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MACHINES AND FACILITIES

THE PHOTON-PHOTON FACILITY AT VEPP-4M

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A special system to tag scattered electrons from γγ-processes is described. The system is intended for the experiments at the VEPP-4M storage ring. This system has a high detection efficiency and good invariant mass resolution.

1. INTRODUCTION

The possibility to study γγ interactions at e^+e^- colliding beams is based on the fact that the field of the fast charged particle can be presented by the photon flow. Therefore e^+e^- beams can be regarded as a source of "photon beams" (Fig. 1).

The electron and positron radiate virtual photons which produce a C-even state X. The reaction kinematics is fixed by the initial and final 4-momenta of the scattered electron and positron. The final electron and positron will be called below Scattered Electrons (SE). The photon energy spectrum resembles the bremsstrahlung one ($\sim 1/\omega$) and the photons are emitted mainly at small angles with respect to the beam. The SE angles are related to the photon angles by momentum conservation and are also small.

The detection of both SE's ("double-tag" experiment) determines the parameters of the γγ-system with the precision depending on the resolution of the detection system.

Due to the small emission angles of the scattered electrons the detection system should be located as close as possible to the beam (especially to study a low invariant mass region when electrons lose a small fraction of their energy). The important step in the development of detection methods for the study of two-photon processes was made by providing a detector with a special system to tag scattered electrons, electron Tagging System (TS). The review [1] contains a brief description of such systems constructed for a number of different detectors. To attain the high detection efficiency tagging of electrons emitted from the interaction point at zero angle is necessary. This can be done by a bending magnet deflecting from the beam those electrons which have lost part of their initial energy.

This paper describes TS that is now under construction for experiments at the VEPP-4M collider with the detector KEDR [2]. Its accuracy of the γγ system invariant mass measurement is approximately an order of magnitude better than in the previous systems. Another advantage of this TS is that in spite of its high detection efficiency it does not inhibit the attainment of maximum luminosity due to its natural inclusion in the interaction region beam optics.

The main problems of two-photon physics that can be investigated with the help of such system are:

- Study of the total cross section γγ ⟶ hadrons at low Q^2;
- Study of C-even resonances;
- Search for exotic states.

2. THE IDEA AND GENERAL DESCRIPTION OF THE TAGGING SYSTEM

As it was already mentioned in the introduction, the main parameters that characterize the TS and its capabilities are the SE energy resolution (and consequently the resolution in invariant mass of the γγ system) as well as the tagging efficiency in the necessary invariant mass region.

The kinematics of two-photon processes makes necessary the detection of electrons emitted from the interaction point at zero angle. The bending magnet with the doublet of mini-β quadrupoles would be natural to use as a focusing magnet-spectrometer for the SE energy measurement.

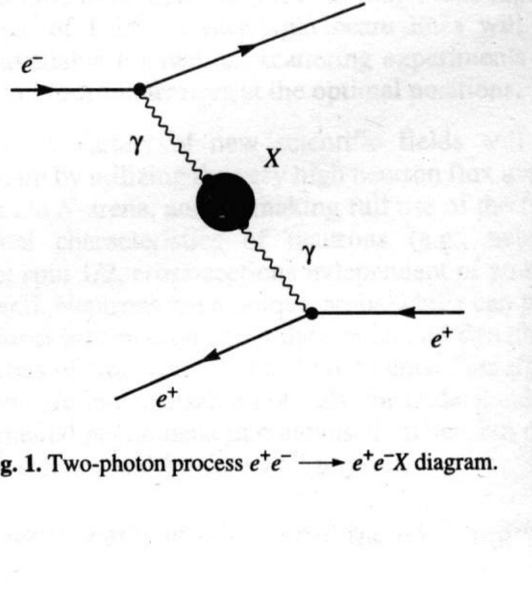

Fig. 1. Two-photon process $e^+e^- \longrightarrow e^+e^-X$ diagram.

The basic idea of the system is to use quadrupole lenses not only as accelerator optic elements but as an essential part of the spectrometer at the same time. This solution allows, firstly, to put the lenses closer to the interaction point and therefore not to contradict the attainment of the high luminosity at VEPP-4M and, secondly, to improve the SE energy resolution.

Let us consider the scattered electron with the energy $E < E_0$ (E_0 is the beam energy) emitted from the interaction point and passing through quadrupole lenses and then a bending magnet.

Due to the focusing properties of the quadrupoles, there is some distance from the interaction point where the transverse coordinate of the particle will be independent of its initial angle. Installing a tagging system at that place to measure the coordinate one can unambiguously determine the energy of the particle without measuring its angle. It is important for the energy resolution because measuring the angle well enough needs a lot of space for tagging system. Besides, the critical limitation on the angle resolution would be multiple scattering at the tagging system entrance. In order to protect the system from the synchrotron radiation background some extra material is necessary in front of TS, that would strongly influence the angle resolution but not so much the coordinate one.

So the ideal approach is to place the tagging system at the "image point", where the coordinate is independent of the emission angle. However, mini-β quadrupoles are chromatic (their focusing distance strongly depends on the particle energy). So in fact there is not one "image point", but the whole "image surface" formed by such points for each energy. To avoid designing a very complicated and huge tagging system, the authors decided not to do it exactly along the "image surface", but to fit roughly this surface with the help of few separate systems. Each of these systems should detect some energy region, and the focusing energy (for which coordinate in the system is independent of the angle) should be about the middle of the tagging energies region. In this case nonzero emission angle leads to an error in the measurements for the energy, different from the focusing one. The more the energy differs from the focusing energy, the larger is the error in the energy measurements due to the absence of information about the angle. Having, firstly, sharp peaking behavior for the SE angular distribution for the γγ processes and, secondly, several systems to divide the total energy region, one can provide a small enough uncertainty in the energy measurement.

As a result of looking for the optimal scheme from the point of view of both good detection efficiency and energy resolution, the following solution was chosen [3]. The bending magnet should be divided in two parts. There are four tagging systems to measure the coordinate of SE, two of them are behind the first magnet, two others are behind the second one.

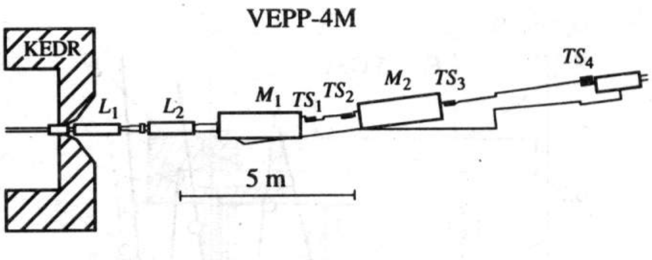

Fig. 2. Layout of VEPP-4M experimental region with KEDR tagging system. L_1, L_2 are quadrupoles, M_1, M_2 are bending magnets.

The layout is shown in Fig. 2. The SE coming out from the interaction point passes through the main detector magnet with longitudinal magnetic field, compensating solenoid, quadruple lenses L_1 and L_2 and bending magnets M_1 and M_2. Then SE is detected by one of four tagging systems TS_1–TS_4, whose basic parameters are presented in the Table.

One can see from the table that the total energy region available for tagging is from $0.39E_0$ to $0.98E_0$.

While the energy resolution of other similar tagging systems is determined mainly by the space resolution of the detection system, the most important contributions in the energy resolution of SE at the describing system are due to the spread in the initial e^+ and e^- energies and angles. Such contributions depend on accelerator parameters and are the following:

- The angular spread in the beam;
- The beam energy spread;
- The transverse beam size in the interaction point. This size is partly determined by the energy spread through the dispersion function η, another part of the beam size is due to the betatron oscillations.

One of the features of the VEPP-4M collider is a rather big dispersion function at the interaction point ($\eta = 79$ cm) [4]. Therefore, the initial energy and the position of the interaction are not independent. So the errors in the energy of SE due to the beam energy spread and due to the beam size correlate and compensate each other. The level of this compensation depends on the SE energy, and at some energy there is absolute compensation.

In Fig. 3 one can find the results of the Monte-Carlo simulation of the SE energy resolution σ_ω/E_0 shown as a

Parameters of KEDR tagging systems

TS number	Tagged energies E_{min}/E_0–E_{max}/E_0	Focusing energy, E_f/E_0	Size of TS, cm
1	0.39–0.59	0.58	7.7
2	0.60–0.72	0.66	4.3
3	0.73–0.85	0.80	8.9
4	0.85–0.98	0.91	15.8

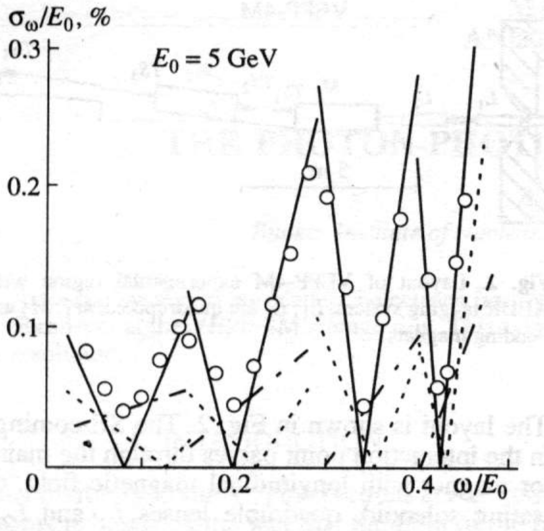

Fig. 3. Resolution of scattered electron lost energy.

function of the SE lost energy fraction ω/E_0 ($\omega = E_0 - E$). The points present the total resolution taking into account all the accelerator factors mentioned before and, besides, the presence of nonlinear elements (sextupoles of the experimental region). The solid line is the contribution of the beam angular spread, the dashed one is that of the energy spread together with the beam size due to synchrotron oscillations, the dotted-and-dashed line is the contribution of the beam size due to the betatron oscillations.

The double-tag detection efficiency ε for different beam energies is presented in Fig. 4. So the region of tagging for our system begins actually from the threshold of hadron production and continues up to 4 GeV.

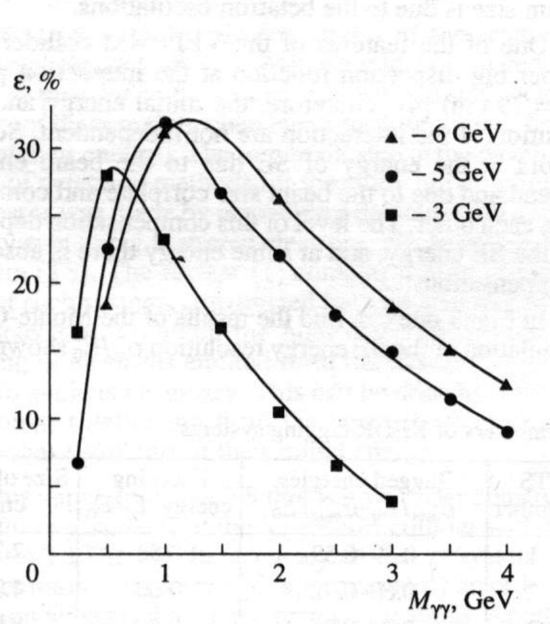

Fig. 4. Double-tag detection efficiency.

The resolution in the reconstructed invariant mass of the two-photon system for different beam energies is given in Fig. 5. It was calculated by the Monte-Carlo simulation taking into account not only the accelerator factors discussed earlier but also the emission angle of SE due to the angular distribution of the two-photon production process and the space resolution of the TS chambers ($\sigma = 300$ μm).

So the resolution for the invariant masses 2–3 GeV should be about 10 MeV. It is much better than other tagging systems had. Besides that, such resolution is close to the natural width of *C*-even resonances (e.g., $\eta_c(2980)$ with the total width of about 10 MeV).

3. DESIGN OF THE COORDINATE SYSTEM

From the Monte-Carlo investigation of the energy resolution and the detection efficiency and taking into account the background conditions, the requirements to the tagging system itself can be formulated:

- As follows from the analysis of different contributions to the energy resolution, the necessary spatial resolution is 0.3–0.6 mm.
- It would be useful to measure the entrance angle of the SE into the detecting system with the accuracy of $\sigma_\theta \le 10^{-3}$. Such information is needed not directly for the energy reconstruction, but for some background suppression.
- The detection system has to work with a counting rate of more than 10^6 Hz.
- Several particles detected simultaneously should be separated.
- The detection system should provide as small insensitive area at the edge as possible.

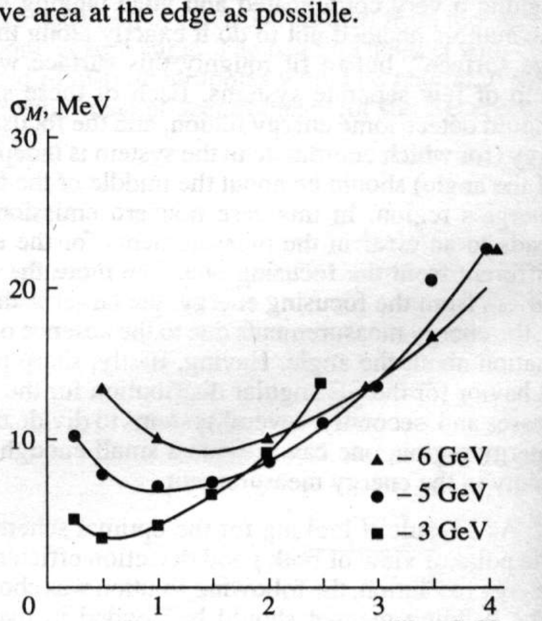

Fig. 5. Invariant mass resolution.

- It is necessary to foresee the possibility to "switch off" a region of the TS corresponding to a vertical emission angle at the interaction region of less than some value (≈0.2 mrad) for background rejection.

Most of the requirements are satisfied in the best way by using a hodoscope of drift tubes (DT's). Each TS includes one hodoscope designed as an independent module which contains six detecting planes (Fig. 6). The plane is made of two rows of stainless steel drift tubes with 6 mm in diameter and 90 μm wall thickness. The pitch of the tubes in one row is 8 mm, rows are shifted by 4 mm one to another. In the TS_1, TS_2 and TS_3 modules each row contains 12 DT's. The TS_4 module has a 24 tube row. The total number of tubes in the TS is 1440.

The most crucial problem which should be solved in the TS design is the ability of the system to work for a long time under high counting rate conditions. Most of this counting rate is inside a thin layer ±5 mm around the beam orbit plane. To manage this problem the system will be operated at the lowest possible gas gain (about 5×10^4). The possibility of the vertical hodoscope movement is provided in order to decrease the density of irradiation.

To study the problem of radiation hardness some test experiments were done with single-tube modules, flowed by different gas mixtures. Tubes were irradiated using a ^{90}Sr source and an X-ray tube. A gas mixture 90% CF_4 + 10% C_4H_{10} [5, 6] was chosen as quite satisfactory for the tagging system conditions. The measurements have shown that a dose of 5 C/cm did not destroy the DT working parameters. It would give the possibility to work for a few years with expected counting rates.

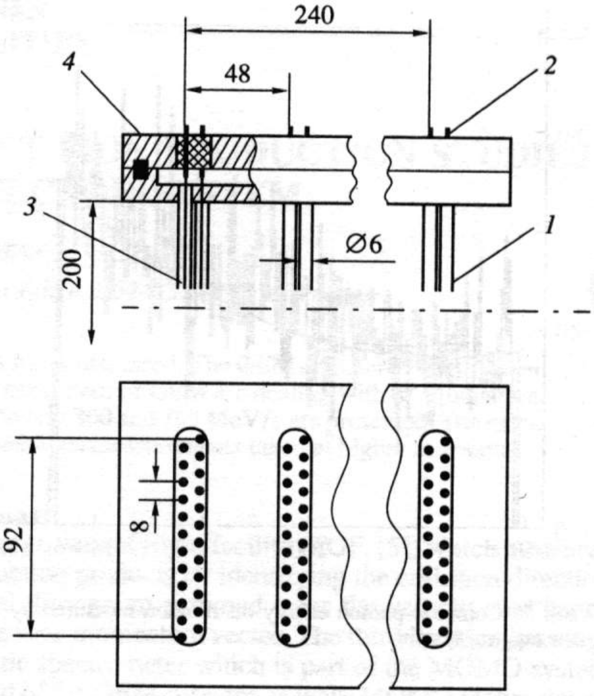

Fig. 6. Drift tube hodoscope. *1* – drift tube, *2* – pin to fix anode wire, *3* – anode wire, *4* – flange.

4. CALIBRATION SYSTEM AND THE EXPERIMENTAL TEST OF THE TS ENERGY RESOLUTION

The absolute calibration of the energy measured by the tagging system becomes very important because of the high relative accuracy of the tagging electron energy at the level 10^{-3}. The ideal opportunity for this could be to obtain electrons whose energy is within the range $(0.4–0.98)E_0$ and is known with 0.1% accuracy. The real way to have this opportunity is to use the process of the backward Compton scattering where electrons lose a part of their energy giving it to the electromagnetic wave. The energy spectrum of the electrons after interaction has a sharp edge depending on the well-known laser and beam parameters. The maximum lost energy for the Compton electron is following: $\omega = 4\gamma^2\omega_0/(1 + 4\gamma\omega_0/m_e)$, where γ is a relativistic factor for electrons of the initial beam, ω_0 is the energy of the laser photon and m_e is electron mass. The natural width of the spectrum edge, which corresponds to the maximum energy loss, is determined by the radiative corrections which are small in our situation due to the fact, that the photon energy at c.m.s. is small as compared to the m_e. Therefore, one can measure the energy resolution of the tagging system with the help of the shape of the Compton spectrum edge.

The method of the backward Compton scattering of laser photons at the electron beam in storage rings was actively developed for measuring the transverse radiation polarization and nuclear physics experiments (see, for example, [7]). This method allows the absolute calibration of the TS with an accuracy not worse, than 10^{-3} in the wide enough range of the particle energies by using several harmonics of laser radiation.

The choice of the set-up parameters is determined by the existence of four detection systems TS_1–TS_4 and the desire to calibrate each of them independently. The range of the particle energies detected by each system was presented in the Table. The wide range of the laser light wave length from infrared up to ultraviolet is necessary to obtain in Compton interaction scattered electrons and positrons with sharp low energy edges in each detection system region.

The electrons with the energy of 5 GeV after the interaction with the first neodym (Nd : YAG) laser radiation harmonic (the energy 1.17 eV) lose 10% of their initial energy. Therefore the lower edge of electron spectra will lie in the detection region of TS_4. The second harmonic photons will allow to calibrate TS_4 and TS_3 depending on the collider beam energy. TS_3 and TS_2 may be calibrated by the third and the fourth harmonics

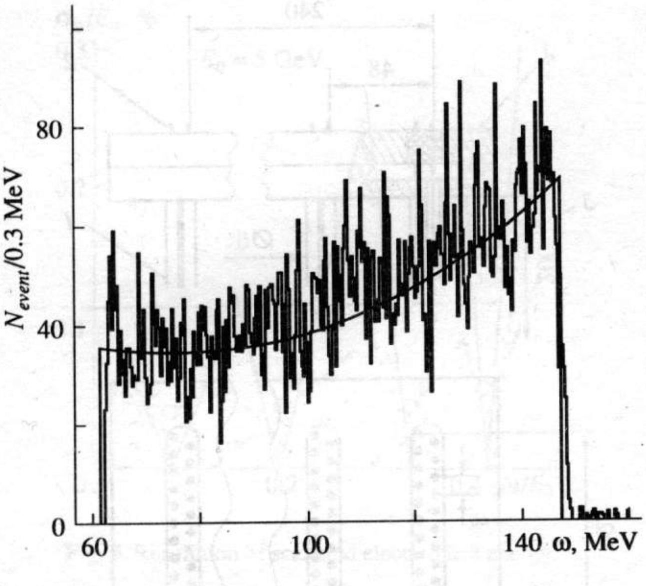

Fig. 7. Compton photon energy distribution measured by the tagging system.

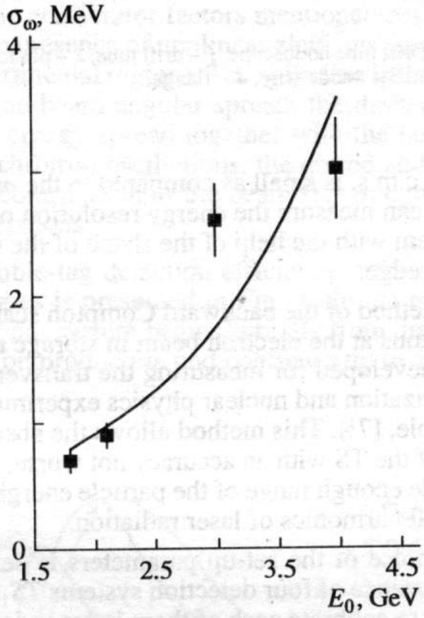

Fig. 8. Energy resolution of TS_4.

of laser radiation. The calibration of the closest to the interaction region TS_1 by the edge of the spectra is confronted with considerable difficulties connected with the obtaining of high radiation harmonics and their absorption in the quartz glass of the set-up optical elements. But due to the fact that TS_1 and TS_2 are situated after the same magnet M_1 (see Fig. 2) the calibration of TS_2 only probably is enough.

This method will give the opportunity of calibration during the experiment to control the spectrometer parameters.

In order to test the tagging system main principles, TS_4 has been installed at VEPP-4M. The measurements were done with electrons from the interaction with the second Nd : YAG laser harmonic (2.34 eV) at the beam energies of 1.8, 2.1, 3.0 and 4.0 GeV. The spectrum over the Compton electron lost energy at the beam energy of 2.1 GeV, is shown in Fig. 7. The resolution of TS_4 at different VEPP-4M energies obtained from the Compton spectrum edge is shown in Fig. 8. The points with errors are the experiment, the line is the result of Monte-Carlo calculations.

5. CONCLUSIONS

The described tagging system for studies of two-photon physics is a part of the multipurpose detector KEDR and e^+e^- collider VEPP-4M at Novosibirsk. Use of some accelerator magnetic structure elements allows to obtain high double tagging efficiency and resolution in e^+ and e^- energies. The "Double-tag" method giving the two-photon mass without reconstruction by its decay products has serious advantages and is complementary to the commonly used "no-tag" and "single-tag" approaches. It is expected to be especially useful for measurements of the two-photon width of resonances and the total cross section of two gammas into hadrons.

The measured energy resolution does not contradict the expected one. So we can hope to obtain in the real experiment the same high invariant mass resolution as we had in Monte-Carlo calculations.

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