Reflection of Electrons by Standing Light Waves: Experimental Study*

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The reflection of electrons by standing light waves, i.e., the stimulated Compton scattering predicted by Kapitza and Dirac, has been studied experimentally. It has been found that the electron scattering observed in a preliminary study was spurious. Subsequent experiments were performed with greatly improved circuitry and augmented laser intensity. Deflections suffered by 1.6-kV electrons traversing the intense radiation field in the cavity of a giant-pulse laser were measured directly. In many dozens of experiments, electrons were observed to recoil at roughly the expected Bragg angle and with a probability of the predicted order of magnitude. The limited resolving power of the experiment and the uncertainty in the spatial distribution of laser intensity prevented an unequivocal verification of the Kapitza-Dirac theory. It was also found that the electron beam experienced an appreciable field when the laser pulse struck certain parts of the cavity wall. This field took a significant time to develop and sometimes exhibited erratic fluctuations over a period of dozens of microseconds after the laser pulse abated.

I. INTRODUCTION

IN 1933, Kapitza and Dirac suggested that a standing light wave can serve as a diffraction grating for a beam of electrons.[1] They designated the predicted phenomenon "stimulated Compton scattering" and based their treatment of it on the following point of view: The recoils suffered by electrons upon collision with photons in a standing wave differ from those sustained in a running wave (ordinary Compton scattering) in that stimulated Compton recoils tend to be highly directed. This directionality is imparted because a standing wave is a superposition of two oppositely directed running waves, one of which functions as an incident beam while the other serves as a stimulating beam. Electrons may absorb photons from the incident beam and be stimulated to emit them in the opposite direction. The trajectories of such recoiling electrons can satisfy energy and momentum conservation, then, only if Bragg's law is obeyed. Of particular importance is the fact that the probability of the stimulated effect increases with the *square* of the light intensity, whereas that of the ordinary effect increases only *linearly*. At high photon densities, therefore, the stimulated effect can predominate. Since the publication of the original paper of Kapitza and Dirac, several alternative treatments of the problem have appeared.[2–5]

However interesting an experimental test of the Kapitza–Dirac prediction might have been at the time of its formulation, such a test was clearly impossible. The strongest light sources of the day were calculated to reflect only one in 10^{14} electrons in the most idealized experiment. The situation was changed dramatically by the advent of the laser. Intensities now obtainable with commercial lasers are sufficient to induce saturation of the effect, according to the theory of Kapitza and Dirac. Nevertheless, the experiment is fraught with formidable difficulties even today. Some of the more important of these are as follows. The Bragg angle for electrons of convenient speed ($\approx 10^3$ eV) is only a few hundredths of a milliradian. Electron reflection probabilities remain excessively small unless giant laser pulses are used. Conventional electron optical arrangements with adequate resolving power give such weak electron beams that relatively few electrons traverse the laser beam during the brief duration of a giant laser pulse. The electrical discharge of the optical pump produces a magnetic pulse from which it is difficult to protect the electron beam. A giant laser pulse impinging on a mirror to generate a standing wave also generates a cloud of neutral and charged particles which can deflect the electron beam.

Notwithstanding these difficulties, a study of the interaction between free electrons and intense light waves seemed feasible and potentially worthwhile. Therefore we initiated research in this direction several years ago. At the outset of our experimental work it was impossible to anticipate the severity of the aforementioned and other complications. Consequently, we designed an exploratory apparatus with a view more to adaptability than to precise measurement.

Since the design requirements for the experiment and the framework for interpreting results are best discussed in terms of the theoretical relations presumed to describe the phenomenon, these relationships are outlined in the next section.

II. THEORY

The diffraction of an electron beam by a standing light wave is governed by the familiar Bragg equation

$$n\lambda_e = 2d \sin\theta_B \tag{1}$$

in which λ_e is the electron de Broglie wavelength and

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[1] P. L. Kapitza and P. A. M. Dirac, Proc. Cambridge Phil. Soc. **29**, 297 (1933).
[2] L. S. Bartell, J. Appl. Phys. **38**, 1561 (1967); L. S. Bartell and H. B. Thompson, *Physics of Quantum Electronics* (McGraw-Hill Book Co., New York, 1966), p. 129.
[3] H. Dreicer, Phys. Fluids **7**, 735 (1964).
[4] I. R. Gatland, Phys. Rev. **143**, 1156 (1966).
[5] J. H. Eberly, Phys. Rev. Letters, **15**, 91 (1965).

the interplanar spacing d is half the photon wavelength λ_p. Because of the $\cos^2$ distribution of the scatterer, the diffraction order n cannot exceed unity for scattering from a broad, ideal standing light wave.

In this section we shall consider several limiting cases for an electron plane wave encountering a plane-polarized superposition of light waves. More general relations are outlined in Ref. 2. We shall consider that the component light waves are traveling in the xz plane, the plane of incidence of the electrons, at an angle of η with respect to the vertical (z) axis. The intensities in energy per unit area per unit time of the incident wave train (running upward) and the stimulating wave train (running downward), integrated over frequency and angular divergence, are denoted by I_0 and I_0', respectively. It will be assumed, further, that one of these wave trains is generated from the other by reflection from a horizontal mirror or prism, and is uniform in intensity along the length l of the reflector.

A. Case of Fully Coherent Standing Light Wave

For practical purposes the light wave is fully coherent when $\Delta\nu$ is small compared with v/l and when the divergence $\Delta\eta$ is much smaller than λ_p/l, where v is the electron velocity. The fraction of electrons reflected by such a light wave is

$$N/N_0=(l/v)KI_0I_0'g(\theta)\,, \tag{2}$$

where K is equal to $(le^4/m^2c^2h^2\nu^4v)$. The function $g(\theta)$, which is unity for perfect alignment and expresses the allowable latitude in the setting of the angle of incidence in a stimulated Compton experiment with an ideal standing wave, has the form

$$g(\theta)=\frac{\sin^2[2\pi l(\theta-\theta_B)/\lambda_p]}{[2\pi l(\theta-\theta_B)/\lambda_p]^2} \tag{3}$$

in which the angle $\theta-\theta_B$ is the deviation between the actual angle θ of entry of the incident electrons and the correct Bragg angle.

In the event that l is comparable to or smaller than $\lambda_p^2/2\lambda_e$, it can be seen from $g(\theta)$ that the θ for reflection is no longer rigorously restricted to the Bragg value. This relaxation of the Bragg law merely permits the angle of incidence to deviate from the angle of reflection. It does not invalidate the Bragg formula

$$\lambda_e=2(\lambda_p/2)\sin(\tfrac{1}{2}\phi)$$

for ϕ, the total angle of scattering.

B. Case with $\Delta\eta\approx 0$, $\Delta\nu\neq 0$

If the spread $\Delta\nu$ in frequency of the light wave is large compared with both v/l and $(2v/\lambda_p)\Delta\eta$, the fraction of electrons reflected by the light wave is given, at the optimum angle of incidence, by the expression[6]

$$N/N_0=(1/\Delta\nu)KI_0I_0' \tag{4}$$

in which $\Delta\nu$ is defined by

$$\Delta\nu=I_0I_0'\Big/\int I(\nu)I'(\nu)d\nu\,,$$

where

$$I_0=\int I(\nu)d\nu\,.$$

Clearly, the reflection probability is smaller than that given by Eq. (2). In compensation, the range of angle of incidence over which reflections may be observed is larger by $(l\Delta\nu/v)$-fold.

C. Case with $\Delta\nu\approx 0$, $\Delta\eta\neq 0$

A third limiting form for the reflection probability becomes appropriate in case the angular divergence $\Delta\eta$ of the light is large compared with both $\lambda_p/2l$ and $(c/2v)(\Delta\nu/\nu)$. That is, the light, which may or may not have a small frequency spread $\Delta\nu$, is considered to be a superposition of independent plane waves with momentum P_i in which the individual waves have small components of momentum, $\Delta P_i=\eta_iP_i$, along the direction of the electron beam. If the angle between the electron trajectory and the x axis is θ_B, and if the standing waves are generated by a totally reflecting mirror or prism, the probability reduces to

$$N/N_0=(\lambda_p/v\Delta\eta)KI_0I_0' \tag{5}$$

in which $\Delta\eta$ is given either by

$$\Delta\eta_a=I_0^2\Big/\int I^2(\eta)d\eta$$

or by

$$\Delta\eta_b=I_0^2\Big/\int I(\eta)I(-\eta)d\eta\,,$$

where

$$I_0=\int I(\eta)d\eta\,.$$

The expression for $\Delta\eta_a$ pertains to a mirror and to a Porro prism with vertex in the xz plane of incidence whereas that for $\Delta\eta_b$ applies to a prism with vertex perpendicular to the plane of incidence. Since the divergence of the light gives rise to a superposition of Bragg planes spanning an appreciable range of tilt, electron reflections should occur at angles as far as $\Delta\eta$ rad away from $\theta_B{}^0$, the Bragg angle corresponding to horizontal

[6] In Ref. 2, it is incorrectly stated that Eq. (4) of the present manuscript [Eq. (25) of Ref. 2] applies only in the vicinity of the mirror generating the standing wave. For incident light with random phase relationships between waves of different wavelengths, Eq. (4) applies at any distance from the mirror.

planes. The price paid for this increase of ease of electron beam alignment is a corresponding decrease in reflection probability. In the event that the standing-wave axis is not optimally oriented with respect to the electron beam, the more complete expressions of Ref. 2 are useful.

Of the three limiting cases above, case B corresponds to the original formulation of Kapitza and Dirac[1] except for the fact that Kapitza and Dirac treated the light as unpolarized and, consequently, arrived at a reflection probability half as large as that of Eq. (4). The most pertinent case for lasers of sufficient power to achieve high reflection probabilities, however, is case C. The divergence of pulsed laser beams, at present, poses a more severe limitation than does the wavelength spread.

The above ideas can be extended readily to more complex patterns of light waves corresponding to various experimental conditions. If, for example, an electron beam encounters a series of standing waves generated from spatially separated "filaments" of laser emission, and if each of these meets the above conditions on $\Delta\nu$ and $\Delta\eta$, the reflection probabilities N/N_0 for the individual filaments are additive. (For the case of vanishing $\Delta\nu$ and $\Delta\eta$, it is the *amplitudes*, rather than the *intensities*, of the scattered electron waves which are additive, of course.) Such a series of separated standing waves could occur if the terminal reflector were a mirror, but a Porro prism reflector could not turn the filaments back upon themselves or upon each other, except fortuitously, to form standing waves. With a mirror, the Bragg planes formed from a plane wave are parallel to the mirror plane irrespective of the angle η of the wave. Therefore, if it occurred that the individual filaments had divergences m-fold less than the angular disparity $\Delta\eta$ between the various filaments, the alignment requirement of the electron beam would be m-fold more severe than for spatially blended components with a divergence of $\Delta\eta$. The optimum N/N_0 would be m-fold greater, for a given mean light intensity along the electron path. With a prism the vertex of which is in the xz plane, the Bragg planes of the standing wave formed from a given incident plane wave are perpendicular to the wave direction rather than parallel to the front face of the prism. Accordingly, the range of Bragg-plane orientations formed from a series of incident waves would be the full range $\Delta\eta$ of the incident wave directions. If, then, the prism were at a considerable distance from the laser rod and constituted an end reflector of the laser cavity, the standing wave near the prism would have a minimum of filamentary structure and its form would approach that assumed in the derivation of Eq. (5), case C. In the experiment discussed below, a Porro prism nearly a meter away from the laser rod capped the laser cavity and formed the standing waves encountered by the electron beam.

III. EXPERIMENTAL

A. Design of Experiment

The decision to use electrons in the range of 1.5 kV established the over-all design characteristics. Electrons with substantially higher energies would exhibit extremely small scattering angles and present problems of resolution. Slow electrons are more difficult to generate in an intense, monochromatic, and spatially coherent beam. The deleterious influence of extraneous fields on the electron beam decreases or increases, as the electron wavelength decreases or increases, roughly in proportion to the Kapitza-Dirac deflection to be studied. Therefore, apart from convenience in production, we found no compelling reasons for using electrons more or less energetic than 1.64 kV, the value we adopted.

A ruby laser appeared to be a reasonable choice for a light source in view of its power, wavelength, state of development, and availability. It appeared wise to select a model with external reflectors for versatility and to enable the experiment to be carried out inside the laser cavity itself to take advantage of the highest possible intensity.

The Bragg angle for 1.64-kV electrons reflected from the 3470 Å interplanar spacing characteristic of ruby radiation is only 0.044 mrad. Since the 10^{-2} mrad resolving power required is needed in only one direction, it was decided to use cylindrical electron lenses rather than spherical lenses in order to preserve electron intensity as much as possible. In practice, in the face of the electromagnetic inhomogeneities encountered along the electron path, our electron optical system was not particularly efficient. The portion of our focussed electron beam incident on the slit of our detector corresponded to a current of only about 5 electrons/nsec when the beam was stopped down to give acceptable resolving power. This unfavorable situation introduced rather obvious requirements of laser power. According to Eq. (5), peak reflection probabilities for a representative normal burst mode laser ($\approx$0.3 MW, several mrad divergence) and for a giant-pulse laser ($\approx 10^2$ MW, several mrad divergence) are about 10^{-6} and 0.2, respectively. A given pulse in the normal burst mode lasts $\approx 10^3$ nsec whereas a giant pulse is only $\approx$10 nsec long. It is evident that a giant pulse is needed if the electron intensity is only a few electrons/nsec. The above conditions call for a detector sensitive to individual electrons and capable of measuring electron beam profiles to 10^{-5} rad.

B. Apparatus

The diffraction unit constructed to study stimulated Compton scattering is illustrated in Fig. 1. Its operation, in brief, is as follows. A beam of 1.64-kV electrons is passed through the cavity of a ruby laser. The angular profile of the beam emerging from the cavity is monitored by sweeping the beam across the entrance slit

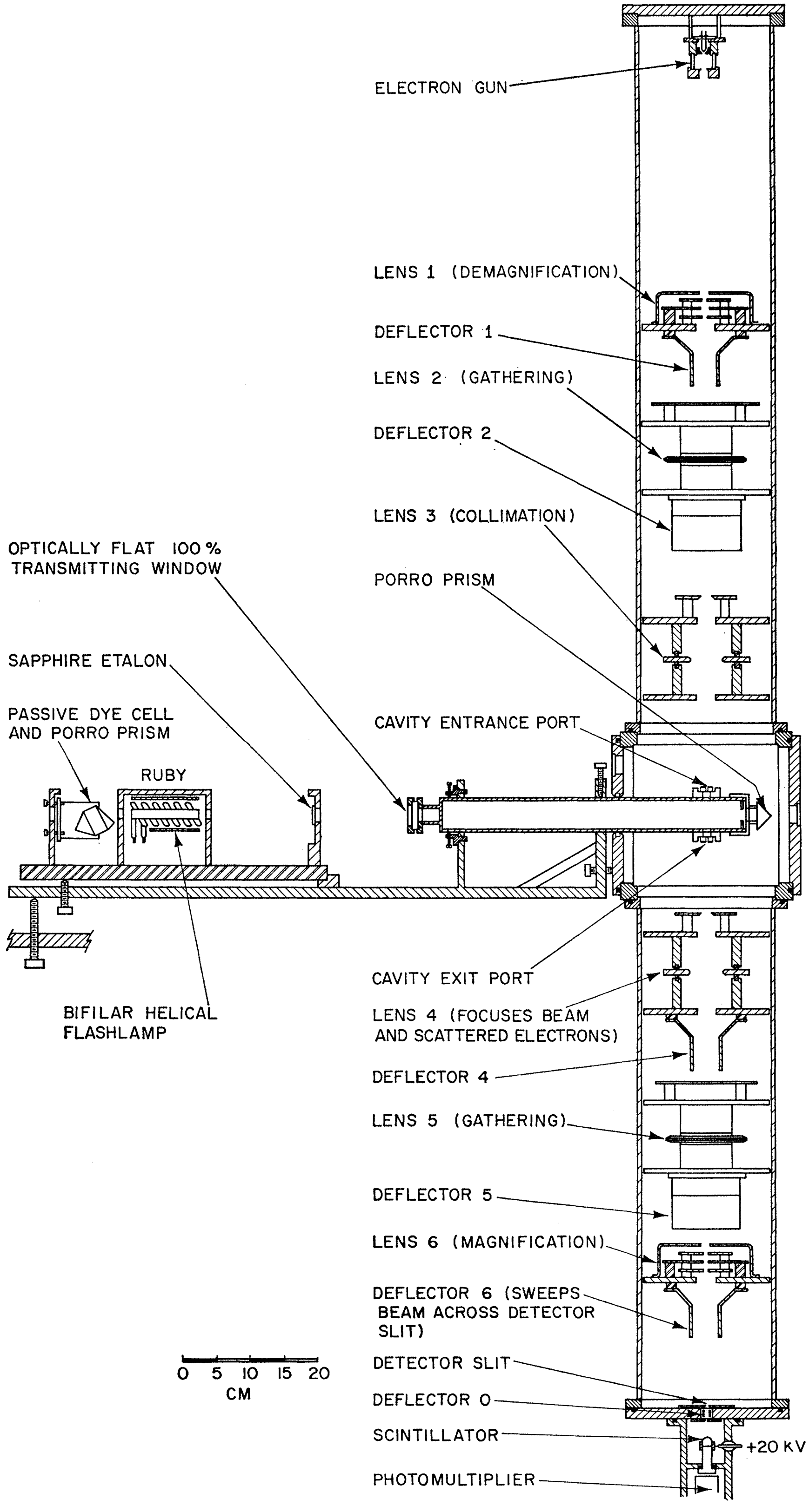

FIG. 1. Apparatus for studying the scattering of electrons by standing light waves.

of a scintillation detector and displaying the output of the associated photomultiplier tube on an oscilloscope screen. Electrons which are scattered ahead of (or behind) the undiffracted beam are recorded before (or after) the main peak. An electron scanning rate of 10^{-6} rad/μsec was found to be convenient. Inasmuch as a giant laser pulse lasts for only about 10^{-2} μsec, a signal for reflected electrons should be observed when the laser fires only if the scan angle at that instant corresponds to an allowed angle of scattering. Obviously, the portion of the scattering pattern that can be surveyed during one pulse is minute and a characterization of entire diffraction pattern would take many separate laser shots. The laser could be preset to fire at arbitrary scan angles to within its normal jitter of about 40 μsec. This jitter, in large measure, dictated the practical working range of electron scan rate. Experimental details are outlined below in sufficient detail to convey an understanding of our approach to the problem. Further details on design and technique have been described elsewhere.[7]

1. Electron Optical System

The electron source is a conventional self-biased gun operated at a plateau current of about 50 μA. The optical components shaping the beam in the direction in which high resolving power is required are the unipotential cylindrical lenses 1, 3, 4, and 6, with axes perpendicular to the plane of Fig. 1. Lens 1 demagnifies the crossover of the electron gun approximately 25-fold to obtain a fine electron image at the principal focus of lens 3. Lens 4, which is identical to lens 3, focusses the residual incident and the scattered beams to lines above lens 6. The symmetrical disposition of the lenses guarantees that the projections of the electron trajectories on the plane of Fig. 1 are parallel as the electrons traverse the laser cavity. Lens 6 projects magnified images of the focussed incident and scattered electron beams onto the plane of the detector slit. Its primary function is to magnify 16-fold the separation between undeflected electrons and electrons deflected by the laser beam to avoid the necessity of using an extremely fine slit in front of the detector. Under optimum conditions the resolving power approached 1.5×10^{-5} rad. Unfortunately, under the usual working conditions, the focus was often poorer by severalfold.

Lenses 2 and 5 are cylindrical with axes in the plane of Fig. 1. They serve only as gathering lenses. As a rule lens 2 was adjusted to focus electrons to a line in the laser cavity. Because the line image formed above lens 6 was usually appreciably curved by inhomogeneities in the system, lens 5 was seldom used to regather the electron beam. Instead, the straightest and most intense portion of the beam was selected for scanning across the detector slit.

[7] R. R. Roskos, doctoral dissertation, Iowa State University, 1966 (unpublished).

To facilitate alignment, the electron gun was tiltable and a set of electrostatic deflector plates was attached to the bottom of every lens except lens 3. The deflector supplying the scanning voltage was attached to lens 6.

The entire electron optical system was evacuated with a 6 in. diffusion pump which, with the aid of a trap cooled by liquid nitrogen, maintained a pressure of 10^{-6} Torr.

For certain reasons of expediency it was decided to construct the unit of nonmagnetic materials. In order to reduce the highly disturbing influence of the earth's magnetic field, the entire unit was tilted to direct its axis along the earth's magnetic lines of force. In addition, the unit was wrapped uniformly along its length with a current-carrying coil which could be controlled to cancel in large measure the earth's field in the interior of the apparatus.

A more severe problem was reducing to tolerable levels the magnitude of the magnetic pulse generated by the flash lamp assembly when it discharged. The flashlamp itself was a bifilar helix wound so that the magnetic field produced by half of the coils cancelled the field produced by the other half. Even with this precaution it was necessary to move the laser head away from the electron beam to a distance of nearly 1 m and to arrange the geometrical configuration of the power cables with exceptional care. Attempts to shield the diffraction unit by sheathing it or the laser head with sheet metal of high permeability were not notably successful.

2. Timing System

The ever-present 60-Hz disturbance from power circuits produced serious problems; these were largely eliminated by basing the entire timing cycle on a 60-Hz reference signal. The circuit arrangement is indicated in Fig. 2.

The scintillator detector rapidly became noisy when swept repeatedly by the electron beam. This noise was greatly reduced if only two or three sweeps were made each 60-Hz cycle. In the schematic diagram of Fig. 2 the sweep-gate time b is somewhat exaggerated; normally this period was 1 msec or less.

The oscilloscope was triggered each 60-Hz cycle during preliminary focussing and alignment. Then the camera was put in position, and both the oscilloscope and the laser were triggered on the first 60-Hz cycle following the opening of the camera shutter, which was set at 1/50 sec. Timing of the observed oscilloscope trace relative to the beam sweep could be varied widely using the horizontal position, sweep rate, and scale expander controls on the oscilloscope. A separate variable delay was provided for the laser trigger.

3. Electron Detector

The entrance slit to the detector was constructed from two stainless-steel razor blades spaced 0.12 mm apart. A lower slit offset with respect to the entrance

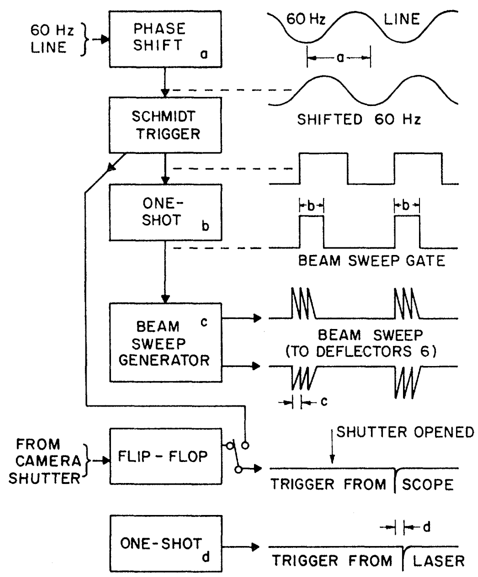

FIG. 2. Timing circuits. Letters a–d indicate variable timing adjustments and the circuits in which they are made: (a) 60-Hz phase adjustment; (b) beam sweep on-time; (c) beam sweep period; (d) laser trigger delay.

slit was inserted to help exclude light from the electron gun filament and the laser. Electrons were guided through the second slit by deflector 0.

The electron detector itself was similar to one described by Everhart and Thornley,[8] consisting of a plastic scintillator, a light pipe and a photomultiplier. An aluminum coating 500 Å thick on the plastic was maintained at a potential of 20-kV positive with respect to ground to accelerate the electrons and enhance scintillations. The coating also acted as a mirror to turn back undesirable laser light and to direct light from the scintillations down the light pipe to the photomultiplier. An interference filter designed to be 100% reflective to the 6940 Å ruby light was inserted between the light pipe and photomultiplier as an additional precaution against laser light reaching the phototube. By the above means, together with the judicious placement of other light traps, it was possible to fire a 100-MW laser pulse without obtaining a detectable signal from the photomultiplier.

Output signals from the photomultiplier were coupled to a cathode follower and monitored with one beam of a Tektronix-551 dual-beam oscilloscope with a type-L plug in amplifier. The other beam was used to monitor the integrated laser energy output. Signals which we interpret as individual electron noise events were about 2–4% of the peak electron beam signal. In order to separate stimulated Compton scattering signals from the noise an electron scattering probability greater than 4% would be desirable. Such a high probability requires a giant-pulse laser.

[8] T. E. Everhart and R. F. Thornley, J. Sci. Instr. **37**, 246 (1960).

4. Laser

The laser employed in this research was the Korad K-1 model with a 9/16 in. diam ruby rod 4 in. in length, pumped by a Kemlite bifilar helical flash lamp. The laser was equipped with a cryptocyanine passive dye cell Q-switch. Owing to the necessity of placing the laser head a meter away from the electron beam, a rather unusual laser arrangement was adopted, as shown in Fig. 1. The laser cavity was bounded at the left end with a totally reflecting Porro prism cemented to the dye cell. It was bounded at the right end, inside the vacuum system, with another totally reflecting prism. In addition, a sapphire resonant reflector was mounted to the right of the ruby rod in the position it would normally have occupied when used as an output reflector. Finally, a coated, optically flat window 100% transmitting to the 6940 Å line was employed to admit light through the wall of the vacuum system. The original function of the sapphire reflector was to provide a reference surface with respect to which the other optical components could be aligned with the aid of an autocollimator. It was discovered, however, that the laser worked essentially as well with the reflector in place as without, insofar as power levels were concerned. For convenience in frequent checking of alignment, therefore, the resonant reflector was left in place.

Happily, the losses to the sides of the very long cavity were high enough to keep intracavity intensities below the limit of severe damage to the ruby, but low enough so that the power level with the long cavity was somewhat higher than that with the normal cavity arrangement. Giant pulses were commonly about 1 J in energy and 10 to 15 nsec in duration[9] (width at half-height) and up to 100 MW in peak power. The divergence was ± 4 mrad from the axis, as inferred from burn spots, but the distribution of intensity with angle was unknown. What influence the complex interplay between the two coupled halves of the laser cavity had on the wavelength spread is also unknown. Presumably this is of only secondary importance since the limiting factor in this research would seem to be the divergence rather than the spread in wavelength.

The laser assembly was mounted on a rigid arm which could be swung over a range of a few hundredths of a radian to adjust the angle of incidence of the electron beam with respect to the laser output.

5. Geometry Adjustment

According to Eq. (3), if an electron plane wave encounters a fully coherent standing wave 1.2 cm in diam, stimulating Compton reflections will occur strongly only if the electron angle of incidence satisfies the Bragg angle to within about 1.5×10^{-5} rad. Such a delicate alignment would be exceedingly difficult to

[9] As measured with a Tektronix-517-A oscilloscope.

attain and preserve. Similarly, an electron beam divergence of much more than 10^{-5} rad would also severely reduce the proportion of electrons reflected. On the other hand, according to the analysis of Sec. IIC, the observed laser divergence of 4×10^{-3} rad would decrease the alignment requirement and the need for electron beam spatial coherence by more than two orders of magnitude (but at the cost of reducing the reflection probability by a like factor). Fortunately, it was simple to achieve parallelism of incident electrons to 10^{-4} rad and it was possible to preset the angle of incidence to within about 10^{-3} rad. This was done as follows.

Two platinum apertures were mounted on the laser cavity tube 50 mm apart, the top one acting as an entrance port and the bottom one as an exit port for electrons passing through the laser cavity. Each port had a slit 0.2 mm wide projecting to one side (directed into the plane of Fig. 1) and the slit axes were adjusted to lie in a common plane parallel to the face of the prism at the right end of the cavity. When the electron beam was pulled aside into the slits by deflector 2, the arm supporting the laser could be adjusted until the electron current passing through the slits was maximized. This operation made the electron beam parallel to the prism face. The prism face had been prealigned to be perpendicular to the laser axis to within a fraction of a milliradian.

6. *Calibration of Scattering Angle*

As electrons are scanned across the detector slit, the horizontal scale of the oscilloscope display is a measure of angular displacement. Since the undiffracted beam is swept across the slit on every scan, each oscilloscope trace contains a reference corresponding to zero deflection. Therefore, modest displacements due to the flashlamp field do not interfere grossly with the measurement of scattering angle. A more serious problem is that the electron optical system is taxed to the limit to achieve the desired resolving power. The use of electrical equipment a floor away sometimes had a deleterious effect on the beam. Even though serious runs were invariably made late at night, controls had to be constantly reoptimized. For this reason, the oscilloscope scale needed frequent recalibration and individual measurements might be more than 20% in error. A small dc voltage capable of deflecting the electron beam at the detector by the same displacement as that suffered in a Bragg reflection, could be applied at will on deflector 4. The corresponding displacement on the oscilloscope screen was readily recorded, as shown in Fig. 3(a). The required voltage for deflector 4 was determined both by direct observation of deflection versus voltage and by the placement in the laser cavity of an electrostatic deflector designed to bend a 1.64-kV beam by 8.7×10^{-5} rad.

An additional nuisance was that the sweep rate was distinctly nonlinear, a fact which necessitated perhaps 20% corrections depending upon the exact position of the beam on the trace. Finally, it should be noted that the calibration of oscilloscope scale was made only when the flash lamp was quiescent. This may not have been entirely adequate. An analysis of many plates suggests

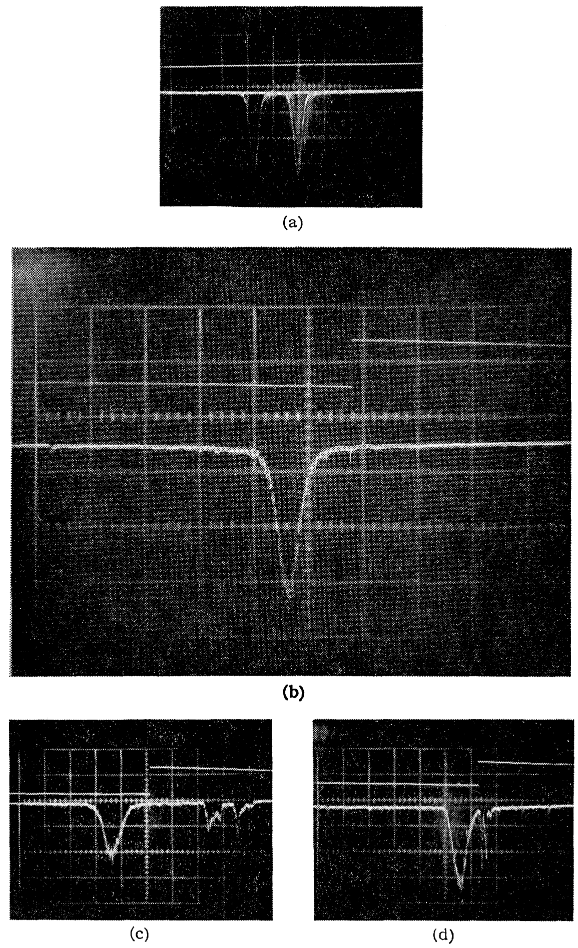

FIG. 3. Characteristic signals and noise events as recorded by dual beam oscilloscope. The upper trace displays the integrated laser output and the lower trace the electron detector response recorded at 40 μsec/cm or $\approx6\times10^{-6}$ rad/cm: (a) double exposure showing 10^{-4} rad beam deflection produced by appropriate voltage on deflector 4 to calibrate sweep adjustments; (b) frame recording electron deflection coincident with laser pulse. Directly under the laser discharge signal (in the upper trace) can be seen the "spicule" indicating reflected electrons (in the lower trace about 1 cm to the right of the incident beam profile). The spicule intensity is about 10% of the beam intensity; (c) frame recording electron deflection coincident with laser pulse followed by broad noise events 100 μsec later; (d) frame recording relatively sharp noise events the first of which starts about 3 μsec after laser pulse, increases to about 10% of the incident beam height, and lasts a little longer than 1 μsec. Noise events tended to disappear when the complex laser cavity was aligned to prevent the laser pulse from grazing metal parts near the electron beam. In frame (d) the prism was only 1.7 cm from the electron beam and a metal aperture struck by the laser beam was only a few mm from the beam. In all frames surveyed for spicules the clearances were much larger and obvious noise events, if any, were much more delayed. Spicules were easily identifiable in the original photographs but suffer some loss of clarity in reproductions.

that the flashlamp discharge slightly changed the focal lengths of the lenses, perhaps because of the divergent magnetic field generated. Unfortunately, circumstances beyond our control forced us to terminate the experiment before a calibration could be made during an actual flashlamp discharge.

IV. RESULTS

A. Discrimination between Signals and Noise

In an idealized experiment, an oscilloscope trace monitoring the electron detector would reveal the profile of a clean-cut beam rising from a null background. It would also display a small signal of reflected electrons a few nanoseconds wide, coincident with a laser pulse and displaced about 9×10^{-5} rad from the undiffracted beam, provided the laser generated a suitable standing wave at the appropriate scan time. A trace with such an appearance is shown in Fig. 3(b) and represents, as far as is known, a bona fide record of electrons experiencing a stimulated Compton recoil. If the laser were fired at an unpropitious scan time, no satellite signals should be observed.

In practice, the situation was often far more complex. A short time after a laser pulse the base line of the electron detector trace would often display erratic bumps of the sort illustrated in Figs. 3(c) and (d). The precise origin of this noise is still obscure. It would sometimes last for over 100 μsec. Since it occurs during a time when the laser is generating no radiation, it is obviously unconnected with the stimulated Compton effect. Potential sources of this noise are discussed in the next section. In the meanwhile we shall concern ourselves with signals which, while they may be noise, cannot individually be eliminated from consideration as genuine electron reflections by available criteria. Such signals shall be designated throughout the remainder of this paper as "spicules," a term which describes their appearance in oscilloscope traces. The criteria to be met if a signal is classified as a spicule are as follows:

(1) A spicule must be coincident with a laser pulse to within the 1 μsec uncertainty associated with measurements on traces recorded at the usual oscilloscope sweep rate of 40 μsec/cm.

(2) A spicule must exhibit no discernible breadth in traces taken at the usual sweep rate.

(3) A spicule must be distinctly stronger than the characteristic level of background noise in the vicinity. Presumably, a true reflection probability for a somewhat incoherent laser pulse would not exceed about 25%, a figure corresponding to half of the electron beam distributed between the two first-order ($n=\pm1$) reflections. Still, a reflection probability of 100% is not prohibited by dynamical diffraction theory under suitable conditions. We shall *not* impose at this time the criterion for spicules that the electron scattering angle satisfy Bragg's law. Instead, we shall examine the distribution of "spicules" to find what behavioral pattern, if any, is exhibited.

B. Distribution of Recoil Signals

1. Angle Dependence

Many hundreds of frames were taken to determine the influence of a laser beam on an electron beam. Many of these were made with normal burst mode outputs and gave no indication, over and above the noise level, of stimulated Compton recoils. Over 240 frames were recorded in which a giant pulse had intersected a well aligned electron beam. Scan angles at the time of firing ranged from zero to twice the expected recoil angle and canvassed both positive and negative angles. In all, 80 frames exhibited spicules. Of these, 41 showed spicules 10 to 30% as tall as the main beam, 36 in the 5 to 10% range, and 3 less than 5% of the undiffracted peak height. Spicules as feeble as the latter could be observed only on very clean traces, of course.

Figure 4(a) gives a graphical representation, for giant-pulse experiments, of the number of frames taken in the various ranges of scattering angles surveyed without regard to the signs of the angles. Figure 4(b) plots the heights of the spicules observed at the angles of observation. Since the survey was of nonuniform density, being weighted disparately at angles somewhat smaller than but close to the expected angle, an alternative plot is presented in Fig. 4(c). This takes into account insofar as possible the unequal sampling by summing spicule heights in individual 0.08 mrad intervals and dividing by the number of shots taken in the intervals. Even this correction has only the roughest validity at best since the individual responses seemed to depend heavily on the precision of alignment and on

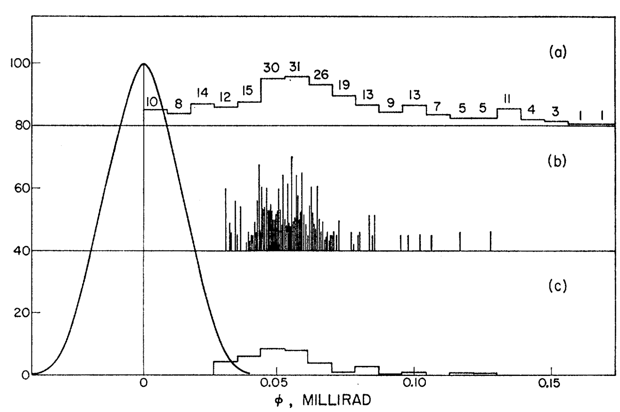

FIG. 4. Angular dependency of scattered electrons. The abscissa represents the angle between the undeflected beam and the detector at the time of a giant laser pulse: (a) the number of attempts to observe stimulated scattering in various angular intervals; (b) the observed "spicules," or electron currents arriving at detector coincident with the laser pulse; (c) average spicule heights (see Sec. IVB). Spicule heights are plotted in percent of the incident beam peak height. A representative incident beam contour is indicated by the bell-shaped curve centered at $\phi=0$.

the nonuniformity of laser intensity over the cavity cross section. Such imponderables could not easily be taken into account.

The plot of Fig. 4 gives some indication of electron reflection probability as a function of total scattering angle but contains no information on whether the reflections were specular or not with respect to Bragg planes of light waves. Since the laser divergence was well over one order of magnitude greater than the Bragg angle $\theta_B=0.044$ mrad, it was not possible to test this aspect of the Bragg law restriction with any delicacy. Empirically, it was found to be essential for the electron beam to be perpendicular to the laser axis to within our ability to measure the alignment (about $\pm 10^{-3}$ rad). Many times when all other factors appeared to be favorable but no spicules could be observed, a recheck of the alignment revealed that adjustments had deteriorated. When proper alignment was restored, spicules reappeared.

2. Intensity Dependence

Spicules were not observed unless high laser powers were employed. Normal burst mode peak powers of 0.3 MW were insufficient. With 80 MW spicules up to 20% of the incident beam height were often observed. It was not possible to complete a systematic variation of laser intensity before ruby damage terminated the experiment but deliberately reduced giant pulses ranging from 15 to 40 MW were tried in approximately 50 frames. Spicules were observed less frequently (9 were recorded) and were lower in height than those observed at higher laser powers.

A factor frustrating any quantitative assessment of spicule height as a function of laser intensity was the nonuniformity of laser intensity over the cross section of the cavity. This nonuniformity in the form of "hot spots" near the center was easily detected but difficult to map quantitatively. Whenever laser conditions gave rise to these "hot spots," it could be expected with some confidence that spicules would be observed provided the electrons were guided through the particularly active region of the cavity. The reflection probability of electrons encountering a hyperintense portion of a giant pulse would be high even if alignment were imperfect. By the same token, of course, if spicules turned out to have some spurious orgin, it would still be reasonable to expect them to be more frequent the higher the intensity.

V. DISCUSSION

A. Criteria for Evaluating Experiments

In the present set of experiments many frames were recorded which showed electron deflections consistent with those expected for stimulated Compton recoils. Experimental conditions were extreme, however, and the experimental variables were too crudely characterized to permit an unequivocal test of the theory of Kapitza and Dirac. Furthermore, in many frames a surprising amount of noise of obscure orgin was encountered in addition to the signals presumed to represent the sought after responses. The question arises, then, as to what means we have of diagnosing the signals themselves. To help resolve the matter in the absence of more quantitative information, we propose a few tests which a bona fide Kapitza-Dirac signal should pass. (1) The signals should meet the criteria listed in Sec. IV for "spicules." (2) The electron reflection probability N/N_0 should be of a reasonable order of magnitude, compatible with that described in Sec. II above. (3) The effect should be observable at total scattering angles within a focussed electron beam width of the expected value $2\theta_B$ corresponding to the Bragg law; the effect should vanish at smaller and at larger angles.[10] (4) The effect should vanish if the angle of incidence of electrons deviates from the Bragg angle θ_B by more than the laser divergence. (5) The effect should be absent when the electron beam passes immediately to the side of the laser beam rather than through it (whereas some sources of noise would tend to remain).

Neither of the two previously published announcements[11,12] describing tentative observations of the stimulated Compton effect meet the above tests. Both reported experiments fail badly in items (1)–(3) and are insufficiently tested in (4) and, perhaps, (5). In both preliminary communications it was recognized that resolving powers (temporal and spatial) were too low to satisfy (1) and (3) but was hoped that subsequent improvements would reveal that the observed responses were the desired ones. In our own work[11] it was discovered after publication that we had naively made erroneous assumptions about our laser cavity, both in intensity and coherence of the radiation. When a substantial error in reflectance of the output reflector was corrected and when Eq. (5) was applied instead of the original relation of Kapitza and Dirac, calculated reflectance probabilities dropped by a factor of over 10^4, and made it absurd to associate the poorly defined response we saw with the Kapitza-Dirac effect. A similar magnitude of discrepancy between observed and calculated probabilities is involved in the other published experiment.[12] There is no doubt in our minds that both early observations were of the laser-induced noise, which we shall discuss later, and not of stimulated Compton scattering.

The present experiment, while still crude, was considerably less primitive than the orginal version described in Ref. 11, and was based on measured rather

[10] At larger scattering angles multiple scattering can occur (at integral multiples of $2\theta_B$) if the laser intensity is high and the divergence greater than $2\theta_B$.

[11] L. S. Bartell, H. B. Thompson, and R. R. Roskos, Phys. Rev. Letters **14**, 851 (1965).

[12] H. Schwarz, H. A. Tourtellote, and W. W. Gaertner, Phys. Letters **19**, 202 (1965).

than assumed laser characteristics.[13] It comes enormously closer to meeting tests (1)–(5) above than our original study but falls short of passing the tests unequivocally. Condition (1) concerning the timing and appearance of "spicules" is met adequately. Condition (2) is satisfied, for the apparent reflection probabilities as measured from spicule heights are consistent with those calculated from Eq. (5) to well within the uncertainties of establishing I_0 and $\Delta\eta$. Equation (5) rather than Eqs. (4) or (2) would seem to be the appropriate theoretical expression, since the laser divergence would have to drop more than two orders of magnitude from the observed 4×10^{-3} rad value in order to make the wavelength inhomogeneity become a limiting factor (assuming the linewidth of $\Delta\lambda=0.02$ Å quoted by the Korad Corporation is applicable).

It is apparent from Fig. 4 that test (3) above is met only roughly. The most probable angle of deflection seems somewhat smaller than the calculated value of 8.7×10^{-5} rad. This may, in part, be due to the uncertainties in the calibration of angles alluded to in Sec. IIIB. The resolving power was too low to permit a rigorous test of the absence of deflections in the unallowed region between 0 and $2\theta_B$. Furthermore, a certain amount of bias was involved in the method of selecting events to be recorded as spicules. At large angles from the undiffracted electron beam the baseline noise is sparse and only 2–4% as strong as the beam. At small angles inside the feet of the beam profile, a spicule would have to be perhaps 8% as strong as the beam to be recognized. Furthermore, as indicated in Sec. IVB, the limited sampling accomplished before the ruby failed was rather highly prejudiced.

Conditions (4) and (5) were not tested exhaustively before circumstances terminated this research. In view of the touchy nature of the experiment, it is hard to be dogmatic about the *absence* of a signal in a test, anyway, since so many delicate conditions must be satisfied besides the variable under test. Be that as it may, we did not observe spicules if the electron-beam–laser-beam alignment deteriorated by much more than a milliradian and if, when "hot spots" were present, the electron beam failed to traverse through them.

The above discussion quite explicitly calls attention to shortcomings in the present work which it would be desirable to overcome in future studies. Of primary importance would be a more efficient gun in a more adequately shielded electron optical system. It would also be advantageous to place several closely spaced detectors along the path scanned by the electron beam. This would make possible an independent monitoring of the space and time dependency of scattering events.

Note added in proof. After this paper was submitted a new paper by H. Schwarz [Z. Physik **206**, 276 (1967)] appeared describing work with a much faster detector than that available in the earlier research.[12] Schwarz's new signals with the mirror very close to the electron beam meet the above criterion (1) concerning simultaneity very well. Inasmuch as the experiment provides no information about scattering angle distribution or laser-electron beam orientation, however, criteria (3) and (4) are not tested. The reported signals represent the difference between upward and downward scattering. As such they apparently fail to satisfy criterion (2) because the large $\Delta\lambda$ for neodymium leads to an extremely diffuse distribution of effective Bragg plane orientations and should make the expectation value of the up-down difference less by orders of magnitude than the scattering in either direction, alone. It was indicated that the difference signal was approximately that expected for the total scattering in one direction.

B. Noise

Before bringing this section to a close a few comments on the noise observed are relevant. Fortunately, noise could be cut down greatly by carefully aligning the system so that metal portions of the cavity were not struck by the giant pulse. Perhaps half of the frames taken disclosed no noise events. Noise of the sort that was observed in Fig. 3(d) is symptomatic of interactions between radiation and matter which are undoubtedly of intrinsic physical interest in themselves. The noise responses are due to a deflection of the electron beam or a part of the electron beam into the slit of the detector. Several phenomena could be involved. Adsorbed molecules vaporized by a laser pulse could scatter the electron beam. Such evaporation requires energy absorption rather than high power levels and, indeed, may be responsible for a significant fraction of the noise seen in early experiments with normal burst mode outputs. It would be expected that noise of this origin would take some dozens of microseconds to develop because of the centimeters of travel from wall to electron beam required of the thermal molecules. Also, because of the distribution in molecular velocity, such noise would be sustained for dozens of microseconds or longer.

The noise observed in experiments with giant pulses was often of a different and puzzling character. It developed sooner and more violently the closer the totally reflecting prism was to the electron beam. At a distance of 1.7 cm the effect was often pronounced, while at the 11-cm distance most commonly used, the effect was often not noted at all. At the 1.7-cm distance the noise might begin to develop almost at once, take several microseconds to achieve maximum intensity, and persist for a few more microseconds. Subsequently the electron beam might be whipped back and forth across the detector slit several more times at irregular intervals over many microseconds. In some series of shots, virtually identical noise patterns would be dis-

[13] With the exception that $\Delta\lambda$ was not measured. A linewidth two orders of magnitude wider than the value quoted by the manufacturer would have been required to alter our conclusions.

played for several frames in a row. One or two oscillations of the electron beam across the detector slit might conceivably be caused by clouds of fast, charged particles of the sort induced by *focussed* giant pulses[14] issuing from the prism and passing through the electron beam. It is difficult to understand the creation of an adequately intense charged cloud with an unfocussed pulse, however, and to deduce how the effect can be regenerated for such a long period of time after the laser action has ceased.

Perplexing as this type of noise is it does not of itself complicate experiments done with single laser pulses. This is because such noise is easily separable, timewise, from the signals sought. The principal reasons for emphasizing it are (a) that it completely obliterates the desired signals in experiments done on slower time scales of detection (cf. both original reports[11,12]) and (b) that it raises nagging questions about processes taking place when intense radiation strikes matter. If noise events with finite breadth and surprising persistence take place which are not easily explained, it is possible that instantaneous noise events of infinitesimal breadth can also occur which resemble bona fide Kapitza-Dirac signals? This vexing question cannot be resolved unequivocally by the present work but tests (1)–(5) outlined earlier in this section provide guidelines for future research.

[14] For discussions of phenomena produced when a laser beam strikes a solid surface see R. E. Honig, Appl. Phys. Letters **3**, 8 (1963); J. F. Ready, *ibid.* **3**, 11 (1963); Industr. Res. **7**, 44 (1965); Phys. Rev. **137**, A620 (1965); D. Lichtman, and J. F. Ready, Appl. Phys. Letters **3**, 115 (1963); W. L. Lindor, *ibid.* **3**, 210 (1963); T. Y. Chang and C. K. Birdsall, *ibid.* **5**, 171 (1964); C. M. Verber and A. H. Adelman, J. Appl. Phys. **36**, 1522 (1965); P. A. H. Saunders, P. Avivi, and W. Millar, Phys. Letters **24A**, 290 (1967).

VI. CONCLUSION

In this research many dozens of frames were recorded in which electrons had been deflected by an intense standing light wave. The observed probability of interaction and the observed pattern of scattering angle were consistent to within the broad limits of experimental error with theoretical expectations for the stimulated Compton effect predicted by Kapitza and Dirac. No known information contradicts the interpretation that the deflections recorded represent stimulated Compton recoils. On the other hand, questions are raised concerning some of the unexpected phenomena which were observed when intense laser pulses struck the walls of the apparatus. These can only be settled by further study under conditions of greater stability of apparatus and greater resolving power.

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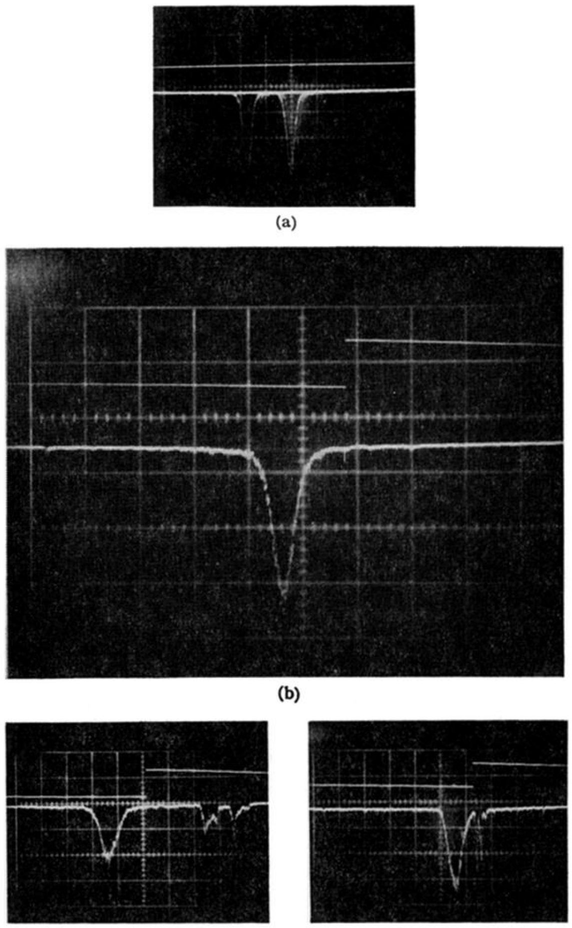

(a) (b) (c) (d)

FIG. 3. Characteristic signals and noise events as recorded by dual beam oscilloscope. The upper trace displays the integrated laser output and the lower trace the electron detector response recorded at 40 μsec/cm or $\approx 6\times10^{-5}$ rad/cm: (a) double exposure showing 10^{-4} rad beam deflection produced by appropriate voltage on deflector 4 to calibrate sweep adjustments; (b) frame recording electron deflection coincident with laser pulse. Directly under the laser discharge signal (in the upper trace) can be seen the "spicule" indicating reflected electrons (in the lower trace about 1 cm to the right of the incident beam profile). The spicule intensity is about 10% of the beam intensity; (c) frame recording electron deflection coincident with laser pulse followed by broad noise events 100 μsec later; (d) frame recording relatively sharp noise events the first of which starts about 3 μsec after laser pulse, increases to about 10% of the incident beam height, and lasts a little longer than 1 μsec. Noise events tended to disappear when the complex laser cavity was aligned to prevent the laser pulse from grazing metal parts near the electron beam. In frame (d) the prism was only 1.7 cm from the electron beam and a metal aperture struck by the laser beam was only a few mm from the beam. In all frames surveyed for spicules the clearances were much larger and obvious noise events, if any, were much more delayed. Spicules were easily identifiable in the original photographs but suffer some loss of clarity in reproductions.