INTERFERENCE EXPERIMENTS WITH SINGLE X-RAY QUANTA

A. A. SANIN, A. V. ZHARKO, V. I. IVERONOVA, A. A. KATSNEL'SON, and V. I. KISIN

Nuclear Physics Institute, Moscow State University

Submitted July 12, 1968

Zh. Eksp. Teor. Fiz. 56, 78—82 (January, 1969)

Reflection of x rays from a crystal at the Bragg angle is investigated. It is demonstrated that the ordinary reflection laws also apply to single quanta (in the absence of correlation) at intensities down to 10^{-1} quantum/sec.

INTRODUCTION

DONTSOV and Baz'[1] observed in their experimental work a deviation from the usual interference pattern in the case of low-intensity light flux.

The complete identity of the interference patterns produced in one case by quanta passing through some instrument singly, i.e., when only one quantum is in the instrument at a time, and in the other case by a flux of quanta of considerable density follows directly from the most fundamental assumptions of quantum mechanics.

It is natural that the attention of investigators has been drawn continuously to the experimental verification of this fact. Dempster and Batho[2] showed that the indicated assumption is in fact justified at a flux intensity of only 95 photon/sec and a wavelength of 4471 Å. Analogous results were obtained by Biberman, Sushkin, and Fabrikant[3] for electrons with a flux density of 4.2×10^3 electron/sec, by Jánossy and Naray[4] for photons with a flux density of 10^5—10^6 photon/sec, and by others.

However, Dontsov and Baz'[1] experimenting with a Fabry-Perot interferometer at a lower intensity limit of 2×10^2 photon/sec found that if the decrease of the intensity is attained by decreasing the density of excited atoms in the light source or by attenuating the beam by means of a gray filter then the contrast of the interference pattern decreases sharply; if, on the other hand, the intensity decrease is obtained by covering the beam with a diaphragm the interference remains the same as at the higher flux density.

This paradoxical result is explained by the authors as follows. According to their view interference is produced only by correlated quanta. In all the preceding experiments the quanta passed through the instruments not singly but in groups; the same occurred in the experiments of these authors when the density of the primary beam was decreased with the aid of a diaphragm. On the other hand, when the authors decreased the intensity with the aid of a gray filter or by decreasing the density of excited atoms, they really obtained single photons, as a result of which an abrupt weakening of the interference pattern took place.

This explanation encounters, in our opinion, serious difficulties which we shall discuss below. However, on the other hand, preceding papers in fact did not show clearly that interference is also observed in the absence of correlated quanta.

We have undertaken the present investigation in order to resolve this contradiction.

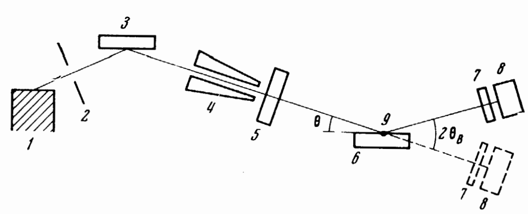
In order to check whether only correlated quanta are in fact able to produce interference, it is logical to make use of a radiation detector which would make it possible to determine whether the quanta incident on it are single, or grouped in twos, threes, etc., and which would record these selectively. We decided, therefore, to transfer our investigation to the x-ray region using as the detector a scintillation counter which with the usual parameters of the crystal, the photomultiplier, and the electronic circuit should, as is readily seen, for an incident group of n quanta yield a signal n times larger than the pulse obtained when a single quantum acts on the counter.

An additional advantage in going over to the x-ray region was the possibility of working at appreciably lower intensities on account of the comparatively low intrinsic noise level and high counting efficiency.

In addition, corpuscular properties appear more strongly and wave properties more weakly with increasing energy of the quanta. If one is therefore able to find normal interference for single quanta in the x-ray region then it should exist all the more in the optical region.

EXPERIMENT

The schematic diagram of our setup, analogous to that in[1], is shown in the figure. The radiation source 1 was a BSV-2 x-ray tube with a copper anode. A fixed crystal 3 of a double-crystal spectrometer assembled from a URS-60 setup and a GUR-3 goniometer placed before the entrance hole of the collimator served as a monochromator. The function of the multiple-wave interferometer in[1] was fulfilled by the analyzer crys-



Double-crystal x-ray spectrometer in the (1, -1) setting: 1 — anode of the BSV-2 tube, 2 — enterance slit of the monochromator, 3 — monochromator crystal, 4 — collimator, 5 — filter No. 1, 6 — analyzer crystal, 7 — filter No. 2, 8 — SRS-1-0 scintillation counter, 9 — axis of rotation of the crystal.

tal 6 mounted on the single-crystal attachment of the goniometer table. Both crystals were cut from a large single crystal of germanium with a dislocation density $\lesssim 10^3$ cm^{-2}. The dimensions of the monochromator were $10 \times 10 \times 0.5$ mm; the analyzer was in the form of a disc with a diameter of 5 mm and 0.5 mm thick. The surface of the cut was parallel to the crystallographic (111) plane.

Because of the high degree of perfection of the crystals, the beam incident on the analyzer 6 at an angle close to the Bragg angle θ_B had a horizontal divergence which did not exceed 1′ (total width of the rocking curve) for each line of the Cu Kα doublet. The intensity I_2 of the beam reflected by the analyzer depends on the angle of incidence θ. For a small rotation of the crystal 6 about the axis 9 $I_2(\theta)$ produces the so-called rocking curve which has a maximum at the position at which the (111) planes of crystals 3 and 6 are strictly parallel. The rocking curve can be described by the half-width $\Delta\theta$ and by the reflection coefficient $R = I_{2\,max}/I_1$ where $I_{2\,max}$ is the intensity of the reflected beam at the maximum of the rocking curve, and I_1 is the intensity of the monochromatic radiation incident on 6 measured with the analyzer removed from the beam. For sufficiently perfect crystals R is close to unity and $\Delta\theta$ measures some tens of seconds of arc. In our device we used the (111) reflections of both crystals in the $(1, -1)$ setting. In this case the rocking curve has no dispersion and its parameters do not depend on the source dimensions and on the angular divergence of the beam before the first crystal.[5]

The intensity of the incident and diffracted beams was registered by a SRS-1-0 scintillation counter connected to a SSD registration circuit. The rocking curves were recorded by a ÉPP-09 potentiometer with the counter stationary and the analyzer rotating at a constant rate of 26.5″ per minute. This low rate of turning was achieved by introducing an additional 1 : 137 reducing gear into the GUR-3 rotation mechanism. With the chart of the recorder moving at a rate of 1440 mm/min, the instability in the operation of the double reducing gear led to an error in the determination of $\Delta\theta$ from the record of no more than 2″. The position of the maximum of the rocking curve was determined with an accuracy of 30″. The setting and width of the differential discriminator were chosen such that only single quanta were recorded. The counting time required for a given accuracy for signals comparable with the noise level was determined by the standard method.

A decrease of the intensity of the photon beam was achieved by either decreasing the anode current and the voltage of the x-ray tube or by introducing the filter 5 (see the figure) into the beam between the crystals. Aluminum, copper, and nickel foils and organic glass with an attenuation factor up to 1×10^4 were used as filters. The dead time of the recording system amounted to $\sim 2 \times 10^{-6}$ sec; therefore, when measuring intensities greater than 10^4 photon/sec we placed before the counter an additional calibrated attenuator 7 (aluminum foil with an attenuation factor of 1×10^3).

The long-term instability in the operation of the x-ray tube and the inaccuracy in reproducing the analyzer setting at the maximum of the reflection led to an error of no more than 5 percent in the determination of R. The method of detection made it possible to cover a range of intensity variation from 1×10^{-1} to 2×10^6 photon/sec, whereas the x-ray apparatus made it possible to control the beam intensity after the first crystal only within the range of $2 \times 10^1 - 2 \times 10^6$ photon/sec. Further weakening of the flux density was achieved by means of filters. However, it was to be expected that the appearance of small-angle scattering would decrease R and would on increasing the filter thickness produce a false effect of decreasing R with the intensity. In order to check this assumed "filter effect," we placed between the crystals aluminum foil with an attenuation factor of about 1×10^4 and, by changing the operating conditions of the x-ray tube, measured $R(I_1)$ in the range $1 \times 10^{-1} < I_1 < 4 \times 10^2$ photon/sec. The curve had a common section with the dependence obtained without the filter in the range of $2 \times 10^1 - 4 \times 10^2$ photon/sec. Since these two curves were in good agreement on their common section, we obtained the entire $R(I_1)$ dependence in the range $1 \times 10^{-1} < I_1 < 2 \times 10^6$ photon/sec by successive introduction of filters with constant operating conditions of the tube.

According to conventional ideas, neither the reflection coefficient R nor the width of the reflection range $\Delta\theta$ should depend on I_1. If, on the other hand, the effect described in[1] is observed in the x-ray region, then the $R(I_1)$ curve should exhibit a decrease and $\Delta\theta(I_1)$ an increase on attenuating I_1 down to sufficiently low values.

The experiment showed that in the entire investigated range of I_1 the reflection coefficient retains a constant value $R = 0.43 \pm 0.03$. The half-width of the rocking curves was measured in the range of $10 - 2 \times 10^6$ photon/sec. It also turned out to be constant and amounted to $\Delta\theta = (28 \pm 2)''$ without depending on the material and thickness of the filter.

As has already been noted in the Introduction, in all papers, with the exception of[1], no attention was paid to the question of the correlation of quanta. If it is assumed (see[6]) that the deviation of the distribution of the number of pulses recorded in a given time interval from a Poisson distribution is a criterion of the presence of correlation, it appears necessary to check this phenomenon. The distributions were obtained with unfiltered radiation after the first crystal for $I_1 \sim 40$ photon/sec, and with the radiation after the beam passing through a hundredfold aluminum filter for $I_1 \sim 10$ photon/sec.

From the obtained curves we determined the ratio of the dispersion D to the mean number of recorded pulses $\overline{N}$, $\alpha = D/\overline{N}$. It turned out that for samples of $\overline{N} \sim 30 - 40$ pulses used in[1] the value of α is determined very inaccurately: $0.6 < \alpha < 1.3$. With samples of $\overline{N} \sim 170$ pulses α had in both instances a value in the range of 0.8–1.0, and on increasing the samples it approached unity, the value characteristic for a Poisson distribution. It can be maintained that the tendency towards $\alpha > 1$ predicted in[6] for a correlated beam was not observed either before or after the filter.

An investigation of the pulse-height distribution due to quanta proceeding from the monochromator to the analyzer in the absence of a filter showed that if there are correlated quanta in the beam then, at any rate, their number is less than 10^{-6} of the total number of quanta.

DISCUSSION

It can be shown that when a filter is used the percentage of correlated quanta should decrease by a factor of

$$\sum_{k=2}^{n} \binom{k}{n} (-1)^k (k-1) a^{k-1} \qquad (1)$$

where a is the transmission factor of the filter and n is the number of quanta in the group. Apparently the probability that the quanta are correlated in groups of more than two quanta is extremely small. Assuming that pairs of quanta are correlated, we find from (1) that the percentage of correlated quanta should decrease by a factor of a. The maximum filter factor in our experiments amounted to 10^4. In this case the number of correlated quanta was no more than 10^{-10} of the total number of quanta.

On the other hand, we see no other way of explaining the narrowness of the rocking curve except by interference when reflected from a large number ($\sim 10^4$) of atomic planes.

Thus for the x-ray region one can consider the untenability of the assumption that only correlated quanta interfere experimentally proven.

It is hardly possible to explain the contradiction between the data of[1] and this conclusion by assuming that the quanta of the optical and soft x-ray region behave differently, since it appears to us to be extremely improbable that such fundamental properties of quanta as the capability of single quanta to interfere should depend on a wavelength change of 3—4 orders of magnitude.

In addition, an analysis of[7] in which the same type of source as in[1] was in fact used shows that the number of correlated quanta in the optical region also amounts to about 10^{-5} of their total number without the use of filters. The fraction of correlated quanta in the beam incident on the Fabry-Perot interferometer in[1] should according to (1), which is also valid in this case, be even smaller on account of the decorrelation of the beam in reflection by lenses and by the monochromator prism.

It is therefore unrealistic to assume that the presence or absence of an interference pattern is determined by this negligible fraction of correlated quanta while the non-correlated quanta which constitute the overwhelming majority do not participate in the interference (and also, on the other hand, do not give rise to a uniform illumination of the screen on the electro-optical converter).

The data of[1] also contradict the data of[2]. Indeed, the minimum density of excited atoms in the source described in[1] amounted to $\sim 10^2$ atom/cm^3. Even if it is assumed that the volume of the portion of the tube whose light enters the monochromator amounts only to 10^{-1} cm^3 (it is in fact apparently larger; the total volume of the gas in the lamp as calculated from the data of this paper was $\sim 5 \times 10^2$ cm^3) this means that during an emission time of 5×10^{-8} sec this volume emits in the course of a second 2×10^8 photons. With this the authors report that the interference pattern disappears. Yet in another series of experiments in[2] the density of excited atoms is so low that the source emitted only 1.9 $\times 10^5$ quanta/sec and interference was nevertheless clearly observed.

Let us note that the check of the correspondence to the Poisson distribution carried out in[1] is not very convincing because of the somewhat small samples—between 15 and 30 frames and 20—30 flashes per frame.

Considering the above it appears to us that the results of[1] should undergo a careful check.

From the results of this work there follows the unambiguous conclusion that single x-ray quanta interfere exactly as do quanta in the case of an appreciable flux density, or according to Dirac's expression: "Each photon interferes only with itself. No interference ever takes place between two different photons."[8]

The authors express their great gratitude to Professor M. M. Umanskiĭ, I. V. Éstulin, and Assistant Professor T. A. Sanina for fruitful discussions.

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Translated by Z. Barnea
10