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The scattering of X-rays and the induction phenomenon

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Abstract : This paper discusses the well-established Faraday's Law of Induction and the associated Lenz's law and compares these laws with a similar law which appears to exist in the triplet production process achieved by bombardment of emulsion with 0–90 Mev X-rays. This comparison shows that an induction-like process occurs during triplet production, leading to the supposition that a force which may be called the 'Matteromotive force' exists for triplet production. An associated Lenz's-law-like law also appears to exist in this process. For this study, 1935 triplets were observed in 54433 fields of view of the microscopes, out of these, 1872 triplets were measured in the energy interval of 2–90 Mev In addition, the angular distribution of recoil electrons was observed, and is presented here

Keywords : Scattering of X-rays, induction phenomenon, triplet production

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1. Introduction

As is well known, Michael Faraday (1791-1867) carried out the detailed experiments that led to Faraday's law of induction. He showed that when the magnetic field through a closed loop of wire changes, a current flows in the loop. This is a transient current that exists only as long as the magnetic field continues to change. Since currents are caused to flow through ordinary wires by sources of electric energy such as batteries, he concluded that the changing magnetic field causes an emf to exist in the coil. He called this emf the 'Induced emf'. The Faraday experiments, done with a coil of wire connected to a galvanometer, are shown in Figure 1.

Faraday pointed out that in the experiments of Figure 1, a current flows through the coil only when the magnet is moving. He observed a battery effect, an induced emf, that occurs in the coil each time the strength of the magnetic field in the region of the coil is changed. The emf exists, and the current flows, only when the change is occurring. This change depends on the relative motion of the coil and magnet, as shown in Figure 1.

By analogy with the electric field lines and the electric flux of Gauss's law, we can write change in magnetic flux

$$\Delta\Phi_{\text{magnetic}} = (B\cos\theta)\Delta A = \boldsymbol{B}\cdot\Delta\boldsymbol{A}. \quad (1)$$

where θ is the angle between magnetic field vector $\boldsymbol{B}$ and area vector $\Delta\boldsymbol{A}$.

Thus, the total flux is

$$\Phi_{\text{magnetic}} = \int_{area} \boldsymbol{B}\cdot\Delta\boldsymbol{A}, \quad (2)$$

where the integral is taken over the area in question. With this meaning of flux in mind, we now look at Faraday's experiments in Figure 1. From his detailed experiments shown in Figure 1, he showed that the induced emf ε which appears in the coil of wire containing N turns (loops) is

$$\varepsilon = -N\,(d\phi_{\text{magnetic}}/dt) \quad (3)$$

where ϕ_{magnetic} is the magnetic flux through the coil. For a single turn, this equation can be written as

$$\oint \boldsymbol{E}\cdot d\boldsymbol{l} = -d/dt\int \boldsymbol{B}\cdot d\boldsymbol{A} \quad (4)$$

Consequently, change is at the heart of induced emf.

We now examine the direction in which the induced

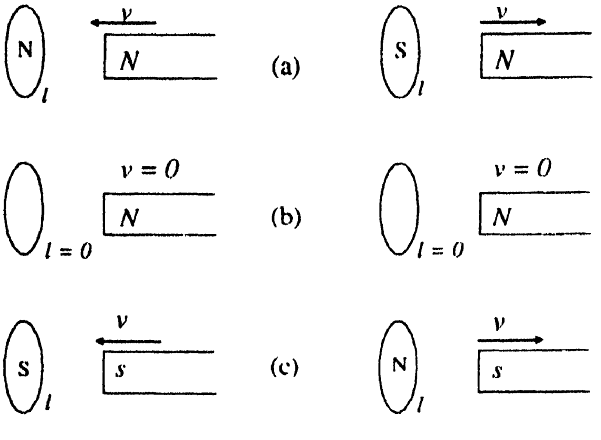


Figure 1. (a) As the north pole of a bar magnet moves towards a circular coil, a current is induced in the coil in a counterclockwise direction; the current is induced in a clockwise direction when the north pole moves away from the coil. (b) When there is no motion of the bar magnet relative to the coil, there is no current in the coil. (c) When the south pole of a bar magnet moves toward a circular coil, a current is induced in the coil in a clockwise direction; the current is induced in a counterclockwise direction when the south pole moves away from the coil.

current is flowing in Faraday's experiments. The magnetic field produced by the induced current in the coil is in such a direction as to minimize or oppose the external change of flux through the coil. When the flux through the coil is increasing towards the right, the induced current causes a flux towards the left in an effort to cancel the increasing leftward flux. This phenomenon can be stated in the form of a rule:

A change in flux through a loop will induce an emf in the loop. The direction of the current produced by the induced emf will be such that the flux generated by the current will tend to oppose the original change in the

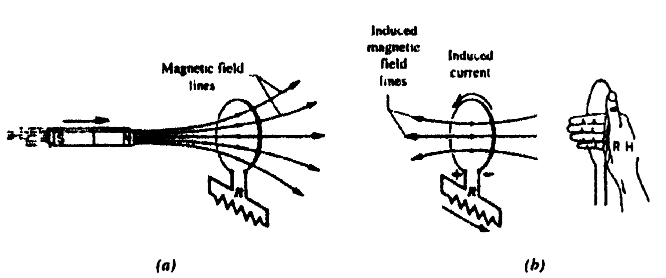


Figure 2. (a) As the north pole of the bar magnet moves to the right, the magnetic flux through the loop increases. The external circuit attached to the loop has a resistance R. (b) To oppose the increase in flux, the direction of the induced magnetic field must be opposite to that of the north pole of the bar magnet, and must pass through the loop from right to left. To create such a field, the induced current must be counterclockwise around the loop, when viewed from the side nearest the magnet. The polarity of the induced emf is indicated by + and − symbols.

This experimentally observed law is known as Lenz's law. Further, Figure 2 shows that the induced emf causes the solenoid to generate a field much like that from a bar magnet. The north pole of this induced magnet is positioned so that it opposes the motion of the north pole of the bar magnet towards the solenoid. Thus, the induced north pole of the solenoid repels the approaching north pole of the bar magnet. A similar situation exists in Figure 1. In this sense too, the induced emf opposes the change that is occurring. Therefore, Lenz's law is stated as follows .

The induced emf is in such a direction as to oppose the change that causes it.

This approach shows that the energy resident in the induced emf is provided by the work done by the agent causing the change – the person moving the magnet in this case.

For comparison of this process with triplet production (*i.e.*, pair production in the matter field of an electron), the experimental arrangement and the results thereof are described below. Since a visual method of detection is particularly well suited to such studies, a nuclear emulsion technique was used to record the events. Although the method is quite laborious, it has the advantage of providing a permanent record of the events which can be inspected and measured at convenience. Triplet production has also been studied [1-3] by the absorption method in the $10 \leq E \leq 300$ *Mev* photon energy range. The absorption technique, however, does not permit such detailed studies as momentum and angular distribution of the recoil electrons.

Theoretical calculations on the momentum distribution by Suh and Bethe [4] have made such studies significant. Hart *et al* [5] using a hydrogen filled diffusion chamber and photons of energy 10 Mev to 1 Gev, have shown that the experimental momentum distribution curves above 100 Mev incident photon energy agree well with those predicted by Suh and Bethe. Below 100 Mev, however, the experimental results differed from those of the theory, and the difference increased with increase of the recoil momentum. More statistically accurate results published by Gates [6] using a hydrogen bubble chamber and photon energies between 2 Mev and 323 Mev essentially confirmed the above observations. Hart *et al* and Gates also studied the angular distribution of the recoil electrons. At present, no theoretical calculations of the angular distribution are available for comparison with experiment.

Our experiment on triplet production was performed with photon energies between 2 Mev and 90 Mev, the region in which the two previous workers reported disagreement with theory.

2. Experimental details

Electron-sensitive Ilford G-5 nuclear emulsion plates of size 1 inch × 2 inch × 400 μ were bombarded by a hardened continuous Bremstrahlung spectrum of maximum energy 90 Mev at the National Bureau of Standards (from 2000, NIST) electron synchroton, Washington D.C. The hardening of the beam was achieved by placing carbon absorbers (2" in diameter with thickness 496.43 gms/cm^2) in the path of the beam. These absorbers were used to eliminate the low energy photons for which the Compton and photoelectron cross sections were high. The background noise was thus appreciably reduced in the nuclear emulsions, and studies of the triplets became possible.

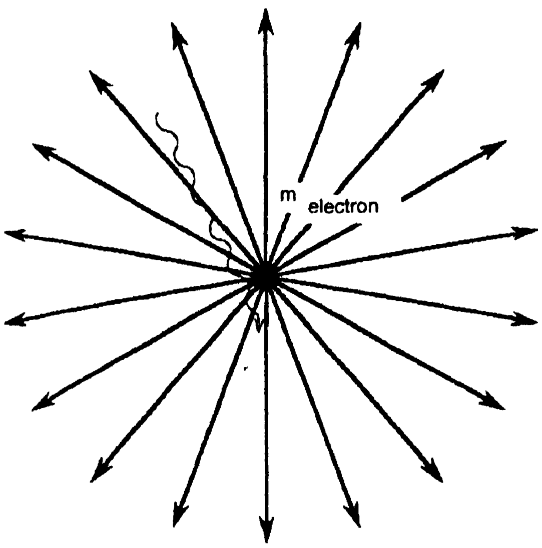
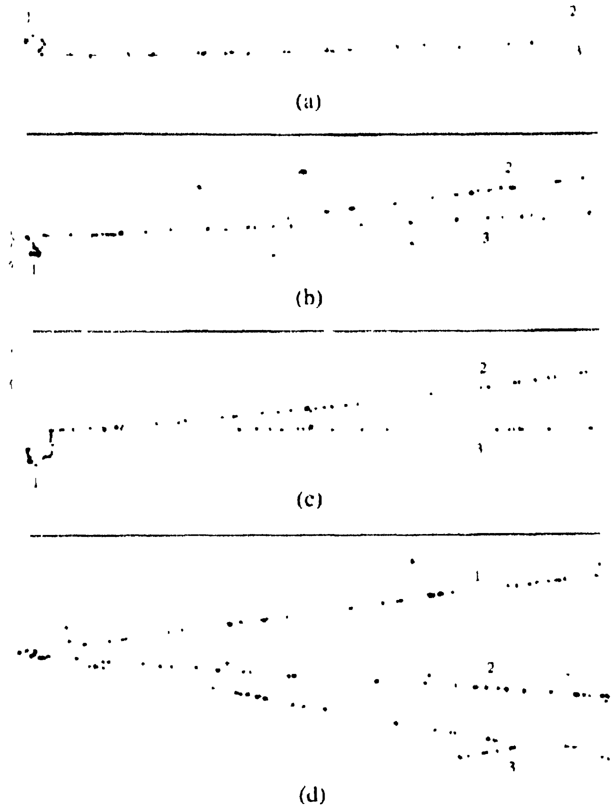


Figure 3. As the photon moves closer to the electron (thus deeper into the matter field), the matter flux experienced by the photon increases. This rate of change of matter flux leads to an induced force (the 'matteromotive force') which results in induced positron (antimatter) production (*i.e.*, a positive electron whose flux decreases the effect of the increasing matter flux due to the target electron crossed by the photon).

A series of plate exposures were made to ascertain optimum exposures. This was needed to obtain a suitable number of triplets per field of view of the microscope and, at the same time, to maintain the signal to noise ratio at such a level as to make the events easily distinguishable. The plates were developed by the temperature development technique [7] and were examined on a Leitz ortholun microscope. The energy of the photon producing a triplet was determined by estimating the kinetic energy of the tracks using Fowler's coordinate method [8], taking into account the energy needed for threshold triplet production. By convention, the smallest partner of a triplet was taken to be the recoil electron. The energy of the recoil electron was usually small and its energy was determined from the range energy relationship [9]; in a few cases, the energy of the recoil electron was ascertained from multiple scattering measurements. For studies of angular distribution of the recoil electron, angles were read by a goniometer attached to the microscope; the estimated total angular error was ± 5°. Typical examples of some triplets are shown in Figure 4. Track 1 caused by recoil electron. Tracks 2 and 3 are due to electron, positron pair.



Typical examples of triplets
Track direction left to right, energy increases (a) to (d)

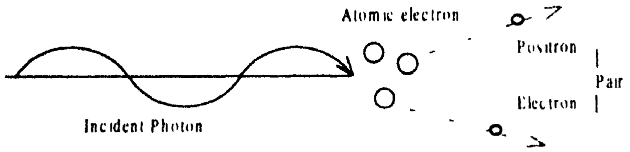
Figure 4. (a),(b), and (c) show the photon as it crosses an increasing matter flux due to the atomic electron (*i.e.*, as it experiences increasing matteromotive force) and converts into a positron and another electron
(d) The incident photon now has enough energy to free the bound electron which moves in the forward direction with the pair created by the matteromotive force

3. Results and discussion

54433 fields of view of the microscopes were examined. The volume of each field of view was $120\mu \times 150\mu \times 220\mu$. A total of 1935 triplets was observed, 1872 of them being measured. The remaining 63 triplets could not be measured because they were scattered out of the emulsion.

Typical examples of some triplets (Figure 4), are taken from the triplets produced by photon energies E = 10–90 Mev. Only a very small number of events were observed below 10 Mev photon energy, and they were not considered further. When an X-ray within this energy range is incident on an electron (Figure 3), the photon crosses a lot more matter lines of force when it is closer to the electron than when it is at a greater distance from it. Therefore, there is a rate of change of matter flux leading to what we term as the 'induced matteromotive force, (mmf). This mmf acting across the photon, produces a positron (antimatter)–electron (matter) pair. In this process, the participating electron experiences recoil, which is generally small; its magnitude was determined from the range/energy relationship.

The presence of the target electron is necessary for materialization of the X-ray (*i.e.* transformation of the X-ray into an electron-positron pair) in the field of the electron in order to conserve energy and momentum in the transformation. Since the recoil is absorbed by the target electron, the threshold required by the conservation of energy and momentum in the laboratory system is $4m_0c^2$. Since two electrons and a positron acquire momentum, the system is known as a triplet ($m_0c^2 = 0.51$ Mev is the rest mass of the electron).



A schematic representation of pair production in the matter field of an electron is shown above. The incident photon materializes into an electron-positron pair as a result of the induced matteromotive force (mmf). Thus, as shown in Figure 3, the rate of change of matter flux causes the materialization of the X-ray in the matter field of the target electron. Figures 4(a), (b), (c), and (d) are typical triplets.

The existence of this mmf is further supported by the occurrence of a Lenz's law-like law during triplet production. In analogy with Faraday's induced electromotive force, this induced emf is such that it opposes that which creates it (*i.e.*, this matteromotive force creates a positron (antimatter)–electron (matter) pair). The antimatter field tries to diminish the effect of the matter field due to the electron on which the photon is incident; thus, the matter destroying antimatter created by the matteromotive force mimics the existence of a Lenz's law-like law in the triplet production process shown in Figure 4.

This Lenz's law-like law is expressed below in eq. (5). The matteromotive force '*M*' is proportional to the rate of change of matter flux ϕ_m. If the flux ϕ_m across the length of the photon (as it travels towards the target electron) in the matter field of the electron changes by the amount $d\phi_m$ during a time dt, the average induced matteromotive force can be written as

$$M\alpha - d\phi_m/dt \Rightarrow M = -(d\phi_m/dt). \quad (5)$$

The minus sign in eq. (5) indicates that the induced matteromotive force produces a positive electron (antimatter) which destroys the matter (electron) instrumental in creating it. (Figure 4).

Let a quantity G be the matter flux density. Let dl be the separation between the ends of a segment of the photon path length. Between the ends of this segment, a matteromotive force ΔM exists. The sum of all these ΔM's along the entire length of the photon is equal to the matteromotive force, namely $-d\phi_m/dt$ is expressed as $\Sigma\Delta M = -d\phi_m/dt$. Thus, when the sum extends over the entire photon path length, one can express it as

$$\int_l M \cdot dl = -\frac{d}{dt}\int G \cdot dA \quad (6)$$

where the integral to the right extends over the area covered by photon cross section, G is the matter flux density and dl is an infinitesimal segment of the photon path length.

The angular distribution of recoil electrons in triplet production [10-14] is described below and is shown in Figure 5.

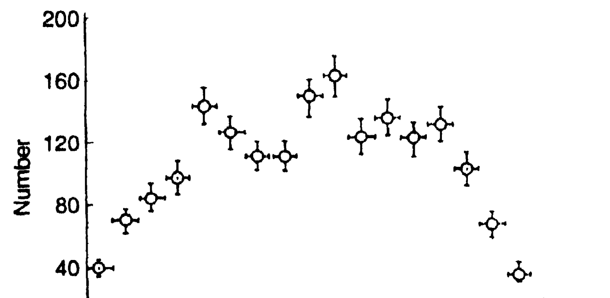


Figure 5. Angular distribution of recoil electrons. The space angle δ between the direction of emission of recoil electron and incident photon is plotted along the abscissa and the number of events is plotted along the ordinate.

From the measurement of the projected angle γ and a calculation of the dip angle from the measured range and depth of the track, the cosine of the space angle has been determined from the relation $\cos\delta = \cos\gamma\cos\beta$, where δ and β are, respectively, the space and the dip angle of the recoil electron. Figure 5 is a plot of the number of recoil electrons *versus* space angle δ. All the events observed for photon energies between 10 and 90 Mev are combined to plot the curves. This is admissible because the angular distribution is virtually independent of photon energy.

If the triplets are produced in the field of free electrons, then from consideration of the kinematics, the recoil electrons must be emitted at angles less than 90°. However, the experimental curve shows nearly equal concentrations of points in the forward as well as in the backward directions. This may be due to two factors : (a) scattering of recoil electrons in the emulsion and (b) the effect of binding energy of the recoil electron. It is extremely difficult if not impossible to take into account the scattering of very low-energy recoil electrons in the composite elements of the emulsion. The effect of binding energy of the recoil electron on its direction of emission was pointed out by Hart and co-workers [5]. If the energy of the recoil electron is much greater than the binding energy of the atomic electron in whose field the triplets were produced, then the electrons can be considered free, in which case most of the recoil electrons should be emitted in the forward direction. These conditions were realized in the experiments of Hart *et al* [5], and Gates [6], and also approximately in the present experiment (if the recoil electrons of energies ≥ 15 kev are rejected in the plot) A curve was plotted (but not reproduced here) taking into consideration only those recoil electrons whose energies were ≥ 15 kev. The curve showed that ~77% of the recoil electrons were emitted in the forward direction. However, if the triplets are produced in the field of bound electrons, as would be the case in the present experiment when very low energy recoil electrons are included, then one might expect backward emission.

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