Soft photon study at NICA’s facilities

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Abstract. For over three decades there has been no comprehensive understanding of the mechanism of soft photon (energy smaller than 50 MeV) formation. Experimental data indicate an excess of their yield in hadron and nuclear interactions in comparison with calculations performed theoretically. In JINR, in connection with the building of a new accelerator complex NICA, it has become possible to carry out such studies in pp, pA and AA interactions at energies up to 25$A$ GeV. We prepared the extensive physical program for soft photons that covers the wide region of investigations in high energy physics. To carry out this program our group develops the conception of an electromagnetic calorimeter on type “shashlik” based on gadolinium-gallium garnet (GaGG) crystals, which have a significantly lower threshold for the registration of photons. The first tests of electromagnetic calorimeters manufactured at the Joint Institute for Nuclear Research on the basis of the GaGG crystals and a composite of tungsten and copper are reported.

1. Introduction

Our SVD-2 Collaboration has carried out searching for collective phenomena in the high multiplicity region at U-70 accelerator. This project called “Thermalisation” was quite successful \cite{1}. After its completion, we still have an unresolved question about the mysterious origin and properties of soft photons (SP), which we also planned to study at the beginning of the project. For over more than three decades this phenomenon does not have comprehensive understanding. A few experimental groups found out the increased yield of photons in the region of low transverse momentum, $p_T$, smaller than 50 MeV/$c$ \cite{2-10}. These photons are not the decay products of short-living particles (including resonances).

According to QCD, at high energies, $q\bar{q}$, $qq$ and $gg$ interactions lead to the emission of photons called direct ones. Our activity is aimed at studying direct SP. Despite the fact that the majority of photons in high energy interactions comes from decays of secondary hadrons (neutral mesons and others), the direct photons present unique opportunity to study the soft gluon component of a nucleon and a stage of hadronisation. Direct photons interact with surrounding medium only electromagnetically as opposed to strong interaction of hadrons. So SP keep more information...
about medium at all stages of interaction. This is especially valuable along with information about the secondary hadrons.

The goal of this report is to introduce the content of our scientific program. We are going to carry out it at the Joint Institute for Nuclear Research (JINR) using proton and nuclear beams of the Nuclotron and the future collider NICA (particularly the SPD setup). First of all we plan to manufacture a space saver electromagnetic calorimeter with the low registration threshold. We have produced and tested the heterogeneous calorimeter, “spaghetti”, and now we came up with the necessity of manufacturing a “shashlik” type. That type provides higher energy resolution and can be easily transformed to the homogeneous calorimeter in the case of registration of more low-energy gamma quanta. We use crystals of gadolinium-gallium garnet (GaGG) as scintillator and composite of tungsten and copper in the capacity of absorber.

Section 2 is devoted to the analysis of some experiments corroborating the excess of SP yield. The content of our physical program is presented in section 3. The preparation for SP yield study is informed in section 4. Section 5 states the conclusions.

2. Experiments in which there is an increased yield of SP

The first convincing experiment that detected SP has been carried out at the Big European Bubble Chamber (BEBC) [2]. The SP spectrum in $K^+p$ interactions at 70 GeV/c beams of $K^+$-mesons after subtraction of all known hadron decays indicated their excess in comparison to expected from QED inner bremsstrahlung as shown in figure 1(a).

The next series of experiments have been executed at higher energies [3–7]. The excess of the SP yield consisted fourfold or even higher, eightfold exceeding. It was observed in $K^+p$ and $\pi^+p$ (280 GeV/c) [4], $\pi^-p$ (280 GeV/c) [5, 6], $pp$ (450 GeV/c) [7] and at nuclear targets $p$–Be (figure 1(b)), $p$–Al (450 GeV/c) [3]. The detection of SP was carried out by using either
Figure 2. Energy release in BGO calorimeter with a pre-shower in d+C (a) and in Li+C (b) interactions at Nuclotron. Monte Carlo simulation (the red line) and data (the blue line).

crystal electromagnetic calorimeter or/and TOF measurements. The experimental (real) data were compared to the theoretical estimations of inner bremsstrahlung for the certain multiplicity of charged hadrons taking part in the interaction.

The last European experiment has been realized at the SPS accelerator, CERN by the DELPHI Collaboration [8]. Photons were detected in hadron decays of Z⁰ bosons in the reaction \( e^+e^- \rightarrow Z^0 \rightarrow \text{hadrons} \). SP formed in \( q\bar{q} \) jets of hadrons converted in front of the DELPHI main tracker (TPC). The yield of SP as a function of the neutral pion number turned out to be completely unexpected. The neutral pions were more effectively radiating than the charged ones [9]. The excess over predicted inner bremsstrahlung rates as a function of the neutral multiplicity in the quark jet turned out to be seventeen-fold for the largest recorded number of pions \( N_{\text{neu}} = 6 \). Muon bremsstrahlung photons in the reaction \( e^+e^- \rightarrow Z^0 \rightarrow \mu^+\mu^- \) has demonstrated a good agreement of the observed photon rate with predictions from QED for the muon inner bremsstrahlung contrary to the anomalous soft photon excess observed in hadronic \( Z^0 \) decays [10].

After the completion of “Thermalization” project which was aimed at searching for collective phenomena in high multiplicity events, we are going to carry out active experimental research of SP in proton and nuclear collisions at the Nuclotron (the JINR’s setup) and further we plan extending this exploration at the future accelerator centre NICA [11]. To begin with, we manufactured the electromagnetic calorimeter (ECal) on the base of BGO (bismuth ortogermanate) scintillators [12]. BGO crystals have a small radiation length \( X_0 = 1.12 \text{ cm} \) that permits reducing considerably the volume of our device. Moreover, this scintillator has small sensibility to neutrons. During the Nuclotron’s run (2015 year), we irradiated with deuteron and lithium 3.5 \( A \) GeV beams a small carbon target. Our BGO calorimeter was set at an angle of 16° relative to the beam direction at the NIS-GIBS setup registered energy release of gamma quanta. The Monte Carlo simulation has been also carried out under the conditions of the last assembly and the beam energy 3.5 \( A \) GeV. We used uRQMD and Geant-3.21 software for that.

After data processing, spectra of photon energy release in deuterium-carbon (figure 2 (a)) and lithium-carbon (figure 2(b)) interactions have been obtained. In the region of energy release below 50 MeV, a noticeable excess over the Monte-Carlo simulation is observed. It agrees well with the other SP experiment [8].

We would like to note that there are a few phenomenological models which have been worked out to describe the SP spectra [13][16]. The most attractive among them is the model of the cold quark-gluon plasma of L. Van Hove [13]. But until now, a complete comprehensive understanding of the nature of the anomalous yield of SP has not been achieved.
3. The scientific program of SP study

We started searching for collective phenomena in high multiplicity events at U-70 in pp interactions at 50 GeV/c proton beam from the design of the gluon dominance model (GDM) [16, 17]. It is built as the convolution of two stages. The first stage is described in QCD as a quark-gluon cascade. For the second one, the phenomenological scheme of hadronization is applied. The GDM evidences that the sources of secondary particles are gluons, we call them active, and an abundance of soft gluons can be sources of SP. They are picked up by newly born quarks with a subsequent dropping of energy by the SP emission: $g + q \rightarrow \gamma + q$ or $q + \bar{q} \rightarrow \gamma$.

At that valence quarks are staying in the leading particles.

We also estimated the emission region for SP in the case of an almost equilibrium state, using black body radiation for $pp \rightarrow \text{hadrons} + \text{photons}$ at U-70. Its linear size exceeds the typical hadronisation region (1 fm) and reaches a value of about 4–6 fm [17]. We are going to continue studying the soft gluon component of proton because it is relevant for understanding of the spin structure of nucleon.

The formation of the pionic (Bose-Einstein) condensate in the region of high total multiplicity ($N >> <N>$, $N = N_{ch} + N_0$, $<N>$ – the average multiplicity of charged and neutral pions) can be related with the increased yield of SP [14]. Using the electromagnetic calorimeter of the SVD-2 setup and its silicon detector we retrieved the number of events with certain multiplicity of $\pi^0$-mesons for given charged multiplicity and calculated the scaled variance $\omega^0 = (\langle N_0^2 \rangle - \langle N_0 \rangle^2)/\langle N_0 \rangle$. The ratio of experimental value of $\omega^0$ to Monte-Carlo codes predictions (and the Poisson distribution as well) achieves 7 standard deviations at the high total multiplicity $N = 25$. According to theoretical prediction in [18], this is the evidence of the BEC formation. We are going to investigate the SP yield in the region of the pionic condensate and to test the hypothesis [14] as the reason of this excess.

The increasing yield of photons with low energy gives us the opportunity to calculate two particle correlations of direct photons. The similar results were obtained by the WA98 Collaboration [19]. The deviation from theoretical predictions is at the level of a fraction of a percent.

There is the little-known experimental fact that the $\eta$-meson yield in AA interactions in terms of nucleon is higher than in pp collisions [21]. We are ready to test this fact. It is important for understanding of the mechanism of the strangeness formation. Apparently, the mechanisms of its formation in nucleon and nuclear interactions are different.

The next item of our scientific program appeared thanks to the RHIC experiment, namely with using the variable flow or $v_2$. There is the interesting prediction in [22] about the growth of $v_2$ in the region of small $p_T$ of photons. This dependence can evidence about the SP coherent emission. Our program proposes testing of that behaviour.

And finally, the last item of our program is the proposal of the scientist Cheuk-Yin Wong [15] from the US. He develops an intriguing model of open string QED mesons to explain and describe $p_T$-spectrum of SP. Wong considers, since $q$ and $\bar{q}$ can not be isolated, that the intrinsic motion of the $q\bar{q}$ system in its lowest-energy state lies predominantly in 1+1 dimensions as in the open string with $q$ and $\bar{q}$ at its two ends. He studies these states and shows that $\pi^0$, $\eta$ and $\eta'$ can be adequately described as open string $qq$ QCD mesons.

By extrapolating into $qq$ QED sector in which $q$ and $\bar{q}$ interact with the QED interaction, he finds an open string QED meson state at $17.9 \pm 1.5$ MeV and QED meson state at $36.4 \pm 3.8$ MeV. These predicted masses of the isoscalar and isovector QED mesons are close to the masses of the hypothetical X17 [23] and E38 [24] particles observed recently, making them good candidates for these particles. This hypothesis has generated a great deal of interest [25].

The decay of these particles can show up as an excess of $e^+e^-$ and $\gamma\gamma$ pairs in the SP phenomenon [15]. C.-Y. Wong includes them into the thermal model, which describes well the $p_T$-distributions in the production of hadrons of different masses in the high-energy pp interactions.
Cheuk-Yin Wong was a PhD student of John Archibald Wheeler. And so he puts forward an unexpected conjecture that these QED mesons can be candidates for particles of primordial dark matter. Wang shows that an astrophysical object consisting of a large assembly of QED mesons such as the X17 particle with a mass $m_X = 17$ MeV will be an electron-positron and gamma-ray emitter. If the temperature of such an assembly is low, it can form a Bose-Einstein condensate. Such assemblies of QED mesons present themselves as good candidates as $e^+e^-$ emitters, gamma-ray emitters, or a part of the primordial cold dark matter. He makes estimates of mass and radii of such assembly and gives advice where they may be found.

4. The preparation to experimental SP study

To carry out our scientific program we have to manufacture a space saver electromagnetic calorimeter (ECal) capable of detecting low energy gamma quanta. As is known the production of homogeneous crystalline ECal’s is expensive. Usually physicists prefer making heterogeneous assemblies [26]. They are cheaper and at that possess satisfactory properties. Our activity was aimed at testing of two types of ECal’s. The “spaghetti” type was the first prototype that we produced and irradiated with the photon beams in Germany [27].

We substituted light scintillator material for a very dense (heavy) crystal having the high specific light yield [28]. It allowed us to build the device that is capable of keeping the considerable compactness (space-saving about 30%). To produce the “spaghetti” type we have chosen a mono-crystal of gadolinium-gallium garnet, Gd$_3$Al$_2$Ga$_3$O$_{12}$:Ce (GaGG), as a scintillator and tungsten+copper composite by way of the absorber. We expect the decay time of $\sim 90$ ns; a light yield of $\sim 45,000$–$55,000$ ph/MeV; price of about 25–35 $/cm^3$ of volume, and good radiation resistance.

GaGG crystal is a fast-acting scintillator, its light yield is 4 times greater than BGO crystals have. And we can acquire these crystals from the well-known domestic firm “Fomos-Materials”. In spring of 2019 the experimental tests have been carried out by ourselves in Mainz (Mainz Microtron, Germany). Two manufactured cells were irradiated by 41, 51 and 69 MeV photons. In figure 3 the result of these tests is presented for photon beams 41 and 69 MeV. It is seen that in the case of an even number of rods a narrow photon beam hits in the centre of the cell and it turns out in the absorber plate. We are only observing the tail of the Gauss distribution. The Monte Carlo simulation of such a cell and our experimental result demonstrated the similar behaviour. At the same time the Monte-Carlo simulation have shown that the necessary energy resolution for SP in the case of the ECal “spaghetti” type turns out lower than at using the interactions and comes to good agreement with experimental $p_T$ spectra for the SP yield.
Figure 4. (a) The typical scheme of “shashlik” calorimeter. (b) The energy resolution of the “spaghetti” (the red line) versus the “shashlik” (the blue line) types of calorimeters.

“shashlik” type. In figure 4 (a) the typical view of the ECal “shashlik” type is shown.

Colleagues from IHEP (Protvino) and our group are currently busy assembling the ECal “shashlik”. It is assumed that it will consist of 16 GaGG plates (100×100×3)mm³, 15 plates of 2-mm-absorber (W:Cu composite, 1:19), and his total length will be about 138 mm. In figure 4 (b) the energy resolution of the “spaghetti” (the red line) versus the “shashlik” (the blue line) types of calorimeters is presented. The dimensions of both assemblies were optimised by the Monte-Carlo simulation to achieve the required characteristics. The “shashlik” design allows expanding its size up to any length. We also can remove W/Cu absorber from the “shashlik” and then to assemble the homogeneous device for detecting MeV photons if the energy resolution of ECal will not be good enough.

5. Conclusions

We have prepared the extensive physical program of SP phenomenon study, and not only. It is planned to carry out this program at the SPD-NICA setup under construction, and other facilities.

MC simulation evidences that using the ECal “shashlik” with the GaGG crystal as high-quality scintillator and the W/Cu composite as absorber will allow us to receive better energy resolution at low energy. This activity is in progress.

We are also investigating the opportunity of using Glass and Glass Ceramic Stoichiometric and Gd³⁺ heavy loaded BaO*2SiO2:Ce(DSB:Ce) scintillation material for ECal application.

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