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COHERENCE EFFECTS ON BREMSSTRAHLUNG IN THE NUCLEAR MEDIUM*

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Photon angular distributions and energy spectra up to the kinematic limit have been measured in 190 MeV proton reactions with light and heavy targets. For the first time photon spectra in dependence of scattered protons have been measured to investigate the influence of the multiple-scattering process on the photon production. Based on predictions for the free *pn* bremsstrahlung amplitude a strong suppression of bremsstrahlung relative to a quasi-free production model is observed in the low-energy regime of the photon spectrum in p+nucleus reactions. We attribute this effect partly to modifications of the bremsstrahlung amplitude in the nuclear medium and partly to interference of photon amplitudes due to multiple scattering of nucleons.

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1. Introduction

In collisions between nucleons bremsstrahlung can be emitted due to the rapid change in velocity if at least one of the nucleons is charged. Similarly, in collisions between nuclei the constituent nucleons collide with each other, and the individual collisions contribute to the nuclear bremsstrahlung cross section. Earlier experiments with protons and heavy ions [1] indicated

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that bremsstrahlung is dominantly produced in the first proton-neutron encounter of the nuclear reaction. Consequently, dynamical nuclear reaction models include bremsstrahlung production in the incoherent quasi-free collision limit, *i.e.* free nucleon–nucleon (NN) bremsstrahlung cross sections are employed assuming on-shell nucleons and the bremsstrahlung intensities of the individual scattering processes are added rather than amplitudes.

For the first time coherent bremsstrahlung could be demonstrated in the $\alpha + p$ system studied at 50 MeV/nucleon [2]. Because of the strong binding of the α-particle, the quasi free process can only lead to bremsstrahlung with $E_\gamma < 22$ MeV, while at higher energy, up to the kinematic limit of $E_{\rm max} = 39$ MeV, bremsstrahlung can only be produced coherently in this reaction. In fact, we find coherently produced hard photons to be the dominant radiative process in the $\alpha+p$ system. After transformation to the $\alpha+p$ center of mass frame the photon energy spectra at all angles exhibit the same characteristic shape as shown in Fig. 1. The shape of this spectrum is very different from that of the hard photons in nucleus–nucleus reactions, for which exponential slopes are observed. The low-energy photon spectrum appears to have a classical $1/E_\gamma$ shape. Photons with energies close to the kinematic limit have been associated with direct capture to the two lowest states of the unbound ^{5}Li. The data have been compared with model calculations in

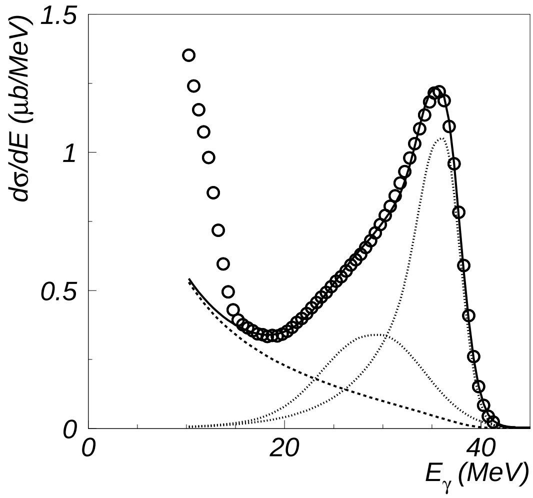

Fig. 1. Inclusive photon energy spectrum (in the CM frame) for the $\alpha + p$ reaction at 50 MeV/nucleon. The statistical errors are smaller than the symbols. The global fit (solid line) is decomposed into the classical bremsstrahlung spectrum (dashed line) and two contributions representing capture to the two low-lying resonances in ^{5}Li, *i.e.* the unbound ground state and the first excited state (dotted lines).

which coherent bremsstrahlung and direct capture are treated consistently as one and the same process. The calculations qualitatively reproduce these two features of the data.

At sufficiently high energies, the multiple scattering process becomes important in p reactions with nuclei. A significant effect on the radiation process is expected due to the influence of the multiple scattering and off-shell propagation of nucleons. In this case the individual bremsstrahlung contributions may not be added incoherently. This effect was predicted by Landau, Pomerančuk and Migdal [3] 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 experimental verification has been reported for the suppression of pair creation from cosmic-ray photons [4] and bremsstrahlung from high-energy electrons [5] in accelerator experiments. The general importance of coherence-time effects on particle production and absorption in (non-)equilibrium dense matter has been discussed in the literature [6–9]. This effect is *e.g.* relevant for soft dilepton production in hot hadronic matter [10]. However, no quantitative analysis for nuclear bremsstrahlung has been reported due to the lack of consistent data and quantitative predictions.

2. Experiment

To study the various medium effects the energy spectra and angular distributions of photons up to the kinematic limit were measured in reactions of 189.6 MeV protons with a number of nuclear targets. The present study was part of the experimental program with the photon spectrometer TAPS [11–13] at the AGOR facility of the KVI Groningen. Protons with a typical intensity of 0.5–2 nA were incident on solid targets of Au, Ag, Ni, and C with surface densities ranging from 20 to 56 mg/cm^2. External conversion of photons was minimised and kept below 1% by the use of a 70 cm diameter carbon-fibre 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 a vertical acceptance of 42°. The granularity of the TAPS setup resulted in an angular resolution better than 5°. Photons were separated from nuclear particles via their time-of-flight with respect to the radiofrequency signal (RF) of the cyclotron. The time resolution was about 1 ns (FWHM). In addition, pulse-shape discrimination was employed. The event trigger required an energy deposition of at least 5 MeV in a BaF_2 module. 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. Photons in the energy range between 10 and 40 MeV are measured with an energy resolution better than 8 %. 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 and the 15.1 MeV photons originating from inelastic proton scattering on ^{12}C. A small residual background from cosmic-ray muons within the trigger gate was removed by subtracting a photon spectrum obtained by gating on a random time window with respect to the RF.

3. Inclusive photon spectra

The photon spectra were corrected for contributions from π^0 decay within a systematic uncertainty of 5 %. Uncertainties due to beam current and target thickness contribute another 5 %. In order to obtain the accurate decay contribution, the two-photon invariant mass spectra from events with two coincident photons were analysed. The raw π^0 distributions were corrected for the finite acceptance and the response of TAPS. The measured pion distribution was extrapolated into regions of missing acceptance by analysing the angular distributions in small energy bins of 2 MeV. Fig. 2 shows the photon yield from π^0 decay in comparison to the raw photon spectrum. A significant contribution is noticed around photon energies of 70 MeV with little influence, however, on the shape of the photon spectrum. In order to isolate medium-dependent from quasi-free production processes TAPS also

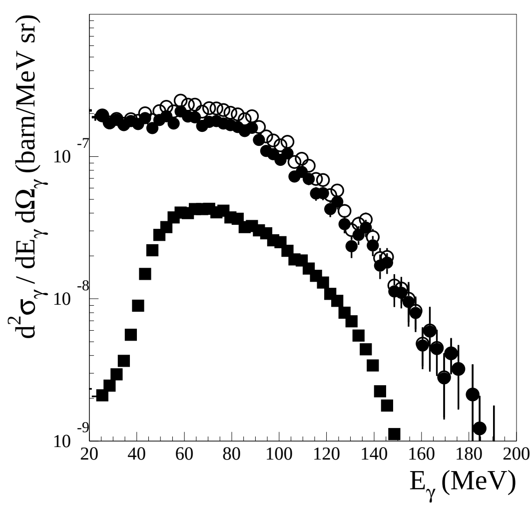

Fig. 2. Comparison of the raw photon spectrum (○), the π^0 decay contribution (■), and the corrected photon spectrum (●) for the C target at a laboratory angle of 75°.

served to measure scattered protons in coincidence with photons. Quasi-free scattering extends only to about 90° in the laboratory frame, whereas in multiple-scattering events particles can be emitted at larger angles. Selections on energy and angle of the coincident protons thus allow to enhance multiple-scattering events.

Fig. 3 shows the compilation of photon spectra for various nuclear targets at a laboratory angle of 75°. The double differential cross sections have been normalised to the geometrical reaction cross section. The spectra extend up to the kinematic limit which implies a coherent mechanism for about 10 MeV of the highest photon energies. For all four targets the shape

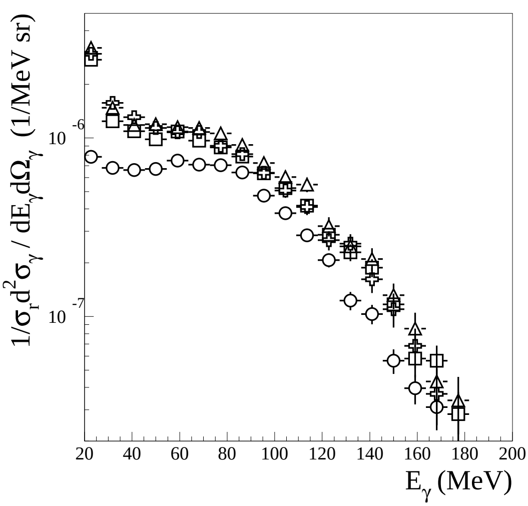

Fig. 3. Target-mass dependence of inclusive photon spectra for the C (○), Ni (△), Ag (□), and Au (+) targets at a laboratory angle of 75°. The double differential cross sections have been normalised to the reaction cross section.

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 where exponential slopes have been observed above 30 MeV photon energy. The rise at photon energies below 30 MeV for the heavier target can be attributed to statistical photon emission. Comparison with photon spectra from literature at incident proton energies from 72 to 168 MeV [14] reveals that the characteristic plateau develops systematically as a function of increasing beam energy.

In order to confront our experimental results with dynamical model calculations including the multiple-scattering process we employ the Intra-Nuclear Cascade (INC) code of Cugnon [15]. The INC model is rather fast due to the simple treatment of the mean field and conserves the correlations between scattered particles. This is a necessary feature as we have included the NN bremsstrahlung production in a non-perturbative manner with the kinematically correct $pn\gamma$ process using the Soft-Photon Approximation (SPA) for free pn-bremsstrahlung [16]. We found that the optimal way to implement Pauli blocking in INC was achieved by requiring the final scattering states to lie above the Fermi surface.

The results of the INC model have been compared with the experimental differential proton cross sections for proton energies above 30 MeV. There is an overall good agreement within 20 % between data and calculation at the various angles and for the different target mass numbers.

From this observation and the fact that INC globally reproduces results obtained with the BUU model, we conclude that the nucleon dynamics is treated in the INC model with sufficient accuracy.

4. Photon–proton coincidences

Exclusive photon spectra, *i.e.* photons measured in coincidence with protons ($E_{\rm proton} > 30$ MeV), are presented in Fig. 4 with increased bias towards multiple scattering by selecting more backward angles. These data reveal

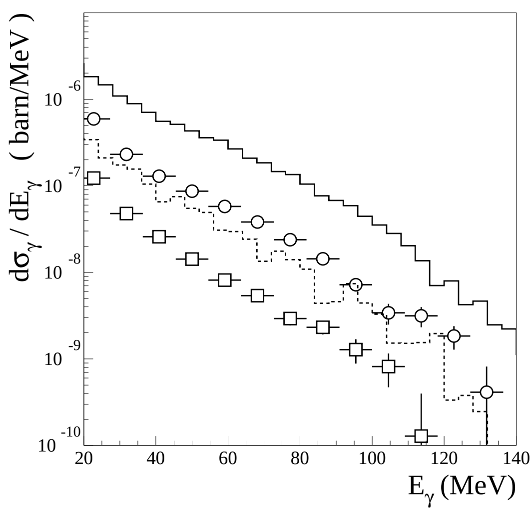

Fig. 4. Exclusive bremsstrahlung determined from photon-proton coincidence. The photon spectrum for 190 MeV p+Au is integrated over all photon angles but gated on protons between 60° and 90° (∘) and backward protons between 100° and 170° (□). Data are compared with results from the INC model (solid and dashed histogram, respectively).

a purely exponential slope distinct from the inclusive data, but well described by the INC model. This indicates again that the kinematical conditions imposed by the nucleon dynamics are well described in the model.

The INC photon yield, however, needs to be scaled down by a factor of 4 for the selection on backward angle protons to obtain agreement with the experimental cross section. Obviously, the suppression of the soft-photon cross section is caused by a reduced photon probability in subsequent scattering processes. Therefore we attempt a phenomenological description of the observed inclusive photon spectra using the analytical shape introduced by the LPM effect when the incident photon undergoes a series of hard proton-neutron collisions.

5. Soft-photon quenching

In the nuclear medium the mean free path $\lambda_{\mathrm{mfp}} \approx 3.3$ fm and, therefore, nuclear bremsstrahlung can be quenched for a photon wavelength $\lambda \geq \lambda_{\mathrm{mfp}}$ or a photon energy $E_\gamma \leq \hbar c/\lambda \approx 60$ MeV. The strength of quenching of course increases with decreasing photon energy. In a simplified model on basis of the classical description of bremsstrahlung production in hard collisions we estimate the analytical shape of the LPM effect in a two-step $p+$nucleus reaction [17]. Each segment of the proton trajectories defines a production amplitude with a definite relative phase and therefore must be added coherently. Averaging over the distribution $P(t) = \frac{1}{\tau_0}\mathrm{e}^{-t/\tau_0}$ of the time t between two collisions, characterised by the mean collision time $\tau_0 \simeq \lambda_{\mathrm{mfp}}/(\beta c)$, we derive the quenching factor

$$\mathrm{QF} = \xi\left(1 - \frac{\alpha}{1 + \left(\frac{E_\gamma}{\hbar}\tau_0\right)^2}\right). \tag{1}$$

The maximum strength of the LPM suppression is determined by the parameter α. Quenching due to the modification of the in-medium pn cross section [18] is essentially independent of the photon energy because one can factorize the $pn\gamma$ cross section in the SPA as $\sigma_{pn\gamma} = \sigma_{pn}P_{pn\gamma}$. Therefore the quenching of the photon yield from pn-collisions in matter has been expressed by an overall factor ξ. The INC calculation was adjusted in an ad hoc manner to account for medium effects by applying the quenching factor QF from Eq. (1) whose analytical form is also motivated in several theoretical publications [6,7,10]. The physical meaning of the parameters used here depends strongly on the specific collision model and will serve in this work only to indicate the existence of the quenching effect and its systematical behavior.

Fig. 5 shows the photon spectrum for the Au target at a laboratory angle of 75° in comparison with the INC and BUU [19] results. Photon production in BUU has been implemented perturbatively and hence the BUU results

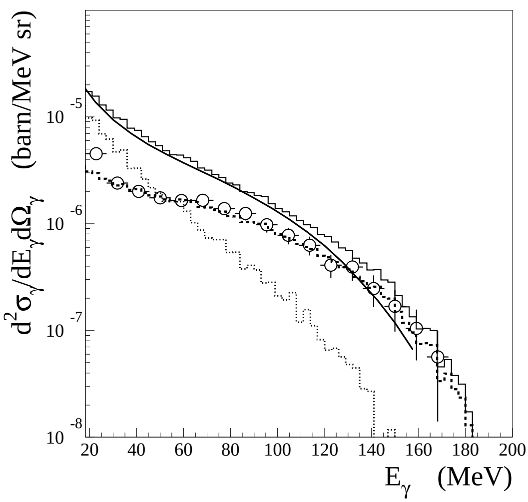

Fig. 5. Inclusive photon spectrum for 190 MeV $p+$ Au at a photon laboratory angle of $75° \pm 5°$, compared with results from the INC model (solid histogram) and BUU (solid line). The dotted histogram shows the multiple-step contribution from the INC model. The dash-dotted line is obtained when the INC result is multiplied with the quenching factor QF from Eq. (1).

can only be used to compare with inclusive data. The multiple-step contribution from INC, dominating the soft-photon part, has been indicated separately. Most notably is the large discrepancy of the models with the experimental data in the soft part of the photon spectrum. Below $E_\gamma \approx$80 MeV the models agree very well with each other and exhibit the characteristic soft photon ($1/E_\gamma$) dependence. Much better agreement between the experimental data and the calculations is found in the hard part of the spectrum, even near the kinematic limit. The differences between the models at these high photon energies are associated with the implementation of *e.g.* the Fermi-momentum distribution and the Pauli blocking. It seems as if multiple-scattering processes, which dominate the soft-photon yield are overestimated. However, the angular dependence of proton yields at large scattering angles, where multiple-scattering processes are essential, agree within the error margins for all targets studied. Therefore, multiple scattering is well described. By fitting the experimental data with the product INC $\cdot$ QF, where INC represents the INC result, we find a mean collision time $\tau = 2.4\pm$ 0.4 fm$/c$ for the Ni, Ag and Au targets and 3.7$\pm$ 0.2 fm$/c$ for the C target. These values are much smaller than the expected time interval between two hard NN collisions in nuclei (ca. 11 fm/c).

From this observation one must conclude that in addition to LPM-quenching of soft photons in multiple hard NN collisions there are probably other effects, *e.g.* multiple soft collisions, contributing to the overall suppression of the photon yield. In addition, the dynamical behaviour of the nuclear system may cause a modification of the elementary photon production process. This hypothesis is supported by the observation that the dipole contribution in the angular distribution appears to be absent in the reactions studied here. 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.

6. Soft photons in quantum transport theory

The available dynamical models are all of semiclassical nature and thus not reliable enough. The new data indicate the need for a quantum transport theory which includes consistently the medium modifications and the interference phenomena. The development of this theory for photon production in intermediate-energy proton+nucleus reactions has been initiated recently [9, 20]: This approach goes beyond the conventional quasi-particle approximation. The in-medium photon production cross section is calculated from a microscopic NN interaction including the spectral width of the baryon propagators. Two sources of multiple-scattering effects can be identified: scattering of final state nucleons before or after photon radiation; this turns out to be a minor effect compared to the multiple scattering during nucleon propagation between strong and electromagnetic interaction. Preliminary results [20] for a 200 MeV $p+\text{nucleus}$ reaction indicate that this approach leads to a remarkable suppression of the soft-photon spectrum below 80 MeV. The quenching amounts to a factor 2 at 30 MeV photon energy for a quasi-particle width of 7 MeV which corresponds to a nuclear temperature of about 3 MeV. Next steps will include a better approximation of the nucleon momentum distribution and calculations of double-differential cross sections for a more detailed comparison to available data.

7. Conclusions

In summary, new experimental data have been presented for bremsstrahlung from the soft-photon region up to the kinematic limit in proton+nucleus reactions. We observe a strong suppression of the bremsstrahlung cross section in the soft part of the photon spectrum for both inclusive and exclusive data. The latter data relate the observed effect to the multiple scattering process of nucleons. In addition to the LPM quenching of soft photons an overall suppression of the bremsstrahlung rate due to the nuclear medium is required in order to explain the absolute magnitude of the observed effect. First results from calculations of bremsstrahlung production in nuclear matter derived from a realistic NN interaction indicate the suppression of bremsstrahlung in the soft part of the photon spectrum. Future experiments will aim at sharper coincidence data for a direct comparison of photon production from quasi-free and multiple-scattering reactions.

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