Presented at the 3rd Rochester
Conference on Coherence and
Quantum Optics, June 21-23, 1972

LBL-967
Preprint

LOCALIZATION OF PHOTONS

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June 1972

AEC Contract No. W-7405-eng-48

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LOCALIZATION OF PHOTONS

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In a popular quantum mechanics textbook one reads..."If we have some indications that classical wave theory is macroscopically correct, it is nevertheless clear that on the microscopic level only the corpuscular theory of light is able to account for typical absorption and scattering phenomena such as the photoelectric effect and the Compton effect, respectively. One must still ascertain how the photon hypothesis may be reconciled with the essentially wave-like phenomena of interference and diffraction..."[1], and in another "...We have, on the one hand, the phenomena of interference and diffraction, which can be explained only on the basis of a wave theory; on the other, phenomena such as photoelectric emission and scattering by free electrons, which show that light is composed of small particles."[2]

Recent considerations, however, have called into question whether or not actual experiments have unambiguously established a particle nature for photons. Thus, the observations usually thought to do so — those of the photoelectric effect,[3] the Compton effect,[4] spontaneous emission,[5] and the Lamb shift [5] — can all be predicted semiclassically with surprising accuracy. A particle nature for photons is apparently not required for the description of these experiments; they may be described with photons acting solely as waves. These results are indeed surprising, since photons are the simplest and presumably the best understood elementary particles. Naturally, it is highly desirable to experimentally demonstrate unambiguously their particle-like behavior.

What is the simplest and most conspicuous difference between particles and waves? It is evidently the fact that only particles are localizable to arbitrarily small volumes. A quantum mechanical description of electromagnetic radiation predicts photon localization through the "collapse" of a photon's wave function, which occurs as the result of position measurement. This collapse is foreign, however, to classical waves, and neither semiclassical theories nor any other linear classical-wave picture predict a localization of photons to dimensions smaller than the size of their classical interference patterns.

It must be recognized that any theory in which the radiation field is to be described specifically by the classical Maxwell's equations, will yield predictions which violate the observed polarization correlation of atomic-cascade photons.[6] It may be possible, perhaps, that there are classical-wave theories not describable by Maxwell's equations, to which the arguements of Ref. 6 do not apply. The following discussion applies to any linear classical-wave theory of electromagnetic radiation.

It is the purpose of this paper to first review various experiments which suggest a localization of photons, and show that they are not in conflict with a simple wave description. Included are the Compton effect, and the photon angular correlations in π^0 and/or positronium $\rightarrow 2\,\gamma$ decays. Next we discuss Lamb and Scully's semiclassical treatment of the photoelectric effect, and describe a situation in which its predictions are in conflict with those of a usual quantum mechanical treatment of the electromagnetic field. The difference is found in the localizability of electromagnetic emissions. Finally the requirements for a conclusive experiment are derived, and existing experimental tests are reviewed but found inconclusive. A distinguishing experiment to actually demonstrate this particle-like localization is currently being performed at this laboratory.

Correlation Experiments

When one is asked to think of processes in which photons act as localized particles, those of positronium annihilation, $\pi^0 \rightarrow 2\gamma$, and Compton scattering immediately come to mind. In these, the detection of a γ-ray (or an electron in the case of Compton scattering) localizes the remaining γ-ray. Since the γ's may be emitted with a spherically symmetric distribution, it seems that these experiments locate them to a volume much smaller than the size their classical interference patterns.

The following simple consideration shows that this is not the case. Consider a Gedankenexperiment in which a positronium atom is confined in the x direction to a dimension Δx, perhaps by a system of slits as is shown in Figure 1. The momentum of the atom in the x direction is thus rendered uncertain by an amount $\Delta p_x \gtrsim h/\Delta x$.

Suppose now that the atom decays into two γ-rays, and one of these is detected by a detector subtending an infinitesimal solid angle, and located on the -z axis. The sum of the x components of the γ momenta must be uncertain by the same amount Δp_x, thus the γ's will not be exactly collinear. If the momentum of the first γ is denoted by p_γ the momentum of the second γ will have a distribution of angles with respect to the z axis. The beam width will thus be,

$$\Delta\Theta_{QM} \simeq \Delta p_x/p_\gamma \geq \hbar/(p_\gamma \Delta x)$$

Next let us consider the above process viewing the γ's as waves. The positronium atom with transverse dimension $d = \Delta x$ coherently radiates the second γ-ray. The classical-wave picture suggests that the radiation may be sent out in a beam with width $\Delta\Theta_{SCT} \geq \lambda/d$ where $\lambda = h/p_\gamma$ is the γ-ray's wavelength. This "diffraction limit" is characteristic of any linear wave theory. The semiclassical beam width is thus given by $\Delta\Theta_{SCT} \gtrsim h/(p_\gamma \Delta x)$. Comparing this with the previous result, we find equal minimum beam widths in both descriptions. Thus a particle picture and a classical wave picture both predict that the 2γ's will be found collinear only to the same angular precision. The predictions for this experiment are then consistent with a semiclassical theory in which the atom sends out thin diffraction limited beams of classical waves - not particles!

A similar analysis applied to Compton scattering achieves the same result. Such an analysis has in fact been carried out in detail by Schrödinger and Gordon[4] who present a semiclassical theory which predicts identically the results of the usual quantum mechanical treatment of the radiation field for the γ-ray's wavelength shift and electron recoil direction, and to a close approximation the γ-ray intensity dependence. It is conceivable that the residual differences may be accounted for by higher order effects not included in these calculations, and/or the breakdown of Maxwell's theory implied by Ref. 6.

Photoelectric Effect, à la Lamb and Scully

Lamb and Scully have shown for the simple case of radiation propagating from a source to a detector that both the wave and particle pictures can predict the same results for the photoelectric effect.[3] In the particle view a source atom may emit a particle which then strikes an atom in the photocathode and ionizes it. (See Figure 2.) In the wave view a source atom may emit a spherically expanding wave which will have a certain probability for photoionizing any of the atoms in the screen. Lamb and Scully show that in a semiclassical description the probability of a photoionization is proportional to the classical field intensity, and becomes applicable without the time lag necessary for an accumulation of the classical field energy. Thus experiments of this type may only establish the localization of photoionizations, not photons themselves.

When one views the source with two detectors preceded by different wavelength filters resonant to opposite wavelengths of a two-photon cascade, coincidences are observed. Again both models apply. From the particle view, two particles are emitted in sequence. In the wave view the observation of coincidences implies that for a single photon the wave must manifest itself as a short pulse (perhaps similar to the usual wave packet). Thus in a cascade two pulses are successively emitted, each with the appropriate wavelength. Indeed, the semiclassical theory of Jaynes, Crisp and Stroud exhibits exactly this model.[5]

Suppose now that one places two detectors within the interference pattern of a single photon pulse and employs two wavelength filters both resonant to the same transition, as is shown in Figure 3. Here the similarity between the two viewpoints ends. A particle model predicts that for each pulse only one photoelectron will be liberated at one of the detector photocathodes. Indeed this is the prediction by a quantum mechanical description of the radiation field. Von Neumann's reduction postulate requires the photon wave function to "collapse" when one of the detectors responds. The probability of a second response at the other detector immediately vanishes. In this way, energy conservation is assured.

The collapse does not occur in a simple wave model, however, since the wave-packet reduction is unique to quantum mechanical systems. Indeed, no classical process can be responsible for the collapse when the arrivals of a given pulse at the two detectors have a space-like separation.[7] Thus a classical pulse will be present simultaneously at both detectors, and there is a certain probability that photoelectrons will be simultaneously liberated at the photocathodes of both detectors! This will be true even though only one photoelectron is liberated per pulse on the average. Given an ensemble of idential pulses, for some of these, more than one electron will be liberated, and for others, none will be liberated.

Thus there is a difference for this Gedankenexperiment between the predictions of the classical-wave and quantum mechanical descriptions of the electromagnetic field. The former predicts an "excess" coincidence rate for the two detectors. We shall consider the conditions necessary for an actual experimental test of this difference, and find that no distinguishing experiments have been performed so far. Before we do this, however, a digression is warranted concerning energy conservation in this semiclassical scheme.

Energy Conservation in Semiclassical Theories

A frequently voiced objection to Lamb and Scully's description of the photoelectric effect is that superficially it appears to violate energy conservation. Before condemning the theory on this ground, however, one should carefully re-examine what energy conservation actually means. In descriptions of the electromagnetic field two physically different measures of the field energy arise for a single photon. First there is the total classical energy as calculated from Maxwell's equations, thus

$$E_C = \int dV\, (|\underset{\sim}{E}|^2 + |\underset{\sim}{H}|^2)/8\pi \tag{1}$$

Second there is the energy-frequency relation given by

$$E_Q = h\nu \tag{2}$$

To be sure, in a quantum field theory these are equal, but in a semiclassical theory this restriction does not hold. Thus if ever $E_C \neq E_Q$ applies, the conservation of at least one of these is violated. Indeed the nonconservation of E_C occurs in a semiclassical description of the photoelectric effect. It is most dramatically demonstrated by the process in which two photoelectrons are liberated following a single atomic decay. E_Q is, however, conserved for each individual process.

But to dismiss semiclassical theories for this reason alone is prejudicial. Physics is an experimental science, and one may argue plausibility only on experimental grounds. What then is the experimental evidence for the equality of E_C and E_Q and for their simultaneous conservation? Reasonably accurate comparisons of E_C and E_Q have only been made for average values of E_C and E_Q, (e.g. bolometric measurements) which we have seen, can easily be accounted for by an appropriate statistical balance between processes in which several photoelectrons are emitted, and others in which none are emitted. Accurate wavelength comparisons for atomic systems (the Ritz combination principle) again can only test conservation of E_Q for individual radiative transitions. A demonstration of point-wise conservation of E_C must come from an analysis of experiments of the type currently being discussed.

Indeed the notion of statistical energy conservation was considered earlier by Bohr, Kramers, and Slater,[8] in response to Einstein's discussion of thermodynamic equilibrium.[9] They theorized that energy is conserved only statistically in all radiative processes, but were forced to abandon this idea when Bothe and Geiger observed electron-γ momentum correlations in Compton scattering.[10] In the present light we see that this dismissal may have been premature. The straightforward prediction by a semiclassical theory permits a classical-wave picture for both Compton and photoelectric effects, and employs statistical conservation of the classical field energy only for the latter process.

Experimental Requirements

We now discuss the necessary experimental conditions for a realization of our Gedankenexperiment to distinguish the semiclassical from the quantum mechanical prediction. If E pulses per second are emitted per unit time by a source, and if p is the average probability per pulse that a photomultiplier will yield a count, then the count rate at that detector is $S = Ep$. In either theory we will have $p = Q \times L \times \Omega/4\pi$ where Ω is the solid angle subtended by the detector, Q is the photocathode quantum efficiency, and L represents other losses, either in the optics, electronmultiplier or electronics.

In this experiment it is necessary to assure that both detectors are within the interference pattern of a given pulse, and are equally illuminated by it. The easiest way to do this is to use a beam splitter as is shown in Figure 3b. That this will occur is evidenced by the fact that transmitted and reflected components of a single photon can be made to interfere. (e.g. in a Michelson interferometer.) All photons will then have approximately the same probability for generating a count at either detector. Thus the expected excess coincidence rate predicted by a classical-wave theory is given approximately by

$$C \approx p^2 E. \tag{3}$$

Assuming negligible detector dark rates, the accidental coincidence background rate from which C must be distinguished is

$$A \approx p^2 E^2 2\tau \tag{4}$$

where τ is the resolving time of the system. One can now calculate the time required to measure to a precision of N standard deviations the difference between the excess coincidence rate given by (3) and the zero excess rate predicted by quantum mechanics. Doing this we obtain

$$T \approx (1+4E\tau)N^2/(p^2 E) \tag{5}$$

which in the limit of high source rates takes the form

$$T \approx 4N^2 \tau/p^2. \tag{6}$$

Measured detector efficiences in cascade experiments employing fast optics, and the most modern photomultiplier tubes and electronics typically yield values[12] $p \approx 10^{-3}$. For equation (3) to apply, τ may not be shortened to less than the length of a given pulse, which is presumably the order of the atomic state lifetime (~ 5nsec. for typical allowed atomic transitions). Taking N = 5, we see from equation (6) with the above parameters that a total integration time of T=1 second suffices.

Experiment of Ádám, Jánossy and Varga

In 1954 Ádám, Jánossy, and Varga performed an experiment to search for an effect similar to the one discussed above.[13] Their experiment is frequently referenced in discussions of the wave-particle paradox.[14] As the only existing test of this aspect of photon localization, it is worthwhile to examine it carefully.

Figure 4 reproduces a diagram of their experiment. In it they selected the light of a single spectral line with a monochrometer, and focused it through a beam splitter onto two photomultipliers operating in coincidence.

They assumed their detector efficiency to be $p = 1/300$. With a resolving time $\tau = 2.3\mu sec$ (good by 1954 standards) one calculates from (6) $T = 20.7$ sec for $N = 5$. They claimed thus to be able to easily detect the expected excess coincidence rate, if present.

However, their efficiency $p = 1/300$ is the efficiency for detection of photons in a beam, not that for wave-like pulses emitted spherically by the source. Their use of this value ignores the serious loss in efficiency suffered because of the narrow acceptance solid-angle of their monochrometer. Conservatively estimating from their diagram this additional loss of efficiency to be 1/400, their actual detector efficiency for wave like pulses was undoubtedly less than 8.3×10^{-6}, in which case the required integration time for even $N = 1$ becomes $T \approx 1.3 \times 10^{5}$sec. This is an order of magnitude longer than the duration of their experiment. Thus the experiment of Ádám, Jánossy and Varga appears to be considerably less conclusive than has usually been assumed.

It is noteworthy that similar experiments -- those measuring the Brown-Twiss effect -- accept light within only very small solid angles from the source, and thus are inapplicable for the same reason. Moreover the excess coincidence rate predicted by a semiclassical theory should be easily distinguishable from that of the Brown-Twiss effect. The latter occurs only for small detector solid angles with the excess coincidence rate varying with the square of the excitation rate. The excess coincidence rate predicted by a semiclassical theory, on the other hand will occur only at large detector solid angles, and will vary linearly with excitation rate.

Conclusions

The most conspciuous difference between particles and waves is that only particles may be localized. In the foregoing discussion we have indicated that there is apparently no existing experimental result which requires photons be viewed as particles. Any linear classical-wave description of the photoelectric effect, though, does lead to an experimentally observable distinction between its predictions in which photons are not localized, and those by a quantum mechanical treatment in which they are. An experimental test is currently in progress at this laboratory.

These experimental results, in addition to their relevance to the foundations of quantum mechanics and to a consideration of semiclassical radiation theories, will be significant in another respect. They are related to experiments which seek to determine whether or not nature may be viewed objectively. It seems reasonable to assume that photons objectively exist, propogate, and in so doing carry information independently of external observers. However, extensions of Bell's theorem have shown that any objective model of nature must be in conflict with the quantum mechanical predictions for suitably devised polarization correlation experiments.[15] Since fully conclusive experiments are presently technologically difficult (due to low available polarizer and/or photo detector efficiencies), conclusions drawn from present experimental results have had to rely upon additional assumptions concerning the behavior of photons. One of these assumptions is that photons may be described as localized particles. The above experimental results may thus lend additional support for the experimental evidence found by Freedman and Clauser[16] against such models.

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Philosophers, Evanston, Illinois 1949), p. 207.

[11] Similar situations will be encountered in a consideration of point wise momentum conservation. For example, a curious phenomenon arises when $\lambda >> d$ applies, as it does in the case of optical emissions from thermal atoms. The classical interference pattern of the emitted radiation then fills all space. Evidently a single photon should here be described classically as a spherically expanding wave. Symmetry implies that a spontaneously radiating atom will then experience no radiation recoil. It is unfortunate that the only experimental attempt to directly observe the recoil following spontaneous emission was not conclusive. [R. Frisch, Z. Physik, 86, 42 (1935)]. With only statistical momentum and energy conservation, Einstein's thermodynamic argument against classical-wave models (Ref. 9) does not apply.

An observation of recoil, however, would not alone invalidate semiclassical radiation theories, since it is possible to classically generate the asymmetric radiations patterns necessary to achieve a recoil. The usual semiclassical radiation patterns do not, however, exhibit such asymmetries.

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Figure Captions

Fig. 1

Scheme for attempting to localize a γ-ray to a volume smaller than its classical interference pattern. A positronium atom is confined in the x direction by slit system to a dimension Δx, and the annihilation quanta are detected by detectors 1 and 2.

Fig. 2

Comparison of wave and particle views of the photoelectric effect. In the particle view a particle-like γ has a certain probability for striking any of the atoms in the photocathode. In the collision there is a certain probability for the ejection of a photoelectron. In the wave view, a wave impinges upon all of the atoms in the photocathode, and the resultant oscillating electric field has a certain probability for photoionizing any of them.

Fig. 3

Experiments to distinguish between semiclassical and quantum mechanical predictions of photoelectric effect. (a) Two detectors are placed within the interference pattern of a single photon and coincidences are sought. (b) Alternative scheme which assures equal illimination of both detectors. Scheme (a) localizes photons in the θ and ϕ coordinates, while (b) localizes them in the radial coordinate.

Fig. 4.

Optical system of Adám, Jánossy and Varga. Light from source F is focused through a monochrometer on photomultipliers M_1 and M_2 via beam splitter T. (Figure after Adám, Jánossy and Varga).

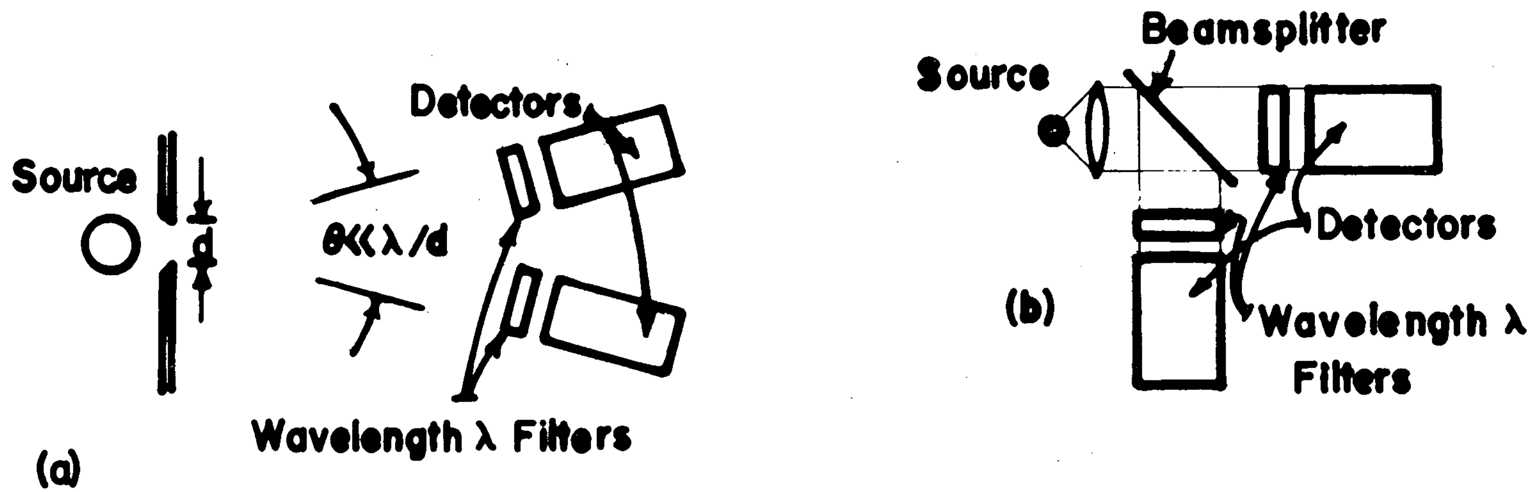

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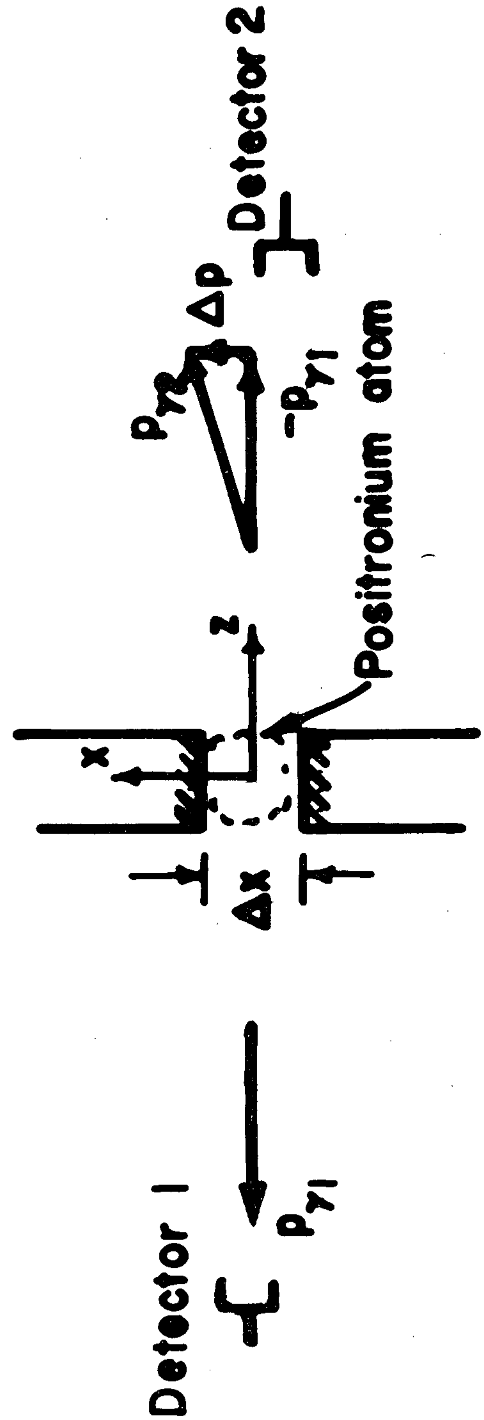
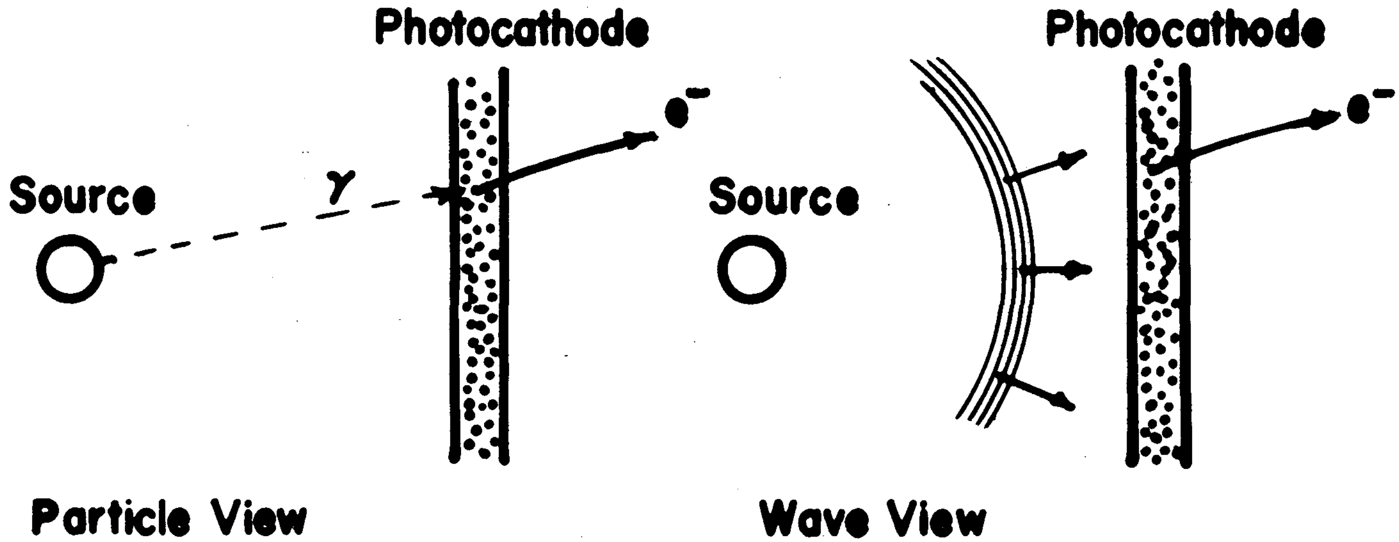
Fig. 1



XBL 726-1058

Fig. 2



XBL 726-1060

Fig. 3

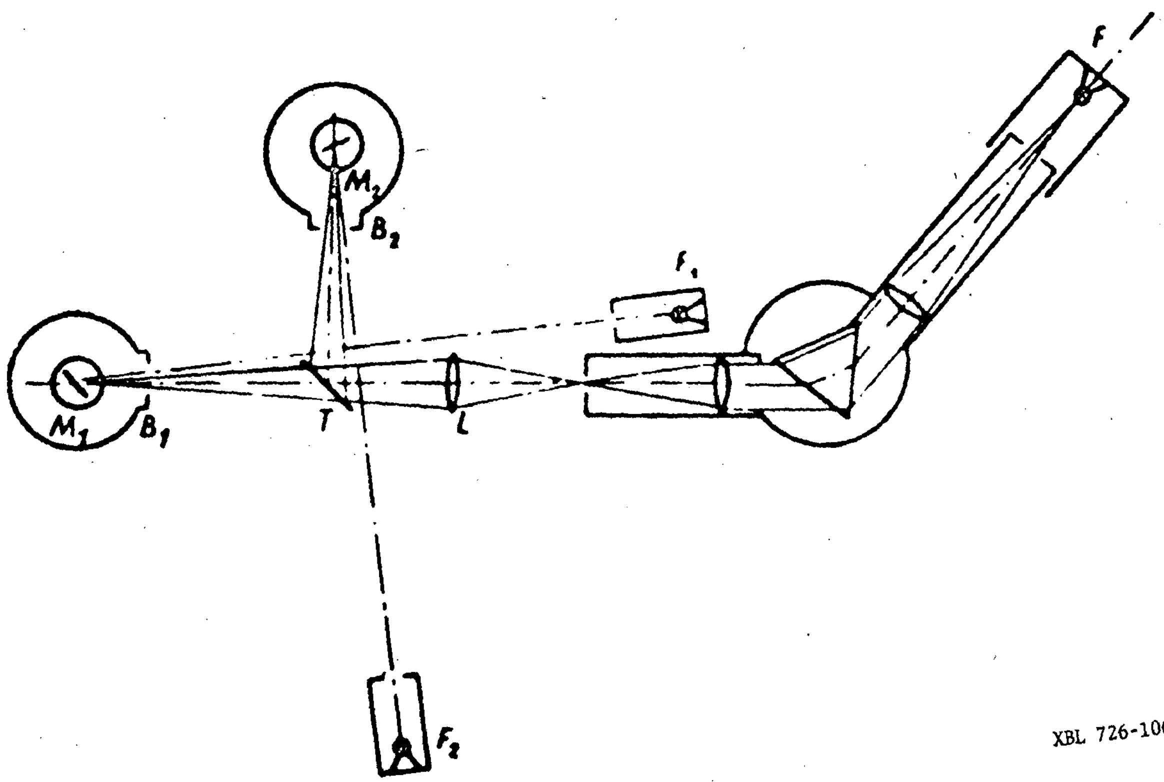


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Fig. 4

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