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From soft photon study at Nuclotron and U-70 to NICA*

Soft photons

E. Ardashev[1], V. Avdeichikov[2], V. Balandin[2], G. Bogdanova[3], V. Dunin[2], O. Gavrishchuk[2], V. Golovkin[1], S. Golovnya[1], S. Gorokhov[1], A. Isupov[2], A. Kazakov[5], A. Kholodenko[1], A. Kiryakov[1], E. Kokoulina[2,a], A. Kutov[4], N. Kuzmin[2], I. Lobanov[1], V. Nikitin[2], Yu. Petukhov[2], G. Pokatashkin[6], M. Polkovnikov[1], V. Popov[3], S. Reznikov[2], V. Rogov[2], V. Ronzhin[1], I.A. Rufanov[2], V. Ryadovikov[1], Yu. Tsyupa[1], V. Volkov[3], A. Vorobiev[1], N. Zhidkov[2], and L. Zolin[2]

[1] Institute of High Energy Physics, Protvino, 142281, Russia
[2] Joint Institute for Nuclear Research, Dubna, 141980, Russia
[3] Lomonosov Moscow State University, Scobeltsyn Institute of Nuclear Physics, Moscow, 110000, Russia
[4] DM Komi SC UrD RAS, Syktyvkar, 167982, Russia
[5] Smolensk State University, Smolensk, 214000, Russia
[6] Gomel State University, Gomel, 246000, Belarus

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Abstract. Experimental and theoretical studies of direct photon production in hadronic collisions essentially expand our insights in multiparticle production mechanisms. These photons are useful probes to investigate nuclear matter at all stages of the interaction. Soft photons play a particular role in these studies. Until now we have no explanation for the experimentally observed excess of soft photons. These photons have low transverse momenta $p_{\mathrm{T}} < 0.1\,\mathrm{GeV}/c$, $|x| < 0.01$. In this domain their yield exceeds the theoretical estimates by 5–8 times. The registration of soft photons at Nuclotron (LHEP, JINR) has been carried out by the electromagnetic calorimeter built by the SVD-2 Collaboration. Soft photon electromagnetic calorimeter was tested at U-70, IHEP (Protvino). For the first time the soft photon yield at interactions of $3.5A\,\mathrm{GeV}/c$ per nucleon deuterium and lithium beams has been measured. The obtained energy spectra confirm the increased yield of soft photons with their energy less than 50 MeV (in the laboratory system) in comparison with theoretical predictions and agree with previous experiments at high-energy interactions. It is planned to continue soft photon study at the future accelerator complex NICA with heavy-ion beams.

1 Introduction

Direct photons (DP) by definition are not products of decay of any known particles [1–3]. In accordance with quantum electrodynamics (QED) they may be emitted in the process of charged particle scattering, bremsstrahlung in a parton or hadron cascade. In particular, $q\bar{q} \to g\gamma$ and $gq \to \gamma q$ parton interactions lead to photon emission. The higher the density and the longer the system lifetime, the more DP should be emitted. The produced photons interact with the surrounding matter only electromagnetically, and therefore they keep information about the environment surrounding them during the whole history of evolution.

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[a] e-mail: `kokoulin@sunse.jinr.ru`

Special attention is devoted to low-energy DP, soft photons (SP), whose experimental yield surpasses the theoretical predictions by 5–8 times [4–8]. This concerns K^+p and $p\bar{p}$ interactions at $70\,\mathrm{GeV}/c$ [4,5] as well as $\pi^{\pm}p$ and K^+p interactions at 250 and $280\,\mathrm{GeV}/c$ [6–8]. The recent results on this subject by the DELPHI collaboration [9, 10] are devoted to studying SP inside hadronic jets originating from the process $Z^0 \to q\bar{q} \to \mathrm{jet} + X$. The authors claim that a clear excess of SP relative to a hadronic jet in comparison with the theoretical prediction gives a factor 3 when all particles in the jet are charged and a factor 17 when the jet includes only neutral particles.

In fig. 1 the difference between the transverse-momentum spectrum of SP and predictions of the Parton Shower Monte Carlo (MC) model are presented. Photons emitted close by the jet axes are selected. The jet results from the decay $Z^0 \to \mathrm{jet} + X$. DELPHY data are used. Triangles show the bremsstrahlung spectrum calculated from QED [9,10].

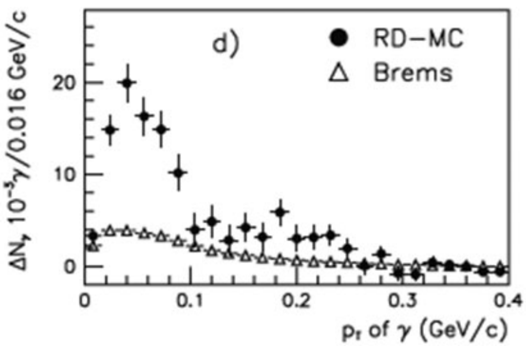

Fig. 1. Closed circles indicate the difference between transverse-momentum spectrum of SP emitted close to the jet axes in the hadronic decays of Z^0 at e^+e^- annihilation collected in DELPHI experiment at LEP1 (RD, real data) and predictions of the Parton Shower Monte Carlo (MC) model. Triangles show the bremsstrahlung spectrum calculated from QED. The errors are statistical [9,10].

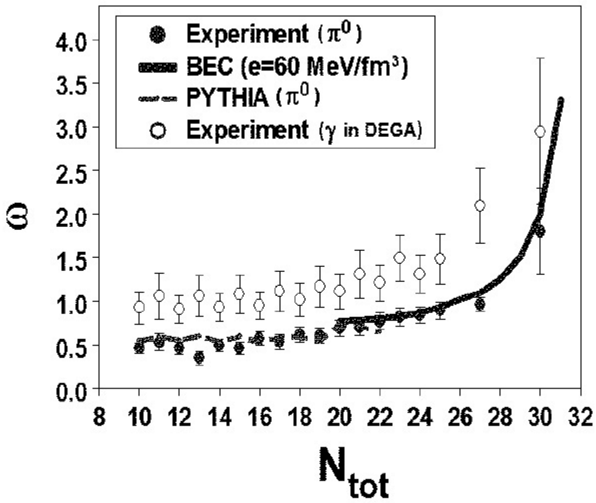

Fig. 2. Experimental values of scaled variance, ω, of number of a neutral pions (•) and photons (○) as a function of the total number pions N_{tot}. Solid line: theoretical prediction [27], dashed line: Monte Carlo simulation of pp interactions with 50 GeV proton beam [25,26].

The SP surplus can be assigned to an unknown physical processes. For a qualitative explanation of this effect the assumption of the formation of a cold spot of quark-gluon plasma (QGP) or hadronic gas has been made in a number of theoretical models [11–14]. It is argued that a cold spot is relatively stable and radiates SP. These photons testify the existence of a new phenomenon connected with the collective behaviour of particles, see for example [15].

In ref. [11] the formation of a cold zone of the QGP in a hadronic gas is assumed (model cQGP). The authors believe that cold partons have lack energy for fast hadronisation. So they recombine in hadrons rather slowly. The cold QGP droplet has a big lifetime and it reveals itself as a source of low-energy DP. The idea of a cold spot of pion gas is considered in ref. [12]. Slow pions are repeatedly reflected from the border of hot and cold areas and have a large lifetime. Again at the cost of a long lifetime the cold spot radiates SP with low energy in the c.m.s.

A new interesting idea has been advanced in ref. [16] where the analogy between expanding hadronic fireball and expanding universe was supposed. In both cases the spectrum and intensity of emerging photons can be described by a black-body radiation formula. DP appear as an analogue of the cosmic microwave background radiation. A semi-qualitative description of the available experimental data has been achieved.

In accordance with a gluon dominance model (GDM) [17–23] the energy of colliding hadrons is transformed to the energy of initial particles and a formed quark-gluon system. This model describes well the high-multiplicity region [24]. Half of the active gluons (about 47%) produce hadron jets and the remaining gluons can be sources of SP.

GDM gives estimations of the linear size of the SP radiation system. It is $L \sim 4$–6 fm depending on SP momentum (p_T).

It is well known that the temperature of secondary hadrons is higher than the temperature of SP. Remaining soft gluons cannot transform into hadrons and turn into SP. The measured dependences of the yield of SP on the charged, neutral or total multiplicities can be useful to understand of their nature.

In a thermalised cold and dense hadronic gas a number of collective effects may appear as a consequence of multiboson interference. In particular, an increase in the rate of DP results from bremsstrahlung in the partonic cascade, in a dense and cold pionic gas or a condensate. The production of a multipion coherent semi-bound state is possible. It emits soft pions in the course of its formation. The partonic cascade leads to a high multiplicity of particles in the final state. Many of them are accompanied by bremsstrahlung radiation. At high densities an additional γ-source [13,14] is predicted: pion annihilation $\pi^+\pi^- \to n\gamma$. Close to the region of the chiral phase transition the masses of the constituent quarks are decreased what leads to an increase of radiation (bremsstrahlung and annihilation processes). This effect may serve as a more reliable tool to measure density and temperature of the system.

It is necessary to note that the DP discussed here have energies in the c.m.s. of $E_{c.m.}(\gamma) \leq 50$ MeV or wavelength $\lambda \geq 60$ fm. Obviously, this size is much greater than the size of the formed hadron system. Therefore, such photons should be radiated by the system as a whole instead of the separate particles. It can happen if the pion system forms a condensate [15]. Experimental signals for the Bose-Einstein condensation of pions have been obtained (fig. 2) by the SVD-2 Collaboration [25,26]: the sharp growth of the scaled variance $\omega = D(\pi^0)/\langle N_0 \rangle$ (D is the variance, $\langle N_0 \rangle$ is the mean multiplicity of π^0-mesons). Such behaviour of ω is predicted in the high-multiplicity region in the ideal pion gas model [27].

The study of SP spectra seems especially interesting for the future accelerator complex NICA [28] as it aims to deal with a high-density system [29,30]. The goal of the proposed experiment is the investigation of collective behaviour of particles in the process of multiple hadron production in pp, pA and AA interactions at the colliding beam energy $E \approx 5\,\text{GeV}$ per nucleon. The domain of high multiplicity (central collisions) will be interesting for SP study depending on the multiplicity of charged or neutral secondary particles. This gives the possibility to study the dependence of the yield of on the multiplicity of charged and neutral particles.

Having two electromagnetic calorimeters we can search for new states of neutral particles, study interference of SP and solve other tasks [28].

2 Manufacture of electromagnetic calorimeter with low-energy threshold

For studying of SP spectra the electromagnetic calorimeter SPEC has been manufactured. A specific feature of this photon detector is connected with capability to measure low energy deposit with a threshold $E_{\text{thresh}} \approx 1\,\text{MeV}$ [31]. Still none of the known experiments has reached such a small value of the photon energy detection. As has been mentioned above, it is importance for check of some exotic theoretical models. Our Collaboration manufactured a SP electromagnetic calorimeter (SPEC) on the base of BGO crystals. The dimension of its one cell is equal to $3\times3\times18\,\text{cm}^3$. In this case the spatial localisation of a photon is $\sim 3\,\text{cm}$. One should take into account the transverse dimension of the photon shower $\sim 3\,\text{cm}$. From this very qualitative consideration we concluded that the calorimeter transverse dimensions should be $\sim 20\times20\,\text{cm}^2$. Four central cells with a total area of $36\,\text{cm}^2$ provide a high efficiency photon detection. The longitudinal dimension should be ~ 16 radiation lengths. For BGO this is equal to $\sim 18\,\text{cm}$. The important problem is taking into account the dissipated particle background in the experimental hall. Reduction of background may be provided by the calorimeter pre-shower.

According to refs. [4,5] the integrated cross section of the SP production in the domain $-0.01 \le x \le 0.01$ and $p_{\text{T}} \le 0.1\,\text{GeV}/c$ is equal to 2–4 mb/nucleon. Assuming an SP isotropic angular distribution we get an averaged differential cross section $\text{d}\sigma/\text{d}\omega = 0.2\,\text{mb/strad/nucleon}$. For a proton beam luminosity at NICA collider $L \approx 10^{30}\,\text{cm}^{-2}\,\text{s}^{-1}$ the SPEC counting rate is equal to approximately $1\,\text{s}^{-1}$. For Au + Au collisions with luminosity $L \approx 1\times10^{27}\,\text{cm}^{-2}\,\text{s}^{-1}$ the count rate is about to $0.4\,\text{s}^{-1}$. During one day of runtime a statistics of $\sim 5\times10^4$ SP will be accumulated. SP may convert into e^+e^- pairs in the vertex detector material and in the walls of the TPC. Thus another option at NICA can be the detection of low-energy e^+e^- pairs in the TPC. This will lead to one order of magnitude higher statistics due to the higher angular acceptance of the TPC. But the pair detection in the TPC is subject to an additional analysis.

Fig. 3. Disposition of SPEC at Nuclotron hall (run 2015).

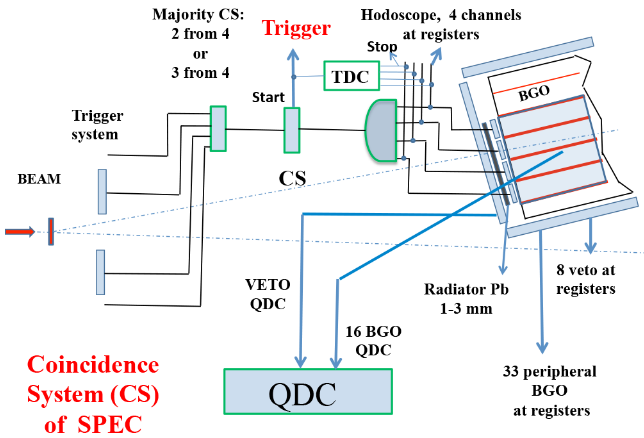

Fig. 4. Simplified scheme of SPEC.

The photon detector with an effective area of $10^2\,\text{cm}^2$ set at a distance of 1.3 m from the fixed target, leads to the following estimation of the DP count rate: 2 events per cycle. One week of runtime will provide a pretty good sample of SP: approximately 2×10^5 events. Let us point to the distinctive features of the present project.

- Photon spectra at several fixed angles will be measured. The lower edge of the spectra is $\sim 5\,\text{MeV}/c$.
- Each SP spectrum will be collected at a certain fixed multiplicity of secondaries in pp, pA and AA interactions.
- We plan to study both phenomena, Bose-Einstein condensation [25,26] and SP yield.

3 Soft photons at U-70 and Nuclotron

The view of SPEC manufactured by the SVD-2 Collaboration located at the Nuclotron hall is shown in fig. 3. This setup was tested at U-70 in 2014. The simplified scheme of apparatus is presented in fig. 4. The basic elements of SPEC are BGO counters (matrix 7×7 crystals) with 49 PMT. The box with counters is surrounded by the scintillator detectors of a guard veto-system. SPEC is placed inside a thermostat.

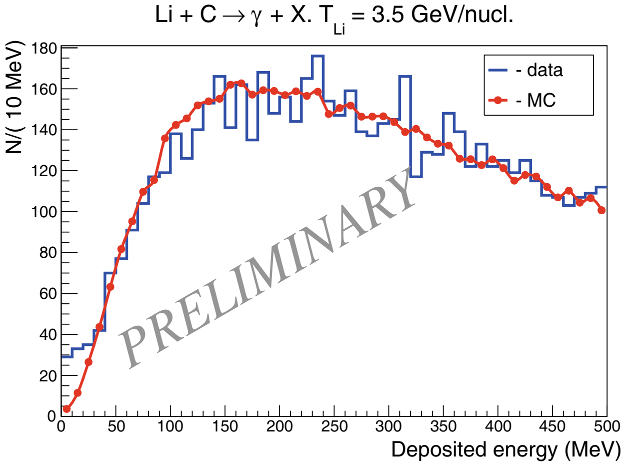

Fig. 5. Energy release in SPEC with pre-shower and MC (uRQMD-3.3 + Geant-3.21) simulation of Li+C interactions with 3.5A GeV/c lithium beam.

The simplified scheme of SPEC setup is shown in fig. 4. The SPEC is supplied with a pre-shower. The first element of the pre-shower is the plastic veto-detector of charged particles ($21 \times 21 \times 2\,\text{cm}^3$). The next element is a 2 mm lead convertor. The assembler of 4 plastics ($18 \times 4.5 \times 1\,\text{cm}^3$) is located in front of the BGO crystals. The event trigger is produced by a set of 4 plastic scintillators placed just behind of the target. There are two veto-counters in front of the target.

Calibration of SPEC has been carried out at the U-70 accelerator [31] at the SVD-2 setup. Secondary high-energy beams of charged particles with average energy deposition about 160 MeV are used. Also cosmic muons crossing the calorimeter in the transverse direction are used for calibration.The BGO crystal noise level is of the order of 50 keV. The resolution of SPEC has been measured using a MIP signal.

During the Nuclotron run, SPEC is set at an angle of 16° relative to the beam direction. The front plane of crystals is away from the target at the distance of 203 cm. The digitization of plastic scintillators is realised with a CAMAC ADCs (Lecroy 2249A) and TDCs (LeCroy 2228A), the digitization of analog signals of the calorimeter is realized with ADC CC-008.

We used CAMAC and a LE-88K crate-controller. The crate-controller is connected to a PC with PCI-QBUS interface. Data acquisition software is developed in the MIDAS framework (`http://midas.psi.ch`). The time of flight between the beam counter and the pre-shower for neutral particles (no signal in the front-veto) is also measured. The time-of-flight resolutions is 0.6 ns for d+C and 0.5 ns for Li+C interactions [32].

In 2014 (49th, 50th) and 2015 (51st) experimental runs have been carried out at Nuclotron in LHEP of JINR with 3.5A GeV/c deuterium, lithium and carbon beams. SPEC has been installed at the location of NIS-GIBS setup (this setup is aimed at hyperon formation study). Spectrum of energy deposited in SPEC at interactions of lithium beams at carbon target is presented in fig. 5.

Estimation of systematic errors obtained from analysis of efficiency of SP registration and correctness of background simulation does not exceed 20% of the value of statistic errors in the energy region of SP up to 50 MeV. Therefore we conclude we get the evidence of existence of SP excess in nuclear interactions (fig. 5).

4 Proposal for future experiments

Our Collaboration plans to carry out the measurements of SP yield in pp interactions at next runs at U-70. At the SVD-2 setup we have the opportunity to change the angular configuration of SPEC relative to the proton beam direction. Also the time-of-flight measurement will be performed on a baseline as long as 10 m. This will provide better discrimination of neutral hadrons and photons.

We will continue our study of SP at Nuclotron with beams of light ions to get more information about SP properties. This experience will be helpful when the collider NICA will begin its work and it is possible that we will approach to the understanding of the SP phenomenon.

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