability per first chance *np* collision. Moreover, the photon probability scales with the inverse slope of the hard photon spectrum as $P_\gamma^{1,np} = M_0 \exp(-E_s/E_0)$, leading to a saturation of the hard photon probability at beam energies well above the hard photon threshold. However, the present measurement of the hard photon multiplicity is almost one order of magnitude larger than the values extrapolated from the previously discussed systematics: $(1.6 \pm 0.2) \cdot 10^{-3}$ [2] and $(1.35 \pm 0.05) \cdot 10^{-3}$ [5]. In contrast the measured inverse slope of the photon spectrum, $E_0 = (53 \pm 2_{(\mathrm{stat})}{}^{-5}_{+8}{}_{(\mathrm{syst})})$ MeV, remains compatible with the systematics: $E_0 = 46 \pm 4$ MeV [2] and $E_0 = 53 \pm 7$ MeV [5].

To gain more insight into the origin of the enhancement of the photon production, we have examined, within a simple model, the evolution of $P_\gamma^{1,np}$ as a function of the beam energy (Fig. 4). The hard photon probability from individual *np* reactions is estimated as

$$P_\gamma^{1,np} = \frac{\sigma_{np \to np\gamma}(\sqrt{s})}{\sigma_{np}(\sqrt{s})} \tag{2}$$

$\sigma_{np \to np\gamma}(\sqrt{s})$ is obtained adopting the parameterization of the elementary mechanism $p + n \to p + n + \gamma$ proposed in Ref. [23], $\sigma_{np}(\sqrt{s})$ is the total np cross section [24], and $\sqrt{s}$ is the available energy in the *np* center of mass, taking into account the coupling of the nucleon Fermi momenta with the beam momentum. The local Thomas-Fermi approximation and a Wood-Saxon parameterization of the nuclear density have been assumed, with a density in the center of the nucleus equal to the saturation density, $\rho_0 = 0.17$ fm^{-3}. The calculated value of $P_\gamma^{1,np}$ (Fig. 4) roughly reproduces the systematics of $P_\gamma^{1,np}$ at energies above the hard photon production threshold ($E_{\mathrm{th}} \sim 2E_s = 60\,A$ MeV), and corroborates the saturation of $P_\gamma^{1,np}$

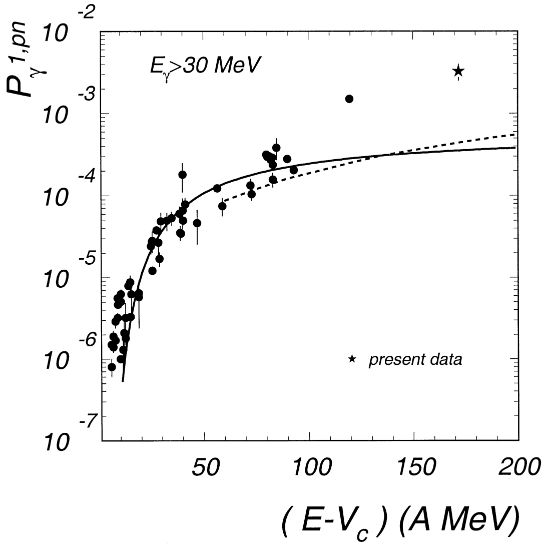

Fig. 4. Systematics of hard photon production $E_\gamma > 30$ MeV (solid line) [2,4,5] compared to the estimation of the photon probability (dashed line) within the simple model described in the text.

at higher beam energies. Assuming that only neutron-proton bremsstrahlung is at the origin of hard photons, the measured enhancement of the hard photon multiplicity, should be searched for in secondary *np* collisions having still enough energy to produce additional photons with similar probability. Within this interpretation, the measured photon multiplicity can then be related to the total number of *np* collisions in the reaction, which can be calculated through:

$$\langle N_{np} \rangle = \frac{M_\gamma}{P_\gamma^{1,np}} \tag{3}$$

where M_γ is the measured hard photon multiplicity and $P_\gamma^{1,np}$ is the calculated photon probability per *np* collisions (Eq. (2)). Using this expression, we obtain $\langle N_{np} \rangle = 27 \pm 7$ for the reaction Ar + Ca at 180 *A* MeV, which is roughly 7 times larger than the number of first chance *np* collisions, $\langle N_{np}^{\text{1st-chance}} \rangle = 4$. This result indicates that about 85% of the hard photon yield is produced in secondary *np* collisions. Dynamical phase-space calculations [25] for the studied system, although, slightly overpredicting the measured hard photon multiplicity (Fig. 3), confirm that about 78% of the hard photon yield is produced in secondary *np* collisions.

In summary, we have measured the hard photon spectrum in the reaction Ar + Ca at 180 *A* MeV, which is for the first time that these have been measured at beam energies close to the pion threshold. The hard photon spectrum exhibits an exponential shape with an inverse slope $E_0 = (53 \pm 2_{(\text{stat})}{}^{-5}_{+8\,(\text{syst})})$ MeV. The measured hard photon multiplicity $M_\gamma = (1.21 \pm 0.03_{(\text{stat})}{}^{+0.3}_{-0.2\,(\text{syst})}) \cdot 10^{-2}$ is almost one order of magnitude larger than values obtained from the systematics [2,5]. We interpret the observed enhancement of the hard photon production as being due to a strong increase of the contribution of secondary *np* collisions to the photon yield at energies well above the hard photon production threshold (60 *A* MeV). We deduce that (27 ± 7) *np* collisions, on average, take part in the hard photon production for the reaction Ar + Ca at 180A MeV.

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