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Tagged photon facility at Centre for Advanced Technology, Indore: Possible scenarios

L M PANT
Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai 400 085, India
E-mail: lmpant@barc.ernet.in

Abstract. Photoproduction of ω in nuclear medium with the ELSA facility at Bonn is discussed in the context of medium modification of hadronic properties. Utilization of Indus-2 at CAT, Indore for producing tagged bremsstrahlung photons and laser backscattered photons has been explored with a comparison between the two techniques for producing tagged high energy photons for the first time in the country with emphasis on the ADSS programme to have a precise information of (γ, n) reactions.

Keywords. Medium modifications; photoproduction; tagger; bremsstrahlung photons; laser backscattered photons; Indus-2.

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1. Introduction

In contrast to all other composite systems like atoms and nuclei, the masses of hadrons with u, d and s quarks are much larger than the sum of the current quark masses. The general features up to the nucleus is that its constituents are observed as free particles and the constituents add up to the total mass, except for the small binding energy corrections. However, in the case of a nucleon, the constituents which are the quarks, barely add up to 2% of the hadron mass and they are never observed as free particles. This is because the masses of these hadrons are generated dynamically. Hadron masses are associated with the spontaneous breaking of chiral symmetry, one of the fundamental symmetries of the quantum chromodynamics (QCD) in the limit of massless quarks. If chiral symmetry was to be realized in nature one would expect hadron spectra with positive and negative parity. However, this is not observed as we know that the nucleon ($J^\pi = 1/2^+$) ground state at 938 MeV and the $S_{11}(J^\pi = 1/2^-)$ state at 1535 MeV correspond to a mass split of 600 MeV. One of the most intriguing problems in modern physics is the particle mass generation mechanism. As such one of the main goals of the present experimental studies, is to better understand quantum chromodynamics (QCD) as the fundamental theory of strong interactions in the so-called non-perturbative regime. This regime is characterized by the concept of confinement and poses a real challenge to understand how the structure of complex systems bound by strong interactions

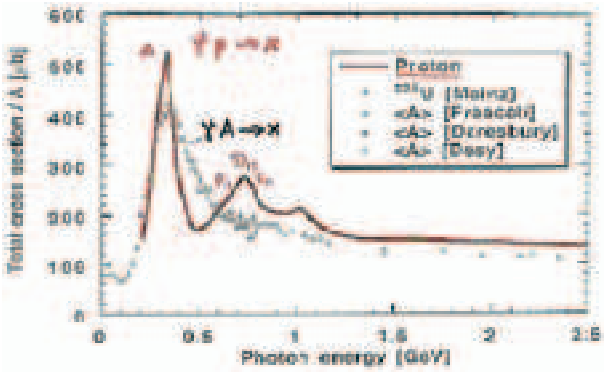

Figure 1. Photoproduction on a free proton (continuous curve) and bound nuclei (data points) [1].

among the quarks lead to the formation of hadrons and eventually the atomic nuclei. The cross-section per nucleon for photoabsorption on nuclei shows different features as shown in figure 1. While the structure assigned to the Δ excitation of a bound nucleon is still clearly pronounced, the bump associated with the second resonance region is washed out [1]. The photoabsorption on a free and on a bound nucleon are distinctly different, indicating a strong medium effect, a modification of hadronic properties in nuclear matter.

Further insight into the generation of hadron masses is expected from studying modifications of hadron properties by embedding them into strongly interacting nuclear matter. It is believed that chiral symmetry is partially restored with increasing baryon density and temperature, leading to a low-lying hadronic spectrum. Experimentally the spectral function of a meson is determined by the sum of the four-momentum vectors p_i of its decay products: $m^2 = (p_1 + p_2)^2$. Two conditions have to be fulfilled to obtain the in-medium spectral function of a meson namely,

(i) The lifetime of the meson has to be sufficiently short and the recoil velocity from the production reaction on the nuclear target has to be small enough such that the meson has a significant probability to decay inside the nucleus.

(ii) The momenta of the decay products should not be distorted by the final state interactions within the nuclear medium.

The present work highlights the ω photoproduction in nuclear medium with the ELSA facility at Bonn. This apart, we are also looking forward to utilize the electron beam at the Centre for Advanced Technology (CAT), Indore for experimental hadron physics in order to step into the intermediate energy nuclear physics regime. Towards the end, a skeletal outline has been given as regards what we can do in our country, in immediate future, with the high-energy electron beam now available at CAT, Indore.

2. Photoproduction of ω at ELSA, Bonn

The cleanest way to investigate the vector meson (ρ, ω, ϕ) properties in nuclear matter is provided by exploiting the photoproduction of these mesons from complex

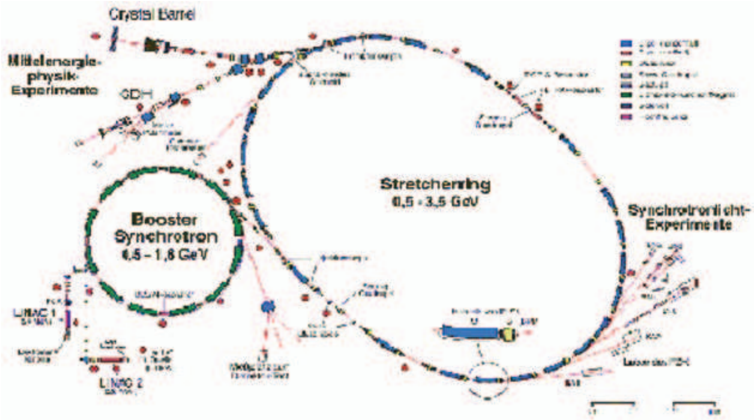

Figure 2. The ELSA facility at Bonn. It consists of the LINAC injector, Booster Synchrotron and the Electron Stretcher.

nuclei. As compared to heavy-ion collisions, where temperature and density vary dramatically with time, the nucleus stays more or less intact in a photonuclear reaction. Moreover, in contrast to hadron-induced reactions, photoproduction has the advantage that due to its electromagnetic coupling to the nucleons the reaction probability of the photon is almost the same for all the nucleons inside the nucleus. Therefore, all densities of the static density distribution provided by the target nucleus can be probed. As such, an alternative and complementary way to study the in-medium modification of the ω meson is to look for the $\omega \rightarrow \pi^0\gamma$ decay mode. This mode accounts for 8.5% of the total ω decay width, while for ρ it is only 6.8×10^{-4} (a factor 100 less), which makes it a clean probe to study solely the ω meson property in matter. The disadvantage of the $\omega \rightarrow \pi^0\gamma$ decay channel is that the reconstruction of the $\omega \rightarrow \pi^0\gamma$ mode is hampered by the final state interactions of the π^0 meson in the nucleus, which is expected to be pronounced in case of a large nuclei. Events in which the emerging π^0 is absorbed in the nucleus are lost. If π^0 rescatters from a nucleon or the nucleus the momentum of the pion is significantly degraded such that it does not contribute to the invariant mass range near the ω peak.

The experiments were performed at the ELSA facility at Bonn from Jan. 2002 to Dec. 2003 using the Crystal Barrel and TAPS detector set-up. ELSA stands for Electron Stretcher Analag (system). As shown in figure 2, it consists of a 50 Hz machine with LINAC as an injector to the Booster Synchrotron which increases the electron energy up to 1.6 GeV. In order to avoid random coincidences in the experiments, the bunched electron beam is stretched in the Electron Stretcher and finally a quasi-continuous electron beam is extracted to a maximum of 3.5 GeV for generating bremsstrahlung photons. This section focuses mainly on the mass of the photoproduction of ω meson at normal nuclear matter densities. For identifying the $\gamma + A \rightarrow \omega + X$, a coincidence set-up between Crystal Barrel (CB-1290 CsI crystals) and the Two Arms Photon Spectrometer (TAPS-528 BaF_2 crystals) was set-up at the ELSA facility at Bonn. TAPS was configured as a wall and placed at forward angles covering polar angles between 5° and 30°. This set-up allows to

Table 1. Beam times and statistics for ω photoproduction from various targets.

Target	Target density (g/cm^3)	Target length (cm)	Beam time (h)	ω's
LH_2	0.071	5.0	500	2.25×10^5
$^{12}C_6$	1.67	2.0	85	66,000
$^{40}Ca_{20}$	1.53	1.0		
			100	39,500
$^{93}Nb_{41}$	8.51	0.1	185	40,000

measure the scattering angle and energy of all the final state photons with a nearly 4π coverage. The $\pi^0\gamma$ invariant mass can be obtained from the measured momenta of the three final state photons. The CB detector is equipped with an inner detector consisting of scintillating fibres (SciFi) which allow to discriminate between charged particles (leptons, protons and charged pions) and neutral particles (photons and neutrons). It also provides a signal for the first level triggering. Similarly TAPS spectrometer discriminates between charged and neutral particles via thin plastic scintillators placed in front of BaF_2 crystal. Furthermore, massive particles and photons/leptons can be separated by pulse-shape and time-of-flight in TAPS [2]. To avoid experimental ambiguities for the interpretation of a possible in-medium modification of the ω meson the $\pi^0\gamma$ spectra obtained with nuclear targets (C, Ca and Nb) was compared to the measurement on the free proton (LH_2). Data were also taken with deuteron target (LD_2). Though we do not expect any medium modification in case of deuteron target, the data is important to understand the ω production of neutron in a quasi-free kinematics. Table 1 shows the beam times, ω statistics and other relevant parameters for the ω photoproduction from various targets. The fraction of ω decaying inside the nucleus were maximized by requiring the incident photon energy to be close to the production threshold. The photon energy range was chosen at $E_\gamma = 1.2$ GeV with a maximum intensity of 1×10^7 s^{-1}. Within this energy range the average cross-section for ω production is estimated to be $\sigma/A \sim 5$ μb. In figure 3, results obtained for Nb are compared to the reference measurement on a LH_2 target. While for recoiling, long-lived mesons (π^0, η), which decay outside the nucleus, a difference in the line shape of the two data samples is not observed, we find a significant enhancement towards lower masses for ω mesons produced on the Nb target [3]. For momenta less than 500 MeV/c, an in-medium ω meson mass of $M_{\text{medium}} = [722 \pm 4(\text{stat.}) \pm 35(\text{syst.})]$ MeV/c^2 has been deduced at an estimated average nuclear density of $0.6\rho_0$.

3. Indus-1 and Indus-2 at CAT, Indore: Proposal for a tagged photon facility

To understand the physics laws governing the building blocks at low energies, in the non-perturbative regime, where we encounter them in nature, the complex many-body system – nucleon, offers the ideal testing ground for concepts of the strong

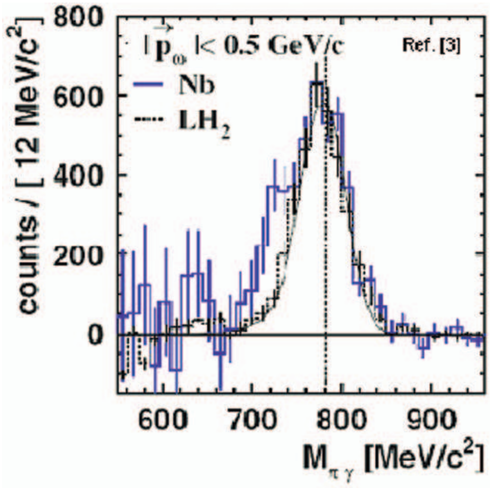

Figure 3. $\pi^0\gamma$ invariant mass for the Nb data (solid histogram) and LH2 data (dashed histogram) after background subtraction. The error bars show statistical uncertainties only. The solid curve represents the simulated line shape for the LH_2 target [3].

interactions. The dominant decay mode of any excited nucleon state is the emission of mesons via the strong interactions and photoproduction of mesons is an excellent tool for the study of nucleon resonances. The high-energy electron beam available at CAT, Indore can be used for nucleon excitation, thereby studying the decay properties of the excited states. Indus-1 is a 450 MeV synchrotron radiation source with a critical wavelength of 61 Å. It was commissioned in June 1999. Indus-2 will be a synchrotron radiation source of nominal electron energy of 2.5 GeV and a critical wavelength of about 4 Å. Both Indus-1 and Indus-2 are national facilities accessible to all researchers from national laboratories, academic institutions and industries in India. With the commissioning of both these facilities, Indian scientists will have powerful sources of photons with wavelengths in the visible, vacuum ultraviolet, soft X-rays, and hard X-rays. Indus-1 is a 1 Hz machine capable of providing an external current of about 0.1 nA and has operated successfully with a current of 200 mA in the storage ring [4].

Indus-2 is nearing completion and when ready would provide an electron beam at 2.5 GeV designed for a storage current up to 300 mA. At present, there is no extraction facility for the electron beam with Indus-2. However, in principle, the beam can be extracted either from the Booster (700 MeV) or Indus-1. Figures 4 and 5 show the schematic and the actual lay-out of the facilities at Indore. The repetition cycle of Booster Synchrotron is 1 Hz, i.e. it accepts the beam of 1 μs width from the Microtron, boosts it and then the extraction process takes place. The magnets are ramped down again to accept the next pulse from the Microtron. The single pulse from Microtron (1 μs) is fed as three bunches in the Booster Synchrotron. The time gap between these bunches is nearly 33 ns. Thus at 1 Hz repetition rate, the Booster delivers a set of three bunches with a separation of 33 ns between them. The bunch width is almost 10 ns. The ramping time is nearly

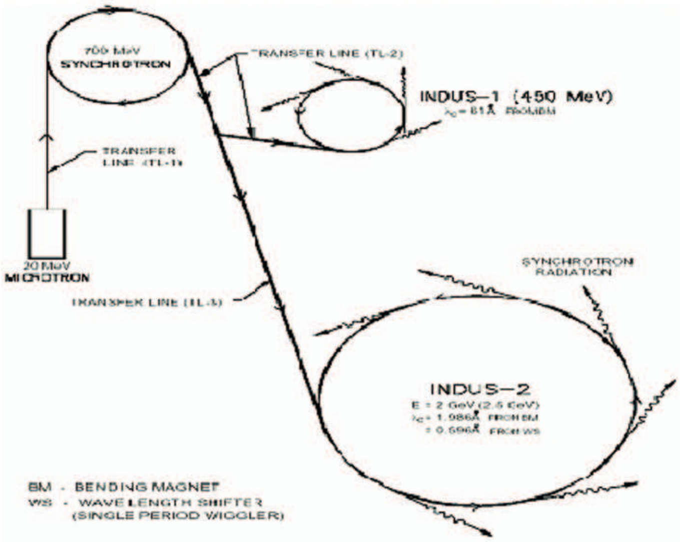

Figure 4. Schematic lay-out of the Microtron, Booster Synchrotron, Indus-1 and Indus-2 facility at CAT, Indore, India

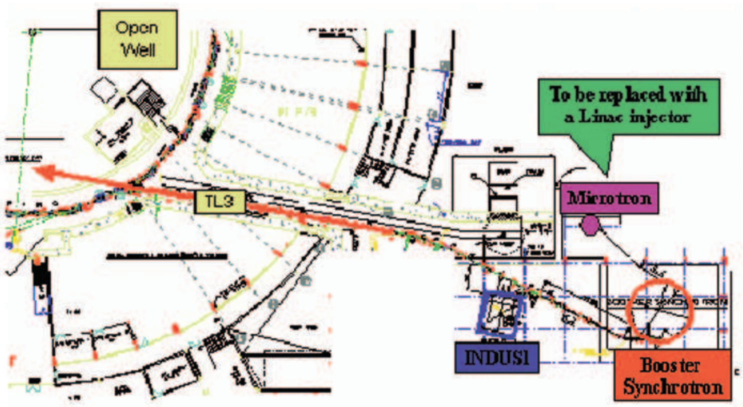

Figure 5. Actual lay-out of the 20 MeV Microtron Injector along with the Synchrotron Booster (700 MeV), Indus-1 (450 MeV Synchrotron) and part of the upcoming Indus-2 (2.5 GeV Synchrotron) at CAT, Indore, India. The transmission line TL3 meets the beam line of Indus-2 at the septum. The same TL3 can be extended into the 'open well' for bremsstrahlung studies.

200 ms, i.e. it accepts the beam at 20 MeV from Microtron and then boosts the energy up to 450 MeV in nearly 200 ms. The average current in the Booster is 2 mA so that about 1.2×10^9 electrons are distributed in three bunches with nearly 10 ns width of each bunch. The current may be increased by a larger amount (∼3–4 times) with the proposed LINAC (high average current) to replace the Microtron.

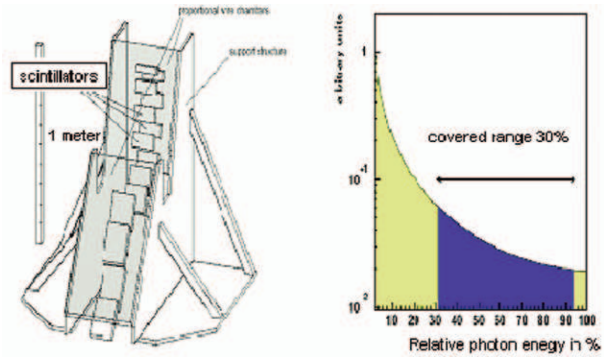

Figure 6. The tagger (left) at ELSA for tagging the electron. The $1/E_\gamma$ spectrum of the bremsstrahlung photons is shown in the right panel. The shaded portion is the range covered with the SAPHIR detector. The tagging system was modified for the CB-TAPS system to have an energy range from 22 to 93% of the electron beam energy.

There are two different techniques to generate the high-energy photons, namely:

1. Bremsstrahlung tagging being used at ELSA, MAMI, JLab etc. and
2. Compton (laser) backscattering being used at BNL, ESRF (GrAAL), Spring8 etc.

Bremsstrahlung photons are generated by extracting the electron beam and impinging it on a radiator and thereafter using a magnet to momentum deflect the electrons and tag their energies in order to know the bremsstrahlung photon energy. This would need a tagger, preferably based on scintillator fibres coupled to photomultipliers. The tagger used at Bonn along with the $1/E_\gamma$ spectrum of the bremsstrahlung photons is shown in figure 6. The shaded portion is the range covered with the SAPHIR detector that was used earlier. The tagging system was modified for the CB-TAPS system to have an energy range from 22 to 93% of the electron beam energy. Knowing the energy of the electron beam from its position on the tagger one can find the energy of the bremsstrahlung photon which is given as

$$E_\gamma = E_{\rm beam} - E_{\rm tagger}. \quad (1)$$

Depending on the tagger design and its efficiency one can have photons with energy almost up to 90% of the incident electron energy. Another tagging system being used at the MAMI (MAinz MIcrotron) facility at Mainz is shown in figure 7. Typical tagged photon fluxes are listed in table 2. At CAT, Indore, the extracted electron beam from 700 MeV Booster could provide $(E_{\gamma_{\rm max}})_{\rm brem.} \sim 630$ MeV. The 450 MeV, Indus-1 can similarly provide $(E_{\gamma_{\rm max}})_{\rm brem.} \sim 405$ MeV. To start with, one can extract the beam from either the Booster or Indus-1 and use the tagged photons to see the behaviour of the large volume BaF_2 and other scintillators owned by various research groups in our country with high energy photons ($(E_{\gamma_{\rm max}})_{\rm brem.} \sim 400$–600 MeV).

Table 2. Beam currents at Indore as compared to some of the international facilities.

Facility	E_e (Electron energy)	Intensity	γ_{tagged} (Photon flux)	Features
GrAAL Grenoble, France	6.04 GeV	200 mA	1.5×10^6 s^{-1}	Laser backscattered photons, polarized beam, flat distribution
ELSA Bonn, Germany	3.50 GeV	20 nA (external)	1.0×10^7 s^{-1}	Bremstrahlung photons, higher flux, $1/E_\gamma$ distribution
Indus-1 CAT, Indore, India	450 MeV	100 mA	–	–
Indus 2 CAT, Indore, India	2.5 GeV	300 mA (designed)	–	–

The high energy beam (2.5 GeV) from Indus-2 is not suitable for bremsstrahlung studies because of the slow ramping of the dipole magnets. The magnets take about 5 min to ramp up for 2.5 GeV and after the ring for Indus-2 is filled with electron bunches, it is to be ramped down to accept the next filling in the ring. Once the ring is filled with electron bunches and taking into account the ramp-up and ramp-down times, the duty cycle is close to 1% which is not suitable to conduct coincidence experiments. However, with the conceptual design for a direct 3 GeV Booster Synchrotron at CAT, the plans can be suitably modified in order to have a continuous beam operation. To have tagged photon facility generated through bremsstrahlung mechanism, we would need the following systems as a skeletal outline:

1. Availability of electron beam at some coordinates may be after the Booster, beyond TL3 into the 'open well'. This would then need a bending magnet (refer to figures 5 and 8).
2. Another magnet (∼1.5 T) for momentum analyzing the electron beam as it hits the radiator for producing bremsstrahlung photons.
3. Tagger for tagging the electrons based on scintillation fibres (SciFi) and PMT's.
4. Preferably a 4π detection system consisting of large volume scintillation detectors (CsI, BaF_2, $PbWO_4$ etc.).

As shown in figure 8 the electron beam from the Booster Synchrotron at 700 MeV can be taken through the TL3 beam line where it injects the beam into the Indus-2 beam line. At the septum, the TL3 can be extended forward in the same direction and then suitably bent with a bending magnet and taken into the 'open well' for generation of tagged bremsstrahlung photons. The electron beam dump for tagged bremsstrahlung photoproduction studies can be configured inside the

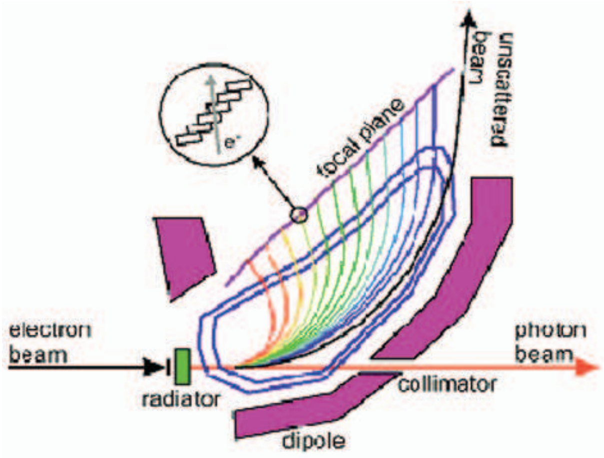

Figure 7. The tagger at the MAMI facility at Mainz.

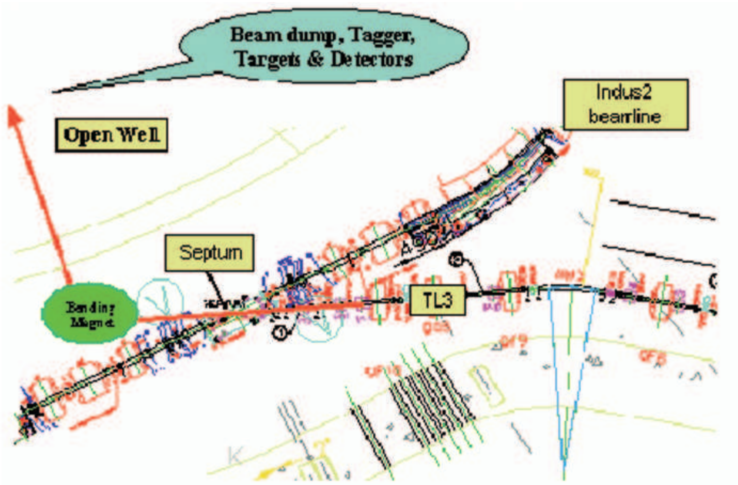

Figure 8. The TL3 beam line merging as an injector to Indus-2. The 700 MeV electron beam from the Synchrotron Booster can be suitably arranged to go straight forward and then bend into the open well for producing tagged bremsstrahlung photons.

ground of the 'open well'. The thick walls of the 'open well' (thickness ∼75 cm) would also provide sufficient shielding to contain the associated radiation.

The other option is to generate a laser backscattered photon. In this technique one does not have to extract the beam from the storage ring. The experiments based on synchrotron light can run parallely in a parasitic mode. The high-energy beam from Indus-2 (2.5 GeV) inside the ring can be utilized to generate laser backscattered photons. Indus-2 has five straight sections where insertion devices can be placed and one such straight sections can be utilized for generating the laser

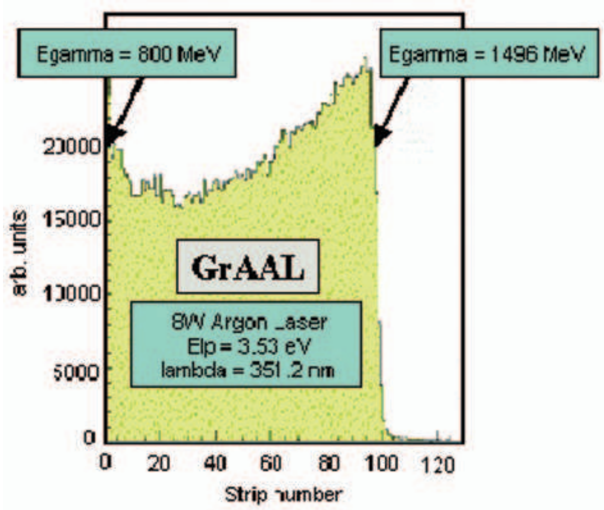

Figure 9. A typical spectrum at GrAAL for the laser backscattered photon [5]. The x-axis shows the strip number of the electron tagger. At GrAAL the electron energy is 6 GeV which provides backscattered photons with argon laser ($E_{\rm lp} = 3.53$ eV, $\lambda = 351.2$ nm) in the range from 800 MeV to 1.5 GeV.

backscattered photons. However, the maximum energy of the electron beam (at 2.5 GeV) and the type of laser used (say, argon laser, $E_{\rm lp} = 3.53$ eV, $\lambda = 351.2$ nm) would define the energy spectrum of the photons with $E_{\gamma_{\rm max}} \sim 295$ MeV. The energy of the laser backscattered photon is given as

$$E_\gamma = \frac{4\gamma^2 E_{\rm lp}}{\left(1 + \frac{4\gamma E_{\rm lp}}{mc^2} + \delta^2\gamma^2\right)}, \tag{2}$$

where $\gamma = E_{\rm e}/mc^2$, $E_{\rm lp}$ is the energy of the laser photon (~3 eV) and $E_{\gamma_{\rm max}}$ is the energy of the laser photon scattered at 180° for which $\delta = 0$. A typical energy spectrum for the GrAAL (Grenoble Anneau Accelerateur Laser) facility [5] is shown in figure 9. The spectrum is in general a flat distribution in contrast to the $1/E_\gamma$ spectrum for the bremsstrahlung photons. The electron energy at GrAAL is 6 GeV and the spectrum for the laser backscattered photon from an argon laser ($E_{\rm lp} \sim 3.53$ eV) is limited between 800 MeV to 1.5 GeV. The laser has to be accordingly tuned to cover different ranges of photon energies ($E_{\rm lp} \sim 2.41$ eV provides a range for E_γ from 600 MeV to 1.1 GeV). The photon fluxes are however a factor 10 less than those generated with bremsstrahlung techniques. The tagging detector, in case of laser backscattering, is one of the most delicate part of the experiment. The device has to be extremely compact (silicon microstrips), reside in the vacuum chamber of the storage ring, as close as possible to the main electron orbit, and must work in the environment of the storage ring, where high fluxes of X-rays are produced. At CAT, Indore, one of the straight sections in the Indus-2 beam line can be augmented for installation of the laser backscattered photon facility. The dipole subsequent to the straight section would bend the electrons undergoing interaction

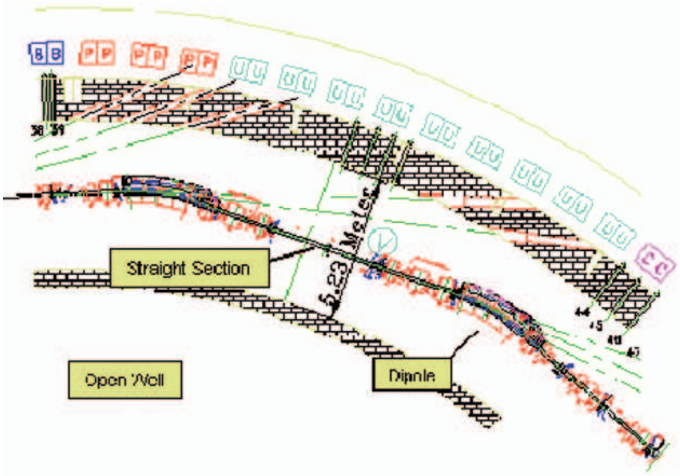

Figure 10. One of the straight sections in the Indus-2 beam line could be augmented for installation of the Laser Backscattered Photon facility. The dipole subsequent to the straight section would bend the electrons undergoing interaction with the laser photon for the purpose of tagging.

with the laser photon for the purpose of tagging. As shown in figure 10 one of the straight sections in the Indus-2 beam line could be utilized for injecting the laser photon and subsequently the backscattered photon would pass through the existing ports on the walls to the user's area. The dipole immediately after the straight section would deflect the scattered electrons and a tagger would have to be designed in the vicinity of the dipole to tag the scattered electrons. Alternatively the angle at which the laser backscattered photon emerges through precision slits, placed in the straight section can also tell us about the range of photon energies – of course with a coarser resolution. One of the most interesting features of the laser backscattered photon beam is its polarization that is obtained very easily: the laser produces completely polarized photons whose polarization is kept during the backscattering process. The backward Compton scattering of laser light against high energy electrons circulating in a storage ring, produces an almost flat energy spectrum with high polarisation, but this technique is really challenging. The laser beam position also needs to be controlled and stabilized with an angular accuracy of $\sim 2 \times 10^{-6}$ radian. Table 2 shows a comparison of the beam currents at CAT, Indore as compared to some of the international facilities.

To augment a laser backscattered photon facility, we would need the following systems as a skeletal outline:

1. A laser system (say, 8 W argon laser, $E_{\mathrm{lp}} = 3.53$ eV, $\lambda = 351.2$ nm or a similar system).
2. Availability of one of the straight sections in the Indus-2 beam line.
3. A compact tagger (preferably Si μ strips) for tagging the electrons bent by the dipole immediately after the straight section.
4. A 4π detection system similar to the one discussed in case of bremsstrahlung.

With the existing photon energies generated either by bremsstrahlung or laser backscattering, one cannot immediately investigate into the frontiers in the intermediate energy nuclear physics. Nevertheless, it could be an excellent starting point for venturing into the new domain of intermediate energy nuclear physics through photoproduction in our country. With trained manpower dealing with the superconducting magnets at LHC (CERN), one can visualize and enhance the electron beam energy at CAT, Indore in the range of 6 to 8 GeV using superconducting dipoles. With the existing infrastructure at least the experimental pion physics can be initiated in our country. The large-sized (∼25–30 cm in length) BaF_2 crystals can be calibrated with the electron/photon beam itself. Photon-induced data will be a very important database in future since any projects for the accelerator-driven sub-critical systems (ADSS) will be required to have precise information of (γ, n) reactions. In future, study of nuclear structure by means of nuclear resonance fluorescence, astrophysics with photoreactions, basic symmetry studies of the parity-violating force in the nuclear medium will be possible with linear and circularly polarized low-energy γ-ray beam ($\sim$ few MeV photons).

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References

[1] C Amsler *et al*, *Nucl. Phys.* **A622**, 315c (1997)
[2] A Martin *et al*, *Nucl. Instrum. Methods* **A417**, 137 (1998)
[3] D Trnka, L M Pant and the CBELSA-TAPS Collaboration, *Phys. Rev. Lett.* **94**, 192303 (2005)
[4] R V Nandedkar *et al*, *Curr. Sci.* (2002) 82
[5] C Schaerf, *Nuclear Physics News* **2(1)**, 7 (1992)