SLAC-PUB-2874 Errata
March 1982
(I)

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Please note the following figure order changes:

For "Figure 2" read "Figure 4"

For "Figure 4" read "Figure 5"

For "Figure 5" read "Figure 2".

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* Work supported in part by the Department of Energy under contracts DE-AC03-76SF00515 (SLAC) and DE-AC02-76ER03075 (Yale), by the German Federal Ministry of Research and Technology, and by the Japan Society for the Promotion of Science.

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ABSTRACT

We report studies of dynamic nuclear polarization of irradiated targets. The polarized target operated at a magnetic field of 5 T and a temperature of 1 K and was irradiated with the 20 GeV electron beam at the Stanford Linear Accelerator. Our results indicate that the temperature at which the target is irradiated is important. The maximum proton polarization attained with radiation was measured for some seven hydrogen-rich compounds. Irradiated NH_3 and ND_3 were polarized to high values of $P_p \simeq 0.75$ and $P_d \simeq 0.25$ with short values of polarization growth time T_p, and with radiation resistance of the polarization about a factor of 30 greater than for normal chemically-doped dydrocarbons. Hence irradiated NH_3 and ND_3 appear very promising as practical polarized target materials.

Submitted to Nuclear Instruments and Methods

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I. INTRODUCTION

Polarized nucleon targets used in high energy physics experiments usually employ the method of dynamic nuclear polarization (DNP) to polarize the nucleons in an alcohol [1]. DNP requires the presence of paramagnetic centers, which are customarily provided by a chemical dopant. These targets have a relatively low polarizable proton content, and suffer loss of polarization when subjected to high doses of ionizing radiation. If the paramagentic centers formed when the target is irradiated can be used in the DNP process, it becomes possible to use materials which have a relatively high hydrogen fraction, but are not easily doped by chemical means [2], such as NH_3 or HD. Furthermore, the polarization of such targets may be much more radiation resistant.

The earliest work on the use of radiation to produce a polarizable target was done on HD at Yale [3], using a bremsstrahlung beam with a maximum energy of 60 MeV. A proton polarization of 3.7% and a deuteron vector polarization of 0.4% were obtained by DNP, with a magnetic field (H) of 1.2 T and a temperature (T) of 1.2 K. Dynamic nuclear polarization of undoped butanol with a proton polarization of about 7% was obtained [4], using a 4 MeV bremsstrahlung beam with $H = 2.5$ T and $T = 1$ K. Recent encouraging results on the DNP of NH_3 irradiated in LN_2 with a proton beam (energy 580 MeV) were obtained at CERN [5], where a proton polarization of about 90% was obtained with $H = 2.5$ T and $T < 0.5$ K. However, a slow growth in polarization and a long spin-lattice relaxation time were observed. Furthermore, two explosions occurred when NH_3 was irradiated in LN_2.

In the Spring of 1979, we initiated our studies at the Stanford Linear Accelerator Center (SLAC), where our polarized target was set up in the high energy 20 GeV electron beam. In this paper we report our preliminary results for NH_3 and ND_3, as well as for a number of other substances with high hydrogen content. Earlier reports on our work have been made [6].

Important results on DNP of irradiated NH_3 and ND_3 have been reported [7] from Bonn. By using higher doses than used in the CERN experiment, the group achieved high proton polarizations with relatively short polarizing and spin lattice relaxation time constants in NH_3 targets irradiated with a 20 MeV electron beam. The Bonn group used liquid argon (80 K), rather than LN_2, to cool the targets during irradiation and did not observe any explosions. Relatively low deuteron polarizations were reported for ND_3.

II. EXPERIMENTAL METHOD AND RESULTS

The Yale-SLAC polarized target system [8] utilizes a ^4He cryostat to maintain 25 cm^3 (2.5 cm × 2.5 cm × 3.8 cm in the beam direction) of target material at 1 K, a superconducting magnet with a 50 kG field, a microwave system operating at 140 GHz, and an NMR system operating at 200 MHz (proton) or 30 MHz (deuteron). The targets were irradiated at SLAC with an electron beam delivered at 10 pulses per second with currents ranging from 2×10^9 to 5×10^{10} electrons per 1.5 μs pulse and with energies ranging from 6 to 20 GeV. The beam spot (~2 mm in diameter) was rastered over the target in a period of about 1 min. The irradiations and the measurements described here were conducted with the target at a temperature of 1 K. Irradiation of targets at higher temperatures in

the range of 20 K to 80 K (the temperatures were only poorly controlled) indicated that much larger radiation doses were required to achieve polarization than for irradiation at 1 K.

We have irradiated and studied dynamic polarization in the materials shown in Table I. For most of these materials, the low polarizations observed make them uninteresting as candidates for polarized target materials. Ammonia and deuterated ammonia, however, offer high polarization and show great promise as polarized target materials. We will therefore present the results of our studies on NH_3 and ND_3 in more detail.

The ammonia targets were prepared by slowly freezing (in a period of about 1 hour) approximately 30 cm^3 of liquid ammonia to produce a clear solid, which was then crushed and sifted to select fragments approximately 1.5 mm in diameter. In our earlier studies [6], we found that the microcrystaline beads, produced by rapidly freezing droplets of liquid ammonia (droplets were allowed to fall directly into LN_2), disintegrated rapidly when irradiated at 1 K. In slowly frozen ammonia, the rate of disintegration is significantly reduced. The problem of finely divided ammonia target material migrating from the target cup, which plagued our earlier studies, was eliminated through the use of slowly frozen ammonia and a redesigned target cup.

The polarization behavior of one of our ammonia targets is shown in fig. 1. The polarization rises smoothly with dose and levels off at the value of ~60% as the target is initially irradiated. Annealing the target at temperatures between 10 K and 40 K causes the polarization to increase to its maximum value of ~75%. A dose of 9×10^{14} e^-/cm^2 given subsequent to the second anneal caused the polarization to decrease from ~75% to ~68%.

For an exponential decrease this corresponds to a depolarizating (1/e) dose of 0.9×10^{16} e^-/cm^2, which is about 30 times larger than for butanol. Actually the decay was not exponential and was relatively slower at high doses. The rate at which the radiation dose could be applied was limited by beam heating and by the cooling power of our cryostat, and hence much longer irradiation times than were available to us would have been required for more detailed studies of radiation damage.

The observed time constants for polarization growth (T_p) and free polarization decay or proton spin-lattice relaxation (T_1) were measured as a function of dose for unannealed targets and are plotted in fig. 2. From a least squares fit to these data, we find that T_p and T_1 decrease roughly as $(\text{dose})^{-1}$. Contrary to the situation in doped materials, the ratio T_p/T_1 changes very little in the 10^{14} to 10^{15} e^-/cm^2 dose range, implying an almost constant proton polarization and a very large depolarizing dose. Annealing at 40 K increases T_1 and T_p by roughly a factor of two, indicating a partial anneal of paramagnetic centers. Annealing at an even lower temperature (~10 K) resulted in an increase in T_1 alone. The observation of anneals of different character at these low temperatures indicates that the effectiveness of radiation depends strongly on the temperature.

Our ND_3 targets were prepared in the same manner as the NH_3 targets. The deuteron polarization rises smoothly as the target is initially irradiated (fig. 3). The maximum polarization achieved was ~25%. Annealing the target did not increase the polarization. The depolarizing (1/e) dose for ND_3 was approximately 1.3×10^{16} e^-/cm^2.

The time constants for polarization growth and free polarization decay are plotted as a function of dose for unannealed ND_3 targets in

figs. 4 and 5. The time constants plotted in figs. 4 and 5 are based on the sum and difference, respectively, of the right (R) and left (L) peak heights of the enhanced deuteron NMR signal. The sum corresponds to the vector polarization while the difference corresponds to the tensor polarization. All four time constants, $T_p(R+L)$, $T_p(R-L)$, $T_1(R+L)$ and $T_1(R-L)$ decrease with dose roughly as $(\text{dose})^{-1}$.

Annealing irradiated ND_3 targets at 10 K resulted in a slight increase in T_1 and T_p. Annealing the targets at 40 K increased T_1 and T_p for the vector polarization by an order of magnitude and greatly reduced the polarization. It was necessary to reirradiate targets annealed at 40 K to recover full polarization.

The absolute polarizations for ND_3 reported here were calculated by the ratio method [9]. While we were able to observe a TE signal, it was too small to allow accurate measurements. The many small structures in the ND_3 enhanced signal, fig. 6, may be due to different orientations of the ND_3 molecules in the crystal field. The fact that our fragments of target material are predominantly single crystals may make these structures more prominent than those observed by other groups using microcrystaline ND_3 target material.

III. CONCLUSIONS

Substantial improvements in polarized nucleon targets are possible by using irradiated ammonia or deuterated ammonia as the target materials. The polarizations attained in NH_3 and ND_3 are as high as those attained with doped hydrocarbons and the depolarizing doses for both materials are more than an order of magnitude above the depolarizing doses for conven-

tional materials. Annealing, if necessary, can be done at much lower temperatures than e.g. in butanol and hence much more quickly. Moreover, the polarizable nucleon content of NH_3 and ND_3 is about 30% greater than that of butanol.

In our recently completed E130 experiment [10] at SLAC we measured the asymmetries in the deep inelastic scattering of polarized electrons by polarized protons. The polarized electron source [11] was based on photoionization of a polarized ^6Li atomic beam and provided about 6×10^{10} polarized e^-/s (polarization $\simeq 0.8$), the polarized target was a butanol (porphyrexide-doped) target. The use of an irradiated NH_3 polarized target in this experiment would have been dramatically superior. Thus for NH_3 the fraction of polarizable protons to total number of nucleons is 0.175, whereas this fraction is 0.135 for butanol. Also since radiation damage would have been small for NH_3, the proton polarization would always have been close to its maximum value. Hence for the same statistical accuracy in the asymmetry the data-taking time would have been only about 0.5 of that used with the butanol target. Furthermore, whereas with our butanol target, radiation damage necessitated either annealing or replacing the target every 2 to 4 hrs. - a process taking about 45 min. - with an NH_3 target these frequent down-times and interruptions of data-taking would have been avoided. In order to reverse the target polarization we might have annealed our NH_3 target (rapidly at 10 K) infrequently.

With the much higher radiation resistant NH_3 polarized targets it is possible to consider doing a polarized e-p scattering experiment with a much higher intensity polarized electron beam. Indeed a higher intensity polarized e^- beam of at least 10^{12} e^-/s (but with lower polarization $\simeq 0.4$)

can be provided by photoelectron emission from GaAs using polarized laser light [12]. Optimum use of such a high intensity electron beam will require a cryostat of high cooling power and may involve problems of transient heating of the polarized bead material. However, the gain in data-taking rate would be substantial and important. Similarly the availability of irradiated ND_3 as a polarized target provides an excellent target of polarized neutrons.

We would like to acknowledge the important contribution of the SLAC Low Temperature Research Group, in constructing and maintaining our polarized target. R. Stanek of Argonne National Laboratory helped during a part of our data-taking period. We are grateful to K. Althoff, D. Hill, W. Meyer and T. O. Niinikoski for useful discussions and information. We would also like to thank Dr. R. E. Taylor of SLAC for encouragement and support, and Dr. S. Ecklund for facilitating our use of End Station A at SLAC. The research was supported in part by the Department of Energy under contracts DE-AC03-76SF00515 (SLAC) and DE-AC02-76ER03075 (Yale), by the German Federal Ministry of Research and Technology, and by the Japan Society for the Promotion of Science.

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TABLE I

Material	Formula	H or D Fraction	Studied at Dose to	Maximum Proton Polarization
Ammonia	NH_3	0.175	4×10^{15} e^-/cm^2	75%
Deuterated Ammonia	ND_3	0.175	5×10^{15} e^-/cm^2	25% (deuteron)
Borane Ammonia	BH_3NH_3	0.194	1×10^{15} e^-/cm^2	30%*
Ammonium Hydroxide	NH_4OH	0.143	5×10^{13} e^-/cm^2	†
Butanol/5% Water	$C_4H_9OH + H_2O$	0.135	8×10^{14} e^-/cm^2	21%*
Ethane	C_2H_6	0.200	6×10^{15} e^-/cm^2	10%
Lithium Borohydride	$LiBH_4$	0.183	1×10^{15} e^-/cm^2	10%
Amino Methane	CH_3NH_2	0.161	3×10^{14} e^-/cm^2	4%

* Polarization after irradiation and anneal. Polarization measured after irradiation only is lower.

† No polarization measurement attempted. Beads of NH_4OH prepared by rapidly freezing in a mixture of $NH_3 + H_2O$ disintegrated rapidly when irradiated.

FIGURE CAPTIONS

fig. 1. Polarization vs time for an NH_3 target, showing the effects of irradiation and annealing. During the breaks in time the target was being irradiated but no polarization measurements were made.

fig. 2. Time constants for polarization growth (T_p) and proton spin-lattice relaxation (T_1) as functions of dose for NH_3. These are combined measurements from three different targets. The scatter of the points is believed to be due to systematic effects, e.g., those associated with cryostat temperature changes over long periods of time, to the use of different targets or to tuning conditions.

fig. 3. Growth of enhanced signal for ND_3 as the target is irradiated at 1 K. For ND_3, the dose rate is 1.65×10^{12} $e^-/cm^2/min$. The dose = 0 at time = 0.

fig. 4. Time constants for polarization growth (T_p) and deuteron spin relaxation (T_1) as functions of dose for the sum of the peak heights in ND_3. These are combined measurements from three different targets. See remark in fig. 2 caption on the scatter of the points.

fig. 5. Time constants for polarization growth (T_p) and deuteron spin relaxation (T_1) for the difference of the peak heights in ND_3. These are combined measurements from three different targets. See remark in fig. 2 caption on the scatter of the points.

fig. 6. Enhanced deuteron NMR signal for ND_3.

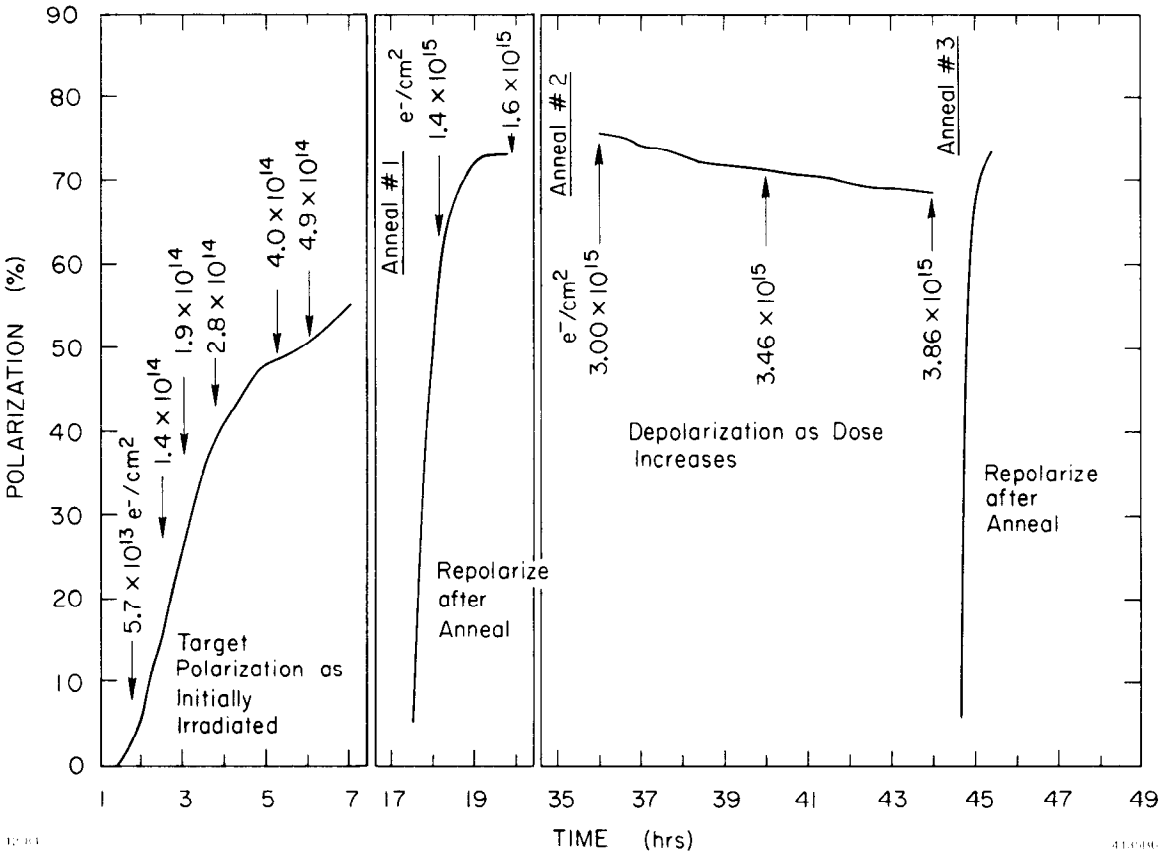
POLARIZATION (%)
TIME (hrs)
5.7 × 10^13 e⁻/cm²
1.4 × 10^14
1.9 × 10^14
2.8 × 10^14
4.0 × 10^14
4.9 × 10^14
Target Polarization as Initially Irradiated
Anneal #1
e⁻/cm²
1.4 × 10^15
1.6 × 10^15
Repolarize after Anneal
Anneal #2
e⁻/cm²
3.00 × 10^15
3.46 × 10^15
3.86 × 10^15
Depolarization as Dose Increases
Anneal #3
Repolarize after Anneal

Fig. 1

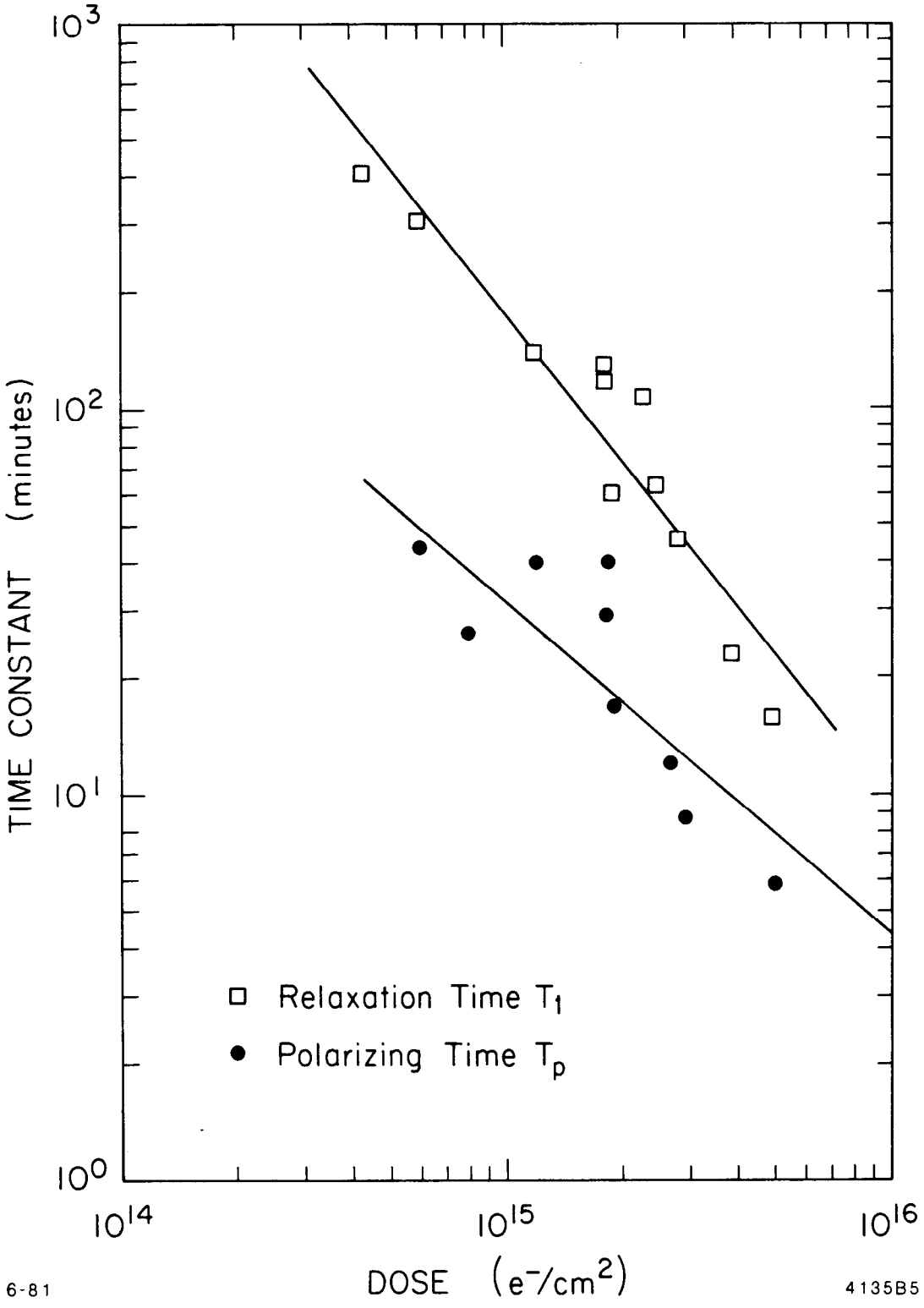
10^3
10^2
10^1
10^0
TIME CONSTANT (minutes)
10^{14}
10^{15}
10^{16}
DOSE (e^-/cm^2)
Relaxation Time T_1
Polarizing Time T_p
6-81
4135B5

Fig. 2

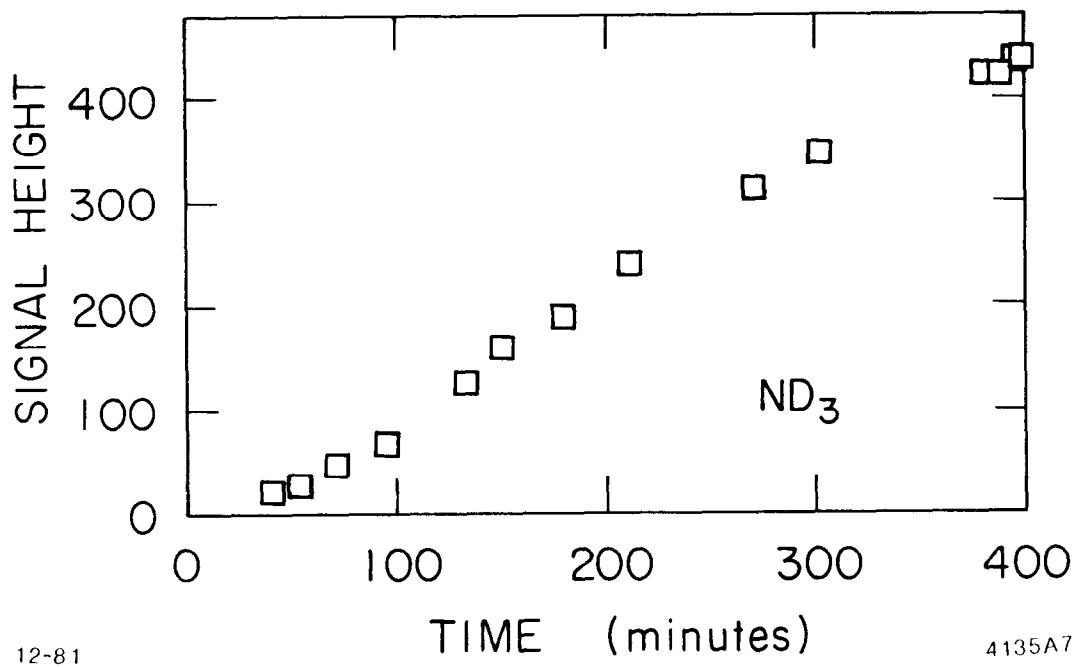
SIGNAL HEIGHT
400
300
200
100
0
0
100
200
300
400
TIME (minutes)
ND_3
12-81
4135A7

Fig. 3

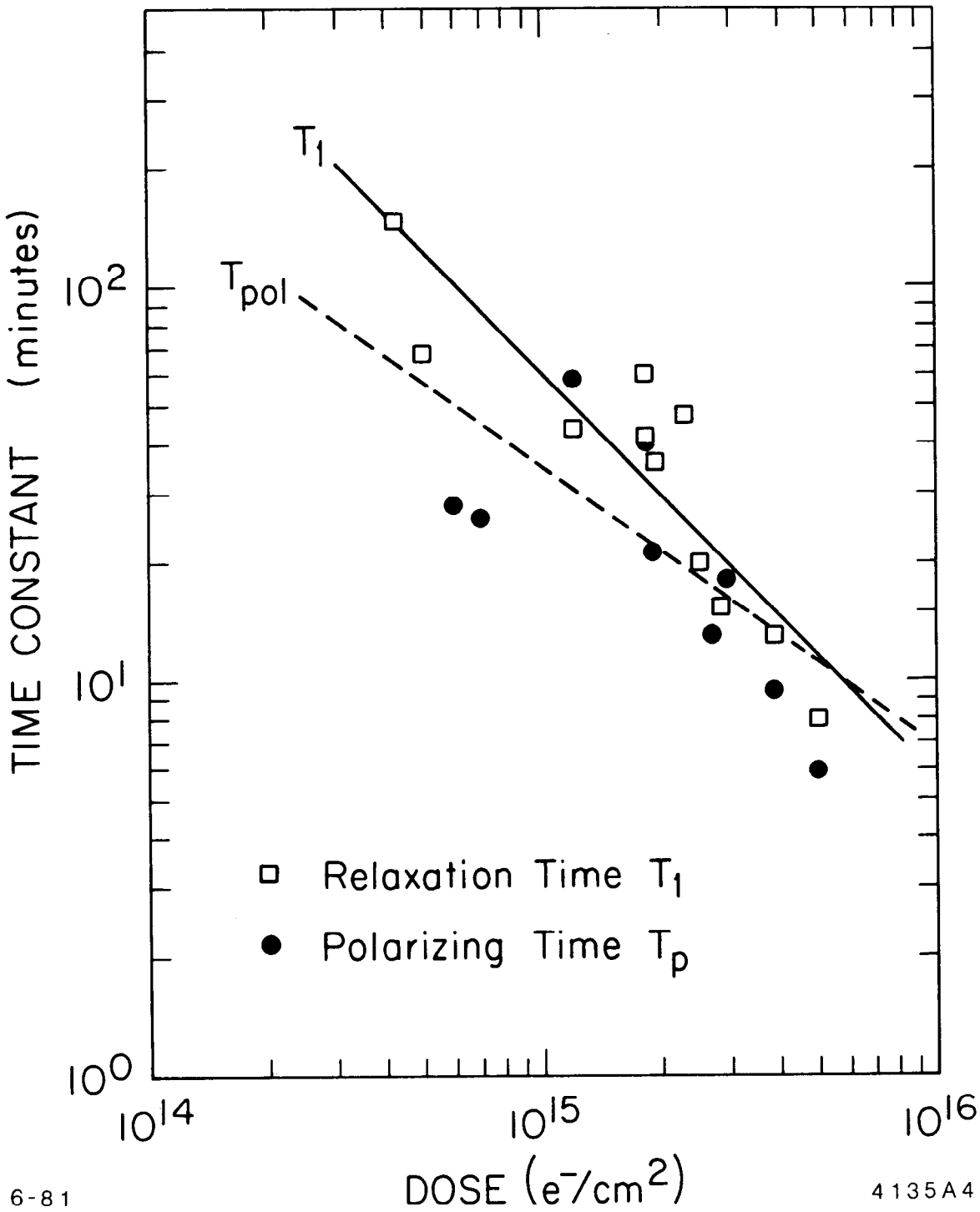
TIME CONSTANT (minutes)
10^2
10^1
10^0
T_1
T_{pol}
Relaxation Time T_1
Polarizing Time T_p
10^{14}
10^{15}
10^{16}
DOSE (e^-/cm^2)
6-81
4135A4

Fig. 4

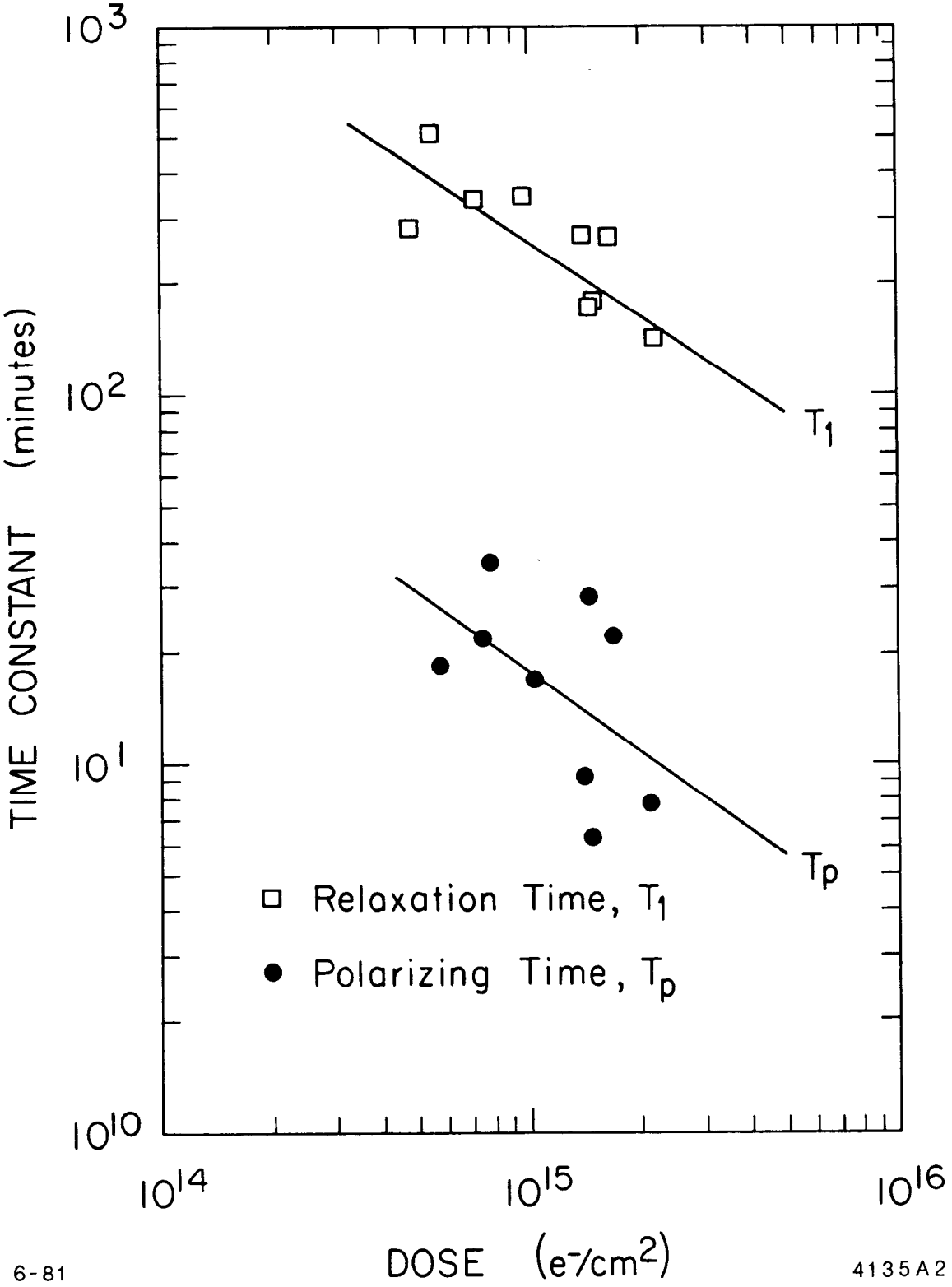
10^3
10^2
10^1
10^{10}
TIME CONSTANT (minutes)
T_1
T_p
Relaxation Time, T_1
Polarizing Time, T_p
10^{14}
10^{15}
10^{16}
DOSE (e^-/cm^2)
6-81
4135A2

Fig. 5

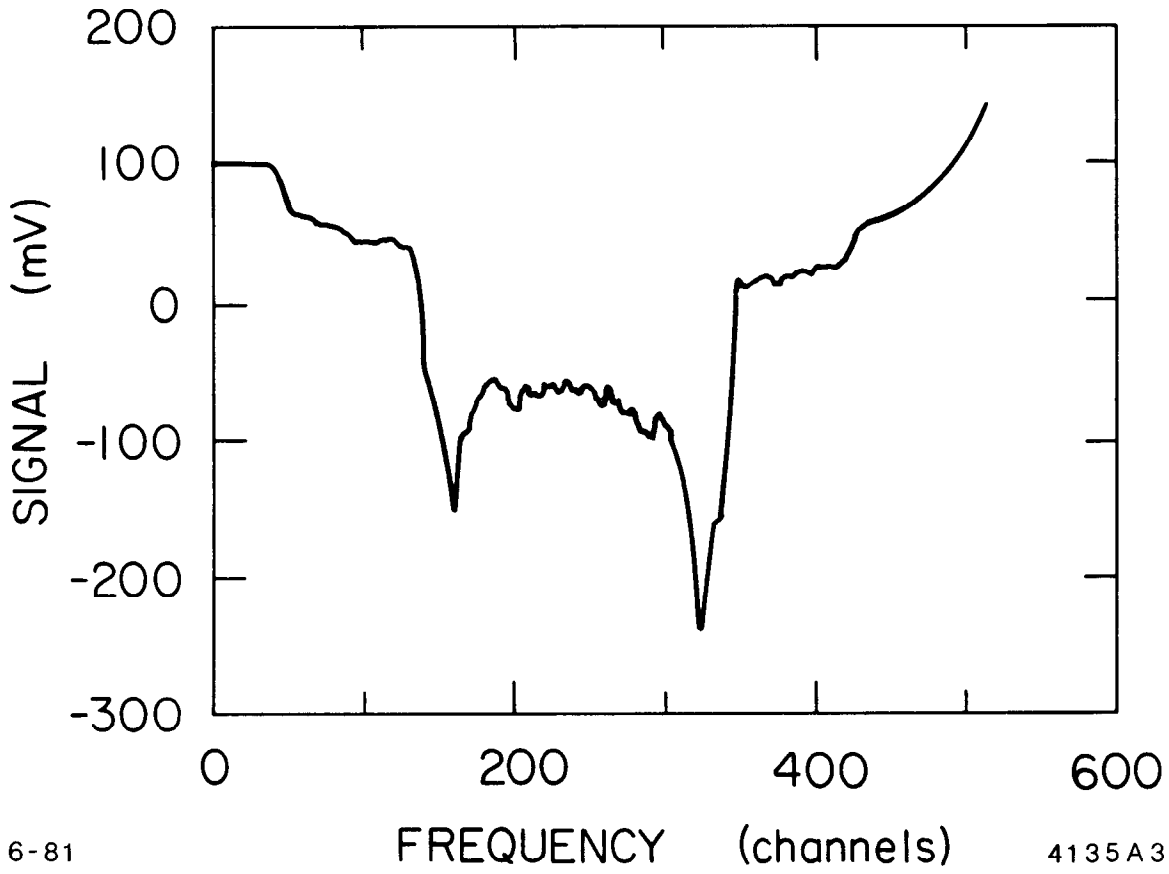
200
100
0
-100
-200
-300
SIGNAL (mV)
0
200
400
600
FREQUENCY (channels)
6-81
4135A3

Fig. 6