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ENERGY OF THE X-RAYS EMITTED BY INTENSE PULSED DISCHARGES IN HYDROGEN

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The maximum energy of the x-rays emitted by an intense pulsed hydrogen discharge has been determined. The energy values presented are obtained from an analysis of the recoil-electron energy spectrum measured in a cloud chamber.

1. INTRODUCTION

It has been reported[1] that strong x-rays are generated by intense pulsed discharges in light gases for certain values of the initial pressure. It has also been observed that under the same conditions the curves of discharge voltage and current exhibit characteristic discontinuities at well-defined instants of time. The appearance of the x-ray burst usually coincides with the appearance of the second break on the current curve. In discharges in heavy gases[2] the x-ray energy is found to be considerably smaller than in light gases. If the discharge takes place in deuterium, neutron bursts are observed in addition to the x-ray bursts.[3]

The neutron bursts from pulsed discharges in deuterium have been studied by a number of authors (cf., for example, references 4 to 6); on the other hand, since the appearance of the first papers in this field there has been practically no information concerning the properties of the hard x-rays produced by a gas discharge in a cylindrical chamber.

The present work describes measurements of the energy of the x-rays characteristic of a hydrogen discharge. These measurements were undertaken in order to obtain data which would serve as a basis for the analysis of the mechanisms which have been proposed to explain the acceleration of charged particles in pulsed high-current discharges.

2. METHOD OF MEASUREMENT

In 1953, when hard x-rays were first observed in intense discharges in hydrogen and deuterium, estimates were made of the upper energy limits of the x-ray spectrum. Various approaches were used in making these estimates: filter measurements, measurements of the length of recoil-electron tracks in nuclear emulsions, measurements with shielded scintillation detectors, and photoeffect measurements [the (γ, n) reaction in Be]. From an analysis of these measurements it was definitely established that the x-ray energies were of the order of hundreds of kev although the voltage across the discharge tube was 10 to 20 kv. However, because of the slope of the spectral distribution curve it was difficult to set an upper limit on the energy.

In the present work, in order to make a more precise determination of the x-ray energy the measurements have been carried out in a cloud chamber. The use of a cloud chamber makes it possible to avoid certain difficulties which are characteristic of the methods cited above. The basic advantage of the cloud chamber in studying short x-ray bursts is the relatively small time during which the instrument is sensitive. Nuclear emulsions record the cosmic-ray background throughout the entire experiment; the cloud chamber is sensitive for only a short period of time so that there is a considerable improvement in the signal-to-noise ratio. Moreover, the possibility of following tracks of recoil electrons or photoelectrons which are formed by single photons, without any interference due to the pulsed discharge, represents a considerable advantage for the cloud chamber as compared with a shielded scintillation detector.

The energy of the electrons was determined from measurements of track length in the chamber. The well-known method by which electron energy is determined from the curvature of the trajectory in a magnetic field could not be used in the present work, because at electron energies of 200 kev the mean scattering angle is considerably greater than the largest angle for which the track curvature can be measured.

To determine the energy of the x-ray photons from the electron energies, one must decide whether these electrons are formed as a result of the photoeffect or the Compton effect. At energies of 200 to 400 kev the probability for the photoeffect in air, with which the cloud chamber is filled, can be neglected as compared with the probability for the Compton effect. However, the production of photo-electrons in the glass walls of the cloud chamber can be important at these energies. The ratio σ_c/σ_{ph}, as a function of energy of the x-ray photons, was computed theoretically for glass; the results of the calculation are shown in Fig. 1. Inasmuch as the purpose of the work was a determination of the limiting energy of the x-ray photons, the Compton probability was computed for electrons acquiring energies from $0.9\,E_{max}$ to E_{max}, where E_{max} is the maximum energy transferred by the photon to the electron in the Compton process. As is apparent from Fig. 1, the predominance of Compton electrons in glass is insignificant in the photon-energy region around 200 kev. However, the probability of Compton formation can be greater for the entire cloud chamber. To verify this point we carried out calibration experiments in which the chamber was exposed to an x-ray flux of known energy from a pulsed x-ray tube.

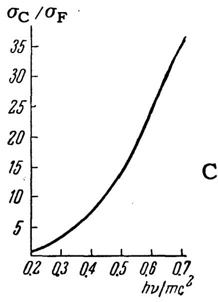


FIG. 1. Ratio for the probabilities of the Compton effect and photoeffect in glass.

3. EXPERIMENTAL SETUP

The pulsed discharges in hydrogen were produced with a bank of twelve capacitors (IM-3/50) totaling 36 μf. The discharges were excited in a porcelain tube 170 mm in diameter and 1000 mm long. In order to reduce the lead inductance of the circuit, the discharge tube was located in a coaxial line and placed directly above the capacitors. The stray inductance of the external circuit was 0.5 μh. The capacitor bank could be charged to 50 kv from a high-voltage supply. The external circuit was closed by triggering a thyratron (cf. Fig. 2). The triggering pulse was obtained from a special system which was controlled by a mechanical synchronizer. After each discharge the tube was evacuated and filled with a new charge of hydrogen gas. The hydrogen was admitted to the discharge tube from a measured volume which was first filled to a known pressure through a nickel filter. Under these conditions a controlled amount of gas could be admitted to the discharge tube regardless of the wall temperature.

The discharges were produced at hydrogen pressures of 6×10^{-2} mm Hg. The maximum x-ray intensity was found at this pressure for the experimental conditions described here. For a pressure of 6×10^{-2} mm Hg and a voltage of 40 kv the peak current was 200 kiloamperes.

The spectrum of the electrons produced by x-ray photons was measured with a cloud chamber with a rubber diaphragm. The chamber diameter was 280 mm and the depth was 80 mm. The chamber was charged with purified air and a water-alcohol mixture (66% alcohol and 33% water) to a pressure of 2 atmos (abs). Illumination was furnished by pulsed lamps (IPK-600). The pictures were taken with a camera with a "Jupiter 1.5" lens. The chamber was triggered simultaneously with the application of the voltage to the discharge tube. The light pulse was delayed with respect to the chamber expansion by means of a special mechanical synchronizing system (Fig. 2). An electronic synchronizing system could not be used because of the interference due to the discharge itself.

It is difficult to follow the tracks produced by high-energy electrons because of the large number of short tracks on the photographs. For this reason, the measurements in the high-energy re-

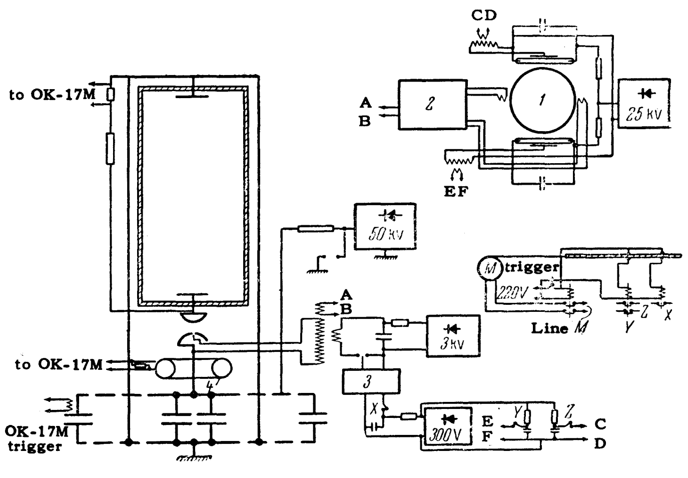


FIG. 2 Diagram of the apparatus. 1) Cloud chamber 2) Control system for the cloud chamber 3) Pulse transformer 4) Rogovskii loop.

gion were made with the cloud chamber shielded from the discharge tube by a thick layer of lead, which is a strong absorber for soft x-rays. The discharge tube was surrounded by lead shields 15 mm thick. Since the maximum x-ray intensity is found close to the electrode which is at the positive potential when the discharge is initiated ("anode"), the cloud chamber was mounted at the same height as the "anode" and at a distance of approximately 1 meter from the axis of the discharge tube.

The time behavior of the discharge was observed with a two-beam pulsed oscilloscope (OK-17M). The current flowing in the main circuit of the pulsed generator was measured with a Rogovskii loop and an RL integrating network. The Rogovskii loop was a toroidal coil which linked the conductor carrying the current. The winding was terminated by a small non-inductive resistance. The voltage across the resistance R is given by the simple formula $V = RI/n$ where I is the current and n is the number of turns in the coil. The voltage from the non-inductive resistance R was applied to one of the pairs of plates of the pulsed oscilloscope. The Rogovskii loop was characterized by the following parameters: $n = 300$ and $R = 0.256\ \Omega$.

The voltage was measured with a low-resistance divider, connected across the discharge tube. The total resistance of the divider was 100,000 ohns. The voltage was fed to the other pair of plates through a 100-ohm resistance. The relative x-ray intensity was measured with a scintillation detector consisting of a FEU-19M photomultiplier and an NaI crystal. The pulse from the multiplier was fed to an amplifier which was specially designed to operate in the presence of the strong interference due to the discharge. The amplifier output was applied to the plates of the oscilloscope; the discharge current or voltage pulse could be applied to the other pair of plates.

The voltage and current pulses and the pulses from the scintillation detector were fed to the oscilloscope through RK-2 cable. All cable connections were carefully shielded. The oscilloscope was triggered from a coil located at the high-voltage input of one of the condensers. A typical current oscillogram and detector pulse are shown in Fig. 3.

The calibration measurements were made with a pulse generator which supplied voltages up to 300 kv. The pulses from the generator were applied to a ZBPM-200 x-ray tube. This tube can be pulsed at 300 kv if it is oil-cooled and operated at reduced filament current (after a suitable period of processing). In order to be sure that the experimental conditions were the same in the discharge experiments and the calibration experiments, the pulsed x-ray tube was shielded by a lead sheet 15 mm thick.

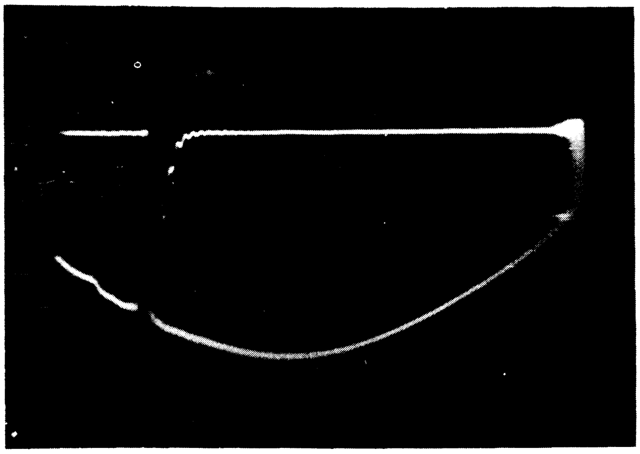


FIG. 3. Oscillogram of the discharge current and the x-ray burst. The total length of the sweep is 20 microseconds.

4. RESULTS OF THE MEASUREMENTS

It is well-known that the intensity of the x-ray bursts varies strongly from discharge to discharge. For this reason simultaneous observations were made of the tracks in the cloud chamber and the pulses from the scintillation detector. If no pulse was observed on the oscillogram the track picture was not used. Thus, in the analysis we excluded track photographs of discharges in which the x-ray yield was small. In some cases the x-ray bursts were so intense that it was difficult to follow individual tracks. Such photographs were also rejected.

Since the tracks were photographed with a single camera the photographs represent the projection of the electron tracks on the plane perpendicular to the optical axis of the camera. If the projected track is highly curved the projected length is $\pi/4$ of the actual length. Curved electron tracks have been studied in reference 7; in this work it has been shown that this correction factor yields a rather high degree of accuracy.

To analyze the experimental data the photographs were enlarged to natural size; the tracks were then traced carefully and the lengths were measured. In order to obtain the true range of the electrons in the chamber the measured track lengths were multiplied by $4/\pi$, as indicated above. The electron energies were determined from an energy-range curve which was plotted using well-known experimental values.

In order to measure the background, the

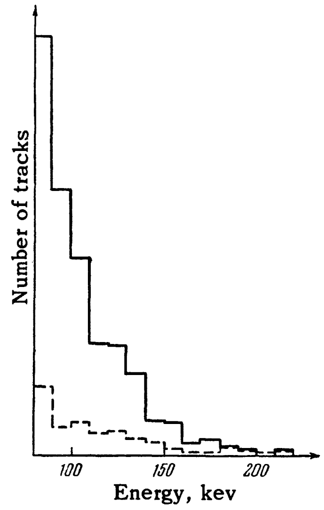


FIG. 4. Energy distribution for the recoil electrons formed by x-rays from a gas discharge.

chamber was operated again after taking each x-ray electron picture, and photographs were made of the tracks due to the cosmic-ray background and the residual radioactivity. A histogram of the energy spectrum of the x-ray electrons from a hydrogen discharge is shown in Fig. 4. The spectrum measured for the background electrons is shown in the same figure (dashed). The same number of x-ray electron track photographs and background photographs were analyzed in plotting these histograms. Of a total of 500 photographs, 189 were found suitable in accordance with the criteria given above.

In Figs. 5 and 6 are shown the calibration histograms for the electron spectra produced in the chamber by x-rays from the pulsed tube. The x-ray tube was pulsed at 240 and 285 kv. The upper limits for the electron energy in these histograms is 120 and 140 kev respectively.

It follows from the theory of the Compton effect that the maximum energy of Compton electrons produced by x-ray photons of 240 and 285 kev is 116 and 145 kev. Within the limits of the present accuracy, these values are in agreement with the experimental results. For these same x-ray energies the maximum energy for photoelectrons ejected from the glass (highest ionization potential approximately 20 kv) is 220 and 265 kev.

Thus, the experimental data indicate that at energies above 200 kev the probability of the Compton effect is considerably greater than the probability of the photoeffect.

An examination of the histogram in Fig. 4 indicates that the upper energy limit for electrons in the cloud chamber is 180 kev for discharges in hydrogen. If we assume that the limiting-energy electrons are Compton electrons, we can find the energy of the x-ray photons. The appropriate calculation indicates that an intense discharge in hydrogen with 40 kv across the capacitor produces x-ray photons with energies of 320 kev. These same experimental data show that the x-ray photons with energies greater than 320 kev represent, on the average, less than 0.1% of the total number of photons from the discharge.

The voltage across the discharge tube was measured by different methods and the results were consistent. The error in all measurements was less than 5%. It may be noted, however, that the upper energy limit was obtained by averaging over a large number of pulses; hence it is possible that the spectrum of an individual discharge may contain photons with higher energies.

5. CONCLUSIONS

A comparison of the experimental data pertaining to neutron and x-ray bursts in intense discharges in deuterium and hydrogen would seem to indicate that the mechanism is the same for both gases.

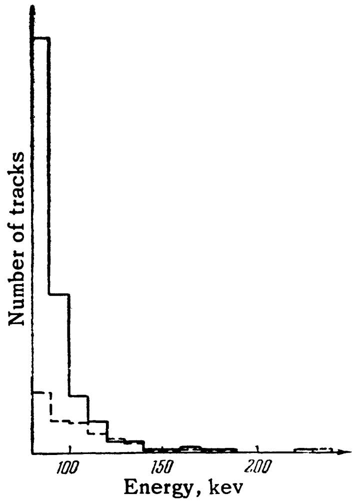
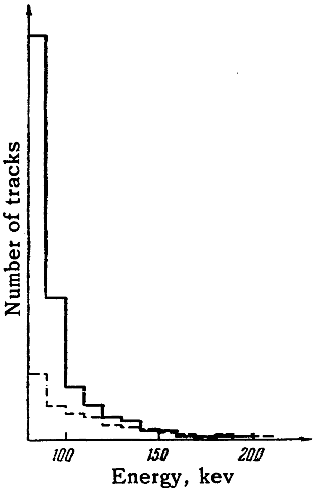


FIG. 5. Distribution of electrons formed by the x-rays from a pulsed x-ray tube.

FIG. 6. Distribution of electrons formed by the x-rays from a pulsed x-ray tube.



It may be of interest to list the presently available experimental facts pertaining to the hard radiation from a gas discharge.

1. The neutron and x-ray bursts are observed at the same time in the development of the discharge.
2. The deuterons associated with the neutrons in a deuterium discharge are accelerated toward the cathode, whereas the maximum x-ray intensity is found in the region of the anode.
3. The x-ray and neutron radiation are observed only for a well-defined region of initial pressures in the discharge tube; this region is the same for both types of radiation.
4. The maximum deuteron energy is estimated as 250 kev. Within the limits of the experimental errors this value is in good agreement with the upper limit of the x-ray spectrum (and consequently the electrons which are produced by x-ray photons) obtained in the present work, which is 320 kev.

All these factors indicate that the neutron and x-ray radiation can not be explained by some type of betatron acceleration mechanism;[8] this conclusion has already been indicated.[1]

The experimental facts indicate that there is a relation between the hard x-rays from intense pulsed discharges and the neutron radiation produced in deuterium discharges. These radiation effects result, apparently, from the production of electric fields along the axis of the discharge tube; these fields accelerate the charged particles (electrons and ions). As has been indicated in reference 1, these electric fields may be produced as a result of the redistribution of current which follows a change in the radius of the discharge column. When certain types of instabilities arise these fields can become very strong; in particular, strong fields can be produced as a result of constrictions in the discharge column.

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