開発した新しいタグシステムは、これからさらなる開発を行い、発電所での実用を目指しています。

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Development of a New Tagging System for GeV-γ Beam at LNS

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We have developed a new tagging system, STB-Tagger II, for the recently constructed GeV-γ beamline at LNS. STB-Tagger II consists of 232 channel scintillating fibers coupled to 29 multi-anode photomultiplier tubes. The tagging system has been installed in the inner vacant space of BM5, one of the C-type bending magnets in the STB ring. An iron fence is employed as a magnetic shield to reduce the strength of the magnetic field in the inner space where the photomultiplier tubes of the tagging system are placed. The energy of the photon beam tagged by STB-Tagger II covers from 0.74 to 1.14 GeV with the RMS energy resolution ranging from 3.5 to 0.5 MeV.

§ 1. Introduction

A series of meson photo-production experiments to study \( N^* \) physics has been performed since 2000, using a tagged photon beam at LNS. The in-medium properties of nucleon resonances, especially \( S_{11}(1535) \) strongly coupling to the \( N\eta \) channel, have been studied via \( \eta \) photo-production at INS [1] and LNS [2]. The elementary process of the \( \text{H}(\gamma, \eta) \) reaction has recently been measured at Mainz [3], GRAAL [4] and JLab [5], and then the \( S_{11}(1535) \) resonance parameters have been extracted. On the other hand, there does not exist precise data of the total cross section of the \( (\gamma, \eta) \) reaction on the deuteron for the incident photon energy covering the whole resonance region. We are preparing for a \( ^3\text{H} (\gamma, \eta) \) experiment to study isospin properties, the electromagnetic coupling strength, and resonance parameters of \( S_{11}(1535) \) excited from the neutron as well as from the proton.

New GeV-γ Experimental Hall was built in July 2002 at LNS and a GeV-γ beamline was constructed. Then we started developing a new tagging system, STB-Tagger II. We planned the new tagging system having wider energy range, especially in the higher energy side from 740 MeV to 1140 MeV, to cover the \( S_{11}(1535) \) resonance region. (The tagging energy range of the existing STB-Tagger I is from 750 MeV up to 1060 MeV [6].) We designed it to be compact so as to install it into the inner space of a dipole magnet in the 1.2 GeV STB ring.

Figure 1 illustrates the experimental setup for GeV-γ experiments. A Bremsstrahlung radiator of a carbon fiber [7,8], 11 \( \mu \)m in diameter, is employed in the STB ring. Circulating electrons at the very
edge of the beam spot strike the radiator. Then Bremsstrahlung takes place and the Bremsstrahlung photons go straight to the GeV-γ Experimental Hall, where the target is placed just 17 m downstream from the radiator. The target is surrounded by the γ detector SCISSORS II.

Fig.1. Schematic layout of the GeV-γ beamline and the location of the beamline components.

The recoil electrons traveling 303 mm go into the magnetic field of the dipole magnet and are detected by the STB-Tagger II. The contamination of electromagnetic shower in the tagged photon beam is excluded by a charge sweeping magnet and shielded by lead blocks and concrete walls in the GeV-γ Experimental Hall. The profile of the photon beam is measured by a γ beam profile monitor, GPM [9], which consists of a 16 × 16 scintillating fiber array located downstream of the target station. A lead glass Čerenkov detector is employed behind GPM to measure the transmission rate of the tagged photon beam during the empty target run.

§2. Tagging System

The requirements for the STB-Tagger II is as follows:

1. An internal radiator will be used in the 1.2 GeV STB ring to have a Bremsstrahlung beam.
2. The maximum energy of the tagged photon beam should be at least 1.1 GeV, although the background effect due to Möller scattering would not be negligible. Figure 2 shows the differential cross sections of Bremsstrahlung and background Möller scattering and their ratio, which suggests that the background contribution of Möller scattering increases inversely with respect to the energy of recoil electrons. However, the background contribution would be smaller than that indicated in Fig.2. Low energy electrons originated from Möller scattering at the radiator go into the magnetic field of the dipole magnet with some incident angles unlike the case of Bremsstrahlung. Therefore, the Möller scattering effect can be reduced if the direction of recoil electrons is defined as well as possible with tagging counters.
3. One of the dipole magnets in the STB ring is used as a momentum analyzer for recoil electrons of Bremsstrahlung. The detector system must be compact so that the whole tagging system can
Fig. 2. The differential cross sections of Bremsstrahlung [10] and Möller scattering for $Z=6$ as a function of the recoil electron energy (upper part), and the effect of Möller scattering (lower part).

be installed into the vacant space in the C-type return yoke of the magnet. The space available for the detector setup is 10 cm wide and 35 cm high along the inner curved surface of the return yoke.

4. The tagging counters would be scintillating fibers with photomultiplier tubes, taking into account high counting rates. Moreover, the scintillating fiber should be directly connected to a photomultiplier tube to collect relatively weak scintillation lights efficiently.

5. There are strong magnetic fields around the tagging detector region. Therefore, we need to reduce the leakage flux of the magnetic field up to the level where photomultiplier tubes work well, and/or we must use photomultiplier tubes which have a well magnetic tolerance.

We designed a new tagging system from these considerations.

2.1 Tagging counters

We employ scintillating fibers and multi-anode photomultiplier (MPM) tubes, Hamamatsu H8711-10, as recoil electron counters. It becomes easy by using the MPM tubes to align the fibers efficiently in a narrow space of the C-type dipole magnet. This is one of the reasons why the MPM tube was selected. Figure 3 shows the size of the MPM tube (A) and one unit of the tagging counters (B). The trigger logic diagram is also shown in the same figure (C). The H8711-10 has a rectangular shape of 30 mm × 30 mm × 45 mm and has 16 channel anode outputs. The size of each independent photocathode surface is 4.2 mm × 4.2 mm, which is just fit for scintillating fibers in a rectangular shape of 4 mm × 4 mm × 70 mm. We utilize only 8 channel photocathodes to realize simply four pairs of coincidence signals from corresponding fiber scintillators. Namely, 8 channel fibers are bunched together into a $4 \times 2$ hodoscope array with 0.5 mm thick partition spacers. The scintillating fibers are directly glued with optical cement to photocathode surfaces without lightguides.
Fig. 3. Single scintillator/photomultiplier unit of STB Tagger II. The H8711-10 has 16 channel independent photocathode surfaces (A). The 8 channel scintillating fibers are coupled directly to each photocathode surface with partition spacers of 0.5 mm in thickness (B). The coincidence signals are collected from 29 channel photomultiplier tubes and form the Tagger trigger (C).

Fig. 4. The scintillating fiber allocation of STB-Tagger II.

The 8-channel anode outputs from a single photomultiplier tube are connected to a printed circuit board, which is placed horizontally in such a way that the photocathode surfaces are located 60 mm below from the height of the electron center orbit because the leakage flux of the magnetic field is smaller there. Each MPM tube is placed on the printed circuit board so that recoil electrons from the Bremsstrahlung radiator pass through the \((2i-1)\)-th and the \(2i\)-th (upstream and downstream) fibers, as
illustrated in Fig.3(B) and (C). The linear output from each fiber is shaped to generate a NIM pulse of 20 ns in width. The coincidence signal of two corresponding fibers, \((2i-1)\) and \(2i\), produces a tagging signal, the width of which is 50 ns. This configuration helps to reduce the background events due to Möller scattering having different passes for low energy recoil electrons. The STB-Tagger II consists of 232 scintillating fibers with 29 MPM tubes. The coincidence signals of 116 channels are used as the tagging signal. A plan view of the whole tagging detectors is illustrated in Fig.4. The Bremsstrahlung photons generated in the internal radiator are delivered to the target station at GeV-γ Experimental Hall. The associated recoil electrons pass through the exit window of 50 μm thick Ti foil of the vacuum chamber and are detected with the scintillating fiber hodoscopes.

2.1.1 Magnetic tolerance of H8711

The new tagging counter system is supposed to be installed where the magnetic field is not negligible. The H8711-10 has 12 layers of metal channel dynodes. The first dynode is located 1 mm away from the photocathode surface and the distance between dynodes is 0.5 mm. The total length of dynode parts is approximately 20 mm. This configuration gives a better magnetic tolerance because of a short electron-cascade length. We have investigated magnetic properties of the H8711-10 with uniform magnetic fields of a dipole magnet. The result indicates that the output is not symmetric around the z-axis. The axes of the magnetic field are defined in Fig.3(B). When the magnetic field of \(B_z\) is induced, the relative output for a radioactive source goes down to about 40% at \(B_z \simeq 50\) G. On the other hand, with respect to \(B_y\), the relative output decreases more gradually to about 50% at \(B_y \simeq 100\) G. It is confirmed that the H8711-10 works very well with no problem in the magnetic field less than 30 G for both \(x\) and \(y\) directions. We have not measured the \(z\)-component dependence because the gap of the magnet we used is smaller than the height of the scintillator/photomultiplier unit. It is reported, however, that the dependence on the \(z\)-component of the magnetic field is almost same as that on the \(x\)-component. Therefore, we require the leakage flux of the magnetic field should be less than 20 G for the place where the tagging counters is installed.

Fig.5. Dipole magnet (left) in the STB ring and its cross sectional view (right). Symbols in the right figure denote, A: pole peace of the magnet, B: coil, C: return yoke, D: detector region, and E: iron fence.
§3. Magnetic Shield

The dipole magnet where the STB-Tagger II is installed is illustrated in Fig.5. A cross sectional view of the lower half of the magnet is also shown in the right side. The MPM tubes are placed in the detector region (D), where the strength of the magnetic field must be less than 20 G.

At first, we measured the distribution of the magnetic field using a Hall gauge around the detector region without any magnetic shield. The result is shown in Fig.6. The measurement was performed for the region from +1 cm to -8 cm along the z direction, the height with respect to the electron beam orbit, and from $d = +22.5$ cm to $d = +29$ cm along the x direction which corresponds to the distance from the electron orbit. The closed squares indicate $B_z$, and open squares denote $B_y$. These field components are too strong for photomultiplier tubes to work.

Some tests of the magnetic shield were made. A shield box of 5 mm thick iron reduced the leakage flux in the detector region down to $B_z \approx B_y \approx 150$ G, which was, however, still too strong. Then a shield with double boxes of iron was tested, giving a good result of $B_z \approx 20$ G and $B_y \approx 15$ G, which was acceptable for the operation of the H8711 photomultiplier tube. But the iron shield of the double boxes was a little bit inconvenient in mounting and dismounting the tagging counters with a lot of cables.

We tried to find a simpler shield. In order to design such a shield, field calculations were carried out using a two-dimensional computer code, POISSON. The main components of the field flux giving a great influence upon the tagging detectors can be classified into two parts. The one component is a leakage flux from the yoke due to saturation of the magnetic flux in the iron material. The leakage flux returns to the coil through the minimum path. The other is an extension of the fringe field from the pole piece of the dipole magnet. These two cause strong horizontal and vertical fields where the tagging
Fig. 7. Calculated and measured magnetic fields in the detector region with the iron fence.

Fig. 8. Photograph of the entrance of the dipole magnet equipped with an iron fence. The symbols are same in Fig. 5.

detectors are placed. We employ a thick iron fence which acts like a small return yoke generating a new loop flux around the coil so as to reduce the saturation effect. It can inhale the saturated flux and also screen the strong fringe field from the pole piece. Thus we have optimized the geometry and configuration of iron materials under the condition that (1) the field strength around the photomultiplier tubes should be at most 20 G and (2) the disturbance of the field around the electron center orbit must be less than 0.2%, which is a limit for stable operation of the STB ring. The obtained solution is indicated in Fig. 5.
We measured the field map with a Hall gauge and found the field strength reduced from several hundred G to less than 20 G in the detector region. The field strength at the electron orbit went down because of the existence of the iron fence by 0.15% in an average for a 45° bending magnet. It did not give any serious problem for a stable operation of the ring. Consequently, the iron shield of L-type fence, 22mm in thickness, was installed permanently in the inner space of the dipole magnet. Figure 7 plots the field distribution as a function of the vertical direction. The closed (open) squares indicate the measured field $B_y (B_z)$ and the curves are the results of the calculation. Small deviations at most 10 G between measurement and calculation may come from inaccurate inputs for the magnetic permeability of the iron material and from simplicity of the two-dimensional calculation.

Figure 8 shows a photograph viewing the inner space of the C-type dipole magnet equipped with the iron fence. The iron fence is separated to upper and lower parts with a gap of 30 mm. Each part is identical and has the shape of L. The thickness of the vertical fence is 22 mm and that of the horizontal is 24 mm. Brass supports between upper and lower parts are used at both ends of the fence to put the parts together and to push them toward the return yoke to have a good magnetic contact with the yoke.

§ 4. Operation

4.1 Energy resolution

The tagged photon energy $E_T$ is determined by

$$E_T = E_0 - E,$$

where $E_0$ and $E$ are the energy of the circulating electrons and that of the recoil electrons, respectively. The geometrical configuration of the STB Tagger II gives information on the tagging energy and the energy resolution for each pair of the tagging counters.

The tagging range defined by the STB Tagger II is from 0.74 to 1.14 GeV [$E_T = (0.62-0.95) E_0$]. However, there are some more factors to be taken into account for the estimation of the effective energy resolution, such as multiple Coulomb scattering at the exit window of Ti foil, and the electron beam emittance in the STB ring. The energy resolution for the photons tagged by the $i$-th tagging counter is defined as a variance of the recoil electron energies $E_i$. Namely,

$$\sigma_{E_i}^2 = \frac{1}{N-1} \sum_{j=1}^{N} (E_i - \langle E_i \rangle)^2,$$

where $E_i$ means the $j$-th energy of the recoil electrons detected by the $i$-th tagging counter and $\langle E_i \rangle$ denotes the mean value of $E_i$. The estimated energy resolutions are $\sigma_{E_1} = 3.5$ MeV at 0.74 GeV to $\sigma_{E_T} = 0.5$ MeV at 1.14 GeV, respectively.

4.2 Transmission rate of tagged photon

The transmission rate of tagged photons is defined as the ratio of the number of Bremsstrahlung photons to that of recoil electrons detected by the tagging counters. The transmission rate for the $i$-th tagging counters $T_i$ is obtained as

$$T_i \equiv \frac{N^i_{on}}{N^i_{on} + N^i_{off}} = \frac{N^i_{on} \otimes N^C_{on} - N^i \otimes N^C_{off}}{N^i_{on} - N^i_{off}},$$

where $N^i_{on/off}$ is the gross count of recoil electrons at the $i$-th tagging counters with the radiator
Fig.9. The measured transmission rate of the tagged photons as a function of the tagging channel. The closed (open) circles indicate the result with the lead glass Čerenkov counter set about 20 m (3 m) downstream from the Bremsstrahlung radiator. The solid line denotes a calculation result for the transmission rate at the target.

on/off, and $N^C$ (on/off) denotes the number of photon events. A lead glass Čerenkov detector was employed to detect Bremsstrahlung photons for this purpose. The measurements of the transmission rate were made under two different setups to examine the dependence of the transmission rate on the distance from the radiator. The measured transmission rate is shown in Fig.9, where the closed (open) circles are the result when the lead glass Čerenkov counter was placed about 20 m (3 m) downstream from the radiator. The difference between these two results mainly comes from the attenuation of photons due to the air along the beamline. The solid line shows a calculation result for the transmission rate at the target, including the effect of Möller scattering at the radiator. The effect of Möller scattering reduces the transmission rate, particularly at lower energy side of the tagging channels. The mean value of the transmission rate is found to be about 80% at the target.

§5. Summary

The parameters of the STB Tagger II are summarized in Table 1. The STB-Tagger II consists of 232 scintillating fibers which form a 116 channel hodoscope of tagging counters. The multi-anode photomultiplier tubes are working very well in the vacant space of the magnet with the magnetic shield of an iron fence that reduces the leakage flux around the detector region from several hundred G to $\sim$ 20G. The tagging range of our new tagging system is from 0.74 to 1.14 GeV, and the tagging resolution ranges from 3.5 to 0.5 MeV. We have carried out a performance study of the STB Tagger II with the typical tagged photon intensity of $2 \times 10^6$/s. The transmission rate of the tagged photons is about 80%, which has been achieved with dedicated efforts by the accelerator group at LNS.
Table 1. Parameters of STB Tagger II.

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<td>Photon Transmission Rate</td>
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References