VERY ENERGETIC PHOTONS FROM HEAVY-ION COLLISIONS*

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For the first time single photons with energies up to 6 times the beam energy per nucleon have been measured in a heavy-ion reaction. The reaction studied was Kr+Ni at 60 A MeV. In the nucleon-nucleon center of mass system the spectra exhibit an exponential shape with an inverse slope parameter E_o= 20 MeV. Bremsstrahlung in individual NN collisions is the origin of the highest energy photons, as for the lower energy ones.

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1. Introduction

Production of very energetic particles is the unique tool to study the initial phase of a collision between heavy nuclei well above the Coulomb barrier (for a recent review, see [1, 2]). In this first phase of such a collision, where the initial collective motion has not been dissipated, one expects maximum energy density and compression to be reached, allowing to study the equation of state of nuclear matter.

Of great interest is the production of particles like photons, scalar and vector mesons, dileptons and antinucleons, which do not exist as real particles in the nucleus, but are created in the course of the collision. The subthreshold production of these particles (below their free nucleon-nucleon threshold) allows for a clear separation of the initial and final stage of the reaction, as in the latter their production is strongly suppressed because of Pauli blocking. To be detected, the particles have to come out of the nuclear matter where they are produced. Interacting only via the electromagnetic

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(EM) force, photons and dileptons reach the detector almost unaffected and thus provide an undistorted view of the participant zone. All other particles can be absorbed rather easily because of their short mean free path.

High energy photons can be considered as subthreshold particles when the energy is approximately half the beam energy (the NN center of mass energy), and are therefore the most interesting probe. However, the beam energy range where they can be effectively exploited is limited. At high beam energies (above 200 A MeV) abundantly produced neutral pions, which disintegrate into two photons, cause a prohibitive background. The highest beam energy, for which a measurement of high energy photons has been performed, is 124 A MeV [3].

A typical photon spectrum exhibits three basic features. In the low-energy part ($E_\gamma < 15$ MeV), the exponential spectrum originates from photons emitted during the cooling down of the reaction remnants. The bump around 20 MeV is the signature of the EM deexcitation of Giant Resonances excited in the reaction fragments. At higher energies the exponential spectrum is made by photons produced predominantly in first-chance proton-neutron collisions. In a commonly used convention, photons above 30 MeV, *i.e.* above the GR region, are called high-energy photons. It has to be noted, that in the experiments performed in the past decade the range of the measured spectra was rather narrow. In Fig. 1 we show the ratio of the experimentally-established photon spectrum range (corrected for the 30 MeV conventional threshold) over the beam energy for published data. This ratio is about 3 at the lower beam energies and only 2 at higher beam energies. The knowledge of the far-end of the photon spectrum is an interesting challenge to the theoretical models. The production of such energetic photons requires either not yet specified collective phenomena or may be the signature of a very long and unexpected tail of the nucleon momentum distribution within the collision zone. It is also of prime importance since it allows to enter the region where one expects to observe the EM decay of baryonic resonances. This could be a unique way to study the behaviour of the Δ resonance within hot and compressed nuclear matter.

In this contribution, we present results from the reaction Kr+Ni at 60 A MeV, where the photon spectrum has been measured up to 350 MeV, *i.e.* almost 6 times the beam energy per nucleon.

2. Experiment

A natural Ni target has been bombarded for 200 hours using a 60 A MeV Kr beam delivered by the GANIL accelerators. Photons were detected by the Two (Three) Arms Photon Spectrometer TAPS [4], arranged for the purpose of this experiment in 5 blocks of 64 modules each. Each module

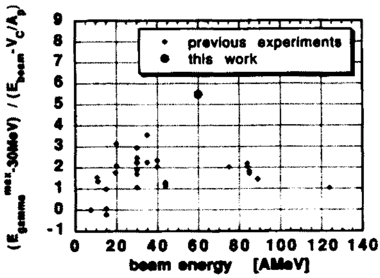

Fig. 1. Ratio of the maximum of the experimentally observed photon spectrum to the beam energy, as a function of the beam energy, for all published experimental results. In this ratio the maximum energy is corrected for the conventional 30 MeV threshold, while the beam energy is corrected for the Coulomb repulsion.

consists of a 25 cm long BaF_2 calorimeter (12 radiation lengths) of hexagonal shape (5.9 cm inner diameter) equipped on the front face with a 5 mm thick plastic scintillator used for the identification of charged particles. The blocks were installed around the target at a distance of 60 cm. A 60-element forward phoswich hodoscope served as a reaction trigger.

The main goal of this experiment was to study the hard-photon correlations (see the lecture of Y. Schutz [5]), which required as the top-level trigger two neutral particles in coincidence with the reaction trigger. Fortunately, this trigger is also very useful for the detection of single high-energy photons. Since the electromagnetic shower developed by a high energy photon has significant lateral dimensions, it may fire two or more adjacent modules above the discriminator threshold (15 MeV in this experiment). This situation can be easily recognized in the off-line analysis, and the photon energy is reconstructed using the total energy deposited in several detectors forming a continuous cluster. It has to be mentioned, that the analysis of the TAPS data allows for a redundant identification of photons based on the time-of-flight, pulse-shape analysis of the BaF_2 signal and charged/neutral separation provided by the plastic scintillator. This redundancy is of primary importance as the photon signal is very weak compared to the flux of hadrons from heavy ion collisions.

It is well known, that calorimeters based on scintillators are sensitive to the background generated by cosmic rays. Even the very good time resolution of BaF_2 scintillators is not sufficient to reduce this background which is recorded in random coincidence with the reaction trigger. Indeed, extensive showers created in the concrete roof of the experimental area may easily simulate good events in the forward hodoscope. To reduce the background coming from cosmic rays a special software method, based on shower linearity and multiplicity restrictions, has been applied to the data. This method, developed on the basis of simulations, has been verified and allowed for a significant reduction of the background in the energy range > 150 MeV [6].

3. Results and discussion

The source velocity obtained from photon spectra, accumulated with the requirement that one neutral particle is detected in coincidence with the reaction trigger (provided by the hodoscope), supports the idea of individual proton-neutron collisions as the source of such photons [7]. The photon global yield and inverse slope parameter of E_o=20 MeV are both in good agreement with the existing systematics [1, 2]. However, this trigger has been strongly reduced during the data taking and the high energy end of the photon spectrum reaches "only" 150 MeV.

The analysis presented in this contribution is based on 2.2×10^5 events, where a single photon of energy exceeding 120 MeV has been detected. Among these events, 80% have been accumulated with the trigger defined by two neutral particles. After the transformation into the nucleon-nucleon center of mass system and the subtraction of the cosmic-ray induced background, the spectra are of exponential shape with a slope independent of the emission angle (Fig.2). Only at forward angles some deviations can be noticed which can be due to the contribution coming from photons following neutral pion decay (the threshold of 120 MeV strongly reduces this contribution at backward angles). The total spectrum is shown in Fig.3. It extends up to 350 MeV, *i.e.* almost 6 times the beam energy per nucleon.

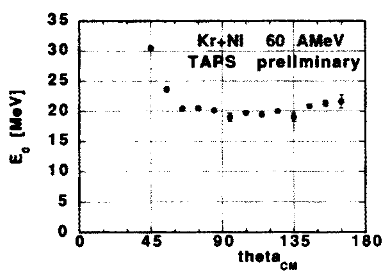

Fig. 2. Inverse slope parameter obtained by fitting an exponential curve to the photon energy spectrum in the NN center of mass system, as a function of the emission angle.

The purely exponential shape and source velocity equal to the half beam velocity indicate, that the mechanism for the production of such energetic photons remains the first chance proton-neutron collision. However, the nucleon pairs participating in collisions producing these very energetic photons must have a CM energy much higher than the energy available from the beam-related velocity and the standard Fermi motion inside the nucleus at rest ($E_F \sim$ 40 MeV). Therefore, the explanation of the observed phenomenon has to be searched in unusually long tails of the momentum

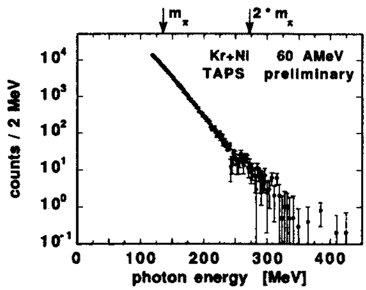

Fig. 3. Integrated energy spectrum of photons in the NN center of mass system. The arrows indicate the energy scale in terms of the pion rest mass.

distribution generated dynamically during the collisions. Production of such energetic particles is clearly related to the deep subthreshold production of mesons like neutral pions or kaons, which was reported at beam energies as low as about 10% of the free nucleon-nucleon threshold. One has to stress here the great advantage of photon as the electromagnetic probe. Compared to the hadronic probes mentioned above, photons experience only weak final state interaction and no in-medium effects (reabsorption), which influence the production yield for mesons. In a more advanced analysis, presently underway, we will soon obtain more details on the characteristics of the production of very energetic photons, *e.g.*, the angular distribution, absolute production yields, neutral pion contribution, *etc.*

4. Conclusion

The hard photon spectrum has been measured in the reaction Kr+Ni at 60 AMeV. It exhibits an exponential shape and extends up to about 350 MeV, *i.e.* almost 6 times the beam energy. The source velocity is compatible with the half-beam velocity, supporting the idea of the production mechanism based on the first chance neutron-proton collisions. The very high energy photons observed for the first time in this experiment suggest that the momentum distribution, as known in the nucleus at rest, may be strongly modified by the dynamics of the collision.

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