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POLARIZED PROTON TARGET FOR USE IN INTENSE ELECTRON AND PHOTON BEAMS*

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ABSTRACT

Constructional details are given for the polarized butanol target which was developed for use at the Stanford Linear Accelerator. A sample preparation technique using ribbed plastic bags was used. The behavior under radiation damage is discussed. It was found to be possible to anneal out much of the radiation damage. Results obtained with a glycol target are also discussed.

INTRODUCTION

Polarized proton targets[1] have proved over the past several years to be extremely useful tools for the study of high-energy particle interactions. In order to use such a target in an intense electron or photon beam, however, it was necessary to develop target materials which exhibited such properties as resistance to radiation damage, high hydrogen content, and absence of elements of high atomic number. With the discovery[2] that one can obtain sizable proton polarization by dynamic orientation of doped hydrocarbons, such experiments became possible. The target to be discussed was used in a series of experiments[3] involving electron scattering and photoproduction at the 20 GeV Stanford Linear Accelerator.

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I. TARGET CONSTRUCTION

The target in question operated at a temperature of 1.0 ^{o}K in a magnetic field of 25 KGauss. A microwave generator capable of producing a few watts at 70 GHz provided the radiation necessary to produce dynamic orientation[4] of the hydrogen nuclei present. The liquid helium cryostat was of the horizontal, continous flow type described by Roubeau.[5] The vapor pressure of the helium was maintained at 0.1 torr with a Rootes rotary blower of pumping speed 2700 liters/second.

This target was designed for use in single-arm experiments (only one outgoing particle detected) in which there was no way to separate scattering by hydrogen from that by heavy elements in the target and cryostat. Therefore special care was taken to minimize the amount of extraneous material in sample holders, heat shields, cryostat flasks and beam windows.

Advantage was taken of the fact that only forward going particles ($\theta \leq 12^{o}$) were to be detected; the design used is shown in Fig. 1. The sample was contained in a rectangular cavity made of 75 μ thick copper plated aluminum (also shown in Fig. 1) which served as liquid helium container, microwave cavity and NMR pickup "coil." The insulating vacuum was continuous with the beam-pipe vacuum (there was a window separating the two which was several meters upstream of the target where it was out of the view of our detector). A rectangular beam hole was cut in the Cu heat shield; it was wrapped with several layers of aluminized mylar. A rectangular beam hole was also cut in the inner flask; it was covered with a 75 μ aluminum window. This design had adequate strength since the pressure inside the flask was always greater than or equal to the

outer pressure.

The "lid" of the target cavity was made of 40 μ thick electro-etched copper screen,[6] which was soldered to the copper plated cavity, and thus could be easily and reliably removed and re-attached. A thin layer of insulation separated the upper edge of the septum (see Figs. 1 and 2) from this screen. The NMR pickup signal was taken between the screen and the septum. Effectively this system constituted a single turn pickup loop. Measurements on similar cavities indicated that the resulting 105 MHZ magnetic field would be quite uniform, ensuring that the NMR polarization measurement would sample the entire sample volume uniformly. This last feature is important when the target is non-uniformly polarized, as after some irradiation by a photon beam (see Section III).

The NMR system itself is described elsewhere.[7] With a 2-1/4 wavelength 50 ohm transmission line and a 1,000 ohm amplifier input impedance, we obtained a signal size of $\frac{\Delta V}{V} = 10\%$ for 35% target polarization.

II. SAMPLE PREPARATION AND THERMAL CONDUCTIVITY PROBLEMS

To obtain high polarization, one must maintain a low temperature throughout the sample in the presence of heat loads from the polarizing microwaves and the possible beam heating. Consider a long cylindrical sample of radius r immersed in a liquid helium bath. Let there be a uniform power density Q of heat unput throughout the sample. Then the central temperature rise will be given by

$$\Delta T = \frac{1}{4} \frac{Qr^2}{\alpha} \qquad (1)$$

where α is the thermal conductivity. For the type of polarized target

discussed here, the heat input Q from microwave heating and also from beam heating is of the order of $Q = 0.01$ watt/cm^3. We have measured the thermal conductivity of an ethanol-water-porphyrexide mixture at 4° K and found it to be 2×10^{-3} watt/cm $^\circ$K, and we estimate a value for butanol-water-porphyrexide at 1° K of $\alpha = 0.5 \times 10^{-3}$ watt/cm $^\circ$K. Thus we find $\Delta T = 5\ r^2$ K/cm^2, and we conclude that, in order to avoid loss of polarization due to heating effects, the characteristic dimensions of the target material must be of the order of 0.1 cm. On the other hand radiation damage considerations (see below) dictate a target with characteristic dimensions of the order of several cm.

In our experience it has been possible to get occasional good results with doped alcohol targets of macroscopic size simply by immersing a cup containing several cm^3 of solution in a liquid helium bath; the results obtained, however, were rather unreproducible. Probably the successful targets were those in which the sample did not freeze into a single mass, but rather froze in pieces with channels in between to allow cooling by liquid helium. Thus, it was necessary to devise a technique for preparing samples made of small pieces; the procedure had to be reliable and simple enough to permit us to carry it out daily in order to replace target material which had been destroyed by radiation damage.

The sample preparation method we divised is illustrated in Fig. 2. Ribbed bags were made of 12 μ thick F. E. P.[8] plastic, a heat-sealable, non-hydrogenous material with good low-temperature properties. The bag size, before filling, was 3 x 20 cm, and each bag had 8 ribs. The following procedure was used for making the bags. Two sheets of the plastic were sandwiched between sheets of glass cloth,[9] and then pressed under

hand pressure between an aluminum die which had been heated to 320° C and a flat aluminum surface covered with a 0.1 cm thick layer of silicone rubber. The die had a pattern of 0.06 cm thick and 0.43 cm deep ridges corresponding to the seams which were desired in the bags. The sample solution was injected using a long hypodermic needle into the ribs; then the bag was sealed off to a length of 16 cm by means of an impulse heat sealer.[10] After filling, the rib diameter was 0.2 cm. Six such bags were prepared, containing a total of about 12 grams of solution. The total weight of plastic was about 1.6 grams. Each bag was folded accordion style, as shown in Fig. 2, and installed in the target can. The whole target thus presented a cross-section of 6.5 cm^2 to the beam. The solution was a 95% 1-butanol, 5% water mixture, saturated with an additional 2% of porphyrexide.

With small samples in our apparatus, we obtained, under optimum conditions, a polarization of 37%. With samples prepared in bags as described above we obtained an optimum polarization of approximately 35%. With the latter samples, we were able to observe a decrease in polarization from beam heating (a reversible beam-on/beam-off effect, as distinguished from the irreversible radiation damage effects described later). Denoting the (small) fractional decrease in target polarization by $\frac{\Delta P}{P}$ and the power input, in watt/cm^3, from beam heating by Q_{beam}, we found

$$\frac{\Delta P}{P} = 4\ Q_{beam}\ (0.2\ \text{cm ribs})$$

Some of our earlier targets were made with targets having 0.3 cm diameter ribs. For these targets we found optimal polarization of 31% and a beam heating effect given by

$$\frac{\Delta P}{P} = 14\ Q_{beam}\ (0.3\ \text{cm ribs})\ .$$

Since the obtainable polarization is found experimentally[2] to vary linearly with inverse temperature, we conclude that (1) the effects observed are consistent with the bulk heating effects estimated above and (2) the power absorbed by the sample from microwave heating is of the order of 0.010 watt/cm^3. For a normal running beam of 2×10^{11} electron/sec, $Q_{beam} \approx 0.006$ watt/cm^3.

In a separate measurement we estimated, from observations of the helium boiloff, the additional heat dissipation due to microwaves at about 0.3 to 0.4 watts. The difference between this amount and the power absorbed directly by the sample represents losses in the cavity walls and elsewhere in the vicinity.

III. RADIATION DAMAGE AND ANNEALING

A typical example of the polarization vs. radiation dose relationship which we observed is shown in Fig. 3, for incident electrons. The relationship is roughly exponential, of the form

$$\frac{P}{P_0} = e^{-\varphi/\varphi_0} \qquad (2)$$

with φ the radiation dose. As can be seen, this exponential form was not followed perfectly; the fractional rate of damage tended to be somewhat greater when the target was fresh. The characteristic dose φ_0 was found to be approximately 4×10^{14} electrons/cm^2. This is the same magnitude as previously found in ethanol.[11]

We found that it was possible to <u>anneal</u> much of the radiation damage.

The procedure was to stop the helium flow to the cavity and to heat it by means of heating resistors. A temperature of 140° K was reached and maintained for ten minutes, after which liquid helium was again admitted to the cavity and the target was re-polarized. It is known[12] that recombination of radiation damage centers in butanol occurs near 120° K. By keeping liquid helium in the separator throughout, it was possible to carry out the entire annealing process in about 30 minutes.

Figure 4 shows the history of polarization vs. radiation dose for a target which had been annealed 8 times. Also shown is $\tau_{1/2}$, the time needed to make the polarization cross through zero when changing sign ("crossover time").

The data of Fig. 4 were taken with incident photons. Since the damage is done only by charged particles in the shower induced by the photons, we will expect the rate of damage to be greater at the downstream end of the target than at the upstream end. In fact if we assume that Eq. (2) holds for incident electrons, and that the radiation dose varies linearly with target depth and is zero at the upstream end, then we expect to find for incident photons the relationship

$$\frac{P}{P_0} = \frac{0.5\varphi_0}{\varphi}\left[1-\exp(-\varphi/0.5\varphi_0)\right] = 1 - \frac{\varphi}{\varphi_0} + \ldots \qquad (3)$$

Here φ and φ_0 refer to the equivalent number of minimum ionizing particles per cm^2 induced by the beam at the <u>center</u> of the target. Within our measurement errors, φ_0 was found to be the same for electron and photon beams.

IV. PROTON RELAXATION AND LOCAL DEPOLARIZATION

The proton relaxation time, T_n, for a freshly prepared target, at 1.05° K was typically between four and five minutes, depending on the preparation. After irradiation T_n decreased to less than two minutes. Upon annealing it became as long or longer than that of the fresh sample.

Several tests were made to verify that there was no local depolarization due to the effects of the intense electron beam striking a small spot on the target. The beam, typically 2 mm in diameter, was swept over the full area of the target in 288 steps, advancing with each accelerator pulse. One wished to be certain that the proton polarization in the region being irradiated was not significantly lower than that measured for the target as a whole.

T_n was measured (with the microwaves off) as a function of beam intensity while sweeping the beam across the target. In all cases the decrease in T_n was consistent with the change in temperature of the overall target by internal heating. In an extreme case, we noted a decrease in relaxation time from 145 seconds with beam off, to 110 seconds with beam on. The beam intensity was then 1.1×10^{11} electrons/second. (The target had already absorbed a dose of 1.35×10^{14} electrons/cm^2). The sample bag had 0.3 cm ribs at this time. The internal temperature rise was estimated, from the observed drop in polarization, as 0.05° K. The change in T_n agreed with the temperature dependence found in Reference 2. If there had been an instantaneous depolarization due to the beam, one would have expected a great decrease in the whole target polarization after a few sweeps of the beam, the microwaves being off. On the contrary, the excess relaxation rate is accounted for here solely in terms

of internal temperature rise.

As a further test against the possiblity of local depolarization, a target was prepared whose dimension was comparable to that of the beam. The nuclear magnetic resonance frequency was set to the proton signal, and the level monitored on an oscilloscope through a circuit whose response time was fast compared to the 1.5 microsecond spill of the Stanford Linear Accelerator. No change in the NMR signal level could be detected in correlation with the beam.

In typical operation the polarization direction was reversed every 3 minutes. The reversal time, from the command to change sign until the polarization attained 70% of its final magnitude, was of the order of one minute, varying within a factor of 1.5 from this at different times. The reversal was made under automatic control of an on-line PDP-5 computer. The microwave attenuators were also switched automatically with each polarization reversal, in an attempt to compensate for differences in the microwave generator's output when the frequency was changed. There was concern that the liquid helium level in the cavity containing the sample might change with microwave power, leading to a difference in the background scattering rate between the two signs of polarization. The liquid level was generally maintained at overflowing the cavity to help avoid this problem.

V. GLYCOL

A target was prepared using a solution of etheylene glycol saturated with potassium dichromate.[13] The proton polarization obtained was 42%. The radiation dose constant was found to be equal, within measurement

error, to that found for butanol targets. Since the glycol solution is only 9% free protons as compared to 13.5% for the butanol solution, and since we were unable to find a way to anneal the radiation damage in the glycol target, it appeared that butanol targets were superior for our particular applications.

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FIGURE CAPTIONS

FIGURE 1 (a) Top view, partially cut away, of the polarized proton target inside the magnet gap

(b) View looking along the incident beam line at the target, partially cut away.

FIGURE 2 The copper-plated aluminum cavity, and two of the ribbed plastic bags filled with the target solution; one is shown fully extended and the other is shown partially folded.

FIGURE 3 A typical curve of target polarization vs. radiation dose for incident electrons. An approximate fit to exponential behavior is shown, with $\phi_0 = 3.7 \times 10^{14}$ electrons/cm^2 for the 6.5 cm^2 beam used.

FIGURE 4 Observed behavior of target polarization and cross over time vs. radiation dose for incident photons, for a target which was annealed a number of times. The dashed line is an exponential fit to the polarization vs. dose curve just after annealing. The dash-dot line indicates the gradual fall off with radiation dose of the polarization obtained at the beginning of each cycle of radiation damage.

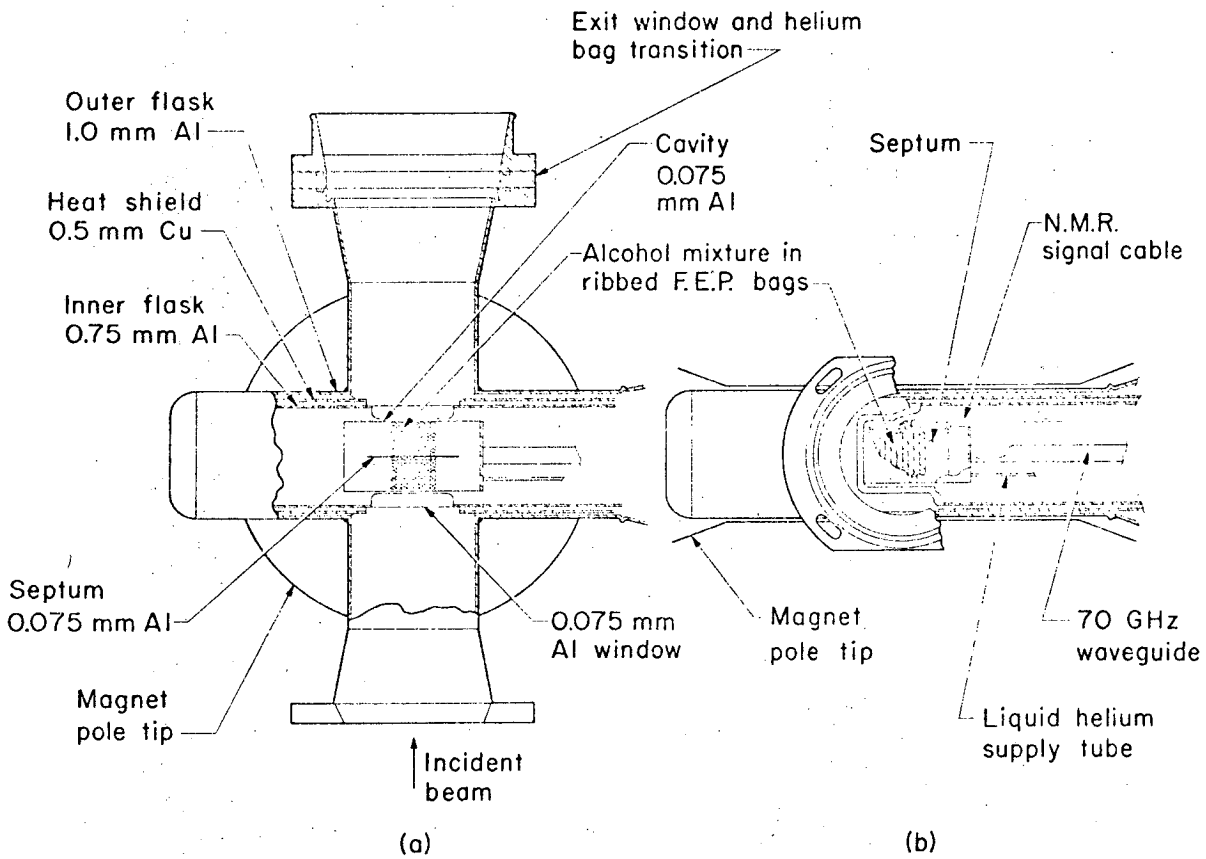

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Fig. 1

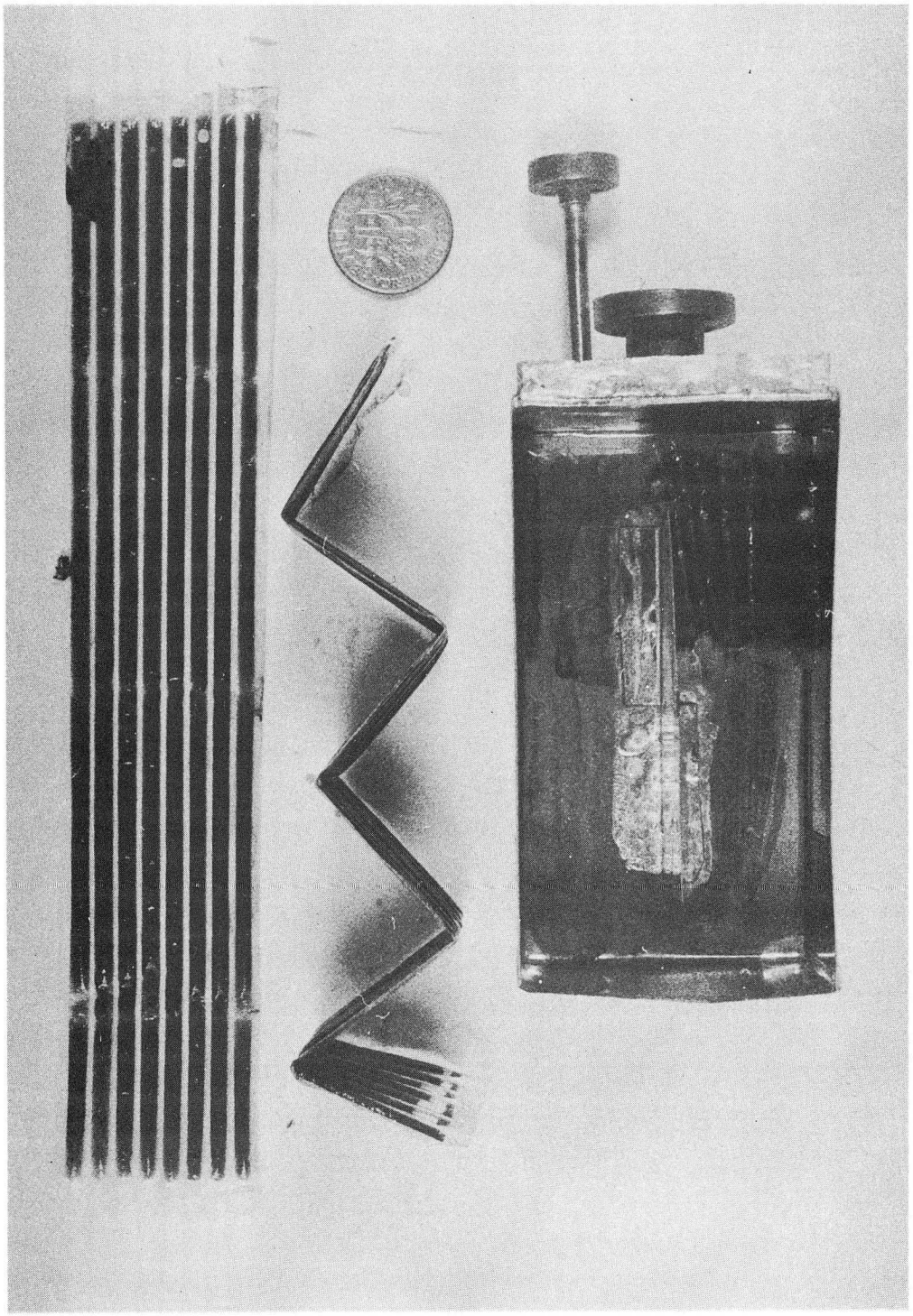

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Fig. 2

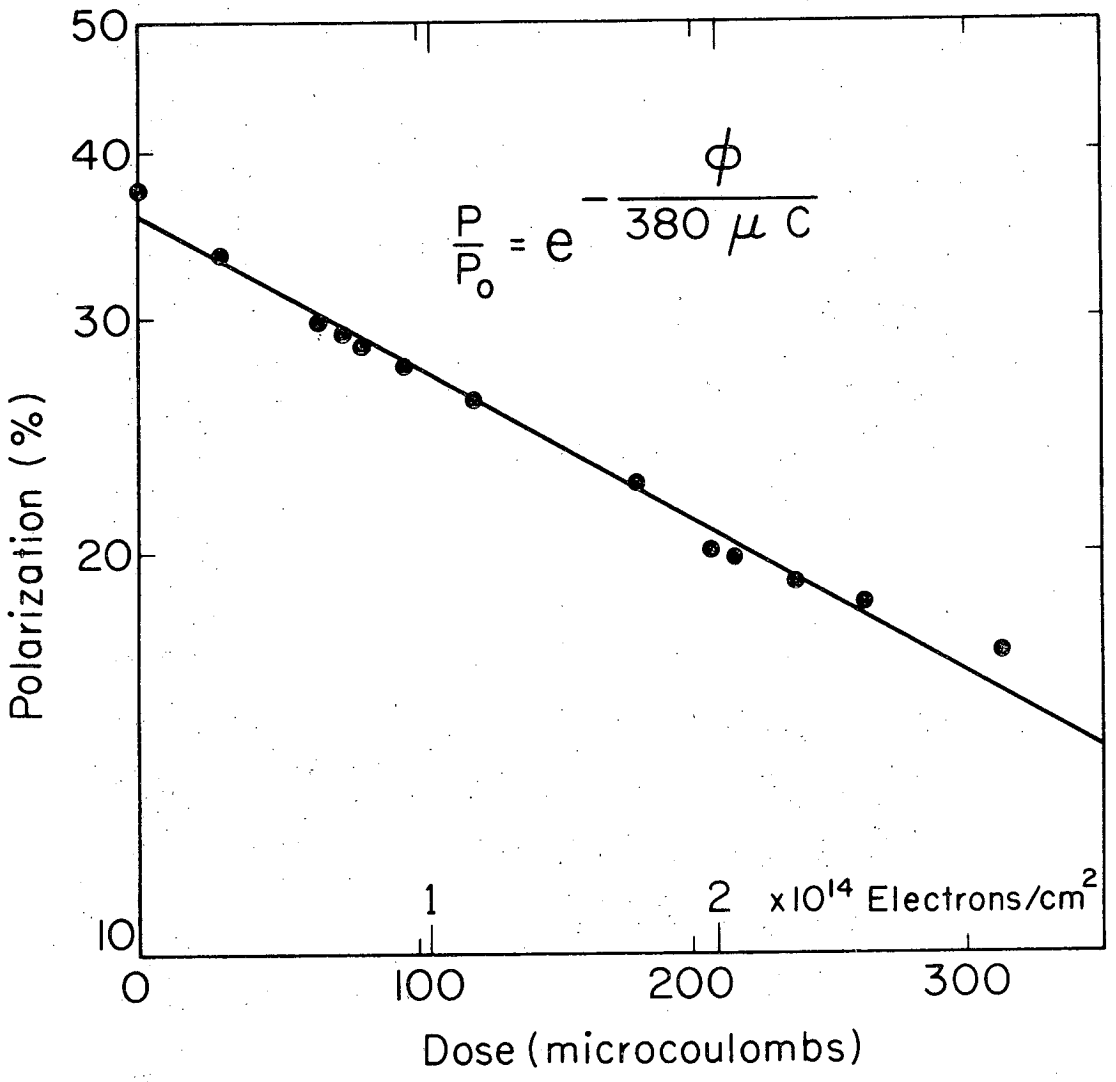

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Fig. 3

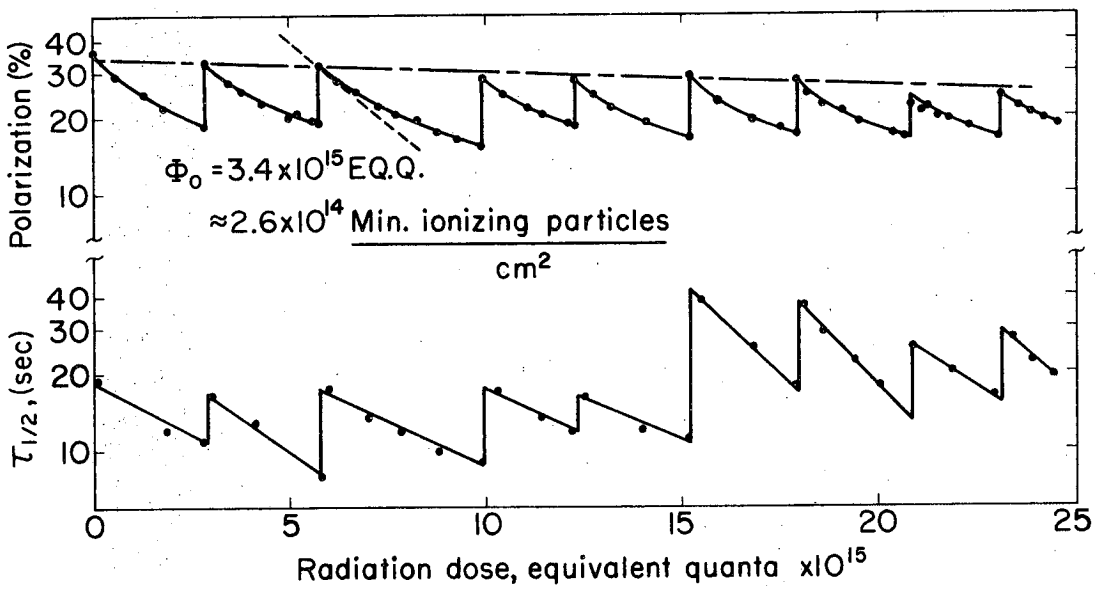

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Fig. 4

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