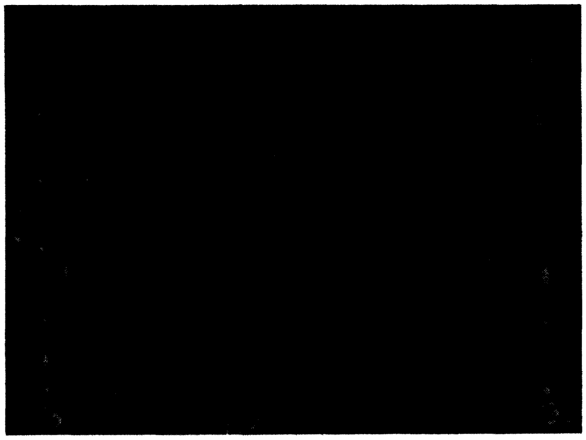

FIG. 1. A typical voltage-brightness relation. The abscissa is the beam voltage in kv, and the ordinate is the photocurrent.

as the voltage at which electrons pass completely through the phosphor and begin to give up energy in the glass. In the Thompson-Whiddington relation

$$V_0^2-V^2=bx,$$

where V_0=initial energy in electron volts, and V=energy after traveling a distance x, the value of b calculated on this basis is 5.5 kv^2/cm.

Since electrons are scattered in passing through the medium, the beam intensity must decrease with depth, and the law of beam energy as a function of depth of penetration in the medium becomes

$$E=i_0[(V_0^2-bx)/V_0^2]^{\frac{1}{2}+a/b},$$

where a is the scattering constant defined by

$$-dN/dx=N^a/V^2,$$

where N is the number of electrons in the beam. The value of a/b determined for ZnS is 2.4. These results indicate a large initial rate of loss of energy by an electron beam passing through a phosphor. Nearly 90 percent of the beam energy is lost in a distance of half the range of the electrons.

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On the Lifetime of the Negative Pi-Meson*

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THREE determinations of the lifetime of the positive pi-meson have recently been made.[1-3] All of these values are significantly higher than the lifetime obtained for negative pi-mesons by Richardson,[4] who first measured this quantity with cyclotron-produced particles. A summary of the reported results is given in Table I.

TABLE I. Summary of π-meson lifetimes.

Author	Meson	Lifetime
Martinelli and Panofsky	π^+	$1.97^{+0.21}_{-0.25}\times10^{-8}$ sec
Kraushaar, Thomas, and Henri	π^+	$1.65\pm0.33\times10^{-8}$ sec
Chamberlain, Mozley, Steinberger, and Wiegand	π^+	$2.65\pm0.12\times10^{-8}$ sec
Richardson	π^-	$1.11^{+0.45}_{-0.35}\times10^{-8}$ sec

The negative pi-meson lifetime has been redetermined, using the external meson beam of the Nevis cyclotron. The competition of nuclear capture prevents the application of the elegant electronic techniques employed by Chamberlain *et al.* and Kraushaar *et al.* with positive mesons, stopping in scintillation crystals. Instead, the decays are observed in the course of the flight of pi-mesons through a 16 in. magnet cloud chamber. To verify that the process $\pi^-\rightarrow\mu^-+\nu^0$ is actually the mechanism responsible for the negative pi-meson decays observed in the cloud chamber, the previously reported[5] momentum and angle analyses were extended to seventy-five events occurring in favorable regions of the chamber. These gave, for the mass of the neutral decay product, $m_{\nu^0}<30m_e$. If the neutrino rest mass is taken as zero, the mu minus mass obtained from these data is

$$M_{\mu^-}=209.8\pm2.2m_e,$$

where the pi-meson mass is taken as $276.1\pm1.3m_e$.[6]

The mean free path for $\pi\rightarrow\mu$ decay was obtained from the total length of pi-meson track classified as acceptable flux and the corrected number of decay events observed. Particles were allowed as flux if they entered the cloud chamber within a cone of 70° with respect to a fixed reference direction. The momentum interval accepted was 130 to 170 Mev/c. In order to minimize the subjectivity of the flux count, no restriction was placed on the quality of illumination of the track. Instead, all beam tracks were followed until they passed through the chamber or out of the illuminated region.

To reduce the possibility of mistaking a distorted track for a decay, the region of the cloud chamber in which events were counted was rigidly prescribed to be one inch from all vertical surfaces. The flux was then corrected for the reduced path during which decays would be recorded. A map measurer was employed on a full-scale reprojection of the cloud chamber photographs to obtain the actual lengths of the flux tracks.

Decays through angles whose projection is less than 5° in either of the two stereoscopic cameras were not counted. This procedure served to avoid the difficulty of determining the efficiency of stereoscopic scanning for decay events. The correction for the number of decays through angles <5° was made from the geometry of the camera system and the calculated angular distribution of the decays. This yielded 0.33 ± 0.03 as the fraction of $\pi\rightarrow\mu$ decays excluded by the 5° criterion. Finally, a correction was made for the fraction of acceptable flux particles which are not pi-mesons.

The contaminants consist of mu-mesons and electrons. The electron contribution was estimated from the number of multiplication events observed in a 0.6 radiation length lead plate. This was independently checked by the electronic time-of-flight counter telescope.[7] The resultant electron fraction, 10 ± 3 percent, is roughly consistent with that to be expected from the materialization of π^0 decay photons in the $4\times4\times\frac{1}{2}$ in. Be target. The mu-component was determined by an electronic mu-meson detector[8] (counting delayed coincidences between the mu-meson and its decay electron), which yielded a range spectrum of mu-mesons with a geometry designed to simulate that of the cloud chamber. The number of mu's in the proper momentum interval was found to be 9 ± 3 percent.

The mean free path for decay in the laboratory system, based on 188 events, is 9.93 ± 1.10 meters. The error represents the uncertainties in beam composition, efficiency, and statistics, assumed to enter independently. This corresponds to a laboratory mean life of $4.55\pm0.52\times10^{-8}$ second. If the mean free path is reduced to the rest system lifetime by the time dilation factor of special relativity, $\langle m/cp\rangle_{\text{Av}}$, averaged over the momentum spectrum of flux particles, the result is

$$\tau_{\pi^-}=2.92\pm0.32\times10^{-8}\text{ second}$$

in satisfactory agreement with the more recent[3] determinations of the positive mean life.

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* Assisted by the joint program of the ONR and AEC.

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[8] The authors are indebted to Professors J. Steinberger and A. Sachs and to Dr. P. Isaacs for performing these measurements.

On Soft Photon Emission in Radiation Processes*

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In the present note we have investigated the intensity of the soft photon spectrum emitted in ordinary hard photon radiation processes: e.g., x-ray emission and absorption, pair annihilation, etc.[1] The motivation for the work was the reported possibility of a discrepancy between the wavelength of the electron-positron annihilation gamma-ray, λ_{ann}, and h/mc: $\lambda_{\text{ann}}-h/mc \approx 10^{-3}\ h/mc$, a discrepancy[2] which could conceivably be interpreted on the basis of an extended energy conservation relation: $2mc^2=$ energy of the two hard annihilation photons + energy of all the accompanying soft photons.

We first considered the equivalence of the two possible descriptions of the annihilation process: the configuration space treatment of the electron and positron in the sense of Fock,[3] and the customary one-particle treatment.[4] The two descriptions are essentially identical except for the impossibility of the inclusion of the electron-positron coulomb interaction in the latter. For the soft photon emission problem, the coulomb interaction has the role of determining the velocity spectrum of the annihilating particles; however, an appropriate velocity spectrum can always be assigned to the initial and final electron states in the one particle description. The two modes of treatment then become exactly equivalent and in particular, the intensity of the soft photon energy spectrum turns out to be determined by the average relative velocity v of the electron and positron. Quantitatively, the average energy $\bar{E}_{\text{soft}}$ carried off by this spectrum (per individual pair recombination) is approximately given by

$$(2/3\pi)(1/137)(v/c)^2\, 2\, mc^2 \approx 10^{-7}\, mc^2$$

for v/c values appropriate to the annihilation of slowed down positrons in matter. It is seen, therefore, that the soft photon effect is much too small to account for a discrepancy between hc/λ and mc^2 of the order of magnitude reported, even if the corresponding shift of the intensity maximum in the wavelength distribution of the annihilation line were as large as $\bar{E}_{\text{soft}}$ (see below). It is thus very satisfactory that the most recent precise absolute measurements of the energy of the 0.51-Mev ThC″ γ-ray line by Lindström,[5] taken together with the recent precise measurements by Hedgran[6] of the ratio of the energy of this line to that of the annihilation line, yield exact equality of λ_{ann} and h/mc within an experimental error of 3×10^{-4}.

In x-ray emission and absorption the average energy of the accompanying soft photon spectrum (per individual hard photon process) is again given by:

$$\bar{E}_{\text{soft}} \approx (2/3\pi)(1/137)(v/c)^2 E_{\max}, \tag{1}$$

where $E_{\max}$ is the maximum available energy for the soft photons in a single hard photon process and v is the electron velocity appropriately averaged over the initial and final orbits. ($E_{\max}\approx h\nu_{\text{hard}}$, $v/c\approx Z/137$ for mission; $E_{\max}\approx$ photoelectron kinetic energy, $v\approx$ photoelectron velocity, for absorption.) It might therefore be thought that deviations of 1/10 to 1/100 percent could be observed from the Bohr frequency rule, the Ritz combination principle, and the Einstein photoelectric equation in such hard photon emission and absorption. The emitted soft photon spectrum however, is described by the almost flat intensity distribution:

$$\left(\frac{\bar{E}_{\text{soft}}}{E_{\max}}\right)\left(\frac{E_{\text{soft}}}{E_{\max}}\right)^{\bar{E}_{\text{soft}}/E_{\max}} dE_{\text{soft}} \tag{2}$$

with the consequence that in the case of emission, for example, the usual hard photon line shape (derived with neglect of the soft photon effect)[7] is multiplied by a correction factor given approximately by

$$1-\pi(\bar{E}_{\text{soft}}/E_{\max})[(E_{\text{hard}}-E_0)/\Gamma]. \tag{3}$$

Here, E_0 is the energy difference between the initial and final states involved in the hard photon emission, and Γ the hard photon natural line breadth. The energy of an emitted hard photon (or in a similar way, the kinetic energy of an ejected photoelectron) suffers, therefore, a most probable net displacement in the direction of lower energy of only

$$\frac{\pi}{8}\frac{\Gamma}{E_{\max}}\bar{E}_{\text{soft}} \approx \frac{\pi}{8}(\bar{E}_{\text{soft}}/E_0)^2 E_0 \approx \frac{1}{50}\left(\frac{1}{137}\right)^2\left(\frac{v}{c}\right)^4 E_0, \tag{4}$$

Γ in the atomic x-ray region being $\approx(1/10)(1/137)(Z/137)^2 E_0 \approx \bar{E}_{\text{soft}}$. The smallness of this net displacement as compared with $\bar{E}_{\text{soft}}$ is due to the extreme flatness of the soft photon energy spectrum.

Equations (3) and (4) show that any measurement of the emitted hard photon or ejected photoelectron energy, by extrapolation of the corresponding line shape on the high energy side, will be independent of the actual presence of the soft photon emission to about one part per million. Essential agreement with the usual energy conservation relations (neglecting soft photons) is thus always to be expected within this precision.

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† On leave from Washington University, St. Louis, Mo.

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[7] Page 113 of reference 4.

The Isomeric Level of Cd^{111m}

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In a previous investigation of the radioactivity of the 111-isobars,[1] spin and parity were assigned to the several levels, with the result that eight of the nine assignments agreed with the predictions of the shell model.[2] The 48-min isomeric level of Cd^{111} at 396 kev was the exception, being given spin 13/2 and even parity rather than the predicted $h_{11/2}$. This assignment was made on the basis of the usual γ-ray half-life formula,[3] row 3, Table I, and the ratio of 149/247 internal conversion electrons, row 4.

TABLE I. Data for assigning spin and parity to the 396-kev level of Cd^{111}.

	Theory			Expt.
396-kev level	13/2 even	9/2 odd	11/2 odd	
149-kev γ-ray	elec. 4	mag. 2	elec. 3	
149-kev γ, $T_{\frac{1}{2}}$ (sec)	117	8×10^{-4}	8×10^{-4}	2916
149/247 conv. e^-	15.7	10.2	11.4	14.5 ± 1
149/247 γ-rays	0.085	0.43	0.35	0.33 ± 0.06
In^{111} decay ratio	1.9×10^{-8}	2.9×10^{-4}	2.9×10^{-4}	1×10^{-4}