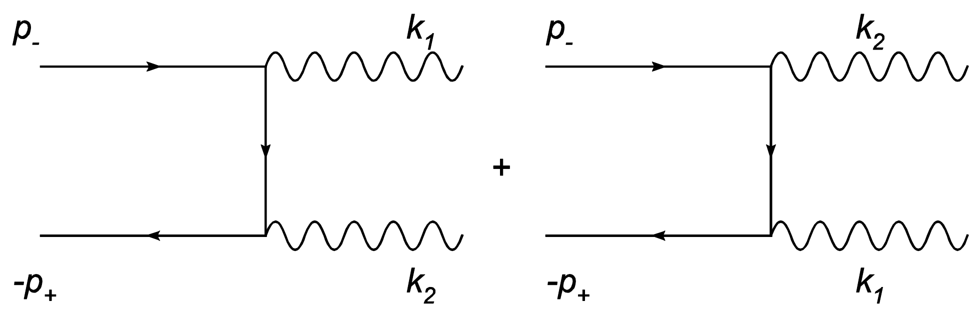

Photon Source from Positron Annihilation

Andrei Afanasev
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WASHINGTON, DC

Positron Working Group Workshop, JLab, 3/25/25

Plan of Talk

- Photons from Positron Annihilation: History
- Formalism and key features of annihilation cross section
- Estimates of annihilation photon yields for Jlab
- Possible experiments with monoenergetic photons
- Summary and Conclusions

High-Energy Photons at JLab

- Hall D – GlueX, coherent bremsstrahlung

(in a diamond crystal),

the spectrum is peaked around 8.5-9GeV

(for 12 GeV electron beam)

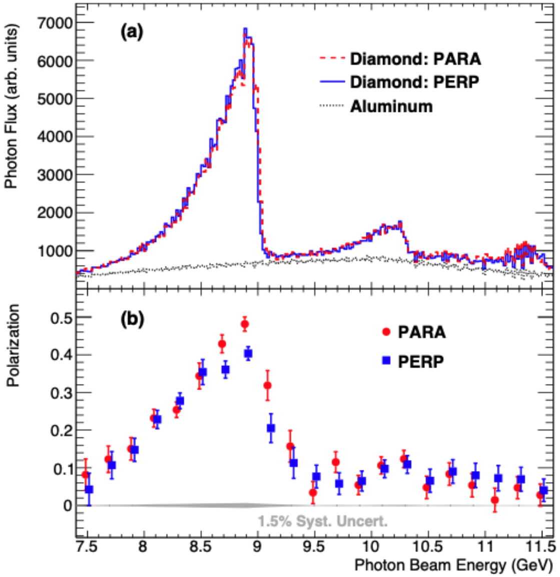


FIG. 1. (color online) (a) Photon beam intensity versus energy as measured by the pair spectrometer (not corrected for instrumental acceptance). (b) Photon beam polarization as a function of beam energy, as measured by the triplet polarimeter, with data points offset horizontally by ±0.015 GeV for clarity.

- CLAS, CLAS12: tagged photons, forward tagger (FT)

Positron Annihilation in Flight

$$e^{+} + e^{-} \rightarrow 2\gamma$$

•Used starting 60s to study photonuclear reactions (LLNL, Saclay) and nucleon resonances (Saclay, Frascati)

•Used positron beam incident on a foil: electrons (almost) at rest

  •Cross section =0.4 10^{-25} cm^2 (E_{lab}=10 MeV)

•Issue at lower energies: bremsstrahlung tail

•Sample studies for MeV energies:

Afanasev et al, Proceedings of IPAC'10, Kyoto, Japan, FERMILAB-CONF-10-691-APC

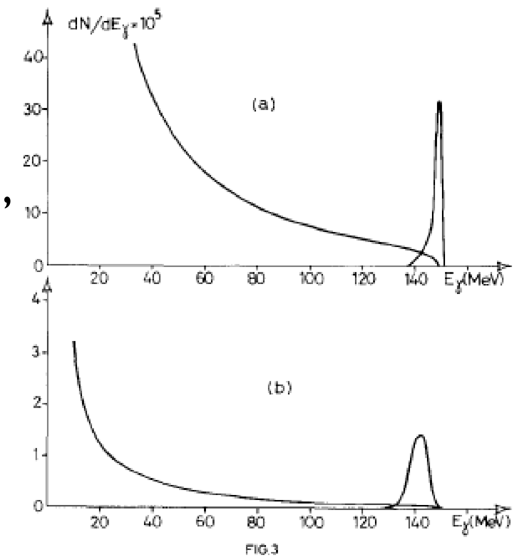


Fig. 3. Spectra of bremstrahlung and annihilation photon for positron energy 150 MeV. (a) for 0.7 g/cm² hydrogen target and photons collected between 0 and 17.5 mrad; (b) for 0.35 g/cm² hydrogen target and photons collected between 17.5 and 26 mrad.

History

NUCLEAR INSTRUMENTS AND METHODS 67 (1969) 283-287; © NORTH-HOLLAND PUBLISHING CO.

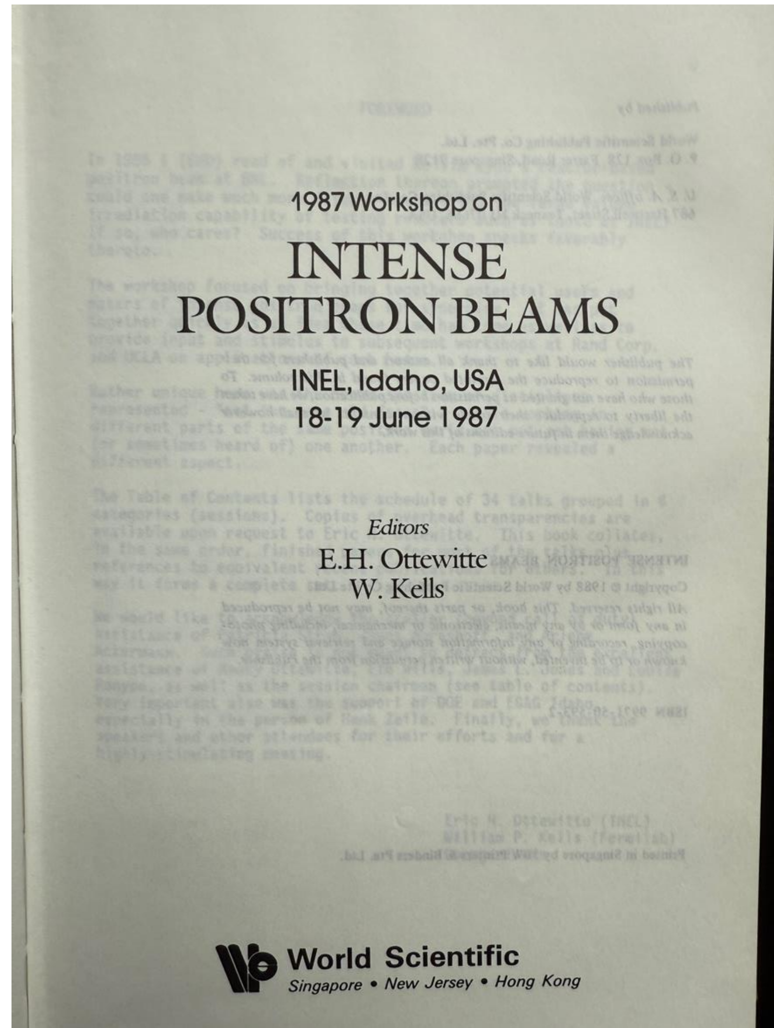
THE PHOTON SPECTRUM FROM POSITRON ANNIHILATION IN FLIGHT *

R. O. OWENS+ and L. S. CARDMAN

Electron Accelerator Laboratory, Yale University, New Haven, Connecticut, U.S.A.

Received 12 July 1968

Figures are presented which enable the target parameters of a positron annihilation in flight system to be chosen to obtain the maximum photon yield consistent with the required photon energy spread in the annihilation "spike".


1987 Workshop on

INTENSE
POSITRON BEAMS

INEL, Idaho, USA
18-19 June 1987

Editors
E.H. Ottewitte
W. Kells

World Scientific
Singapore • New Jersey • Hong Kong

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History

Intense Positron Beams at CEBAF

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I have been asked to give a brief exposition of the possible generation and use of intense positron beams at the Continuous Electron Beam Accelerator Facility (CEBAF) now being built in Newport News, VA, under the aegis of the Southeastern Universities Research Association (SURA).[1,2] The George Washington University is a member of SURA.

The CEBAF accelerator will be a 4-GeV, 100% duty cycle, 200-μA electron accelerator, composed of two 500-MeV superconducting linear accelerators fed by a 50-MeV injector, and enough recirculation lines to achieve the maximum electron energy. Figure 1 shows a schematic diagram of the accelerator.[3]

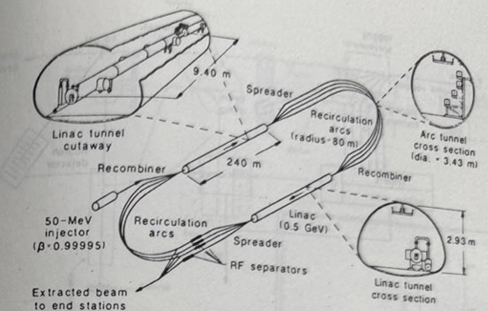

Fig. 1. Schematic of CEBAF superconducting CW recirculating linac.

The beams from the accelerator will feed three experimental end stations, at least one of which will include the capability for generation of a monoenergetic photon beam in the GeV energy range. According to present plans, this photon beam will be produced by the tagged-bremsstrahlung technique,[4] wherein the photon that causes the event being detected is tagged by coincidence detection of the electron that radiated the photon. Figure 2 shows a schematic diagram of a facility for the production of a tagged-bremsstrahlung beam.[5] If a positron beam were available (only about 1 nA of beam current is necessary), the backgrounds would be lower and the effective range of the tagged photons would be extended closer to the bremsstrahlung end-point energy.

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CEBAF Summer Workshop (1985)

POSITRONS AT CEBAF!

Positron Working Group Report

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The interest of the Positron Working Group, attended by about 20 participants during this workshop, was focused on two main topics: positron production and the motivation for implementing a positron beam. We tried to answer the questions: how?, how many?, and why?. We had no time left to work on the cost of the beam, and the project itself is still rather indefinite. Nevertheless, we think that the order of magnitude, given in the previous report, namely, a few percent of the total CEBAF cost, remains correct.

Positron production is discussed in section 1. Reactions using directly the positrons themselves are presented in section 2. The characteristics of secondary photon beams which can be produced by positron beams are detailed in section 3, together with some applications.

3 PHOTON BEAMS PRODUCED BY POSITRONS.

3.1 Forward annihilation in flight of positrons.

A positron can annihilate in flight with an atomic electron of a target into two photons. Because of the center-of-mass motion, the photon emitted in the forward direction acquires most of the energy. At 0° its energy is the total positron energy plus half the electron mass; the other photon has an energy of 0.255 MeV. The photon beam is obtained by focusing the positrons on a low-Z target (to suppress bremsstrahlung production relative to the annihilation radiation) and collimating photons in the forward direction into a small solid angle around 0° (see figure 9). The positrons which do not annihilate in flight are deflected from their initial direction by a sweeping magnet and are collected in a Faraday cup (used for beam calibration). The bremsstrahlung contribution can be measured and subtracted if an identical experiment is done either with electrons of the same energy on the same radiation target or with the same positron beam and a high-Z target where the relative contribution of the annihilation photons is small. This method, used in the giant-resonance region at Livermore and Saclay and in the Δ-resonance region at Frascati and Saclay, produces quasimonochromatic photons with a typical resolution of ~1%.

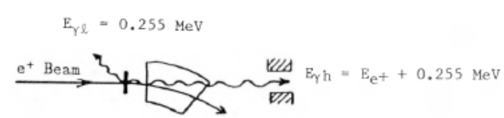

FIGURE 9

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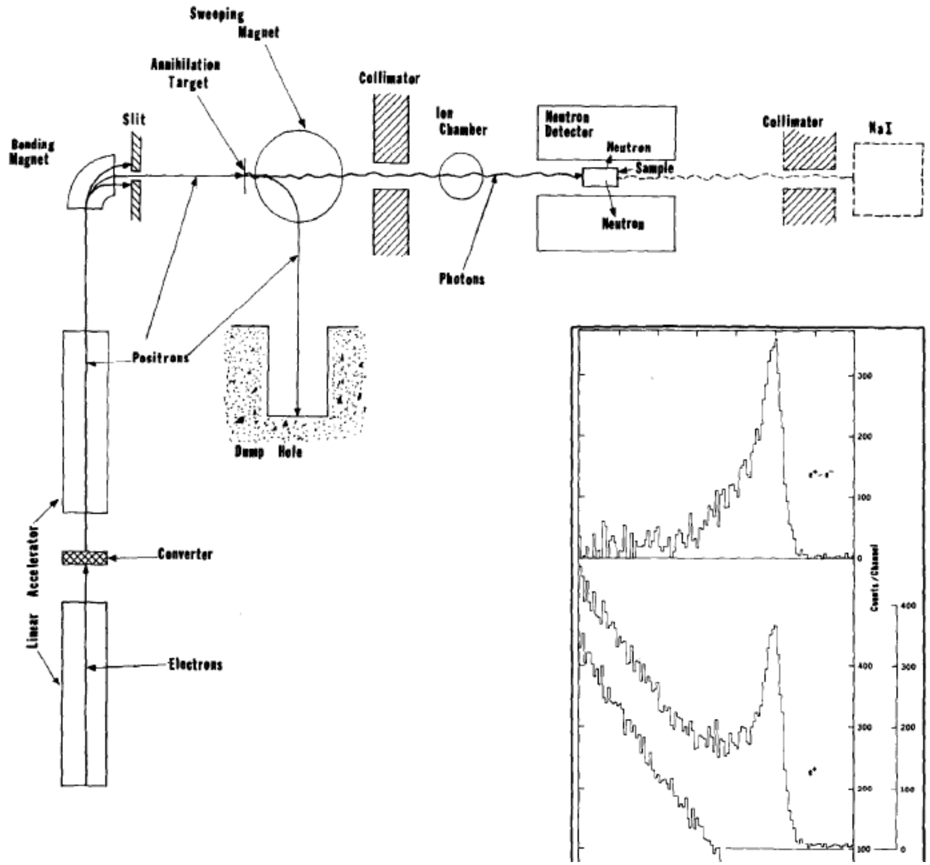
Schematics of annihilation photon source

- From Dietrich, Berman, Atlas of Photonuclear Cross Sections Obtained with Monoenergetic Photons, Atomic Data and Nuclear Data Tables, 1988



Operational Photon Sources from Annihilation

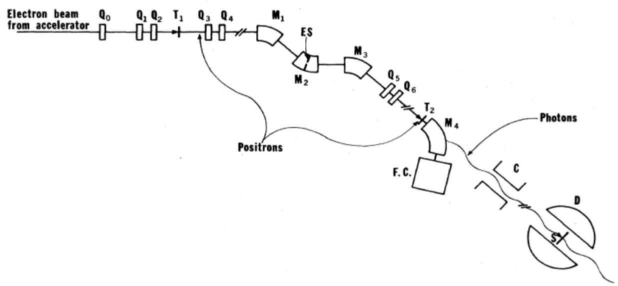


FIG. 2. Schematic diagram of the annihilation-photon beam facility at Saclay: M_i—bending magnets; Q_i—quadrupole magnets; ES—energy-analyzing slit; T_1—positron converter target; T_2—annihilation target; FC—Faraday cup; C—collimator; S—nuclear sample; D—neutron detector. (from Bayart, 1969)

Saclay

20 Nuclear Instruments and Methods in Physics Research 228 (1984) 20–32
North-Holland, Amsterdam

A 130 TO 530 MeV TAGGED PHOTON BEAM OBTAINED BY IN-FLIGHT POSITRON ANNIHILATION

P. ARGAN *, G. AUDIT, J. BECHADE, A. BLOCH, N. de BOTTON, G. COLIN, J.L. FAURE, D. FOUCAUD, M.L. GHEDIRA, C. GUERRA, J. MARTIN, E. MAZZUCATO, C. SCHUHL, G. TAMAS and E. VINCENT

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Rev. Mod. Phys., Vol. 47, No. 3, July 1975

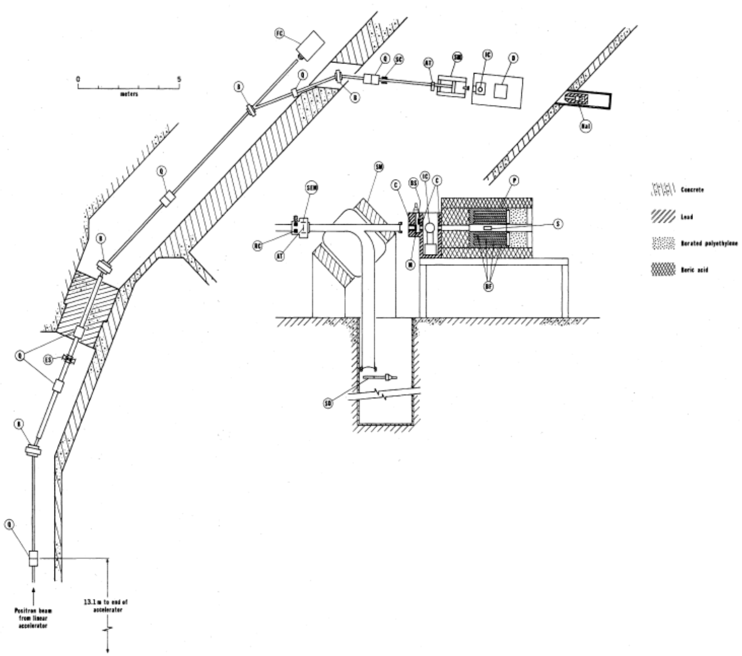
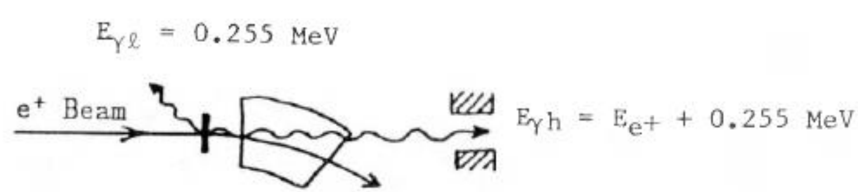


FIG. 3. Experimental layout for one of the annihilation-photon beam facilities at Livermore: B—bending magnets; Q—quadrupole magnets; ES—energy-analyzing slit; FC—Faraday cup; SC—steering coils; AT—annihilation target; SM—sweeping magnet; IC—photon ion chamber; D—detector; NaI—photon spectrometer. Inset: Detail of the 4π photoneutron experiment: RC—removable collimator; SEM—secondary-emission monitor; SD—swept-beam detector; C—collimators; M—beam-tuning monitor: BS—beam shutter; S—nuclear sample; P—paraffin moderator; BF—$^{10}BF_3$ neutron detectors (from Fultz *et al.*, 1973a).

Livermore

Discussed for CEBAF:
Tamas and Berman, Positrons at CEBAF!, Positron Working Group Report, Proc. CEBAF Summer Workshop (1995), p.462.



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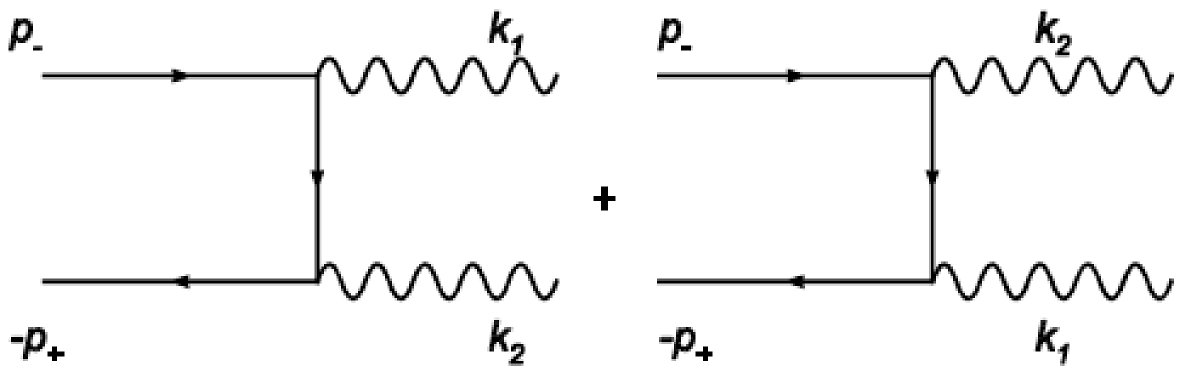
Annihilation: Basic Formalism

Berestetsky, Lifshitz, Pitaevsky, "Quantum Electrodynamics", (2nd ed. ISBN 0750633719)

The process $e^+ + e^- \to 2\gamma$ is described by two Feynman diagrams:



Mandelstam invariants: $s = (p_- + p_+)^2 = (k_1 + k_2)^2,\ t = (p_- - k_1)^2,\ u = (p_- - k_2)^2$. Energy-momentum conservation requires that $s + t + u = 2m^2$.

Differential cross section in terms of Mandelstam invariants valid in an arbitrary reference frame is:

$$\frac{d\sigma}{d(-t)} = 8\pi r_e^2 \frac{m^2}{s(s-4m^2)} \left\{ \frac{1}{4}\left(\frac{u-m^2}{t-m^2} + \frac{t-m^2}{u-m^2}\right) - \left(\frac{m^2}{t-m^2} + \frac{m^2}{u-m^2}\right)^2 - \left(\frac{m^2}{t-m^2} + \frac{m^2}{u-m^2}\right) \right\}$$

The variable t is within the range corresponding to 0 and 180deg angles of photon emission: $-\frac{s}{2} - \frac{1}{2}\sqrt{s(s-4m^2)} \le t - m^2 \le -\frac{s}{2} + \frac{1}{2}\sqrt{s(s-4m^2)}$.

Total Cross Section

$$Total\ cross\ section\ for\ annihilation,\ \tau = (p_+ + p_-)^2 / m^2 :$$

$$\sigma_{annih} = \frac{2\pi r_e^2}{\tau^2(\tau-4)}\left[(\tau^2+4\tau-8)\ln\frac{\sqrt{\tau}+\sqrt{\tau-4}}{\sqrt{\tau}-\sqrt{\tau-4}} - (\tau+4)\sqrt{\tau(\tau-4)}\right],\ r_e = 2.818\times 10^{-13}\,cm$$

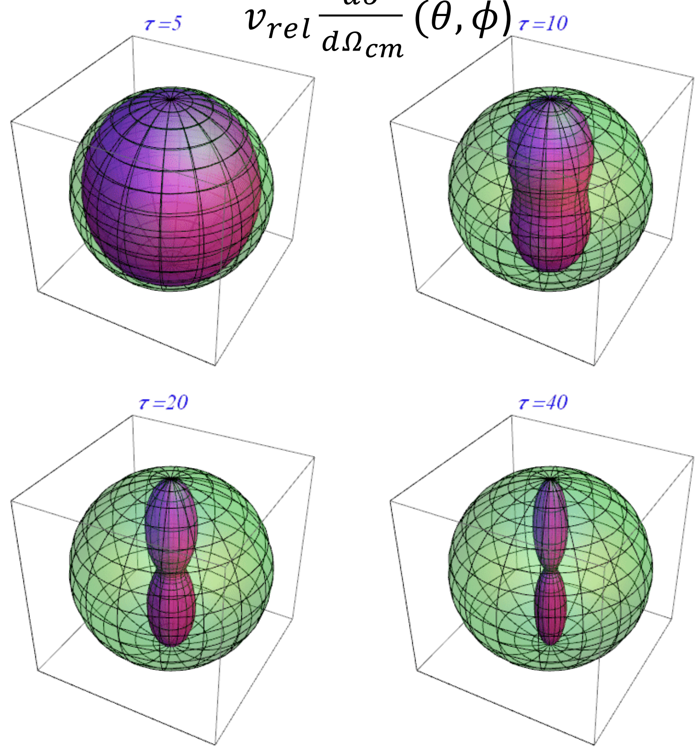
$$For\ small\ relative\ velocity\ v_{rel},\ \tau-4 << 1:\quad \sigma_{annih} = \frac{\pi r_e^2}{v_{rel}}\quad (nonrelativistic\quad case)$$

$$For\ \tau-4 >> 1:\quad \sigma_{annih} = \frac{\pi r_e^2}{2\tau}(\ln 4\tau - 1)\quad (ultra-relativistic\ case)$$

Angular distribution in c.m.s.

- Evaluate angular distribution of produced photons in cms. The results for cross section multiplied by the relative velocity (see below) are shown in the below plot as a function of the invariant τ. As the relative velocity is increasing, the cross section becomes more suppressed at large angles with respect to the collision axis z. The limit of zero relative velocity is spherically symmetric, shown in the below plot by a green sphere, while magenta plots show angular distributions of produced photons at different values of invariant τ
- Differential cross section at zero angle remains constant with energy
- For Ep=12 GeV positrons on an electrc at rest: $\tau=5\text{x}10^4$, high-energy photons are emitted within angular range $\sim m_e/E_p$

$$v_{rel}\frac{d\sigma}{d\Omega_{cm}}(\theta,\phi)$$



Annihilation in Lab Frame

Consider electron and positron beams with momenta along z-axis. Four momenta $p=(p_0;p_x,p_y,p_z)$, are defined as: $p_+ = (E_p;0{,}0,p_p), p_- = (E_e;0{,}0,p_e)$, $k_1 = E_\gamma(1;\sin\theta\cos\varphi,\sin\theta\sin\varphi,\cos\theta)$, where E_γ and θ are the energy and an angle of a produced photon. Same (opposite) signs of p_p and p_e correspond to collinear (head-on) collisions.

Mandelstam variables in terms of lab observables are:

$$s = (p_+ + p_-)^2 = 2m^2 + 2E_pE_e - 2p_pp_e,$$

$$t = (p_- - k_1)^2 = m^2 - 2p_-k_1 = m^2 - 2E_eE_\gamma + 2p_eE_\gamma\cos\theta,$$

$$u = (p_+ - k_1)^2 = m^2 - 2p_+k_1 = m^2 - 2E_pE_\gamma + 2p_pE_\gamma\cos\theta$$

Using energy-momentum conservation, $s + t + u = 2m^2$, photon energy is related to its emission angle as

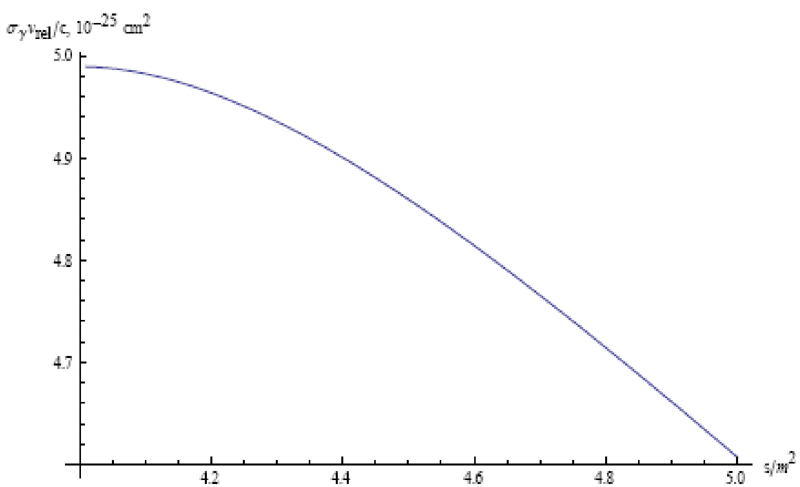
$$E_\gamma = \frac{m^2 + E_pE_e - p_pp_e}{E_p + E_e - (p_p + p_e)\cos\theta} .$$

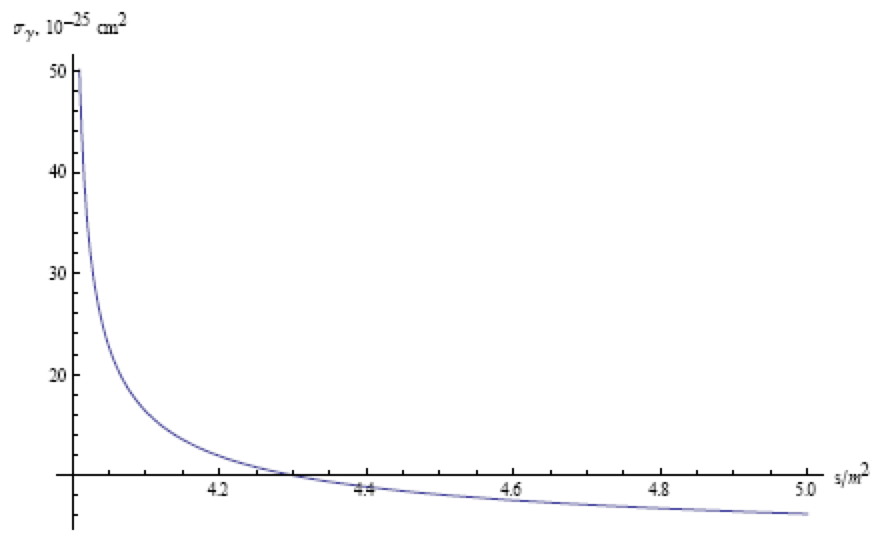
Depending on the relative signs of the colliding particle momenta, the maximum (or minimum) of the produced photon energy corresponds to θ=0 or 180°. In a special case of opposite momenta that are equal in magnitude, the produced photons are mono-energetic with an energy equal to the incoming beam energy, $E_\gamma=E_p=E_e$.

Annihilation in Lab: Numerical Examples

First, we evaluate the total cross section of photon production from electron-positron annihilation as a function of invariant variable $\tau = s/m^2$. The cross section is singular in the limit $\tau \to 4$ that corresponds to zero relative velocity of the colliding beams. Since luminosity of the colliding beams is proportional to the relative velocity, it is instructive to see the product $\sigma_\gamma v_{rel}$, where the relative velocity is defined as

$$v_{rel} = \frac{\sqrt{(p_+p_-)^2 - m^4}}{p_+p_-} = \frac{\sqrt{\tau(\tau-4)}}{\tau-2}.$$





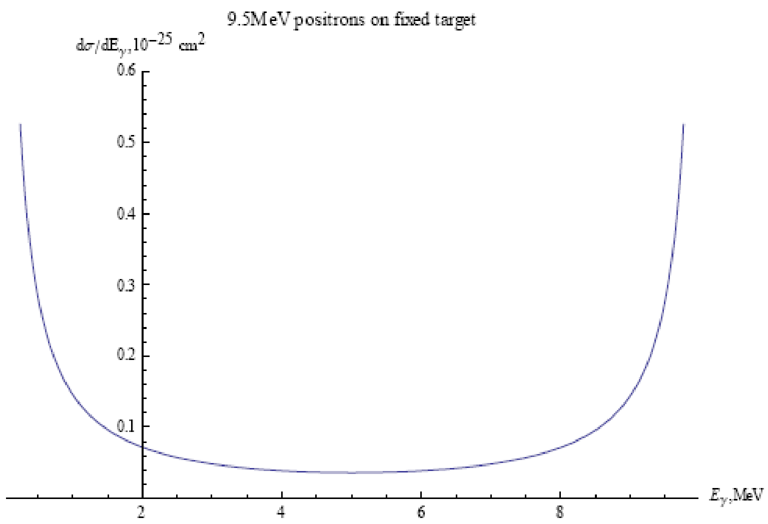
Cross section is infinite for $v_{rel}=0$, but the product $v_{rel}\sigma_\gamma$ (normalized rate) is finite

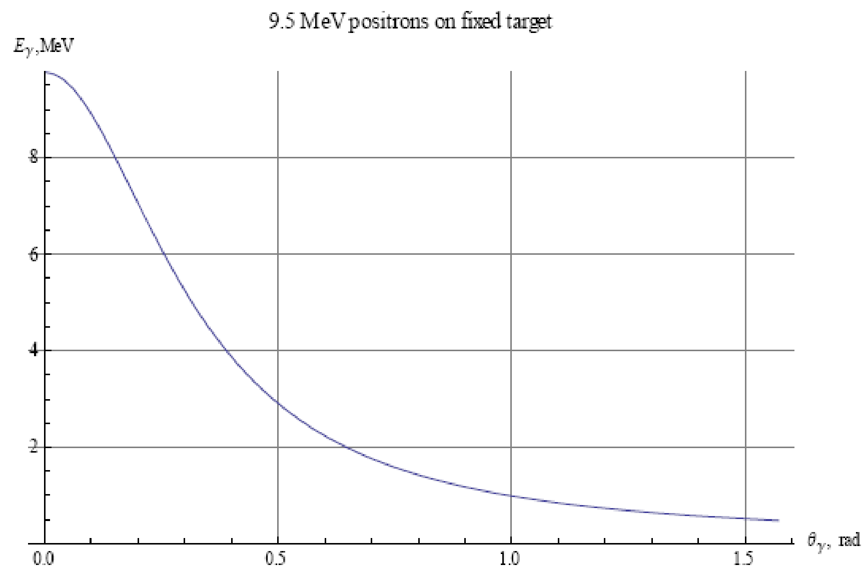
Positron Beam on Fixed-Target Electrons

E_e=0.511MeV, E_p=9.5MeV

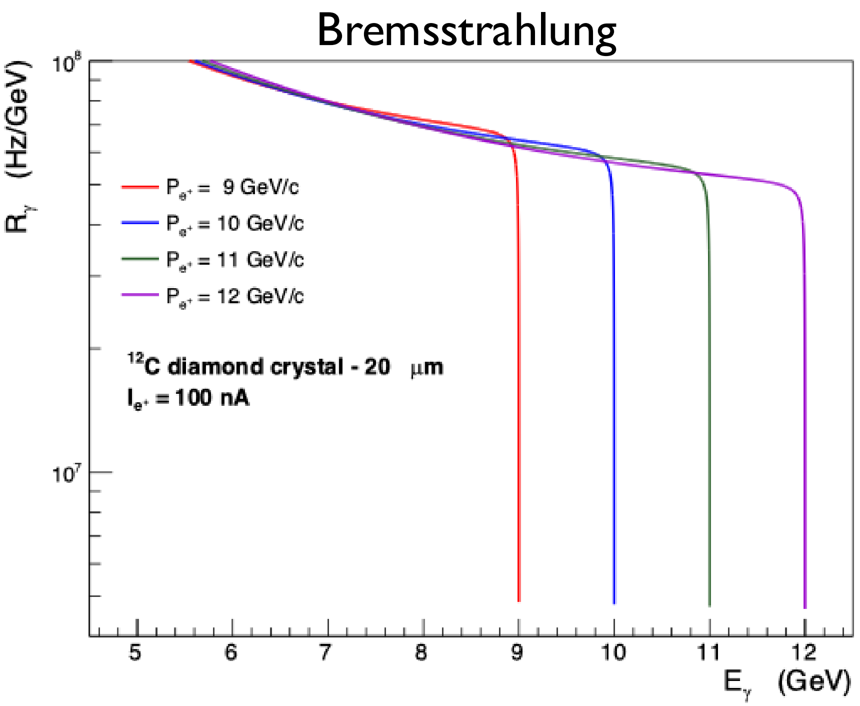
$E_{\gamma;min}$=0.25 MeV; $E_{\gamma;max}$=9.77MeV

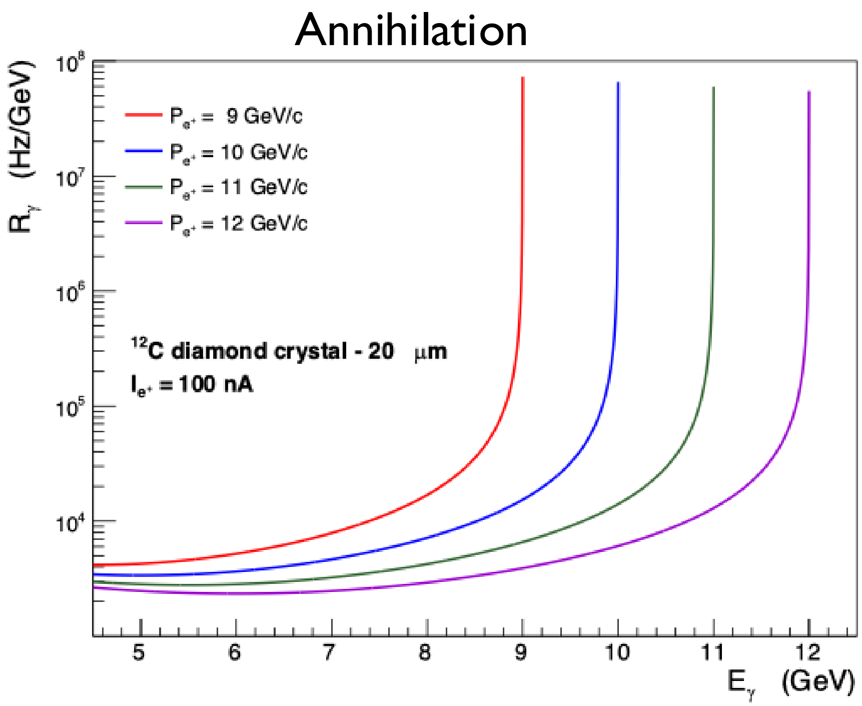
Total cross section σ_γ=0.8 (in units 10^{-25} cm^2)





Annihilation vs Bremsstrahlung at 12 GeV CEBAF





Calculated by Eric Voutier (2/2025)

Rate estimates

<u>Fixed-target converter.</u> The rate of high-energy photon production is $Rate = L \cdot \sigma_{an}$, where luminosity L is given by:

$$L = r_p \, \rho_e \, h,$$

where r_p is a number of incident positrons per unit time, ρ_e is the volume density of target electrons, and h is target thickness.

Diamond converter: $\rho_e = 1.06 \times 10^{24}$ e^-/cm^3 , h=20um, $\rho_e h = 2.12 \times 10^{21}$ e/cm^2

Positron current I_{pos}=100nA, $r_p = I_{pos}/1.6 \times 10^{-19} = 6.25 \times 10^{11} e^+/s$

Luminosity $L = 1.33 \times 10^{33}$ cm^{-2} s^{-1}.

Cross section of electron-positron annihilation at 12 GeV $\sigma_{an} = 1.03 \times 10^{-28}$ $cm^2 = 10^{-4}$ barn

High-energy photon generation rate= $L \cdot \sigma_{an} = 1.4 \times 10^5$ photons/s;

Collimation to select the energy range of 0.05 MeV below maximum leaves 2500 photons/s

Summary

- Estimated 12GeV photon rates of the order 10^5 Hz at 100nA and 20um diamond converter
- Collimation to suppress bremsstrahlung leads to reduction of rate
- Polarization:
  - ✓ No linear polarization
  - ✓ Circular polarization of annihilation photons matches longitudinal polarization of incident positrons
- Further simulations will define photon beam properties under collimation
- Use of low-Z materials (e.g. LiH) may reduce brem background

Physics Opportunities

- Reactions that require high-energy photons

  Exclusive
  - Meson Spectroscopy
  - Baryon Spectroscopy

  Deep-Exclusive
  - Time-like DVCS
  - Wide-angle Compton Scattering and meson production
  - J/ψ production
- Inclusive
  - High-pT photoproduction of mesons in QCD
- Beyond the Standard Model (probing narrow states)

Conclusions

- Availability of the positron beam at CEBAF makes possible a quasi-monochromatic source of photons that match the positron beam energy with a width of about several MeV
- More detailed simulations are in order
- Key physics experiments that require monochromatic photons at highest available energies should be identified