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Development of X-ray Polarimeter by Detecting Secondary Fluorescent X-rays

By

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Summary: A new kind of X-ray polarimeter, which was successfully operated below 2 KeV X-ray, is described. The angular distribution of secondary fluorescent X-rays emitted in the process of photoelectric effect is expected to exhibit an asymmetry correlated with the polarization vector of the initial X-ray. This asymmetrical behavior is utilized for polarization measurement.

I. INTRODUCTION

A positive test of the hypothesis that the X-ray emission from some celestial objects is produced by synchrotron radiation is provided by the polarization measurement of the X-ray continuum. In fact Columbia group has attempted to observe X-ray polarization in Sco X-1 and the Crab nebula [*1*]. Their experiment has given a positive result of polarization of (15.4 ± 5.2) % in the X-ray continuum of the Crab nebula. In their experiment the measurement of polarization was performed by detecting the asymmetry in Thomson scattering of X-ray. At the same time, the polarization dependence of reflection at the Breuster angle was utilized to work in Bragg reflection. Below 5 KeV Thomson scattering method, however, becomes difficult to apply because of absorption of X-ray in the scatterer. Though Bragg reflection method has a high analyzing power, one given crystal is useful in the narrow energy region where the Bragg condition gives the Breuster angle.

A new kind of X-ray polarimeter, which was tested in laboratory below 2 KeV X-ray, is described in this report. In the process of photo-elecctric effect a secondary fluorescent X-ray is often accompanied with decay of the excited atom. The asymmetrical behaviour of this secondary X-ray emission is utilized for the polarization measurement. One of the advantages of this method is that it has an approximately constant quantum efficiency in relatively wide band including the ≤ 5 KeV range.

II. ANGULAR DISTRIBUTION OF FLUORESCENT X-RAY

As long as the incident radiation is approximated by a plane wave, the interaction Hamiltonian, H, of photo-electric effect is reduced to a simple form with respect to the integration of angle [2],

$$H \propto \int e^{i\vec{q}\cdot\vec{r}} P_e \phi d^3r \tag{1}$$

where ϕ is the wave function of the orbital electron which contributes to the reaction, P_e is the projection of the momentum of the photo-electron to the polarization vector and $\vec{q}$ the recoil momentum of the atom. When we take the quantization axis of magnetic quantum number, m, of ϕ in the direction of the recoil momentum $\vec{q}$, the factor $P_e \cdot \exp(i\vec{q}\vec{r})$ does not include azimuthal angle ϕ. Accordingly the component of ϕ with $m=0$ only contributes to the integration. The fluorescent X-ray which we are interested in is the radiation emitted by the atom when this $m=0$ level is reoccupied by the electron initially in the outer shell of the atom.

In the limit of non-relativistic approximation, the recoil momentum of the atom $\vec{q}$ is obtained as

$$\begin{aligned}\vec{q} &= \vec{k} - \vec{p} \\ &\fallingdotseq -\vec{p},\end{aligned}$$

where $\vec{k}$ and $\vec{p}$ is the momentum of the incoming X-ray and of the emitted photo-electron respectively. So we get the angular distribution of $\vec{q}$ by calculating the yield of photo-electric effect as a function of $\vec{p}$. From the interaction Hamiltonian (1), we infer that the angular distribution is proportional to $P_e^2 = p^2 \sin^2\theta \cos^2\phi$. In fact by putting the wave function of orbital electron as the one given by a hydrogen-like atom, we get

$$\frac{d\sigma}{d\Omega} \propto \frac{\sin^2\theta\cos^2\phi}{(1-\beta\cos\theta)^6} \fallingdotseq \sin^2\theta\cos^2\phi \tag{2}$$

for $2s$ electron excitation and for $2p$ electron excitation, where β is the ratio of electron velocity to the light velocity, and the angles θ, ϕ are referred to as illustrated in figure 1. From these relations we know that the momentum of the photo-electron and that of the recoiled atom are preferentially taken in the direction of the polarization vector of the incoming X-ray. The state of $m=0$ has an asymmetrical form, in which the orbital electron distributes almost along the quantization axis or the direction of the polarization vector of the primary X-ray. This vacant level of the orbital electron induces emission of fluorescent X-ray or emission of Auger electron from the atom. Since the process will be well described by electric dipole radiation, the electrons initially in $3s$ ($3p$) state will fall into the $2p$, $m=0$ ($2s$) level for $2p$ ($2s$) excitation. The moment of this dipole radiation in $3s$ to $2p$ transition lies preferentially in the direction of the initial polarization vector because of the asymmetric form of $m=0$ state. The angular distribution of electric dipole radiation has a form of $\sin^2\theta$. Combining this distribution and the recoil momentum

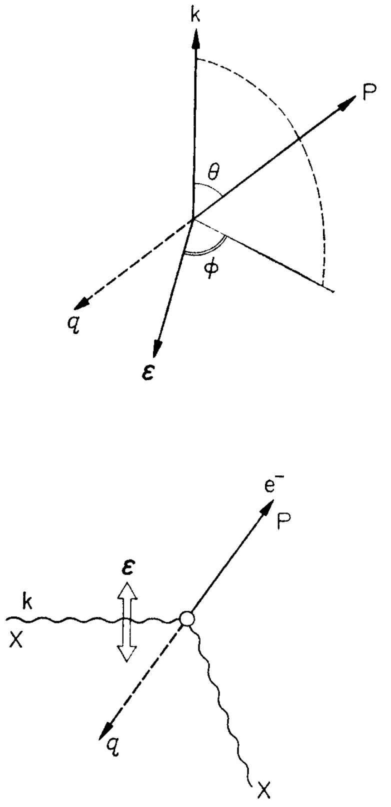


FIG. 1. Definition of angles θ, ϕ.

distribution of the expression (2), we get the angular distribution $f(\theta, \phi)$ of the fluorescent X-ray of 3*s* to 2*p* transition as

$$f(\theta, \phi) \propto 2 - \sin^2\theta \cos^2\phi \qquad (3)$$

It is clearly seen that this distribution gives a larger number of fluorescence counts in the direction perpendicular to the polarization vector of incident X-rays, than the events in the parallel direction. The actual asymmetry of the angular distribution is, however, weakened because of the symmetrical contributions of 3*p* to 2*s* transition, which in the following estimation is put as large as the one from 3*s* to 2*p* transition [3]. The expected asymmetry ratio A is defined by $(N^0_\perp - N^0_\parallel)/(N^0_\perp + N^0_\parallel)$, where $N^0_\perp$ and $N^0_\parallel$ are counting rates for 100% polarized X-ray to the perpendicular and parallel directions to the polarization vector respectively. For the structure of the detection system described in chapter III, we get $N^0_\perp$ and $N^0_\parallel$ by integrating the angular distribution of fluorescent X-rays from $\phi = \pi/4$ to $3\pi/4$ and from $\phi = -\pi/4$ to $\pi/4$, respectively. In this way the ratio A is calculated as 0.10 in the present experiment.

Most of the excited atom lead to the emission of Auger electrons instead of fluorescent X-rays. The probability of the fluorescence yield has been measured

11% and 1% for argon *K*-shell and *L*-shell, and 67% and 8% for krypton *K*-shell and *L*-shell levels, respectively [*4*]. Since the fluorescence energy for a certain designated level increases with *Z*, the atomic number, the probability increases with *Z*. For xenon gas, the fluorescence yield of *L*-shell attains to 21%. In order to apply the present method, the incident X-ray energy should lie between the *K*-shell and *L*-shell excitation energy. Accordingly in the low energy range below 10 KeV, we are obliged to use argon or krypton gas in spite of their small values of fluorescence yield.

III. EXPERIMENTAL APPARATUS

(1) *Proportional counter*

The construction of the gas proportional counter is illustrated in the figure 2. The tube is composed of five regions, each of which is independently operated as a gas proportional counter. The one located at the center measures the escape peak of incident X-rays, or the incident X-ray energy from which the L-shell ionization energy of the gas is subtracted. Fluorescent X-rays are emitted in this center counter. Surrounding four counters detect fluorescent X-rays. Their electric fields are shielded by brass plates from each other and by a cylindrical sheet of stainless steel mesh from that of the center counter.

(2) *X-ray source*

An electron gun for the commercial television cathode ray tube is utilized to produce an electron beam, which is directed to a thick aluminum target. A part of the bremsstrahlung X-ray produced at the target is fed through a collimator into the center counter along the central axis. Though the incident X-ray has a continuous energy spectrum, the individual X-ray energy can be measured by the

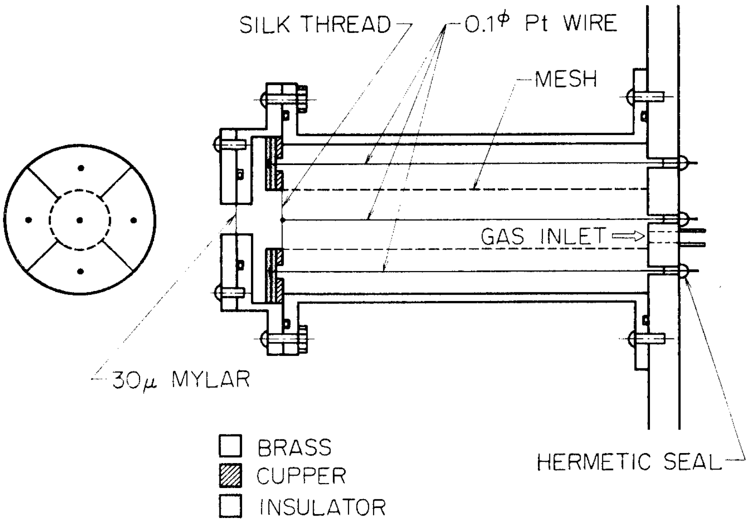


FIG. 2. The structure of the detection system.

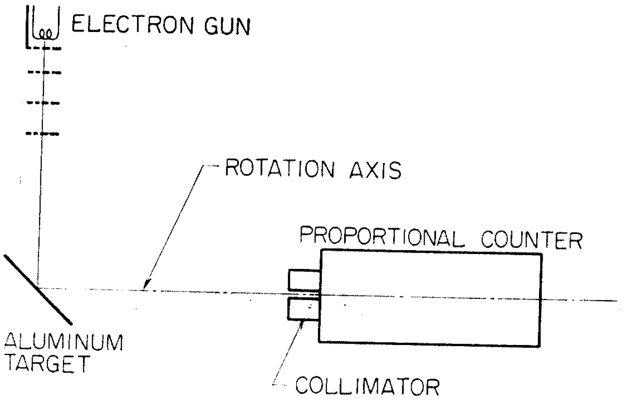


FIG. 3. The schematic layout of the experimental apparatus.

center counter. The maximum energy of the bremsstrahlung is varied through changing the accelerating voltage of the gun. The collimated X-ray thus produced is linearly polarized. The polarization vector lies in the plane which the electron beam and the collimated X-ray make. A reliable estimate of the degree of polarization is not easily calculated because of depolarization effect in the thick target. The experimental check by using a different polarimeter is desiable, but it is not performed in the present stage of our experiment. In order to eliminate the difference in the characteristics of the four counters, the whole gas tube is rotated around the axis shown in figure 3.

IV. OBTAINED DATA

Argon gas with 10% mehane is used in the present experiment. K and L shell absorption edge of argon is 3 KeV and 0.25 KeV respectively. So the cathode voltage of the electron gun was fixed at 2 KeV to obtain the X-rays that can excite L-shell electrons and not K-shell ones of argon gas. The emitted fluorescent X-ray has the energy of 250 eV.

The gas pressure in the proportional counter is chosen as 6 cmHg to have a sufficient depth for the incident X-rays with continuous energy spectrum below 2 KeV in the center counter and to make a large part of the fluorescent X-rays of 250 eV absorbed in the side counters. The mass absorption coefficient of argon gas is about 300 and $5000 \pm 2000\ \mathrm{cm^2/g}$ for 3 KeV and 0.25 KeV X-ray respectively [5]. From these figures almost all of the incident continuous X-rays and about $30\% \pm 10\%$ of the fluorescent X-rays are absorbed in the center counter and in the side counters respectively. The rather small absorption coefficient for the fluorescent X-rays is due to a small depth of the side counter in the direction perpendicular to the X-ray beam.

The outputs of the proportional counters were fed into a pulse height analyzer. A typical pulse height distribution in a side counter is shown in figure 4. The energy corresponding to each PHA channel is calibrated by measuring 5.9 KeV

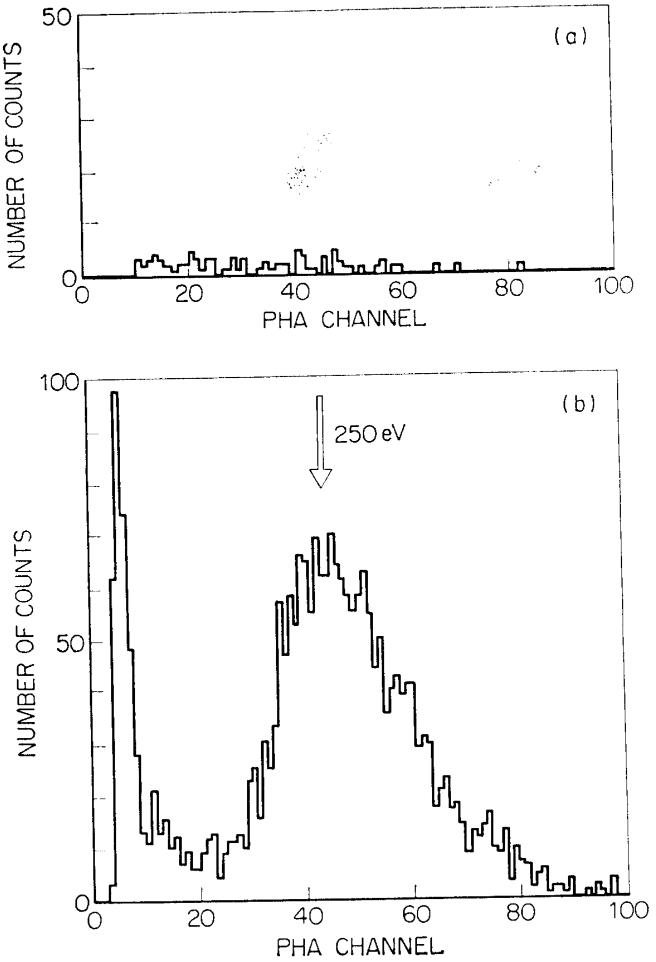
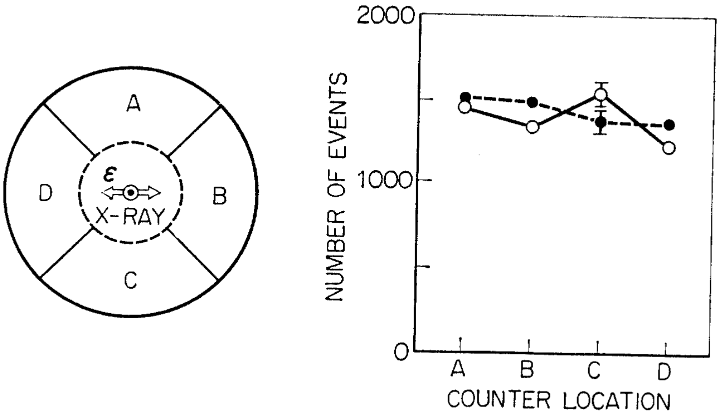


FIG. 4. The pulse height distribution of the observed events when the accelerating voltage of the gun was (a) switched off and (b) set at 2.0 KV.

line of Fe^{55}. The events composing the peak in the energy distribution around 250 eV were selected as fluorescent X-ray events. The counting rate was (1.3 ± 0.01) x 10^4 sec^{-1} and (14.5 ± 0.2) sec^{-1} for the center counter and one of the side counter respectively. From these values we obtain that the ratio of the counting rate of one of the side counter to that of the center counter was $(1.12\pm0.02)\times10^{-3}$. By putting that (30 ± 10)% of the fluorescent X-rays are absorbed in all of the four side counters, we get that the probability of fluorescent X-ray emission is (1.5 ± 0.6) %, which roughly agrees to the value 1% described in Chapter II.

The data were taken at two values of the accelerating voltage of the electron gun, 2.0 KV (case 1) and 3.5 KV (case 2). When the voltage is set at 2.0 KV, the fluorescent X-rays of 3s to 2p transition are expected to show the polarization-angular correlation. When the voltage is 3.5 KV, we measured the fluorescent X-ray of 2p to 1s transition, which is considered to show no correlated behaviour.



(a) (b)

FIG. 5. (a) The location of the side counter against the direction of the polarization vector is designated by letters A, B, C and D.
(b) The observed counting rate is plotted as a function of the counter location in arbitrary unit. White circles and black ones represent the events when the accelerating voltage of the electron gun was set at 2.0 KV and 3.5 KV, respectively.

The observed data for the two different cases are plotted in figure 5. In case (1), we observe an obvious dependence of the counting rate upon geometrical location of the side counter. In case (2), however, no correlation between them is apparently observed. The observed asymmetry ratio Σ, defined by $(N_\perp - N_\parallel)/(N_\perp + N_\parallel)$ where $N_\perp$ and $N_\parallel$ are counting rates of the counter perpendicular and parallel to the polarization vector, is 0.07 ± 0.02 and 0.05 ± 0.02 for case (1) and case (2) respectively. Substituting this value into the relation $\Sigma = AP$, we get $P = 70 \pm 20\%$. From this observed value of X-ray polarization and the asymmetry ratio we conclude that the present method turned out useful for detecting the polarization of the incoming X-ray. In order to get the absolute value of polarization experimentally, we need, however, more careful treatment in obtaining the calculated value of A. Further investigations will be necessary with the X-rays of which polarization is checked by other methods.

V. ACKNOWLEDGEMENT

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[*3*] in order to know more detailed informations.
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[*4*] for example, see
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