DEEP SUBTHRESHOLD PION AND HARD PHOTON PRODUCTION IN ^{36}Ar + ^{197}Au @ 25A MeV*

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New data on deep subthreshold pion and hard photon production in ^{36}Ar on ^{197}Au collisions at 25A MeV beam energy are presented. The experiment was performed with the spectrometer TAPS (Two-Arm-Photon-Spectrometer) at the AGOR cyclotron at KVI (The Netherlands). Preliminary results of hard photon and pion production at this very deep subthreshold energy are reported.

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1. Introduction

One of the most interesting and yet not fully understood phenomena observed in nucleus–nucleus collisions is the production of pions at energies per nucleon significantly lower than the free nucleon–nucleon threshold. The main questions this observation arises are how sufficient energy is made available in the reaction for the creation of these particles and which are the elementary mechanisms of their production in this deep subthreshold regime. An explanation of this phenomenon has been given [1] considering the additional energy necessary to overcome the free nucleon–nucleon threshold as resulting from the coupling of the bound nucleon Fermi momenta to the momentum of the relative motion of the colliding nuclei. This is however not expected to be the only mechanism involved in the pion production process at arbitrarily low beam energies per nucleon. Collective mechanisms, where pions are created as a cooperative and coherent process of all participating nucleons, are expected to be dominant in the deep subthreshold

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regime. So far, there is no model which explains convincingly the production of Deep Subthreshold Pions (DSP). Models based on the Boltzmann transport equation provide reasonable good predictions at and close to the threshold, but fail by orders of magnitude to get the correct cross sections at deep subthreshold energies.

The experiment described in this paper was proposed to measure pion production in ^{36}Ar + ^{197}Au reactions at 25A MeV and was performed with the spectrometer TAPS (Two-Arm-Photon-Spectrometer) [2] at the accelerator AGOR at KVI (The Netherlands). During the various TAPS campaigns, a wide systematics on photon and meson production has been established near and below the free nucleon–nucleon threshold [3]. The experiment described here pushes the systematics into the deep subthreshold regime with the lowest beam energy per nucleon ever used with the TAPS spectrometer for such pion production experiments and with a nuclear system heavier than those used in previous measurements of DSP at the same beam energy [4].

The main goals of this experiment with the spectrometer TAPS are to provide new and more accurate data than the existing ones, taking advantage of the excellent gamma ray identification and cosmic ray rejection of this spectrometer, and to provide new insights into the DSP production problem with the measurement of their inclusive differential cross-sections.

A brief description of the experiment and analysis procedures is presented in the first sections of this paper. The results obtained with the 48% of the available statistics are presented.

2. The experiment

The AGOR cyclotron of KVI delivered an ^{36}Ar^{+11} beam with a nominal intensity of 150 nA and 25.6A MeV energy on a ^{197}Au target of 22 mg/cm^2 thickness. The 384 BaF_2 detectors of TAPS were arranged in 6 rectangular blocks of 8×8 modules each, disposed around the target at a distance of 66 cm. The angles between the beam direction and the center of the blocks were $\pm 76.5^\circ$, $\pm 116.5^\circ$, $\pm 156.5^\circ$. This configuration provides a coverage of about 20% of the full solid angle. Each BAF_2 module was equipped with a thin plastic scintillator counter (CPV) allowing for the selection between neutral and charged particles. The KVI "Forward Wall" which comprises 92 phoswich detectors, was also used in this experiment. It was placed at a distance of 76 cm from the target covering the forward hemisphere in the range $2.5^\circ < \theta < 25.5^\circ$

The detection of pions with the calorimeter TAPS consists in detecting the photons proceeding from $\pi^0 \to \gamma\gamma$ electromagnetic decay (branching ratio 98.798 % [5]). The observables measured are the time, the energy and the opening angle of the two photons.

Events were recorded according to a set of 20 electronic triggers. One of these, the *pion trigger*, has been used in the off-line analysis for pion identification. During the first 20 shifts of the experiment this trigger was defined as two neutral particles in different TAPS blocks. A more efficient pion trigger was defined during the remaining shifts as one neutral particle in each of the two three-block sets placed at the left and right sides of the beam direction, respectively.

3. Data reduction

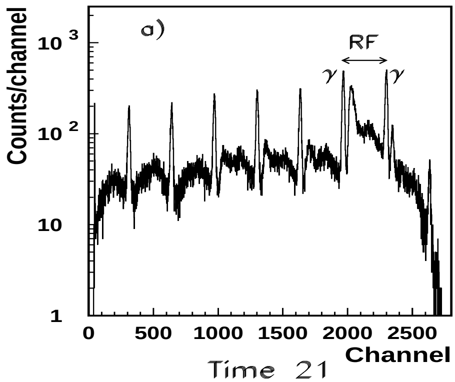
Data were taken during 35 shifts and 165 Gb were recorded in DLT tapes. The analysis was done at the IN2P3 (Institut National de Physique Nucléaire et Physique des Particles) Computer Center [7].

Binary data recorded on tape have to undergo a set of preanalysis steps in order to transform them into meaningful physical values. First steps are time and energy calibration and monitoring and Pulse–Shape Analysis (PSA) which were done with the help of the PAW based code FOSTER [8]. The cluster analysis was performed with the ROOT [10] based ROSEBUD [9] package.

3.1. Time and energy calibration

Time calibration was performed using the repeated time structure generated by consecutive beam bunches. The TDC's range of 200 ns and the cyclotron Radio-Frequency(RF) of 26.878 ns (37.205 MHz) of the experiment allow for the detection of particles from several consecutive beam pulses. This results in the typical structure of the time spectra as shown in Fig. 1(a) for a given detector. The prompt peaks corresponding to photon peaks are followed by wider peaks corresponding to heavier particles (protons, neutrons and heavier hadrons). Time calibration is performed by determining the number of TDC channels between two consecutive photon peaks. Corrections are then performed for the time drift of the RF during the experiment. Photon peaks are all aligned at the photon time-of-flight value of 2.2 ns from the target to the center of the TAPS blocks.

Energy calibration is performed taking advantage of the known total amount of energy that cosmic muons lose when traversing a TAPS BaF_2 crystal. The deposited energy of 38.5 MeV for muons, is however not exactly equal to the energy deposited by photons because of their different light production efficiency in BaF_2 crystals. This effect has been corrected for by a global factor for the photon energy, as suggested by previous studies [6]. A typical energy spectrum for a given detector is shown in Fig. 1(b). The cosmic peak position is determined using a Gaussian + straight line fit to the spectrum.



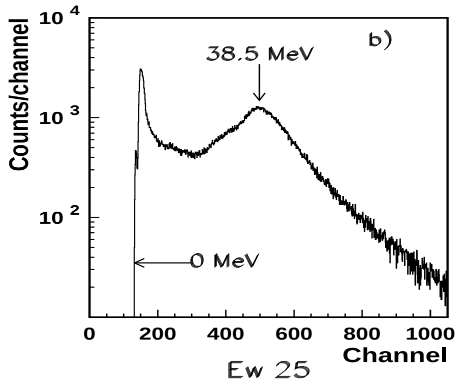


Fig. 1. (a) Raw time-of-flight spectrum of detector module 21 corresponding to 52 run files, (b) raw wide energy spectrum of detector module 25 corresponding to a set of 71 cosmic run files. The pedestal of the QDC (0 MeV) and the cosmic peak position (38.5 MeV) are indicated.

3.2. Pulse shape analysis and particle identification

Besides time and Charged Particle Veto (CPV) signals, the key variable for particle identification is the pulse-shape ratio (PSA) $E_{\rm n}/E_{\rm w}$, where $E_{\rm n}$ and $E_{\rm w}$ are the energy deposited in a given BaF_2 detector integrated within a narrow and a wide time gate (50 ns and 2 μs), respectively. These two energies correspond to the two components of the scintillation light produced in the BaF_2 crystal when hit by a particle. The PSA is typically close to 1 for electromagnetic particles: photons, electrons and cosmic muons, and close to 0.8 for protons and high energy neutrons. The identification of the particle requires in addition the time and CPV signals associated to the hit detector. This time value for a photon stemming from the reaction corresponds to its Time-Of-Flight (TOF) from the target to the detector position, *i.e.* ≈ 2.2 ns (or $\approx 2.2 + \mathrm{RF}$ ns) in our experiment. Signals were classified as corresponding to photons, electrons or nucleons and nuclear fragments if their PSA and TOF values fall into the contour assigned to that kind of particle. Contours were defined for the different energy domains selected in order to minimize the electronic walk effect of the constant fraction discriminators (CFD). The energy domains considered are: $0 \leq E_{\rm w}$ (MeV) < 5, $5 \leq E_{\rm w}$ (MeV) < 10, $10 \leq E_{\rm w}$ (MeV) < 20, $20 \leq E_{\rm w}$ (MeV) < 60, $60 \leq E_{\rm w}$ (MeV)< 100 and $E_{\rm w} \geq 100$ MeV. In Fig. 2 PSA versus TOF values in the energy range $20 \leq E_{\rm w}$ (MeV) < 60 for the 384 TAPS detectors and for the 635 run files considered in this paper are plotted. Since photons develop electromagnetic showers when propagating in BaF_2 crystals, they generate clusters of responding detectors in the TAPS blocks. The analysis of these detector clusters allows the complete identification of photons and the determination of their basic properties, *i.e.* their energy and direction [6]. Cosmic muons taken within a contour of the same shape and dimension as the photon contour were used to subtract the cosmic background from the photon spectra.

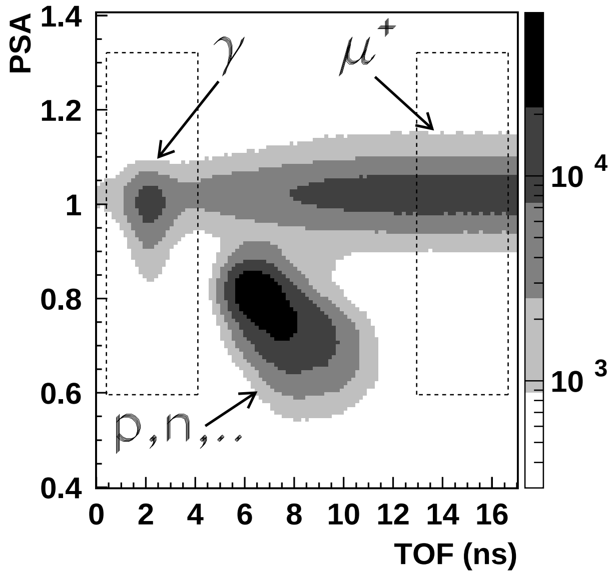


Fig. 2. Pulse shape versus time-of-flight for the energy range $20 \leq \mathrm{Ew}\ (\mathrm{MeV}) < 60$. The 384 TAPS detectors are represented in this plot for a total number of 635 run files. The rectangular contours taken for photons and cosmics are shown.

4. Data analysis and results

The events considered in this analysis were selected by the *pion trigger*. This trigger was used to select photon pairs produced in π^0 decays. The hard photon energy spectra ($E_\gamma > 30$ MeV) presented here also correspond to this trigger. These hard photons are therefore produced in more central reactions than those selected by the single photon trigger. The 635 run files analyzed represent the 48 % of the total available statistics.

4.1. Hard-photon energy distribution

The inclusive hard-photon spectrum in the NN center-of-mass is shown in Fig. 3. The measured energy E_γ of the photons has been corrected for the energy leak of photon showers at the back sides of the BaF_2 crystals and for the different BaF_2 response to photons and cosmic muons. We take this global correction factor equal to the average value of 1.15 according to simulations done in previous works [6]. In the energy range $30 < E_\gamma$ (MeV) < 90, the data are fitted by a sum of a soft and a hard exponential. The soft exponential dominates in the region $30 < E_\gamma$ (MeV) < 60 and corresponds to photons emitted in the thermalization stage of the reaction. The associated inverse slope parameter is $E_0^{\rm therm} = (7.06 \pm 0.03)$ MeV . The hard component fits the region $60 < E_\gamma$ (MeV) < 90 and corresponds to photons originated in first chance NN collisions by the bremsstrahlung mechanism in the earlier stage of the reaction. The corresponding inverse slope parameter is $E_0^{\rm dir} = (10.56 \pm 0.66)$ MeV. The ratio of the thermal to the total integrated intensities (from $E_\gamma > 30$ MeV) is $I_{\rm therm}/(I_{\rm therm} + I_{\rm dir}) \approx 64\%$ which is considerably higher than the value of 19% found for the same system at $60A$ MeV [11]. Thus, the emission of hard photons at $25A$ MeV occurs predominantly during the thermalization phase of the reaction. For the light system ^{36}Ar + ^{12}C at $60A$ MeV, the thermal component is not observed because the small volume of participant nuclear matter does not allow thermalization to take place. This shows that the amount of thermal photons depends on both nuclear system mass and beam energy.

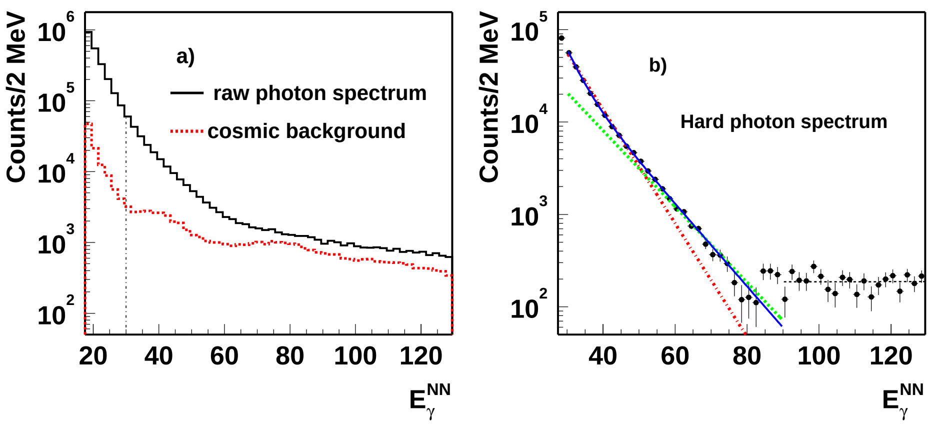


Fig. 3. (a) Raw photon spectrum in the NN center of mass frame and the cosmic background (dashed line). (b) Hard photon energy spectrum. Two exponential slopes are identified for hard photons ($E_\gamma > 30$ MeV). The thermal contribution (dash-dotted line) dominates at energies $E_\gamma < 60$ MeV and the direct contribution (dashed line) in the energy range $60 < E_\gamma$ (MeV) < 90.

4.2. Neutral pion identification

Neutral pions are identified as photon pairs with an invariant mass $m_{\gamma\gamma}$ equal to the rest mass 134.97 MeV$/c^2$ of the π^0 and within a time coincidence window between the two photons defined by the time resolution of the BaF_2

detectors, *i.e.* less than 1 ns. The time coincidence window for photon pairs is $\Delta T_{\gamma\gamma} < 1$ns or RF$< \Delta T_{\gamma\gamma} <$ RF$+1$ns. Cosmic pairs were also selected within the same coincidence window to estimate their contribution to the background. The invariant mass is obtained from the energy of the two photons (E_{γ_1}, E_{γ_2}) and their opening angle $\theta_{\gamma\gamma}$ according to the equation

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{\gamma\gamma})}\,. \tag{4.1}$$

In Fig. 4, plots of the invariant mass of coincident photon pairs (a) and cosmic pairs (b) versus their opening angle are shown. In Fig. 4(b) cosmic events appear to contribute only at opening angles $\theta_{\gamma\gamma} < 40°$ in the pion mass region and for $\theta_{\gamma\gamma} > 70°$ there is almost no cosmic background. Events which could be identified as pions are clustered at opening angles $70° < \theta_{\gamma\gamma} < 180°$ as seen in Fig. 4(a).

For $\theta_{\gamma\gamma} > 120°$ there is some events close and below the pion mass which according to preliminary simulations are due in large part to "degraded" pions, that is pions for which one or both of the decaying photons hit the border of a TAPS block depositing only part of their energy. This geometrical effect does not appear in the restricted angular domain $70° < \theta_{\gamma\gamma} < 120°$. We are studying the possibility of reconstructing "degraded" pions by simulations to increase the pion statistics.

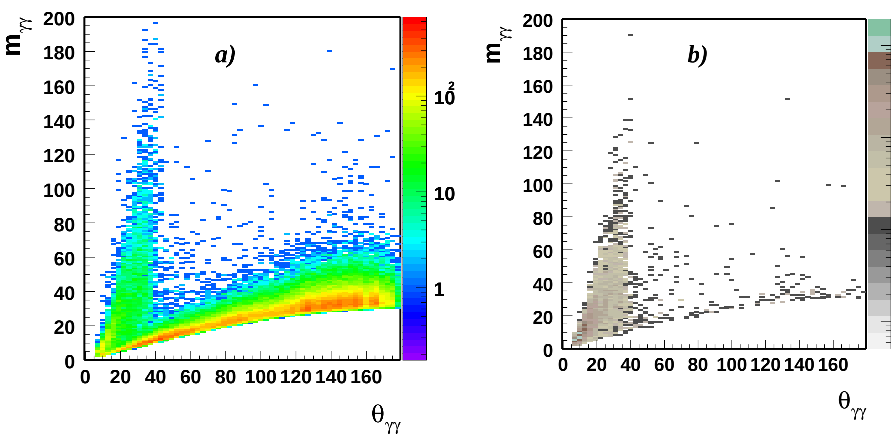


Fig. 4. Invariant mass versus opening angle for photon (a) and cosmic (b) pairs with the same time coincidence condition. Mass is given in MeV and angles in degree.

The invariant mass spectra for opening angles $70° < \theta_{\gamma\gamma} < 120°$ and $70° < \theta_{\gamma\gamma} < 180°$ are shown in Fig. 5.

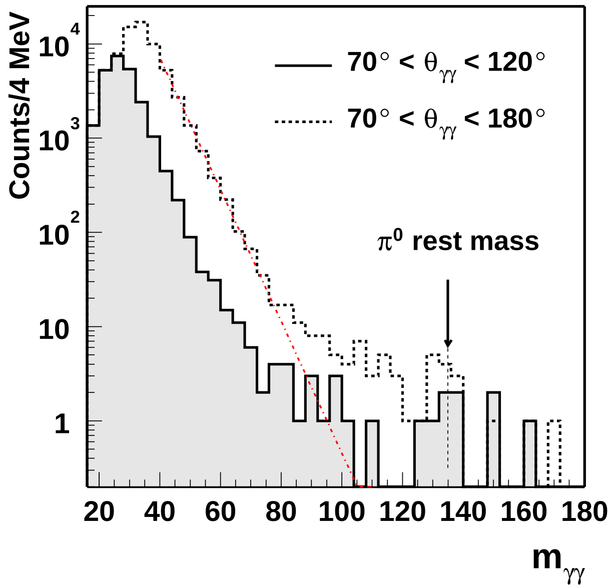


Fig. 5. Invariant mass of photon pairs for opening angles in the $70° < \theta_{\gamma\gamma} < 120°$ and $70° < \theta_{\gamma\gamma} < 180°$ angular domains.

5. Summary and outlook

Data on ^{36}Ar on ^{197}Au collisions at $25A$ MeV show that hard photons are produced predominantly during the thermalization stage of the reaction. Neutral pions have been detected and although the signal is weak it is statistically significant. The remaining 52 % of the statistics and ongoing simulations will allow to give a total cross section for π^0 production at this deep subthreshold collision energy.

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REFERENCES

[1] G.F. Bertsch, *Phys. Rev.* **C15**, 713 (1977).

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

[3] The first 10 years with TAPS, Universität Gießen, Gießen, 1997.

[4] J. Stachel *et al. Phys. Rev.* **C33**, 1420 (1986); G.R. Young *et al. Phys. Rev.* **C33**, 742 (1986).

[5] *Particle Data Group, Eur. Phys. J.* **C3**, 1 (1998).

[6] F. Marqués *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A365**, 392 (1995).
[7] http://www.in2p3.fr/CC/
[8] http://www-subatech.in2p3.fr/photons/taps/foster/
[9] http://www-subatech.in2p3.fr/photons/taps/rosebud/
[10] http://root.cern.ch/
[11] D.G. d'Enterria *et al.*, *Phys. Rev. Lett.* **87**, 022701 (2001).