Suppression of Soft Nuclear Bremsstrahlung in Proton-Nucleus Collisions

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Photon energy spectra up to the kinematic limit have been measured in 190 MeV proton reactions with light and heavy nuclei to investigate the influence of the multiple-scattering process on the photon production. Relative to the predictions of models based on a quasifree production mechanism, a strong suppression of bremsstrahlung is observed in the low-energy region of the photon spectrum. We attribute this effect to the interference of photon amplitudes due to multiple scattering of nucleons in the nuclear medium.

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In collisions between nucleons electromagnetic radiation can be emitted due to the rapid change in the nucleon velocity (bremsstrahlung). Accordingly, in nucleus-nucleus collisions bremsstrahlung is emitted due to the individual collisions of the constituent nucleons. Earlier experiments with protons and heavy ions [1] indicated that bremsstrahlung is dominantly produced in first-chance proton-neutron collisions. Consequently, dynamical nuclear reaction models include photon production in the incoherent quasifree collision limit; i.e., free nucleon-nucleon (*NN*) bremsstrahlung cross sections are employed assuming on-shell nucleons, and the intensities of the individual scattering processes are added rather than their amplitudes.

The classical approach to bremsstrahlung [2] as well as the leading term of the soft-photon approximation (SPA) [3] exhibit an infrared diverging cross section which is characteristic for two-body photon production. In a dense medium, however, the assumption that the number of photons is proportional to the number of scatterings cannot hold. Knoll and Guet [4] recognized that this would lead to violation of electromagnetic sum rules. Therefore, in a multiple-scattering environment a destructive interference of photon amplitudes must occur within a certain coherence volume. The relevant distance scale for coherence is the formation length of a photon, given by the photon wavelength, which must be larger than the mean free path of nucleons scattering in the medium. In this case, the bremsstrahlung amplitudes from different steps in the scattering process interfere and, therefore, the individual bremsstrahlung contributions may not be added incoherently. This so-called LPM effect was predicted by Landau, Pomerančuk, and Migdal [5] for the successive Coulomb scattering of electrons in matter, resulting in a reduced bremsstrahlung rate once the mean free path is shorter than the coherence length. The preceding considerations are of general importance for any type of soft radiation coupled to source particles scattering in a dense medium. Examples are the suppression of pair creation from cosmic-ray photons [6] and suppression of soft bremsstrahlung from high-energy electrons [7] in an accelerator experiment. A significant suppression by 1 order of magnitude has been predicted for soft photon and dilepton production in hot hadronic matter [8] which is important for the diagnosis of the quark-gluon plasma. Implications for neutron-star cooling due to the LPM effect on soft neutrino emission rates have been studied for the process of neutrino pair bremsstrahlung [9]. The general importance of coherence effects on the production and absorption of any kind of particle in (non)equilibrium dense matter has been discussed in terms of classical transport models and within a field theory approach [10–12].

Soft radiation from high-energy nuclear collisions has been debated previously [13]; however, no quantitative analysis of the LPM effect in a strongly interacting dense matter system has been reported so far. For this purpose nuclear bremsstrahlung may be a suitable example accessible to experimental verification. To this end we have measured photon distributions up to the kinematic limit in reactions of 190 MeV protons with a range of targets. A strong suppression of bremsstrahlung relative to a quasifree production model is observed in the low-energy regime of the photon spectrum.

The present study was part of the experimental program with the photon spectrometer TAPS [14,15] at the AGOR facility of the KVI Groningen. A proton beam with a typical intensity of 0.5–2 nA was incident on solid targets of Au, Ag, Ni, and C with thicknesses ranging from 20 to 56 mg/cm^2. External conversion of photons was kept below 1% by the use of a 70 cm diameter carbon-fiber scattering chamber with 4 mm wall thickness. The photon spectrometer TAPS was configured in 6 blocks of 64 BaF_2 crystals each at a distance of 66 cm from the target. The setup covered the polar angular range between 57° and 176° on both sides of the beam with an azimuthal acceptance of $-21° < \phi < 21°$. The granularity of the TAPS setup resulted in an angular resolution of 5.2°. Photons were separated from nuclear particles via their time of flight with respect to the radio-frequency (RF) signal of the cyclotron. The signals from the plastic veto detectors in front of the BaF_2 scintillators were used to select photons and protons on the trigger level. The relative energy calibration was determined from the characteristic energy deposited by cosmic-ray muons. The absolute calibration was provided by the π^0 mass peak and the 15.1 MeV photons originating from inelastic proton scattering on $^{12}\mathrm{C}$.

Two-photon invariant mass spectra from events with two coincident photons were analyzed in order to obtain the π^0 decay contribution. The raw π^0 distributions were corrected for the finite acceptance and the response of TAPS. The measured pion distribution was extrapolated by Monte Carlo simulations [16,17] into regions of missing acceptance by analyzing the angular distributions in small energy bins of 2 MeV. The spectrum of photons from π^0 decay peaks at about 70 MeV with a yield at least a factor of 5 below the inclusive photon yield. After correction for contributions from π^0 decay, photon spectra at laboratory polar angles of 75°, 115°, and 155° in a window of ±5° are obtained with a systematic uncertainty of 5%. Uncertainties due to beam current and target thickness contribute another 5%. Here we present the results near 90° in order to minimize the influence of the reference frame.

Figure 1 shows a compilation of the photon spectra at a laboratory angle of 75° for the four targets studied here. The cross sections have been normalized to the geometrical cross section $\sigma_r = 1.44\pi A^{2/3}$ fm^2 with A the target mass number. The spectra extend up to the kinematic limit $E_{\max} = T_{CM} + Q$, where Q is the Q value of the reaction and T_{CM} the center-of-mass energy. If plotted as a function of the scaled photon energy $E_\gamma/E_{\max}$, all data in Fig. 1 above 100 MeV fall on the same curve [16,18]. The shape of the photon spectra displays a plateau between 30 and 80 MeV and an exponential decrease towards the kinematic limit. This shape is different from photon spectra in heavy ion reactions [19], where nearly exponential slopes have been observed above 30 MeV. The rise at photon energies below 30 MeV for the heavier targets can be attributed to statistical photon emission.

For comparison with dynamical model calculations including the multiple-scattering process we employ the Intra-Nuclear Cascade (INC) code of Cugnon [20]. The INC model was chosen because it reproduces well many aspects of proton-nucleus reactions at these bombarding energies [21] and allows the study of photon-nucleon correlations. *NN* bremsstrahlung production was included in a nonperturbative manner [16] with the kinematically correct $pn\gamma$ process using the SPA for free pn bremsstrahlung [22]. Pauli blocking in INC was achieved by requiring all final scattering states to lie above the Fermi surface. The nucleon phase-space distributions from the INC calculations agree well with those obtained using the Boltzmann-Uehling-Uhlenbeck (BUU) [23] transport model. The BUU results describe the photon spectrum ($E_\gamma > 30$ MeV) from 180*A* MeV Ar + Ca collisions fairly well [19] although slightly overpredicting the yield on the soft side of the spectrum.

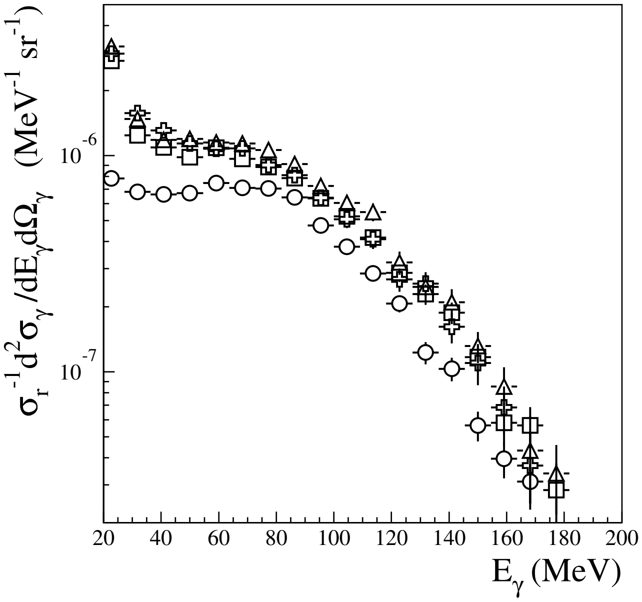

FIG. 1. Target-mass dependence of photon spectra for 190 MeV protons on C (circles), Ni (triangles), Ag (squares), and Au (crosses) targets at a laboratory angle of 75°. The double differential cross sections have been normalized to the geometrical reaction cross section.

Figure 2 shows the photon spectrum for the Au target at 75° in comparison with the INC and BUU results. Good agreement between the experimental data and the calculations is found in the hard part of the spectrum, even near the kinematic limit. Both models agree quite well with each other but overestimate significantly the experimental photon yield at low and intermediate photon energies ($E_\gamma \leq 100$ MeV). It seems as if multiple-scattering processes (indicated separately in Fig. 2) are strongly overestimated in theory. However, the amount of multiple scattering in INC has been checked against the experimental proton yields at large angles. These proton yields, in which multiple-scattering processes are essential, agree within the error margins for all targets studied [16]. Therefore, multiple scattering is well described.

In the nuclear medium the nucleon mean free path is $\lambda_{\mathrm{mfp}} = 1/(\rho \cdot \sigma_{NN}) \approx 2$ fm, based on an average *NN* scattering cross section $\sigma_{NN} = 30$ mb [24] at 190 MeV and the nuclear saturation density $\rho = 0.16$ fm^{-3}. Therefore, nuclear bremsstrahlung can be quenched for a photon wavelength $\lambda \geq \lambda_{\mathrm{mfp}}$ or a photon energy $E_\gamma \leq \hbar c/\lambda_{\mathrm{mfp}} \approx 90$ MeV. The strength of quenching, of course, increases with decreasing photon energy. In a simplified model based on the classical description of

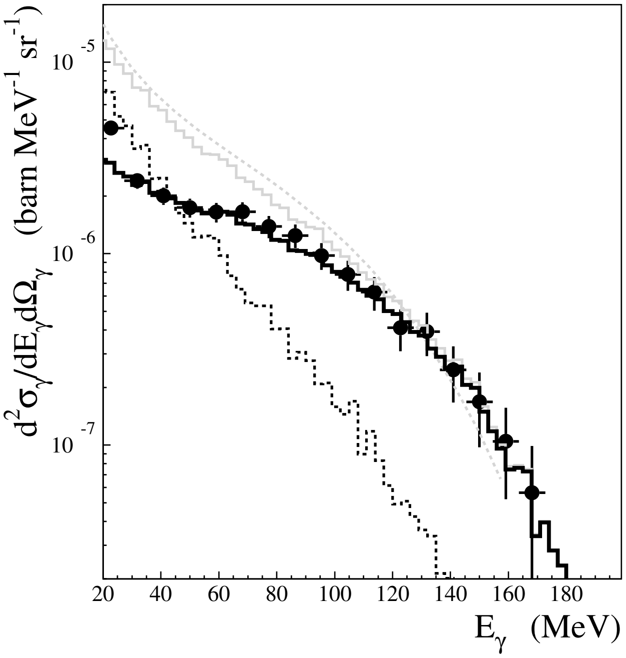

FIG. 2. Photon spectrum for 190 MeV p + Au at an angle of 75° (filled circles), compared to results of the INC (grey histogram) and BUU (dashed line) models. The dashed histogram shows the multiple-step contribution from the INC model. The black histogram is the INC result multiplied with the quenching factor f_q from Eq. (1).

bremsstrahlung production in hard collisions, we have estimated the analytical shape of the LPM effect in a two-step p + nucleus reaction [16]. Each segment of the proton trajectories defines a production amplitude with a definite relative phase and therefore must be added coherently. The time between two collisions is characterized by the mean collision time $\tau = \lambda_{\mathrm{mfp}}/(g\beta_0 c) = \tau_0/g$ with β_0 the incoming proton velocity, i.e., $\tau_0 \approx 4$ fm/c. The factor g takes into account that in subsequent collisions the velocity of the leading particle is reduced. A value $g \approx 0.5$ is expected to describe the mean time between the first and second collisions, i.e., $\tau \approx 8$ fm/c. Averaging over the time distribution $(1/\tau)\exp(-t/\tau)$, we derive the following quenching factor, whose analytical form is motivated by several theoretical calculations [8,10,25]:

$$f_q = \xi\left(1 - \frac{\alpha}{1 + (\frac{E_\gamma}{\hbar}\tau)^2}\right). \qquad (1)$$

The parameter α is related to the fraction of energy remaining for the leading particle in subsequent collisions [16], i.e., $\alpha \approx 1/g^2 \approx 0.25$. ξ is an overall scaling factor. The INC calculation was adjusted in an *ad hoc* manner to account for medium effects by multiplying the spectrum obtained from INC with the quenching factor f_q from Eq. (1).

The experimental data were fitted with the product INC $\cdot$ f_q, where INC represents the full INC spectrum and α, ξ, and τ are free parameters. For the spectra obtained at three different angles of 75°, 115°, and 155° we find $\alpha \approx 1$ and a mean collision time $\tau = 2.4 \pm 0.6$ fm/c for the Ni, Ag, and Au targets and 3.7 ± 0.5 fm/c for the C target. These values for the collision time are much smaller than the expected average time interval between two hard *NN* collisions in nuclei (8 fm/c, see above). From this observation one must conclude that hard *NN* collisions alone are insufficient to explain the quenching of soft photons. Other effects likely to increase the observed collision frequency (reduced parameter τ) may be multiple soft collisions, but also a modification of the elementary photon production process in the nuclear medium. The latter hypothesis is supported by the observation that the dipole contribution expected from the elementary proton-neutron angular distribution appears to be absent in the reactions studied here, as was observed also elsewhere [26]. In our data we observe the corresponding result from the fact that ξ increases from $\xi = 0.96 \pm 0.06$ at 75° to $\xi = 4.3 \pm 2.0$ at 155°.

The separation between dynamical effects and LPM quenching is complicated due to the partitioning of the *NN* interaction in the nuclear medium into a mean field and a collision component in the models. The available dynamical models are all of semiclassical nature and our new data indicate the need to include consistently the medium modifications and the interference phenomena. The development of a quantum transport theory for photon production in intermediate-energy proton + nucleus reactions was already started in Ref. [27] but did not go beyond the conventional quasiparticle approximation; i.e., the correlations and off-shell nucleon propagation in the medium were not taken into account. Recently, new approaches [9,28,29] have been taken incorporating the spectral width of the baryon propagators [28] or the related concept of collision frequency [29]. Both lead to qualitative agreement with our data. For example, the latter approach takes the kinetic equations that determine the evolution of the two-particle Green's function in matter from the transport approximation for soft-photon production. The correlations in the medium allow multiple scattering to occur without requiring multiple hard collisions, thus yielding Eq. (1) with $f_q(\alpha = 1, \tau = \tau_0)$, i.e., $g = 1$, in agreement with the empirical result. We thus obtain an energy dependence of the photon spectrum with the functional form

$$f_E \sim \frac{E_\gamma}{E_\gamma^2 + (\hbar/\tau_0)^2(Z/N)^2}\,\beta_0^2(1 - E_\gamma/E_{\mathrm{max}}). \qquad (2)$$

This spectrum incorporates the factor $1 - E_\gamma/E_{\mathrm{max}}$ to describe the kinematic limit which is absent in the classical soft-photon approach. (The precise form of this limit may vary, cf. [26].) The proton to neutron ratio (Z/N) describes the reduced quenching observed in heavy nuclei. The absolute cross section is determined by the geometrical reaction cross section. The suppression of soft photons can be described quantitatively as shown in Fig. 3 by the dark lines. The amount of quenching can be seen from comparison with the result where the collision frequency (i.e., $\hbar/\tau_0$) is set to zero (the grey dotted lines). This approaches the quasifree result of the INC model. Equation (2) also describes well the published data [18,26,30]

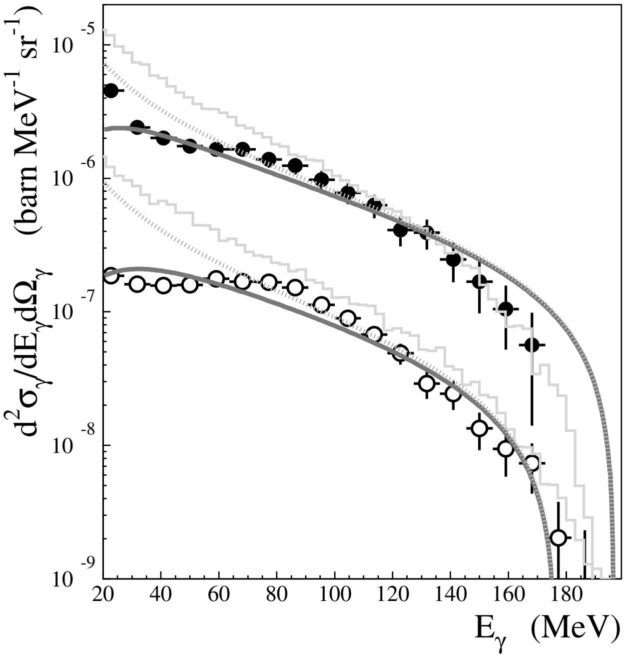

FIG. 3. Photon spectrum at a laboratory angle of 75° for 190 MeV p + Au (top, filled circles) and p + C (bottom, circles). The grey histograms indicate the results from the INC model. The dark lines are obtained using Eq. (2); the dotted grey lines correspond to Eq. (2) with the collision frequency set to zero.

for 168 MeV p + Tb and 145 MeV p + Pb by adjusting only β_0 according to the respective beam energy. This shows that at lower beam energy quenching also occurs, but the effect at photon energies above 30 MeV is small and has gone unnoticed so far.

In summary, new experimental data have been presented for nuclear bremsstrahlung from the soft-photon region up to the kinematic limit in proton + nucleus reactions. We observe a strong suppression of the soft bremsstrahlung cross section in comparison with predictions of transport models that include bremsstrahlung on the basis of quasifree nucleon-nucleon collisions. Applying a phenomenological quenching factor appropriate for sequential hard collisions between nucleons, we can fit the data using the average collision time as a free parameter. We find that its value is much shorter than expected on the basis of the collision times in a transport model. New theoretical models are being developed using simplified reaction dynamics but taking into account various medium effects. An analytical form for the bremsstrahlung production in nuclear matter was obtained which describes the suppression of soft-photon radiation. It remains a theoretical challenge to calculate the photon spectrum explicitly in a quantum field theory for nonequilibrium nuclear matter including the propagation of off-shell particles. Nuclear bremsstrahlung may provide a suitable test case for a theoretical approach, which was so far limited to thermal field theory, but will have widespread applications to, e.g., neutrino and axion radiation from neutron stars and supernovae, and to thermal radiation from a quark-gluon plasma.

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