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# Effects of Magnetic Fields on the Light Yield of Scintillators*

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# Effects of Magnetic Fields on the Light Yield of Scintillators

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## ABSTRACT

We describe studies of the light yield of scintillators as a function of an externally applied magnetic field. The studies involved using fluoroscopic measurements, measuring indices of refraction, employing a wide variety of sources from fission fragments to cosmic rays, and making measurements as a function of the scintillator type and thickness and of the direction of the applied field. We observed the light yield to increase with increasing magnetic field independent of geometry or direction of the magnetic field. The effect was much larger in acrylic scintillator than in polyvinyltoluene or polystyrene based scintillator. We believe that the change in the light yield is due to a local light saturation of the material. As the magnetic field increases the low energy electrons spiral away from each other and the light yield increases.

Submitted to *Nuclear Instruments and Methods*

# 1. Introduction

A magnetic field dependence of the light yield from scintillators has been observed in several studies[1-5] of scintillators, both liquid and solid. The results may be summarized as follows. In 1969, E. Bodenstedt[5] et al reported the scintillator pulse height or sensitivity was affected by magnetic fields surrounding the plastic scintillator material. The pulse height seemed to be most sensitive to small fields reaching an apparent saturation effect at approximately 100 Gauss. The efficiency increase was noted to be on order of 1.5% per Gauss for very low fields and reached a maximum increase of 3.0% overall.

In 1975, E. Jeenicke[3] et al further investigated this phenomenon in a mineral-oil base scintillator. They reported that below 1 Gauss, the scintillator had a sensitivity of less than $10^{-5}$% per Gauss, but above this threshold, the efficiency increased rapidly to 1.5% at 40 Gauss, and finally reached an efficiency saturation of 1.8% at 100 G. It was also noted that this effect depends on the magnitude of B only.

In 1986 S. Bertolucci[1] et al measured the magnetic field dependence of an acrylic scintillator up to 2 kilogauss. They noted a 5% increase in light output for a change of magnetic field from zero to 100 Gauss. The increase was found to be 7% for a 2 kilogauss field. Attempts were made in this experiment to keep spiraling Compton electrons from re-entering the scintillator by wrapping the scintillator with a 5mm thick lead foil. At fields above 1000 Gauss some difference was observed in the output of the shielded scintillator compared with the unshielded scintillator, but at lower fields there did not appear to be any effect indicating that these fields were insufficient to cause electron re-entry. The overall effect appeared to have a logarithmic dependence on the B field with the largest effects evident at low field strengths. An additional measurement was made in which delayed fluorescence was eliminated as a cause.

The work of Jeenicke et al tends to verify the existence of this phenomenon, but leaves some questions as to its source. This same paper attributes the phenomenon to the intrinsic molecular structure of the scintillator, but does little to reveal the actual nature of the effect. Bertolucci et al were unable to determine the cause, but did eliminate delayed fluorescence as the principal factor. A large discrepancy between these 3 experiments in the measured efficiency indicates that the effect is extremely material dependent. However all articles agree that most of the increase occurs quite quickly within the first 100 Gauss.

We employed the simple Helmholtz coil arrangement shown in figure 1 for our non-wavelength dependent measurements and studied the light emission as a function of the magnetic field in the range 0 to 120 Gauss. Our wavelength dependent light output versus magnetic field measurements were performed using the apparatus shown in figure 2. The results of our studies of the intrinsic bulk properties of acrylic scintillator are reported in section 2 and the magnetic field measurements are reported in sections 3, 4, and 5.

## 2. Intrinsic Properties Studies

The increased light output from plastic scintillators in magnetic fields could be caused by several different effects. First, it is possible that the index of refraction of the scintillator material could change in a magnetic field thus decreasing the light loss due to partial transmission. Second, surface phenomena might be responsible for changing the reflectivity of the material. Third, emission or absorption properties of the scintillator might change when placed in a magnetic field.

Studies of possible changes in the bulk properties of acrylic scintillator were performed using material manufactured by Polivar Company in Pomezia, Italy. The material was composed of Polymethyl-methacrylate with 3% napthalene, 1% butyl-BPD, and 0.02% BDB. No detectable change in the index of refraction of this material was observed using fields up to 100 Gauss. The study was made by shining a laser beam through the material near the angle of total internal reflection and by looking for a change in the refraction of the beam. A second study was performed using spectrofluoroscopy.[6]

The primary fluoroscopic test involved irradiating the sample with a constant ultraviolet source at a wavelength of 254 nanometers and monitoring the emission spectrum. This same test was repeated in a field of 125 Gauss established by aligning several bars of magnetized iron with the sample in the central gap of the spectrophotometer. The emission spectra from these two analyses are overlayed in figure 3 and as can easily be seen are indistinguishable.

A secondary test was the measurement of the absorption by the sample over the wavelength range 400 to 800 nanometers. Using a constant incident light spectrum, measurements were made of the transmission spectrum of the sample with a 125 Gauss field either on, ($I_{on}$), or off ($I_{off}$). A comparison of the two spectra was made by plotting $-\log(I_{on}/I_{off})$ against wavelength in figure 4a, (*i.e.* the difference between the absorption spectra with the field on and with the field off). A separate measurement of $-\log(I_{off}/I_{on})$ was also made and is presented in figure 4b. If the magnetic field had no affect on the absorption of the sample then the plots should be flat at zero. The results seem to show the absorption to be smaller in a magnetic field by about 0.15%. However, the same measurements were made with no scintillator sample, (*i.e.*using air as the sample), and these results are shown in figures 4c and 4d. These show the same effect indicating the field affects the instrument in some way. [A likely cause is due to a magnetic field effect on the plasma discharge in the deuterium lamp that supplies the incident light for the spectrophotometer.] Since the effect has the same size and direction with and without the sample, any additional effects on the absorption due to a magnetic field must be much less than 0.15%. The results in figure 4 suggest an upper limit of about 0.02% for the effect of the magnetic field on the absorption of the sample.

The analysis of the above data indicates that there is very little or no change in the fluoroscopic properties of the scintillator material. The primary test also indicates that there is no change in the index of refraction of the material since the light output is the same for both spectra. (A change in the index of refraction would have changed the critical angle for 100% reflection and a change would have been observed in the output.)

## 3. Experimental Apparatus

For both the cosmic ray and the non-wavelength resolved gamma ray measurements, the same basic experimental set up was used. This set up included the following: Helmholtz coil with power supply, 2500 Volt HV DC power supply, RCA 8575 photomultiplier tube (PMT), picoammeter, and cabling. In both portions of the experiment, only the number and types of scintillators were varied.

The Helmholtz coil supply was able to vary from 0 to 20 Amps. The maximum current corresponded to approximately 120 Gauss at the center of the coil. Three feet outside of the coil, at the location of the PMT, the measured field strength was approximately 11 Gauss prior to magnetic shielding.

The PMT was a 12 stage high gain tube. The tube bias varied between 1900 and 2400 Volts depending on the experiment being performed. In all experiments, magnetic shielding was placed around the PMT to eliminate any effects that the field might have on the tube operation. Measurements were made of the field strength next to the tube after the shielding was in place and it was found to be on the order of 0.01 Gauss. The phototube gain and collection efficiency were tested by monitoring the anode output current when small bar magnets were waved around the tube. No change was observed. For the cosmic ray studies an Americium alpha source embedded in a scintillator button was directly attached to the PMT's photocathode. No change in the light source pulse height was observed as the magnetic field changed. Thus we concluded that the gain of the PMT was independent of changes in the magnetic field.

For the cosmic ray and the non-wavelength resolved radioactive measurements, the scintillator construction had the same basic pattern throughout the experiment (see figure 1 ). First, the scintillating material was glued to a plexiglass disk or light guide. This assembly was then wrapped with a light reflective material followed by black tape. The scintillator was coupled to the PMT with either optical glue or grease. The PMT and its base were also wrapped in black tape as was the joint between the scintillator and the tube. In all cases, the assembly was tested for light leakage and any leaks were sealed so that no offset output current was produced. The entire PMT and approximately 5 cm of the scintillator were then magnetically shielded. Measurements were taken from the picoammeter in the following manner: The scintillator assembly was placed in its proper position and was supplied with a bias voltage. The current monitored on the picoammeter (with no source present) was then suppressed. This eliminated any offset which could affect the measurements of current change. With offsets due to background noise and light leakage eliminated, it was then possible to accurately measure the effects the magnetic field strength had on the current output.

The wavelength resolved gamma ray measurements were performed with the set up depicted in figure 2. A rectangular sample ($1.2 \times 1.2 \times 4.0$ cm$^3$.) of the acrylic scintillator was placed between the jaws of a small dipole magnet. A Hall probe monitored the field on the sample during all exposures. The sample plus magnet was placed up against the entrance slit of an ISA HR 320 monochromator. The monochromator was equipped with a 147 groove/mm grating and the output of the monochromator was coupled to a Princeton Instrument's IRY700 intensified diode array. This system gave us approximately a 0.5 nm resolution/diode over the total field of view of roughly 350 nm. The overall gain stability of the diode head was determined to be ± 1%. Since stray fields can effect the performance of the micro-channel plate image-intensifier in the diode head, the field at the intensifier was monitored as the dipole was energized to its maximum current (corresponding to 150 gauss.) No change in the field at the intensifier was observed for a dipole field of 150 gauss. A 2mCi cobalt-60 source was used for scintillator excitation for this study and an integration time of 45 seconds was chosen for each exposure. Both the total integrated photon flux from the scintillator and the shape of the fluorescence distribution were studied as a function of applied field. For each measurement a source off(background) subtraction was applied to the data.

## 4. Cosmic Ray Measurements

The scintillator studied was acrylic of the composition described above, manufactured by Polivar. The scintillator dimensions were 1.25 cm × 7.5 cm × 1.5 m. The cosmic ray experiment involved the use of up to four scintillators. The first as described above and the addition of up to three trigger scintillators which were used for coincidence and discrimination of the signals. Two of the trigger scintillators were directly above and below the primary scintillator. Lead shielding was placed around the scintillators in the region of interest to reduce the cosmic ray horizontal particle component as well as low energy particles passing through the apparatus. This set up was located in the center of the coil. The third trigger scintillator was placed approximately 36″ below the main apparatus. Twelve to 18 inches of lead shielding were placed above this fourth scintillator in order to eliminate any low energy particles which could have significant curvature in the magnetic field. A coincidence from the trigger scintillators was used to gate a Lecroy 2249A 12 channel analog to digital converter. The gate provided an integration time of 180 ns, enough time to include the entire pulse height signal for the scintillator of interest. For each value of field intensity an Americium imbedded scintillator mounted directly on the face of the photomultiplier tube was used to monitor any gain changes during the run. This scintillator was located in a well shielded area and thus any tube drift could be detected. Finally, the results of each event were stored in a computer.

Runs of data were taken for periods of time ranging from 2 to 48 hours, depending on the particular setting. At the end of each run the pulse height distributions were fitted for the peak value, exponential decay constant of the Landau tail, and width of the peak. The fitting function was obtained with a gaussian fit to the leading edge and peak and an exponential fit to the trailing edge of the distribution. The curves were matched by setting the first derivatives of the logarithms of the two functions equal and by adjusting the amplitude of the gaussian at this matching point. A typical plot is presented in figure 5. The dotted curve is the fit to the data. Although the fit is not particularly good, it does measure all the gross features of the data.

Figure 6 presents the results of fits to the peak value from several data runs. The results are referenced to the no field run (Earth's Field– about 0.22 Gauss). The observed effect was greatest at low fields increasing by 1.5% at 10 Gauss and reaching a value of about 3% at 100 Gauss. The effect appeared to have a logarithmic dependence on the magnetic field in agreement with the results of Bertolucci et al. Measurements were made with the magnetic field oriented in different directions (this was accomplished by relocating the sample) with no apparent difference in its effect which verified the claim that the light yield change is dependent only on the magnitude of the field.

Figure 7 shows the results of the fitted gaussian width squared as a function of magnetic field for each of the points presented in figure 6. No correlation with the magnetic field is observed. Figure 8 presents the exponential decay constant as a function of increasing magnetic field. Again no obvious correlation is observed.

Thus, from the cosmic ray experiments we learned that light yield increases with increasing magnetic field. However there are no peculiar features to the distributions. The peak in the ADC distributions just shifts higher while the width and Landau tail have the same values independent of magnetic field. It is expected that the width will slightly change with increased light yield, but the change, if there was one, was within our errors.

## 5. Non-Wavelength Resolved Radioactive Source Measurements

These radioactive source experiments involved the use of only a single scintillator during any one measurement. Four different types of scintillation materials were tested: acrylic, two different polyvinyltoluene[7] paddles, and polystyrene[8] ribbon fibers. As in the cosmic ray experiment, the scintillator was placed in the center of the coil, but the anode output of the PMT was integrated in a picoammeter. With a source it was extremely easy to make measurements and data could be accumulated rather quickly. Usually a gamma ray source of cobalt-60 was used, although for specialized studies alpha, beta, and fission fragments were also used.

Figure 9 shows the results obtained using the acrylic scintillator described above. The percentage change from the no field reading is plotted versus the applied magnetic field. Also presented in figure 9 are the results with copper tape wound tightly around the scintillator. The copper tape was implemented to range out Compton electrons which exit the scintillator and which are bent back inside to count again. A slight reduction in light yield increase with the copper tape in place indicates that there are some Compton electrons which leave the scintillator and come back inside. Both curves demonstrate a logarithmic rise with applied magnetic field.

The results from the different paddles and materials are presented in table 1. The errors on percentage changes are about 0.5%. The main feature of the results is that acrylic scintillator has a significant change in the light yield with increasing magnetic field, while polystyrene and polyvinyltoluene scintillators have a much smaller change. Runs made with heavily ionizing alpha particles and fission fragments show a slightly higher change than those observed with the gamma source.

Because data could be accumulated quickly with a radioactive source, many different studies were performed which are worth mentioning. However in all of the studies the same increase in light yield with increasing magnetic field was observed.

One test involved changing the wrapping material from aluminum foil to paper. In seemed possible that light might be trapped in the scintillator - aluminum interface and as the magnetic field increased the reflectivity of aluminum might change. However, no difference in the light yield with increasing magnetic field was observed when a paper wrapping was substituted for aluminum foil wrapping.

Another test involved wrapping the scintillator with sticky black tape such that only light which started out directly toward the PMT reached the PMT. If a surface effect was responsible for the light increase, then in such a test no increase should be observed. Although the light yield was greatly decreased by wrapping the scintillator with black tape, the percentage increase in light output was the same as when the scintillator was wrapped with aluminum foil.

## 6. Wavelength Resolved Radioactive Source Measurements

These measurements were performed with the setup of figure 2 as described in section 3. Only the Polivar acylic scintillator was studied with this apparatus and in all exposures the scintillator was unwrapped. A typical light output versus wavelength distribution for one run is given in figure 10. The ordinate is in ADC counts and represents total integrated photon flux at a given wavelength (diode). The total light yield was then determined by summing over all wavelength bins. The relative light output data for exposures at fields up to 150 gauss are given in figure 11. Again, we see a saturation effect with a saturation value of between 4 and 5 percent increase in photon yield.

In addition to measuring overall light yield with this apparatus, we can see if the shape of the spectral distribution of light from the sample changes as the field is applied. Figure 12 shows an overlay of the no field data and the applied field equals 75 gauss data. As can be seen there is no apparent change in the shape of the fluorescence distribution. The number of photons emitted increases, but this increase is not does not appear to be wavelength dependent.

## 7. Summary and Conclusions

The light output of acrylic scintillator increases when the scintillator is placed in a magnetic field but interestingly, the light output of polystyrene and polytoluene scintillators is not changed nearly so much. It appears that this light yield effect is highly dependent on the chemical composition of the scintillator. This fact probably accounts for the difference in results obtained in earlier experiments.

Fluoroscopic testing of the acrylic scintillator revealed no change in the emission or absorption properties of the material and indicated that there was no change in the index of refraction. Earlier attempts to measure a change in the index of refraction using laser light also revealed no change in the index of refraction.

For acrylic scintillator, the light output increases about 4% using a $Co^{60}$ gamma source at 100 Gauss over the light yield with no field. The increase is slightly larger when an alpha source and fission fragments are used. The increase is apparently uniform over the pulse height distribution as determined by cosmic ray experiments. The peak pulse height increased with increasing magnetic field, but the gaussian width and the exponential decay parameter determined from curve fitting were constant within an experimental accuracy of less than 5%. In addition, wavelength resolved gamma ray measurements confirm the light output increase and that there is no spectral change in the shape of the fluorescence distribution with applied magnetic field.

Current measurements of the PMT output using a $Co^{60}$ source revealed that wrapping the scintillator with copper tape reduced the effect by approximately 10%. Although curling electrons do contribute to the increase in light yield, they cannot account for the entire increase. The reason for rejecting this cause as dominant is that the light yield effect is greatest at low fields where curling is the least and the path length change is minimal. The path length change can't be the dominant effect.

One theory that supports the experimental evidence is that there is a localized saturation effect in the light conversion properties of acrylic scintillator. Slight differences in Compton electron momenta would cause a separation of the electrons, due to differences in the spiral radius. The greatest effect would be observed at low fields while at larger fields the electrons would already be separating, and large increases in field strength would be required to produce a small increase in output. This type of an effect would also be highly dependent on the chemical composition of the scintillator, namely, on the density of excitation centers within the scintillator. The lower the density of excitation centers the more likely a localized saturation is to occur. Also the effect would be expected to depend on the type of the primary ionizing particle. Heavy ionizing particles create a larger high excitation region within the scintillator than do beta or gamma rays.[9] This creates more potential for a localized saturation effect. This theory is further supported by results that no differences were found in the intrinsic properties of scintillator when placed in a magnetic field. We saw that under both UV excitation and gamma ray excitation the shape of the fluorescence spectral distribution remained constant. However, there was a light yield increase in the case of gamma ray excitation and no similar increase was seen for the UV excitation measurement. Since the deep UV exposures used in our measurements excite both the PMMA base of the scintillator and the primary dopants in much the same way as ionizing radiation, the saturation effect is again indicated as the origin behind the light output increase for the gamma ray exposure. Obviously, under UV excitation no change in the density of excitation centers should occur with applied magnetic field. In this case the density of these centers is purely determined by the intensity of the UV light and the absorption coefficient of the scintillator at the excitation wavelength. While this theory explains the observations, it would be very useful to further test the hypothesis by obtaining a wide variety of scintillators and measuring their magnetic field dependence.

## 8. Acknowledgments

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5. E. Bodenstedt, L. Ley, H.O. Schlenz, U. Wahmann, Nucl. Phys. A137(1969) 33
6. The spectrophotometer work was performed on a Hewlett Packard 8451A Diode Array Spectrophotometer.
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8. The scintillating fibers were polystyrene based doped with 1.25% BPBD and 0.01% Bis-MSB.
9. F. Brooks, Development of Organic Scintillators, NIM 162(1979) 477-505

Table 1. Radioactive Source Results

| Material | Radioactive Source | Percentage change from Earth's Field to 120 Gauss |
|---|---|---|
| Acrylic Scintillator | $Cf^{252}$ (Spontaneous fission) | 4.3% |
|  | $Am^{241}$ (alpha particles) | 4.8% |
|  | $Co^{60}$ (gamma source) | 4.0% |
| Polystyrene Fibers | $Co^{60}$ (gamma source) | 1.0% |
| Polytoluene Paddle (NE114) | $Co^{60}$ (gamma source) | 1.0% |
| Polytoluene Paddle (NE110) | $Co^{60}$ (gamma source) | 1.0% |

# FIGURE CAPTIONS

1. A schematic drawing of the Helmholtz coil experimental apparatus.
2. A schematic of the apparatus used for the wavelength resolved measurements using cobalt-60 excitation.
3. The emission Spectra for acrylic scintillator when excited at 250 nanometers, measured with (a) no field and (b) at 150 Gauss.
4. The difference in absorption spectra (a) with field on minus field off and (b) field off minus field on. Figures (c) and (d) show the same results respectively when no sample was present in the absorption test.
5. A typical cosmic ray pulse height distribution with a sample fit to a gaussian on the left of the peak and an exponential on the right side.
6. The percentage increase in the ADC peak value referenced to zero magnetic field.
7. The gaussian width coefficients for the cosmic ray runs as a function of the externally applied magnetic field.
8. The exponential decay coefficients for the cosmic ray runs as a function of the externally applied magnetic field.
9. The $Co^{60}$ source results using the acrylic scintillator sample as a function of applied magnetic field.
10. Light yield versus wavelength for the 0 field case using the acrylic scintillator and cobalt-60 excitation.

11. Relative yield versus field strength for acrylic scintillator and cobalt-60 excitation using the apparatus of figure 2.
12. Field on (75 gauss) minus field off data for cobalt-60 exposures.

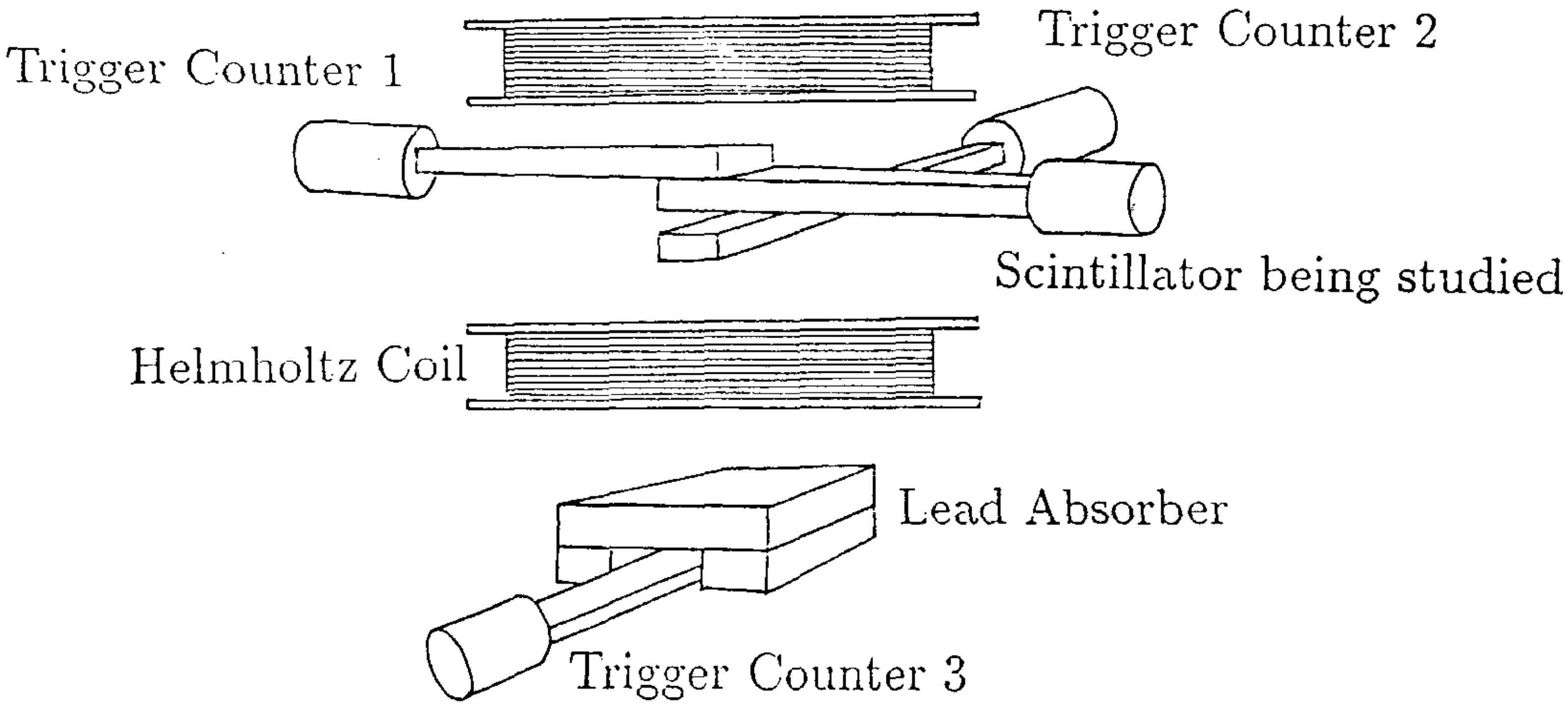

Trigger Counter 1
Trigger Counter 2
Scintillator being studied
Helmholtz Coil
Lead Absorber
Trigger Counter 3

Figure 1

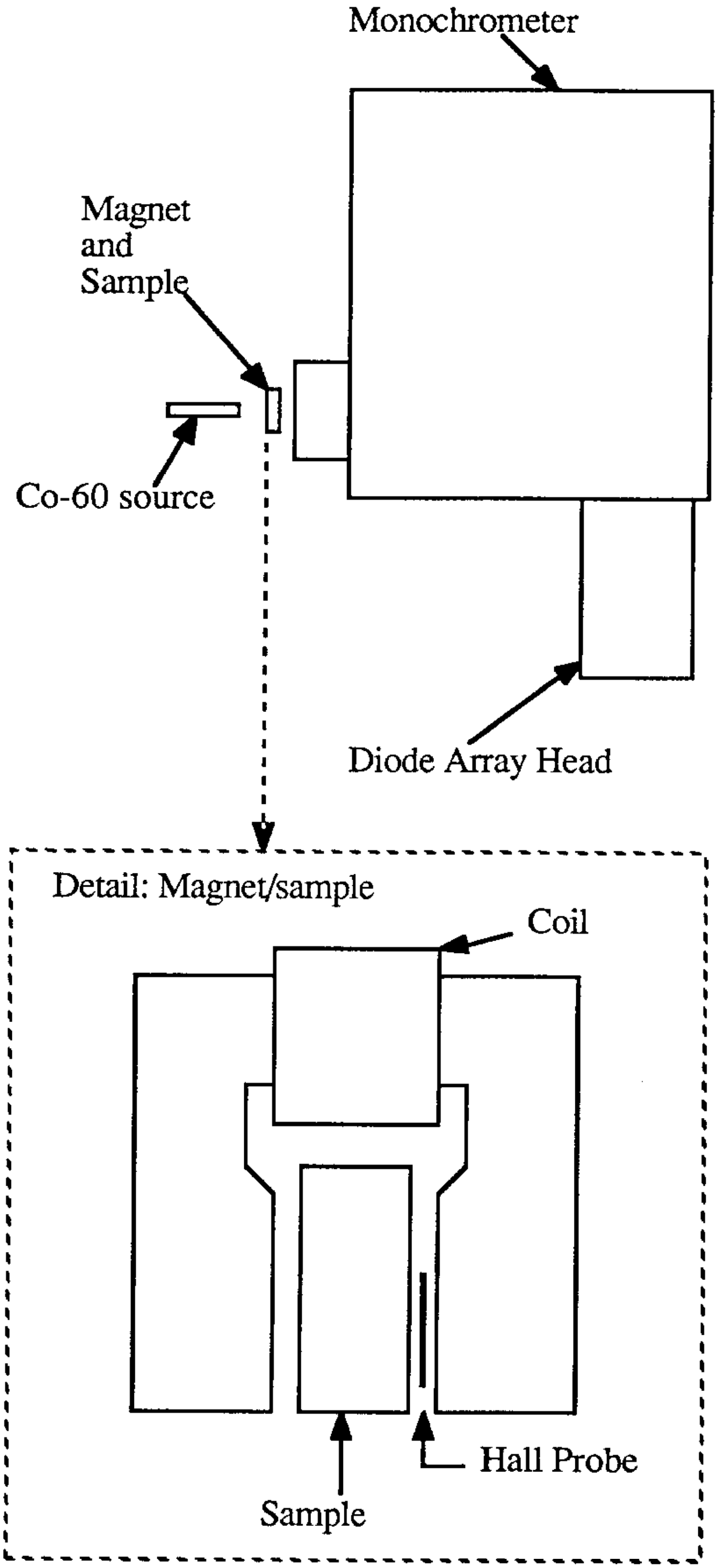

Monochrometer
Magnet
and
Sample
Co-60 source
Diode Array Head
Detail: Magnet/sample
Coil
Hall Probe
Sample

Figure 2

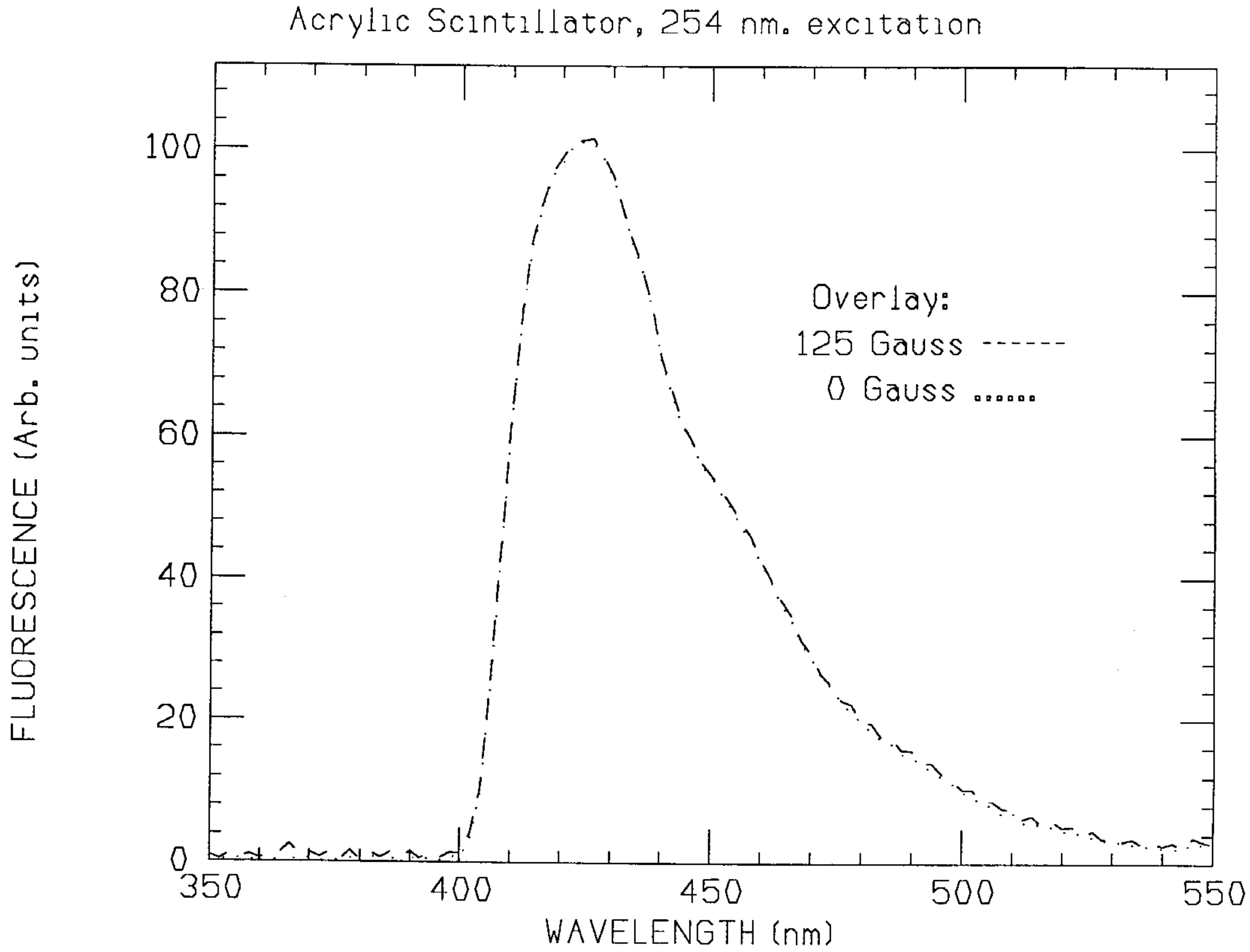

Acrylic Scintillator, 254 nm. excitation
Overlay:
125 Gauss ------
0 Gauss ......
100
80
60
40
20
0
350
400
450
500
550
WAVELENGTH (nm)
FLUORESCENCE (Arb. units)

Figure 3

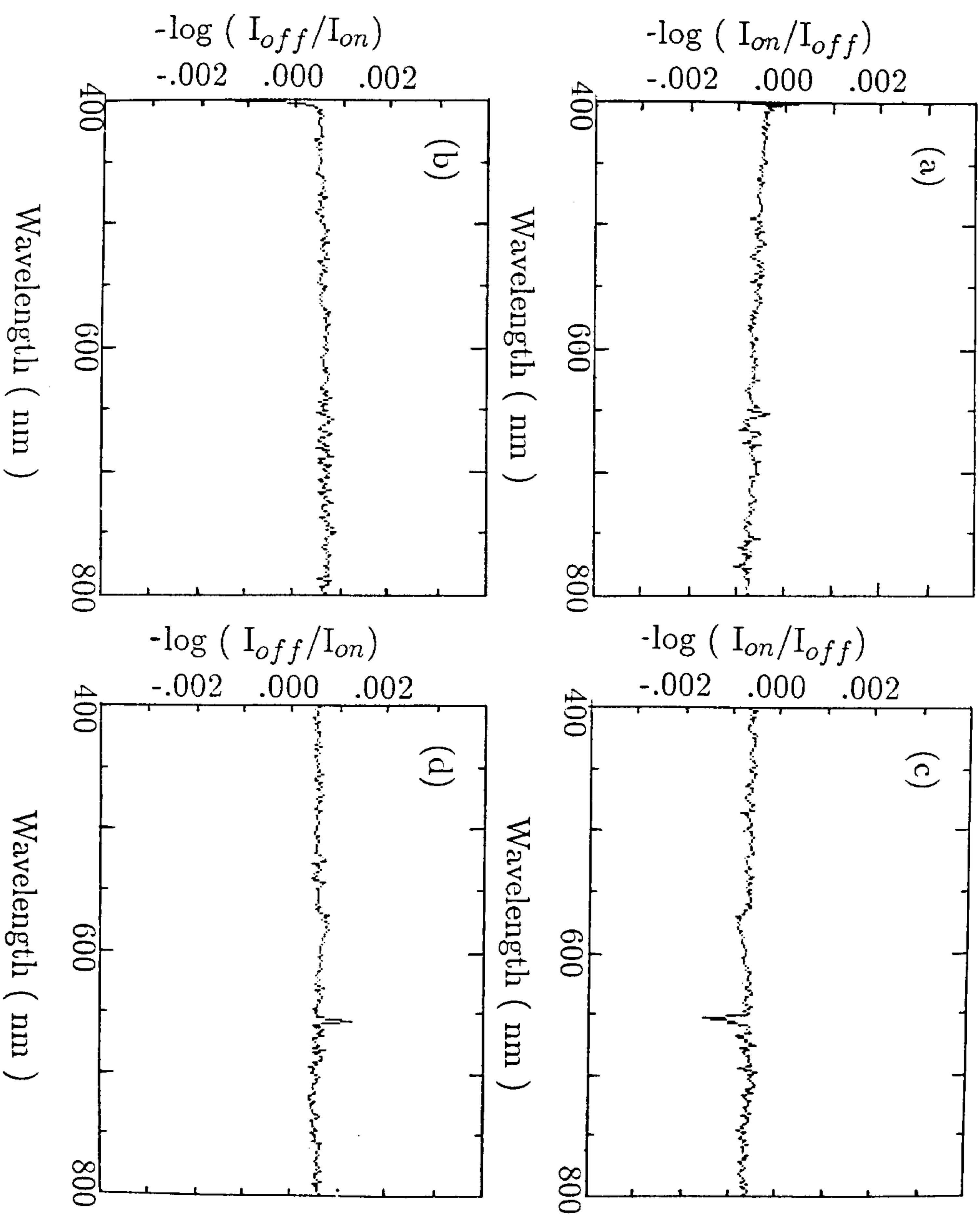

-log ( I_off/I_on )
-log ( I_on/I_off )
-.002
.000
.002
400
600
800
Wavelength ( nm )
(a)
(b)
(c)
(d)

Figure 4

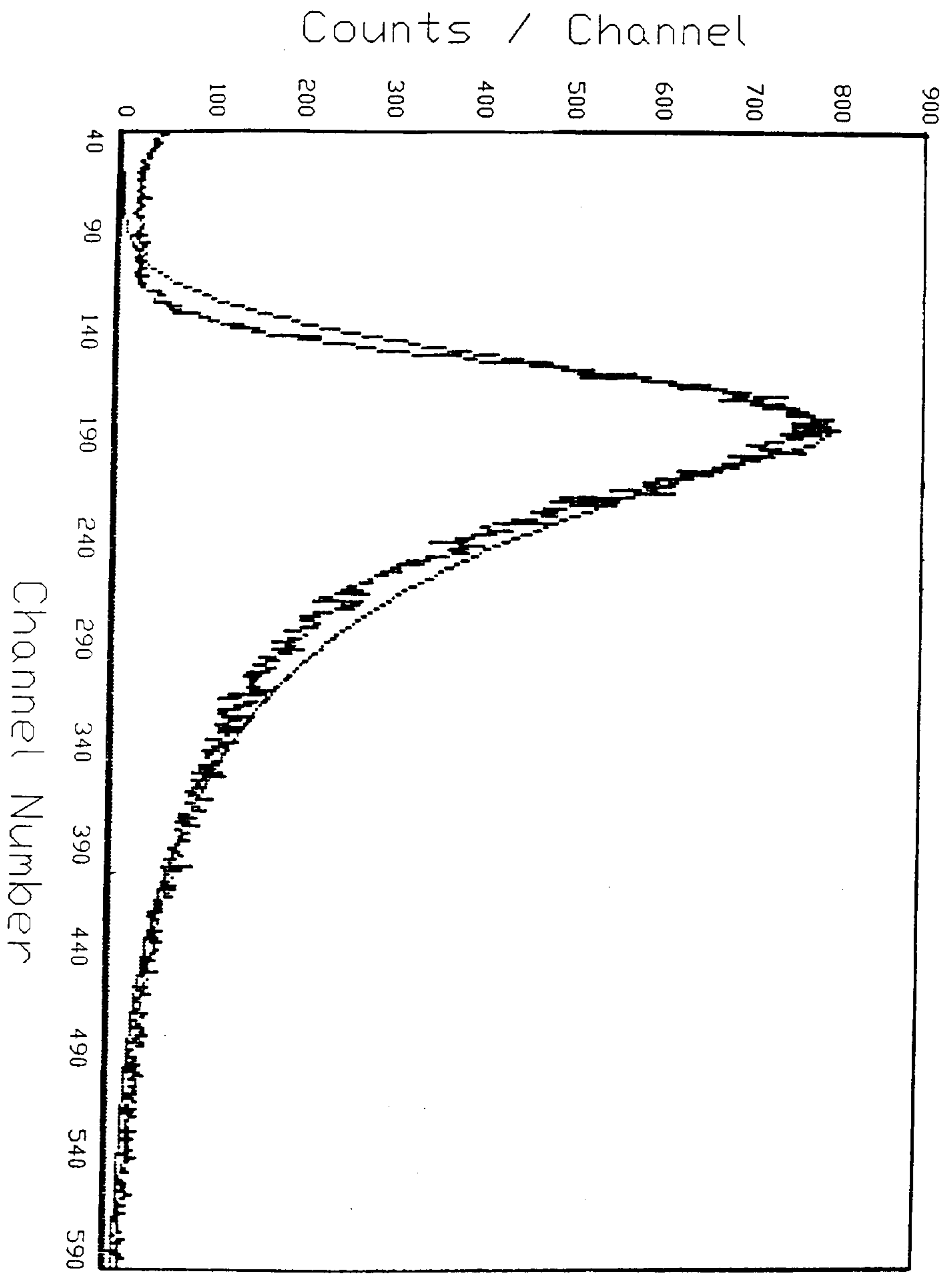

Counts / Channel
0
100
200
300
400
500
600
700
800
900
Channel Number
40
90
140
190
240
290
340
390
440
490
540
590

Figure 5

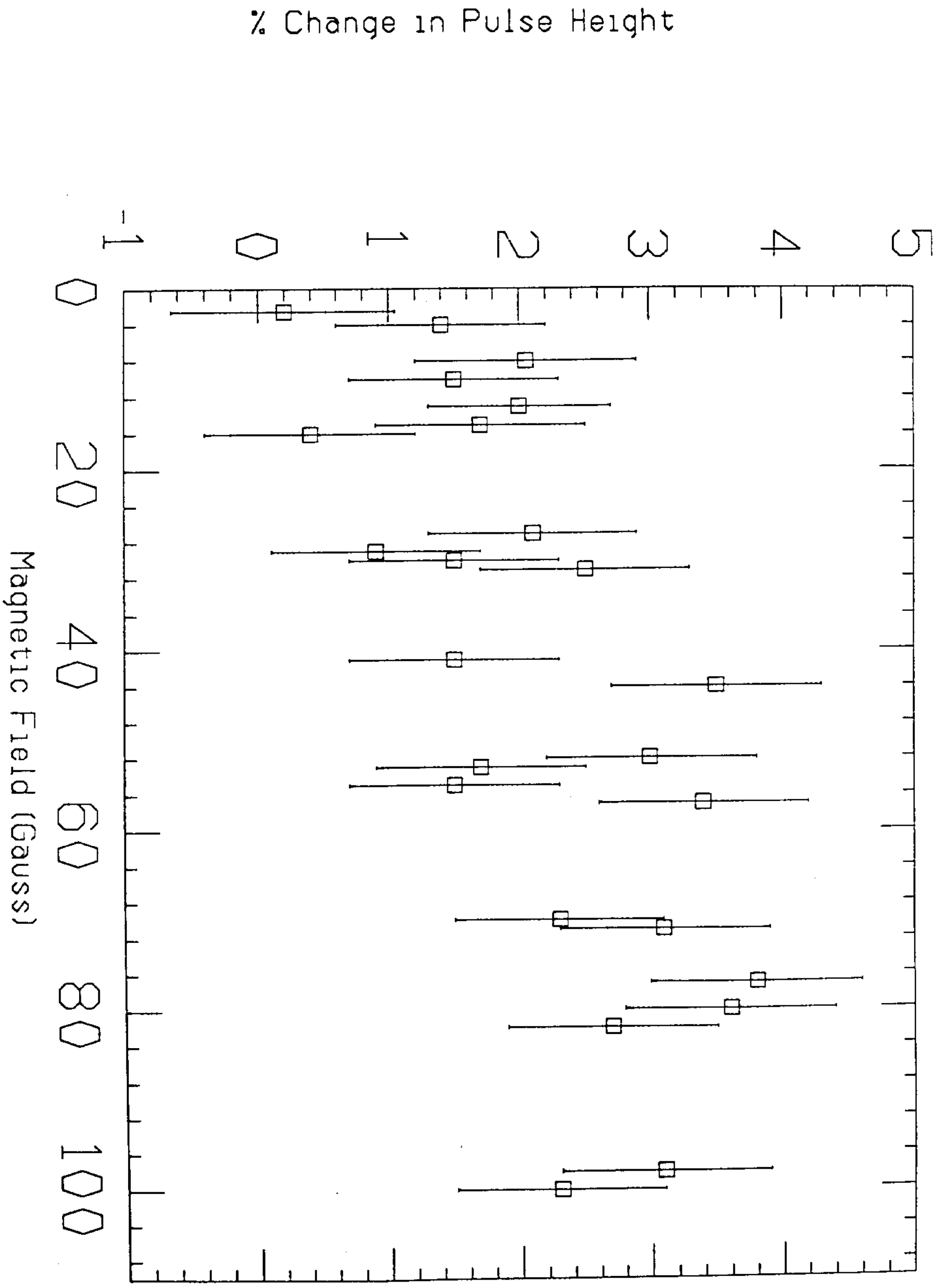

% Change in Pulse Height
-1
0
1
2
3
4
5
Magnetic Field (Gauss)
0
20
40
60
80
100

Figure 6

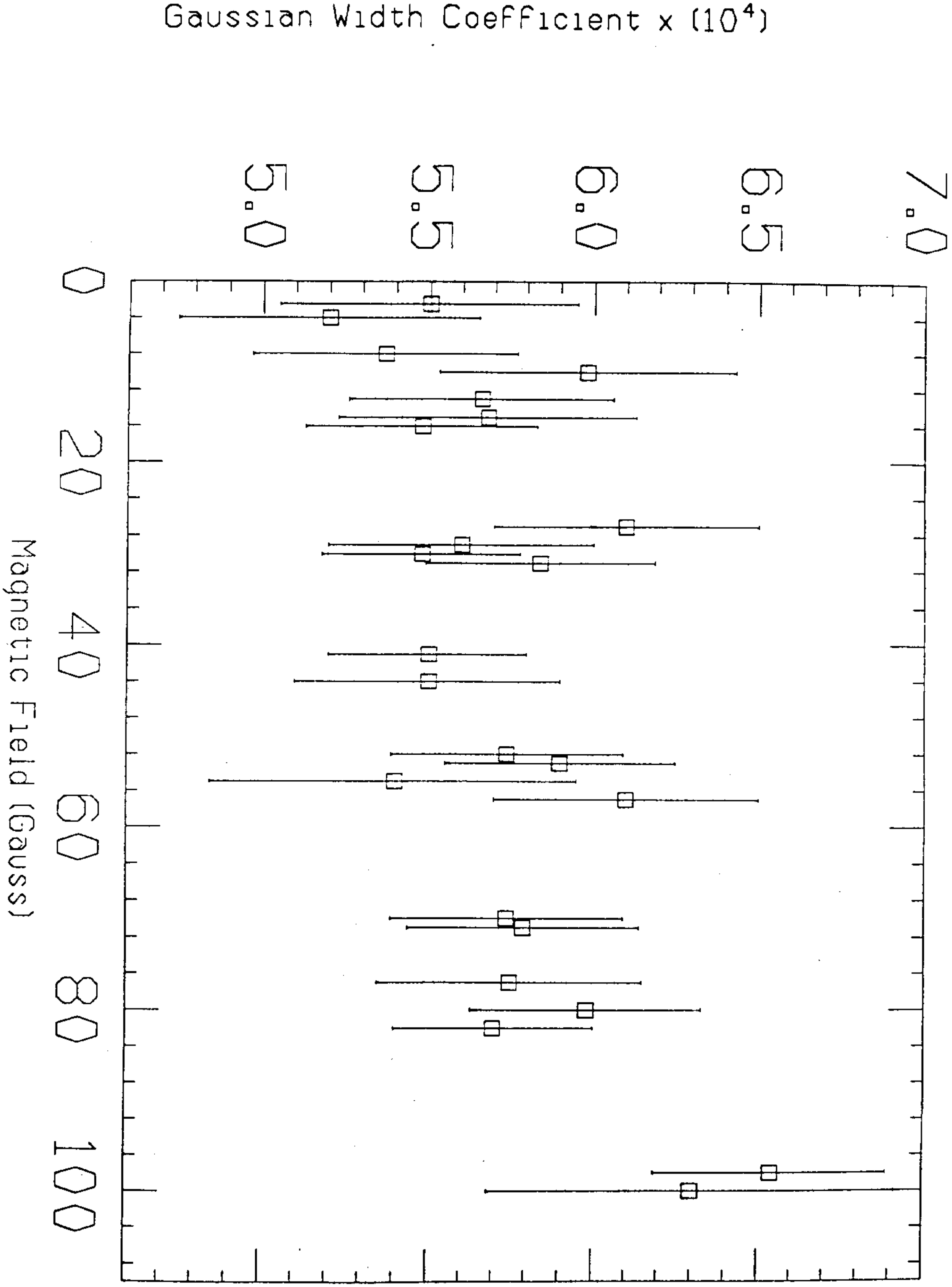

Gaussian Width Coefficient x (10^4)
5.0
5.5
6.0
6.5
7.0
0
20
40
60
80
100
Magnetic Field (Gauss)

Figure 7

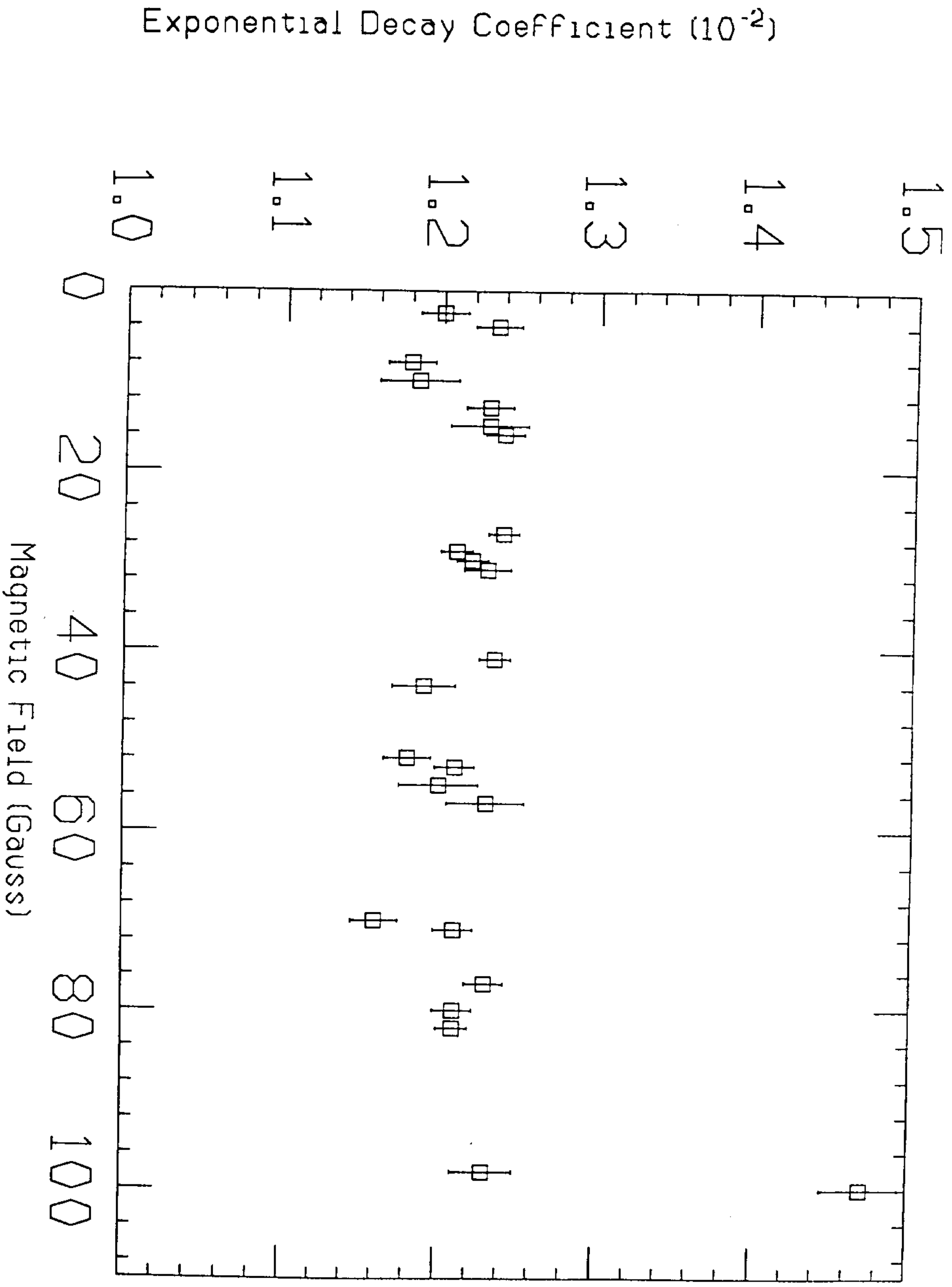

Exponential Decay Coefficient (10^-2)
1.0
1.1
1.2
1.3
1.4
1.5
0
20
40
60
80
100
Magnetic Field (Gauss)

Figure 8

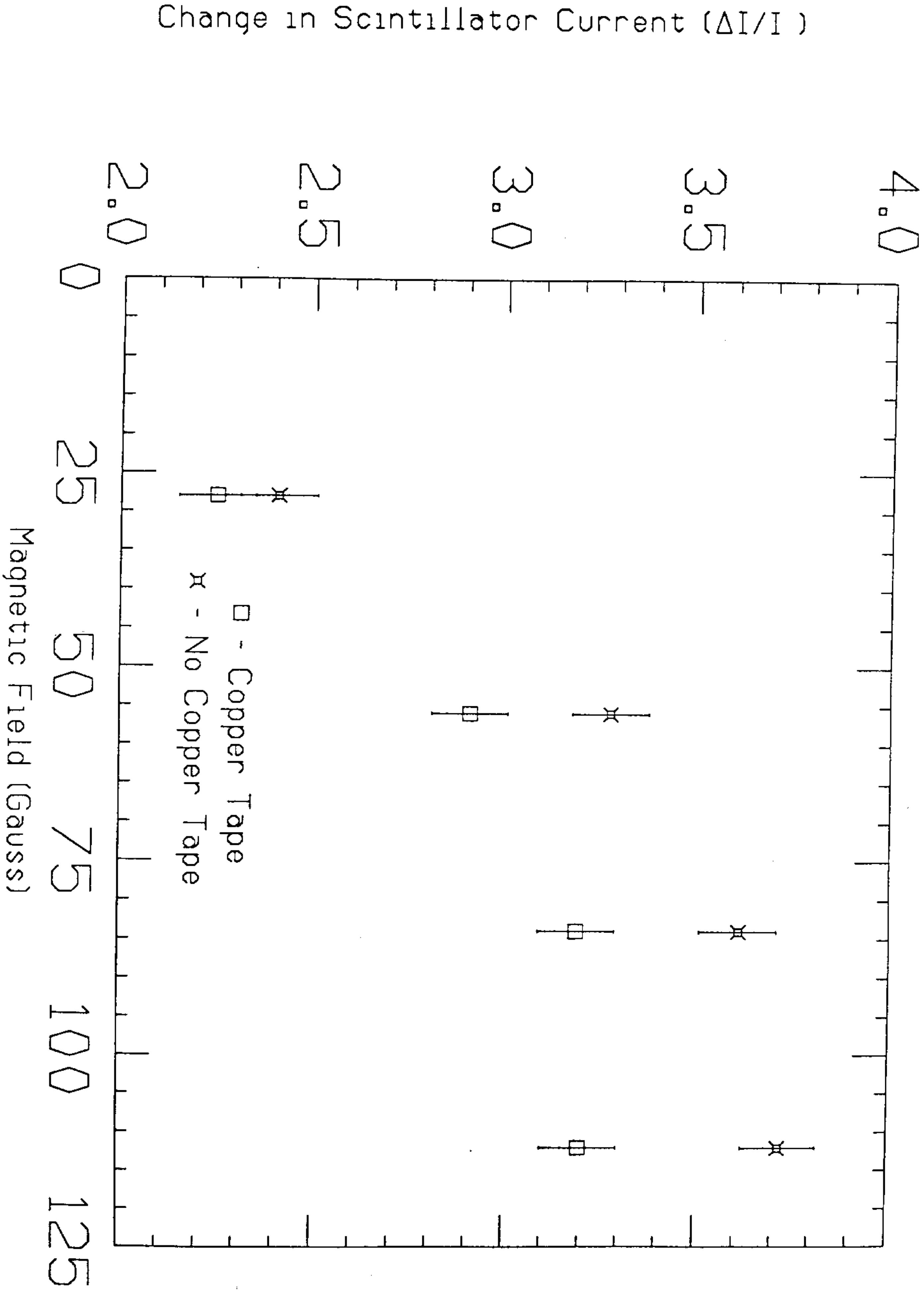

Change in Scintillator Current (ΔI/I)
2.0
2.5
3.0
3.5
4.0
0
25
50
75
100
125
Magnetic Field (Gauss)
□ - Copper Tape
¤ - No Copper Tape

Figure 9

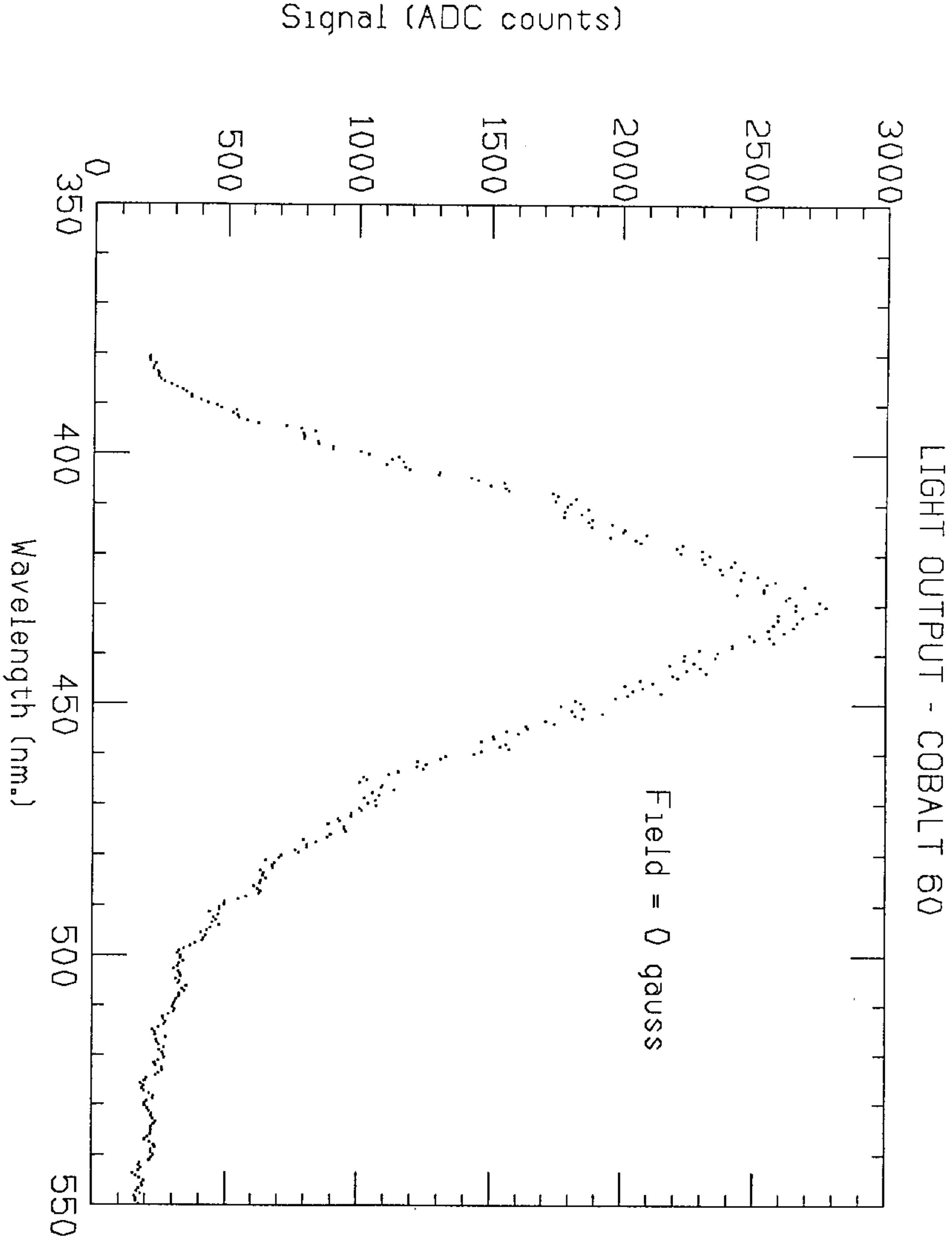
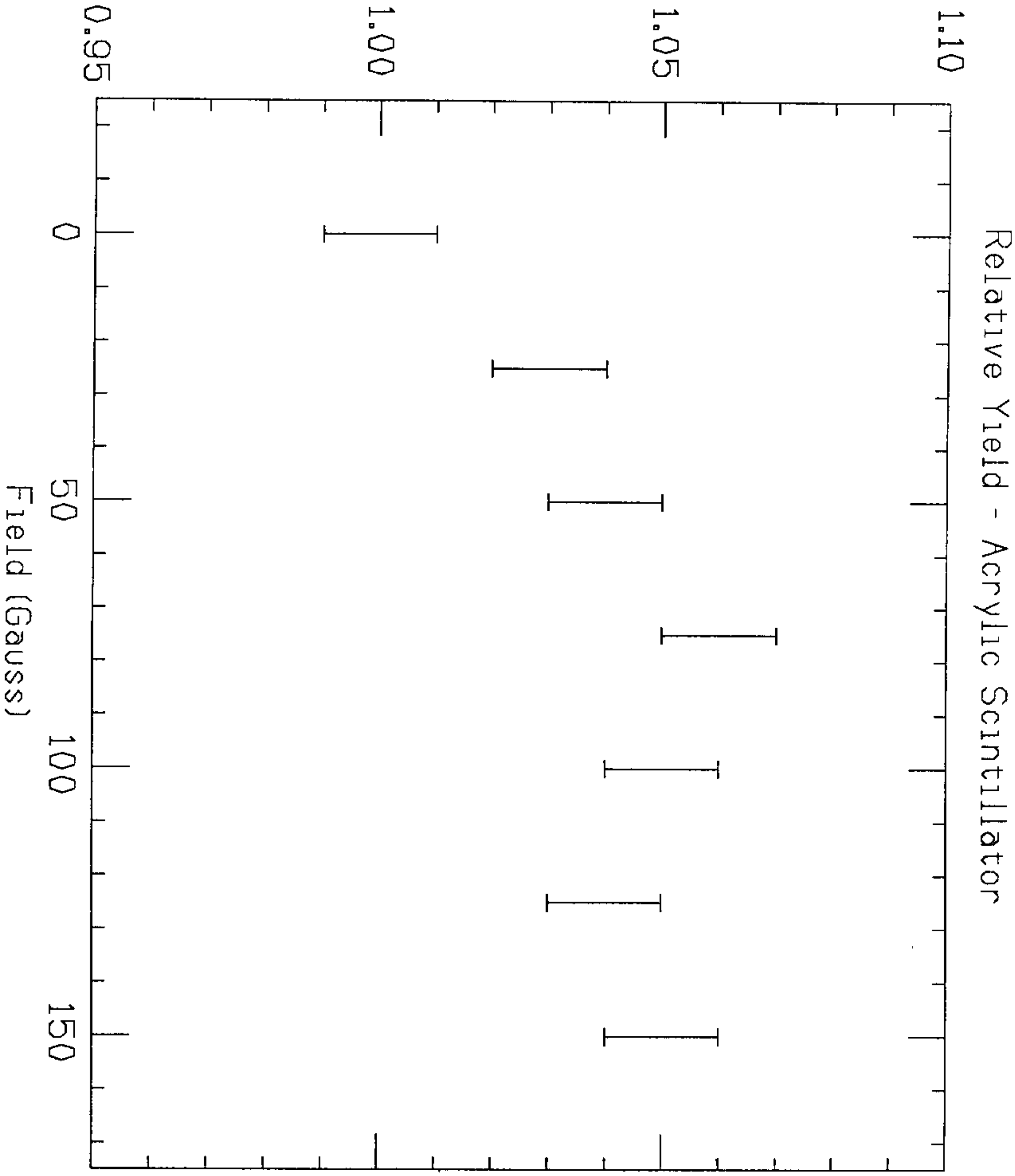

LIGHT OUTPUT - COBALT 60
Field = 0 gauss
Signal (ADC counts)
0
500
1000
1500
2000
2500
3000
Wavelength (nm.)
350
400
450
500
550

Figure 10



Relative Yield - Acrylic Scintillator
1.10
1.05
1.00
0.95
0
50
100
150
Field (Gauss)

Figure 11

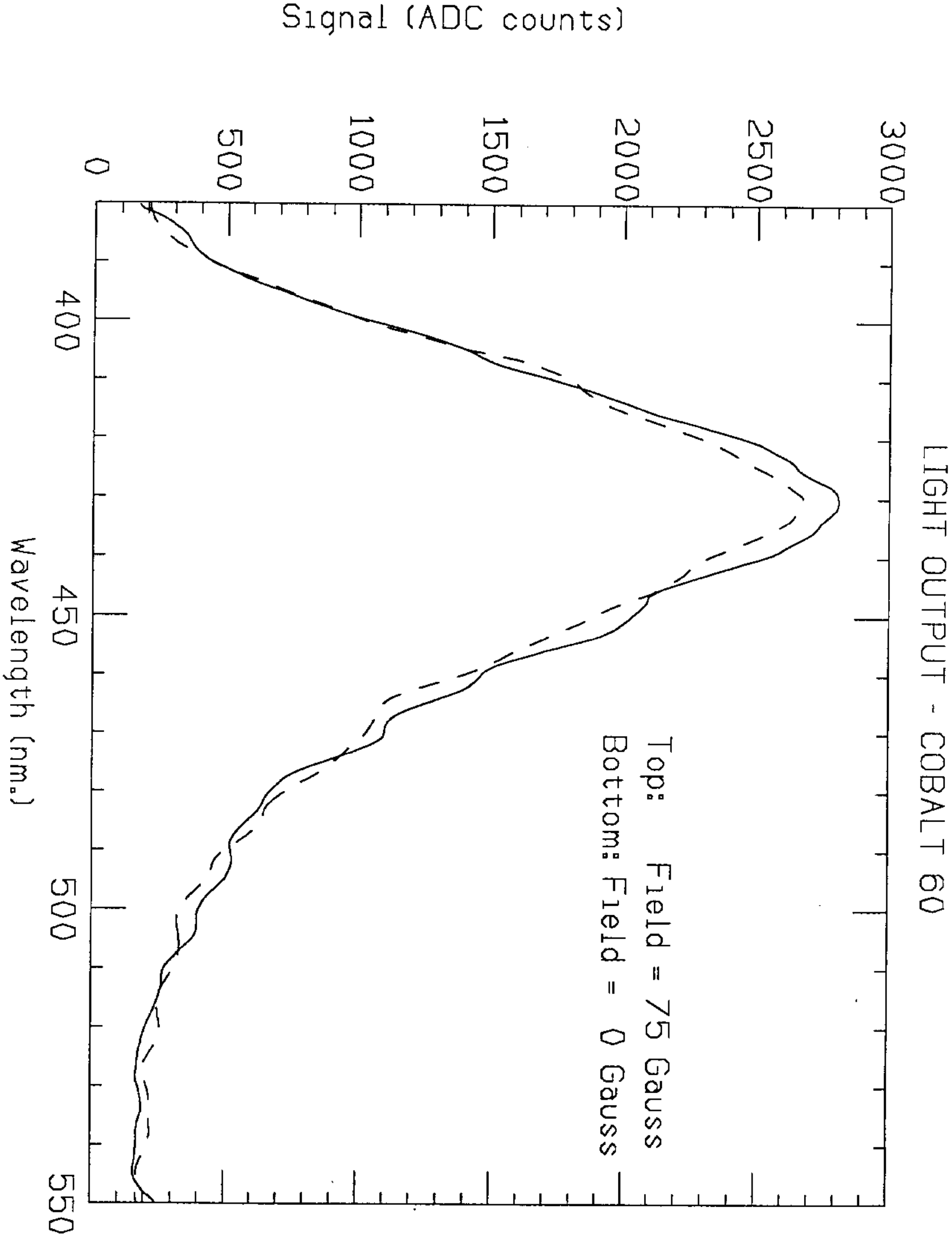

LIGHT OUTPUT - COBALT 60
Top: Field = 75 Gauss
Bottom: Field = 0 Gauss
Signal (ADC counts)
0
500
1000
1500
2000
2500
3000
Wavelength (nm.)
400
450
500
550

Figure 12