Polarized Gamma-Ray Beams

Polarized high-energy photons are excellent probes of protons, neutrons, and nuclei. Nowadays they are readily made by shining laser light at a high-energy electron beam.

Carlo Schaerf

Although photons couple only to electric charge and magnetic moment, they serve as important probes of hadrons—particles characterized primarily by their nuclear interactions. That's true for several basic reasons:

▶ The electromagnetic coupling strength is given by the fine-structure constant $\alpha = e^2/\hbar c \approx 1/137$, the square of the electron's charge in natural units. Because α is much smaller than unity, first-order perturbative approximations often suffice for comparing experimental data with the predictions of theoretical models.

▶ Another consequence of the smallness of α is that cross sections for the interaction of photons with hadrons are much smaller than those for hadrons with each other. For example, the mean free path of a photon in a nucleus is much longer than the diameter of the largest nucleus. That allows photons to explore nuclear cores. Hadronic probe particles, by contrast, interact mostly on the nuclear surface.

▶ To first approximation, interaction of a photon with a nucleon or nucleus is given by the relativistic scalar product of the photon's known vector potential with the often-unknown electromagnetic current that describes the innards of the hadronic system one wants to explore. Therefore, conjectures about the hadron's composition and structure yield calculable predictions for experiments in which the hadron is probed by photon beams.

The uses of polarization

For linearly polarized photon beams, the polarization direction gives a simple and revealing dependence of the differential scattering cross section $d\sigma/d\Omega$ on the azimuthal angle φ between the polarization direction and the production plane:

$$d\sigma(\vartheta,\varphi)/dW = A(\vartheta) + B(\vartheta)\cos(2\varphi).$$

The production plane is defined by the beam and a specified particle emerging from the scattering event and ϑ is the scattering angle between that particle and the beam.

The functions A and B have simple expressions when individual electromagnetic multipole transition-matrix elements dominate the scattering process. That simplification lets the experimenter discriminate among different conjectured transition mechanisms. A famous example is the photon-induced excitation of the proton to its first excited state—the short-lived Δ(1232 MeV) spin-3/2 resonance discovered by Enrico Fermi and coworkers in the early 1950s. Photoexcitation of the Δ(1232) is dominated by a magnetic-dipole spin-flip transition that aligns the spins of the spin-1/2 proton's three quarks to produce a final baryon state with total spin $j = 3/2$.

There is also an electric-quadrupole contribution to photoproduction of the Δ(1232), which contributes a different ϑ and φ dependence to the cross section. Because the electric-quadrupole contribution is very small, it is best determined by measuring Σ, the azimuthal scattering asymmetry—that is, the fractional difference between the photoproduction cross sections at $\varphi = 0$ and $\pi/2$. The best such results yield an electric-quadrupole transition amplitude that's about 3% of the magnetic-dipole amplitude, a result that confirms the presence of tensor forces in the three-quark system.[1]

Circularly polarized photons have a well-defined value of helicity—that is, the component of the particle's spin in the direction of its momentum. The spin of the photon, in units of $\hbar$, is 1, and its possible helicity states are +1 and −1. (Being massless, the photon cannot have zero helicity.) If the spins of the target particles in an experiment are longitudinally polarized (that is, in the photon-beam direction), one can combine the helicities of beam and target to make an initial state of known total angular momentum. For example, in the study of γp reactions, one can produce initial states with spin 3/2 or 1/2, depending upon whether the photon's spin is aligned parallel or antiparallel to the spin of the proton.

A powerful theoretical prediction, the so-called Gerasimov-Drell-Hearn sum rule, relates the difference between the spin-3/2 and spin-1/2 photon-absorption cross sections, integrated over all photon energies, to the proton's anomalous magnetic moment.[2] Now, almost 40 years after the sum rule was first formulated, polarized gamma-ray facilities at the universities of Mainz and Bonn in Germany have made it possible to verify the prediction.[3] Figure 1 shows the large-solid-angle detector used at MAMI, the Mainz electron microtron accelerator, to measure the cross sections for photon energies up to 800 MeV.

For all their advantages, photon beams pose special problems:

▶ Because α is small, electromagnetic cross sections are smaller than corresponding hadronic cross sections by two or three orders of magnitude. For example, the total cross section for the photoproduction of pions on the proton at the energy of the Δ(1232) resonance is only 0.6 millibarns (1 mb = 10^{-27} cm^2). In comparison, the π^+p scattering cross section at the same resonant energy is about 200 mb. That's why photonuclear experiments require high-intensity gamma-ray beams and detectors with very large solid-angle acceptance.

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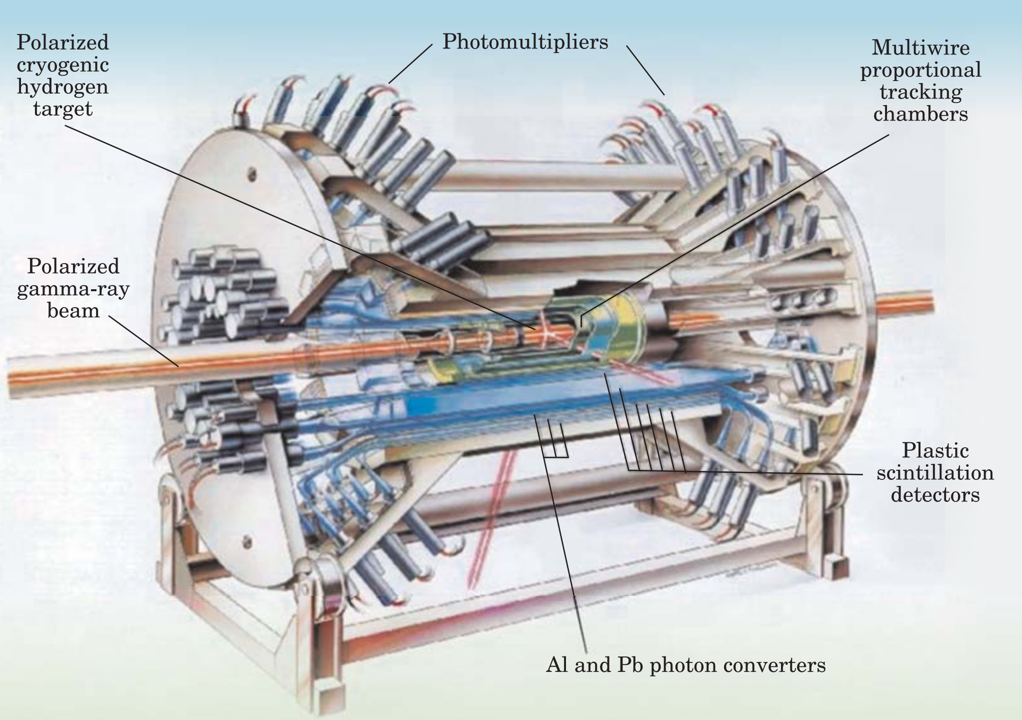


Figure 1. The DAPHNE particle detector at the University of Mainz's electron microtron accelerator (MAMI) records collisions of polarized bremsstrahlung gamma rays with polarized nuclei in the detector's center. The facility was recently used in a pioneering measurement of the spin-dependent absorption cross sections of gammas on protons over a large range of gamma energies.[3] DAPHNE's spin-polarized hydrogen target is surrounded by multiwire and scintillation tracking detectors, aluminum and lead layers for converting neutrals into charged particles, and a segmented calorimeter.

▶ As the energy of a photon increases above 200 keV, its wavelength becomes much smaller than crystal lattice spacings, its cross section for scattering off atoms becomes a smooth function of energy, and its name changes from x ray to gamma ray. Unlike x rays, gammas cannot be selected for energy or polarization through their interaction with matter. The energy spectrum and polarization of a gamma-ray beam must be determined by its production mechanism.

▶ Pure electromagnetic cross sections—for processes like Compton scattering and electron–positron pair creation—are much larger than those involving hadrons. Therefore, a gamma-ray beam hitting an experimental target will produce a large background of electrons and positrons. Fortunately these background particles are highly relativistic and concentrated at very small forward angles. So one can veto most of the background with a gas-Cherenkov detector downstream of the target.

Unpolarized gamma-ray beams

The pioneering studies of photonuclear reactions were performed by James Chadwick and Maurice Goldhaber in the early 1930s with just radioactive gamma-ray sources.[4] But not until the advent of the first electron accelerators could one produce intense beams of unpolarized gammas by bremsstrahlung of relativistic electrons in amorphous heavy-metal targets. These intense gamma beams made possible the first systematic studies of photonuclear reactions and contributed greatly to the understanding of the collective motions of nucleons in nuclei.

In the 1950s and 1960s, bremsstrahlung beams with photon energies of 10–20 MeV yielded much data on the giant electric-dipole resonance in nuclei, allowing it to be understood in terms of collective nucleon motion. At higher photon energies, up to 350 MeV, bremsstrahlung beams produced many measurements of cross sections for pion photoproduction on nucleons and nuclei, thus contributing to the understanding of the $\Delta(1232)$ resonance as a magnetic-dipole transition of the nucleon to its first excited state.[5]

The main limitations of earlier bremsstrahlung beams were their continuous energy spectra and the absence of polarization. Bremsstrahlung, literally "braking radiation," occurs when an electron radiates a photon in the Coulomb field of a nucleus:

$$e^- + N \rightarrow e^- + N + \gamma.$$

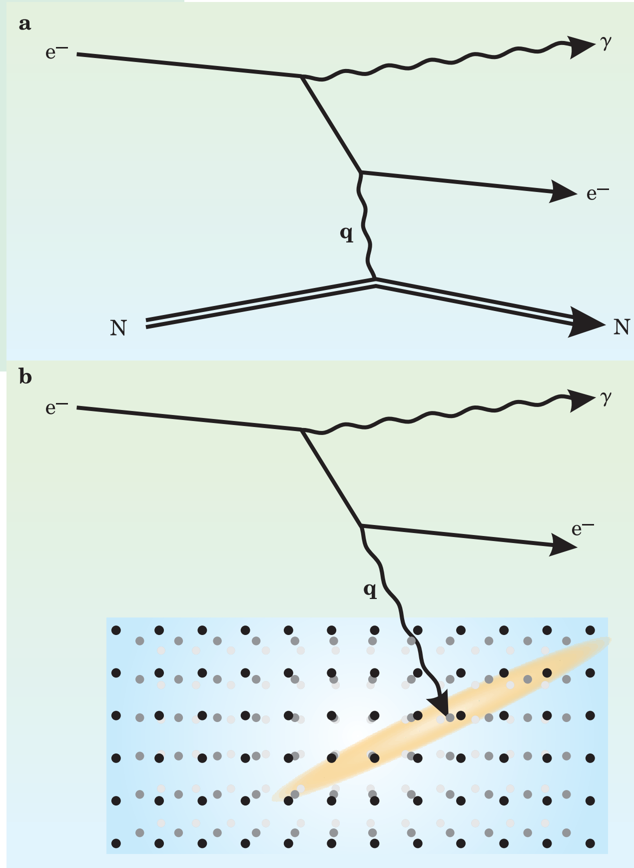
With three bodies in the final state, there is no strong correlation between the energy of the photon and its emission direction. The gammas are emitted roughly in the forward direction within an angular spread on the order of mc^2/E, where E is the energy of the incoming electron and m is its mass. The bremsstrahlung spectrum is continuous, with photon energy k cutting off at $E - mc^2$. Below that cutoff, the spectrum falls roughly like $1/k$.

In some photonuclear reactions, the energy of the incident gamma can be calculated from the final nuclear state. Where that is not possible, several techniques have been developed to infer the gamma's energy. The earliest method of determining the incident photon energy was called bremsstrahlung subtraction: In that technique, each measurement is performed twice, each time with slightly different values of the beam-electron energy. One then attributes the observed difference in reaction rates to the difference between the two gamma spectra, which can be calculated from quantum electrodynamics. But when experimenters sought to make the difference between the two beam-electron energies small enough to yield an almost monochromatic difference spectrum, instabilities of the beam and the detector introduced uncontrollable systematic errors. So one had to look for something better.

Subnanosecond tagging

"Photon tagging" is the name given to the modern technique for matching individual photonuclear events recorded by a detector to the precise energy of the interacting gamma. It's done by looking for time coincidences between a nuclear event and the electron whose scattering produced the photon that initiated it. During

Figure 2. Feynman diagrams for bremsstrahlung. The electron that radiates the gamma can conserve momentum and energy by subsequently recoiling off a single nucleus **(a)** or, coherently, off a group of contiguous nuclei in a crystal **(b)**. In either case the recoil is mediated by a soft virtual photon. Just like the Feynman diagrams, the recoil crystal is represented here in momentum space. Each point of this inverse lattice represents a reciprocal-lattice vector of the crystal. For coherent bremsstrahlung, the momentum **q** transferred by the virtual photon is small and limited to the pancake-like region of the inverse crystal indicated in brown. Only points inside the pancake contribute to the coherent bremsstrahlung. Because q is small, the correspondingly large de Broglie wavelength covers many nuclei.



bremsstrahlung, the kinetic energy acquired by the recoiling nucleus is negligible. Therefore, the gamma's energy is well approximated by the difference between the initial and final electron energies.

In a modern accelerator facility, the beam-electron's energy is known with good precision and an electron's energy after bremsstrahlung can be measured with a high-resolution spectrometer. Improvements in fast electronics have refined the timing resolution of particle signals to a fraction of a nanosecond. That has made gamma tagging an attractive technology for bremsstrahlung electron beams with gamma-ray intensities up to about 10^8 photons per second. Much higher rates would yield too many accidental coincidences.

Positron annihilation became a fashionable source of gammas in the 1960s, when linear electron accelerators were upgraded to produce positron beams. But the quasi-monochromatic gamma-ray peaks produced by annihilation are always contaminated by positron bremsstrahlung. Because the annihilation cross section decreases approximately as the inverse of the incident positron's energy, positron beams lose their interest as gamma-ray sources for photon energies above a few hundred MeV.[6]

Polarized beams

The first linearly polarized gamma-ray beams were made by taking advantage of the natural polarization of bremsstrahlung when the photons are collimated in a small solid angle away from the direction of the primary electrons. The maximum polarization, on the order of 30–50%, is obtained with gamma energies k of about $E/3$ and off-beam-axis angles near mc^2/k. Coherent bremsstrahlung in crystals provides a powerful extension of this natural-polarization technique.[7]

The elementary reaction $e^- \rightarrow e^- + \gamma$, by itself, is forbidden by conservation of energy and momentum. A recoil particle must be present to take away the small amount of excess momentum in the final state. In bremsstrahlung, that momentum is absorbed by the nucleus via a soft virtual photon (see the Feynman diagram in figure 2a).

When the momenta of the final-state electron and the radiated gamma are both close to the electron's incident direction, the momentum transfer **q** to the recoil nucleus is very small; its corresponding wavelength $\hbar/q$ is comparable to the dimensions of a crystal lattice. Therefore several adjacent nuclei can contribute coherently to the bremsstrahlung cross section.

Coherent bremsstrahlung occurs for well-defined values of **q**. The recoil energy E_r absorbed by the participating nuclei is negligibly small. Figure 2b shows a Feynman graph for coherent bremsstrahlung from a crystal. The crystal lattice is represented in momentum space; its points are reciprocal lattice vectors. Their spacing is essentially the reciprocal of the physical lattice spacing. The kinematically allowed values of **q** cover the shaded "pancake" in the inverse lattice. Points inside the pancake contribute coherently to the bremsstrahlung cross section.

With the four-momentum ($\mathbf{q}$, $E_r \approx 0$) transferred to the target nuclei thus constrained, the kinematics of the bremsstrahlung takes on the character of a quasi-two-body scattering process, yielding a correlation between the energy and angle of the radiated gammas. Therefore the coherent bremsstrahlung yields quasi-monochromatic peaks rising above the continuum photon spectrum.

Figure 3 shows the first coherent spectral peaks obtained by the coherent-bremsstrahlung technique, in a 1960 experiment by Giordano Diambrini and coworkers at the 1-GeV electron-synchrotron of Italy's national nuclear physics laboratory in Frascati.[7] The positions of the peaks, their polarizations, and their heights over the incoherent continuum depend on the directions of the radiated photons and the orientation of the crystal lattice with respect to the direction of the incident electron beam. Those directions determine how many reciprocal-lattice points are inside the pancake of coherence. The best peaks appear at gamma-ray energies k of about $E/3$. Moreover, the peaks have a high degree of linear polarization, which can reach 80% with proper choice of crystal orientation. Unfortunately, one cannot optimize polarization and the heights of the quasi-monochromatic peaks at the same time.

Tagging coherent-bremsstrahlung beams lets experimenters associate individual events with specific polarized-photon peaks; but that requires running at lower than maximal photon intensity. Coherent-bremsstrahlung beams are now being used at several laboratories.[8] Crystals with the highest Debye temperatures make the best

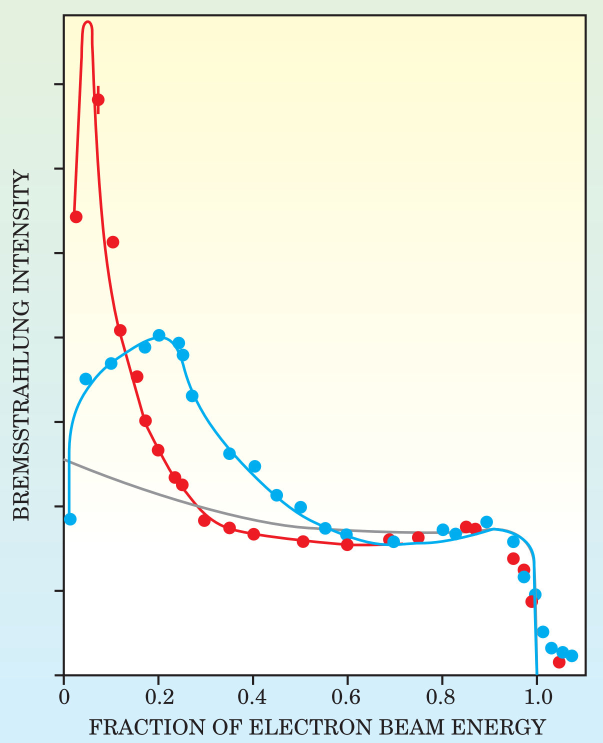


Figure 3. Quasi-monochromatic peaks due to coherent bremsstrahlung were first seen in these 1960 gamma-ray spectra produced by a beam of 1-GeV electrons hitting a single-crystal silicon target at two different orientations of the crystal. The red and blue data points correspond, respectively, to angles of 6 mrad and 1 mrad between the beam and the crystal axis. The curves represent calculated expectations. The gray curve is for bremsstrahlung in a noncrystalline target. (Adapted from G. Bologna et al. in ref. 7.)

targets for this technique because they have the weakest lattice vibrations.

The energy spectrum and polarization for coherent bremsstrahlung can be calculated from quantum electrodynamics and the known crystal structure of the target. But the peaks depend critically on the crystal's orientation. So it's essential to monitor the spectrum and polarization continuously. How does one monitor polarization? Electrodynamic processes like e^+e^- pair creation and Compton scattering are sensitive to the photon polarization, but their analyzing power, as measured by the fractional asymmetry Σ, is only a few percent. Fortunately, the coherent photoproduction of neutral pions in helium has an analyzing power very close to unity; it turns out to be the best way to monitor the linear polarization of photons in the energy range 150–400 MeV.[9] The probability amplitude for the pion production is, to good approximation, proportional to the triple product $\mathbf{k} \cdot \boldsymbol{\varepsilon} \times \mathbf{p}$, where $\mathbf{k}$ and $\mathbf{p}$ are the momenta of the photon and pion, and $\boldsymbol{\varepsilon}$ is the polarization vector to be monitored.

Ladon beams

In 1963, Fabluch Arutyunian and Vigen Tumanian and, independently, Richard Milburn, pointed out that the backscattering of photons off high-energy electrons directed head-on into the photon beam could produce gamma-ray beams of very high energy.[10] The effect was soon verified, and before the end of the decade, Joseph Ballam and collaborators at SLAC were using a low-intensity backscattered gamma beam in bubble-chamber experiments.[11]

In 1967, Renato Malvano, Carlo Mancini, and I pointed out that, by exploiting the power inside laser cavities and the intense electron beams circulating in storage rings, one could produce intense polarized gamma-ray beams for photonuclear-reaction experiments.[12] The first beam of this kind was built in 1987 at Frascati's Adone storage ring.[13] The generic name "ladon beams" now used for such gamma sources not only honors Adone; it also recalls from Greek mythology the River Ladon, which brought forth nymphs and the reeds from which Pan fashioned his flute of seven pipes.

Following the early successes at Adone, ladon beams were built at several other storage rings. Three ladon beams were built in the Novosibirsk laboratory in Russia. Their performance was spoiled, however, first by an accidental fire that destroyed much of the laboratory and then by the demise of the Soviet Union. The table on page 48 lists ROKK-1M, the third of the Novosibirsk ladon beams, and others around the world.

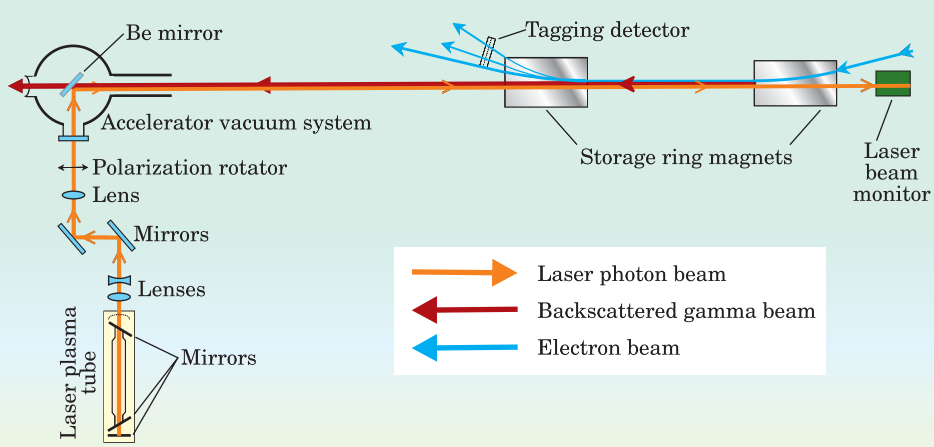


Figure 4. A representative ladon-beam facility, shown schematically, begins with a laser and the attendant optical components that control the low-energy photon beam's polarization and direct it head-on into a beam of GeV electrons in a straight section of a storage ring. Photons backscattered to high energies by collisions with the electrons form a rather tight gamma-ray beam that exits the accelerator's vacuum structure in the direction opposite to that of the impinging laser beam. A fast-electronics tagging detector just downstream of the storage-ring magnets at the end of the straight section determines the energy losses of individual struck electrons from their resulting deflections out of the beam. By timing coincidence between scattered electrons and photonuclear reaction products, the tagging system yields the energies of the individual reaction-instigating gammas.

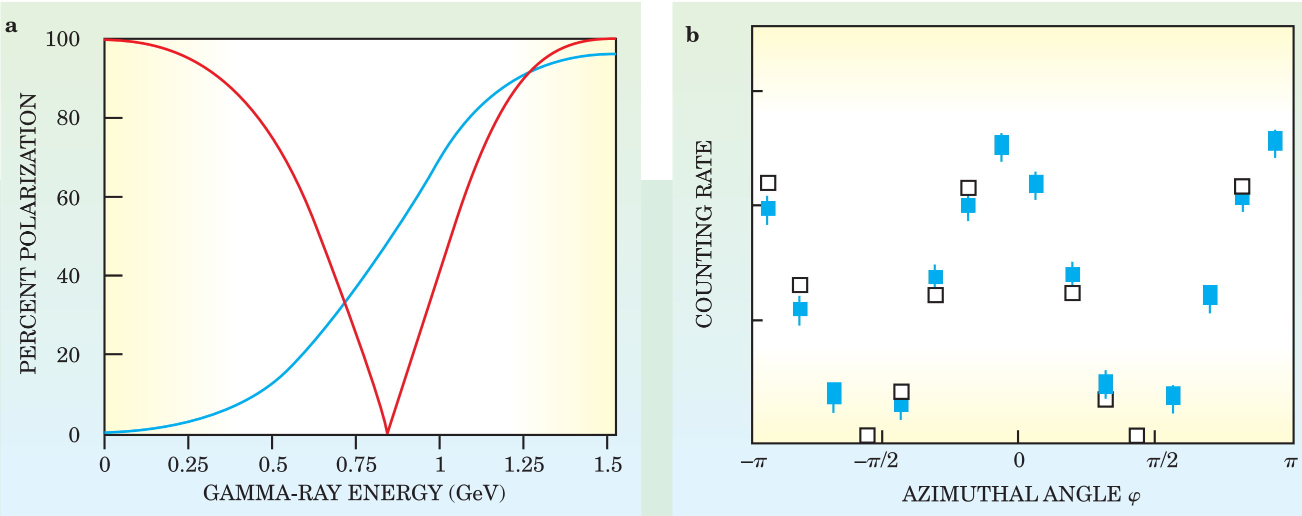


Figure 5. Polarization of gamma rays. **(a)** The calculated fractional polarization of the gamma-ray beam at the Graal ladon facility, as a function of energy. The red and blue curves indicate, respectively, circular (absolute value) and linear polarizations. **(b)** First measurement of the polarization of a ladon beam.[15] The elastic scattering of 15-MeV gammas off carbon-12 nuclei was measured as a function of φ, the azimuthal angle between the gamma beam's linear-polarization direction and the plane that includes the incident and scattered gamma. The observed azimuthal asymmetry (solid data points) is a measure of the gamma beam's polarization. If the polarization is 100%, the cross section should vary like 1 + cos(2φ). The open squares are the data corrected for the finite resolution of the apparatus.

Four of them—LEGS and HIGS in the US, Graal in France, and LEPS in Japan—are currently in operation. Collectively, they cover the gamma-ray spectrum from a few MeV all the way up to 2.4 GeV.

The essential components of a ladon beam are an electron storage ring and a laser. The laser photons collide with beam electrons in one of the storage ring's straight sections to create a narrow cone of backscattered gammas with an opening angle around the electron beam direction of order mc^2/E, which is the reciprocal of the electron beam's Lorentz factor γ.

A backscattered photon acquires a significant fraction of the colliding electron's energy. Photons scattered precisely in the direction of the electron beam acquire the maximum possible energy k_{max}, given by

$$k_{max}/E = Z/(1 + Z),$$

where $Z = 4E\hbar\omega/m^2c^4$ and ω is the laser photon's frequency. But if the photon is scattered into a small angle θ from the backward direction, one gets

$$k/E = Z/(1 + Z + x),$$

where $x = (\gamma\theta)^2$.

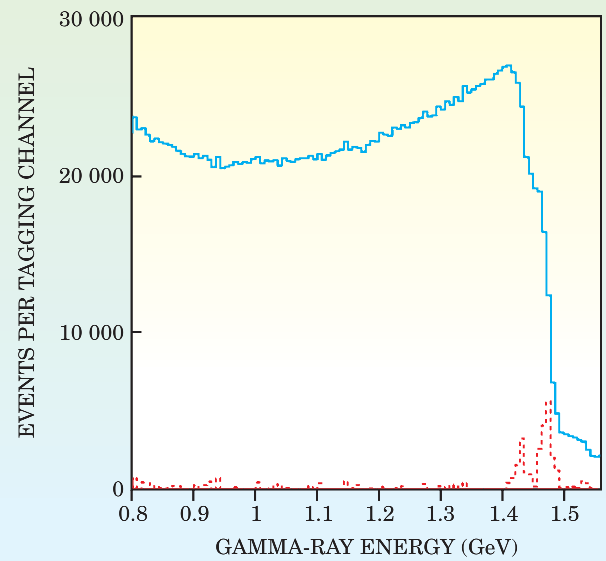
Because the Lorentz factor γ is so large—typically in the thousands—the gamma-ray energy decreases very rapidly with increasing θ. For $\theta = 1/\gamma$, that is, less than a milliradian from the direction of the electron beam, the scattered photon's energy is already down almost to $k_{max}/2$.

For electron energies above 1 or 2 GeV, the backscattered photon beam is concentrated in an extremely narrow backward cone. Therefore it's impractical to use collimators to select the highest photon energies. Tagging the scattered electron provides the energy of the gamma it created. The best energy resolution obtainable with tagging depends on the energy width of the electron beam stored in the ring. That's a machine parameter which, for mod-

Ladon beams worldwide

Project name	Ladon	Taladon	ROKK-1M	LEGS	LEGS-2	Graal	LEPS	HIGS
Location	Frascati, Italy		Novosibirsk, Russia	Brookhaven, US		Grenoble, France	Harima, Japan	Durham, NC US
Storage ring	Adone	Adone	VEPP-4M	NSLS	NSLS	ESRF	SPring-8	TUNL-FEL
Energy defining method	Collimation	Internal tagging	Tagging	External tagging	External tagging	Internal tagging	Internal tagging	Collimation
Electron energy (GeV)	1.5	1.5	1.4–5.3	2.5	2.8	6.04	8	1.0
Laser photon energy (eV)	2.45	2.45	1.17–3.51	3.53	4.71	3.53	3.53	8.2
Gamma-ray energy (MeV)	5–80	35–80	100–1200	180–320	285–470	550–1470	1500–2400	5–225
Energy resolution (%)	1.4–10	5	—	1.6	1.1	1.1	1.25	1
Energy spread (MeV)	0.07–8	4–2	—	5	5	16	30	—
Electron current (A)	0.1	0.1	0.1	0.2	0.2	0.2	0.1	100
Gamma intensity (s^{-1})	10^5	5×10^5	2×10^6	4×10^6	2×10^6	2×10^6	2×10^6	10^6–10^8
First year of operation	1978	1989	1993	1987	1999	1996	1999	1996

Figure 6. Measured spectrum of the tagged gamma-ray beam at Graal. The dashed red curve at the bottom is, effectively, the energy derivative of the spectrum. Its two prominent peaks, at 1.447 and 1.486 GeV, are produced by two lines (at wavelengths 363.8 and 351.2 nm) in the ladon laser's output.



ern storage rings, is on the order of $10^{-3}\,E$. As a result, for tagged ladon beams, the backscattered photon's energy resolution is of order $10^{-2}\,k_{\max}$.

Figure 4 is a schematic layout of the Graal ladon beam at the storage ring of the European Synchrotron Radiation Facility (ESRF) in Grenoble, France.[14] The electron and laser beams collide head-on in a short straight section of the ring to produce the backscattered gamma-ray beam. Lenses and mirrors focus and align the light from the external laser onto the interaction region. Maximum gamma-ray yield requires that the alignment be stable within a few microradians. Those beam electrons that have lost energy to laser photons are deflected out of the circulating storage-ring beam orbit by the ring's magnets and into the tagging area. The tagging counters detect scattered electrons and measure their displacements from the beam orbit. The displacement yields a good measurement of the energy a particular electron has transferred to a laser photon.

The gamma-ray beam thus produced travels in the opposite direction from the incident laser light and enters the experimental area. There it encounters a collimator, an experimental nuclear target, and a monitor. The target is surrounded by a detector that records particles produced in the photonuclear reactions. The Graal detector consists of plastic scintillators, wire chambers, and a "crystal ball" made of 480 bismuth germanate scintillation crystals. The detector's solid-angle coverage of the target is very close to 4π.

High polarization and low background are the main virtues of ladon beams. For relativistic electrons, helicity is a good quantum number: It is not changed by the photon collision. There is therefore no significant transfer of angular momentum from electron to photon. Photons scattered at 180° cannot change their angular momentum or their polarization. Depending on the scattering angle, a laser photon's energy can be raised to several GeV, but its polarization changes very little. Because the linear polarization of the incident laser beams is very close to unity, the polarization of the backscattered gammas of highest energy is also close to unity. Even at lower gamma-ray energies, the polarization remains high. For backscattered photon energies near $0.7\,k_{\max}$, the polarization is still above 70%.

The calculated polarization of the Graal beam is shown in figure 5a. If one rotates the linear polarization of the laser beam, or changes it from linear to circular, one gets the corresponding change in the polarization of the gamma-ray beam. Thus it's easy to alternate between different orientations or types of gamma-ray polarization by using conventional optical components to alternate the polarization of the laser beam.

Figure 5b shows the first experimental measurement of the polarization of a ladon beam, carried out in 1990 at Frascati.[15] The experiment measured the elastic scattering of 15-MeV gammas off carbon-12 nuclei. The scattering is asymmetric with respect to azimuthal angle φ between the polarization direction and the scattering plane. If the polarization is 100%, no gammas can be scattered into the scattering plane perpendicular to the beam polarization. Therefore the observed azimuthal asymmetry becomes a direct measure of the gamma-ray beam's polarization.[15] The polarization of Brookhaven National Laboratory's LEGS ladon beam has been determined with high accuracy by measuring the azimuthal asymmetry of neutral-pion photoproduction on helium.[16]

Unlike the gamma-ray bremsstrahlung spectrum, which falls like $1/k$, the ladon spectrum of the backscattered gamma rays, as shown in figure 6, is reasonably constant from zero to the maximum energy determined by the energy of the beam electrons. Therefore, if one is investigating photonuclear reactions that require high-energy gammas, ladon beams have the virtue of far fewer unwanted low-energy beam photons per interesting event than bremsstrahlung beams have.

The first experiments at the Brookhaven and Frascati ladon-beam facilities revisited the classical problem of deuteron photodisintegration by measuring the azimuthal asymmetry.[1] Further work at the Brookhaven LEGS facility has provided, among other measurements, high-precision determination of the cross section and azimuthal asymmetry for the combined reactions of pion photoproduction and elastic photon–proton scattering. These precise measurements yielded the novel determination of the small electric-quadrupole contributions to the excitation of the $\Delta(1232)$ resonance discussed above.

The Graal experiment at Grenoble has provided very precise measurements of the differential cross sections and azimuthal asymmetries for meson photoproduction, which contributes to the understanding of the structure of baryon resonances. One still-controversial baryon resonance is the "exotic" pentaquark state first reported[17] in 2003 by the LEPS collaboration at Japan's SPring-8 storage ring (see Physics Today, September 2002, page 19 and June 2005, page 9).

The high-statistics gamma-ray spectra that have been accumulated at Graal since 1996 have also been used, in a kind of Michelson–Morley experiment, to test Lorentz rotational invariance to very high precision. Because the storage ring is fixed on the rotating and revolving Earth, one can test the isotropy of the speed of light by monitoring the maximum gamma-ray beam intensities achieved by photon backscattering at Graal as a function of the beam's orientation relative to its motion through the privileged reference frame defined by the cosmic microwave background's observed dipole moment. The Graal collaboration, having recently completed this analysis,[18] finds that any orientation dependence of the speed of light is less than 3 parts in 10^{12}. That's an improvement of more than a hundredfold on the anisotropy upper limit already obtained with space probes.

Advantages, disadvantages, and prospects

Ladon beams have demonstrated several advantages over earlier techniques for making gamma-ray beams:

▶ They yield a high degree of polarization. And the polarization can be altered rapidly with standard optical components.

▶ Ladon beam spectra and polarizations are easily calculated from quantum electrodynamics. Such calculations have been verified by experiment at various gamma energies from 15 to 320 MeV.

▶ The ladon spectrum is reasonably flat out to gamma energies of about $E/4$.

▶ The gamma-ray energy resolution one gets with a ladon tagged beam is about 1–2% of the maximum beam energy. That's good enough for precision investigations of the nucleons and their excited states.

The main disadvantage of ladon beams is their lower intensity when compared with bremsstrahlung beams. That can be partially compensated for by detectors with solid-angle coverage close to 4π and by longer running times. Ladon beams usually operate in parasitic mode at storage rings devoted primarily to producing synchrotron radiation. Making ladon gamma rays subtracts electrons from the circulating beam, thus reducing its current. The maximum gamma-ray intensity available during parasitic running at such a ring is limited by the light-source users' desire for a long-lived stored electron beam not excessively depleted by laser backscattering. Fortunately, the problem of conflicting interests is overcome at modern storage rings whose electron beams can be "topped-up" every few minutes.

The future of backscattered gamma-ray beams depends on the availability of storage rings with electron energies in the region of several GeV. It also depends on the interest of nuclear and particle physicists in experiments at those relatively modest energies. In particle physics, the main topic for ladon beams is the study of baryon physics—that is, the low-energy excited states of the nucleon. Data from LEGS and Graal in the region of the first baryon resonances (with masses up to 1.5 GeV) have already contributed significantly to the refinement of theoretical models of baryon structure. There's much more still to be learned in that energy region. That will require better data, especially on polarization observables.

In Japan, LEPS has extended the ladon-beam energy frontier to 2.4 GeV. Even higher gamma energies can be achieved by replacing the conventional lasers of the present generation of ladon facilities with free-electron lasers that provide higher input photon energies.

Gamma–neutron scattering is important. Directly comparing the results of identical polarized ladon beams bombarding deuterium and ordinary-hydrogen targets lets one interpret the neutron data with minimal complication from the proton–neutron interaction. The recent pioneering verification of the Gerasimov-Drell-Hearn sum rule for protons with tagged-bremsstrahlung beams at the Mainz and Bonn accelerators has shown the importance of verifying basic theoretical results on baryon structure.[3] Similar results on the neutron are eagerly awaited.

The successful operation of the first "frozen-spin" polarized hydrogen and deuterium target at Brookhaven will allow LEGS to study double-polarization observables that couple the polarization of the beam with that of the target protons and deuterons.

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