PVC Rods: A neutral current alternative to Cℓ-salt

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Abstract:

It is suggested that a split-vessel design using PVC rods is preferable to the dissolved Cℓ-salt option for neutral-current detection in the SNO detector. A neutral-current detection efficiency approaching 85% of the time-averaged efficiency for the salt-option would appear to be possible, but would require some research into the transparency and radioactivity of PVC.

1. Introduction

The neutral current (NC) measurement by the SNO detector is one of the most eagerly anticipated results in solar neutrino physics. Two methods are actively being pursued to carry out this measurement. In one, ^{3}He proportional counters will be installed throughout the volume of D_2O, spaced every metre. This is the preferred technique, because it determines the NC-event rate simultaneously with the charged current (CC) rate and independently of the Cerenkov light. The chief difficulties with this method are primarily of an engineering nature—building all of the proportional counters to exacting low-background standards and installing them after the SNO detector is built and filled with D_2O. They have an impact on the CC-measurement in that they absorb or scatter about 18% of the Cerenkov photons and raise the threshold wall by about 0.5 MeV (Los Alamos Nat. Lab. Report FIN-94-ER-E324). In the second method, a chlorine-salt ($NaC\ell$ or $MgC\ell_2$) is added to the heavy water. This method has the fundamental problem that the CC- and NC-events are both measured by Cerenkov radiation and may not be very distinguishable (although new developments in fitter techniques give some hope that some event-by-event distinguishability may be achievable). Consequently the only option is to cycle the amount of salt in the D_2O, and essentially to subtract the rate when there is little salt from the rate when there is a lot of salt. The complexities of this cycling, plus the uncertainties associated with removing radioactive elements from the water and monitoring the water for these elements in the presence of salt, lead to some concern about the viability of the method.

A third option, which has been considered in the past (Earle, E.D. (1990) private communication; Hargrove et al., SNO-STR-90-169) is to confine the chlorine to tubes. Originally, the suggestion was to put salt or brine in sealed tubes.

This report discusses another option; this is the use of transparent, chlorinated plastic tubes for the neutron-detector.

2. Chlorinated Plastics

There are several plastics which might be considered. They are poly-trifluorochloroethylene (Kel-F), polyvinyl chloride (PVC) and polyvinylidene chloride (PVDC). Kel-F ($CF_2{=}CFC\ell$) comes as extruded rods which have a translucent, milky appearance, is very dense, but is rather low in Cℓ content. It is however extremely expensive, about $400/foot for 2" diameter rods. PVC ($CH_2=CHC\ell$) is a very common plastic; its density is around 1.4 g/cm^3. It can be obtained relatively transparent (see below) with some (5-10%) crystallinity; it has an index of refraction of 1.54. A third plastic which was initially very attractive is a copolymer of PVDC ($CH_2=CC\ell_2$) and 5-10% PVC, (Saran is a trade name). It has a lot of chlorine; its density is 1.7 g/cm^3. However, after many enquiries, I was unable to locate anyone who had successfully made it into tubes or rods. The only feasible choice, certainly in the short term, would seem to be PVC.

3. PVC Rods - Basic Ideas

In order to make an estimate of the neutron capture efficiency on PVC rods, it is convenient to use the ^{3}He proportional counter design as a basis to scale from. In the ^{3}He case, there are 900 metres of 5.0 cm diameter tubes of ^{3}He at 3 atmospheres, giving a total of 220 moles of ^{3}He. With a cross-section of 5330 b/atom, the ^{3}He presents a capture area of 6.9×10^{29} b. If we want the same capture area with chlorine, which has a capture cross-section of 33.5 b, we require 2.1 tonnes of PVC. If we also assume a length of 900 m, then the PVC rods have a diameter of 4.6 cm. The mean free path for a thermal neutron in PVC is about 2.2 cm, and calculations by D. Patterson (private communication) give a n-capture fraction on the Cℓ in the tubes of about 41%. This is in agreement with the capture on ^{3}He tubes of the same diameter, judging from fig. 11 of Los Alamos Nat. Lab. Report FIN-94-ER-E324.

In the option where 2.5 tonnes of NaCℓ are dissolved in the D_2O, the total capture area is 8.6×10^{29} b, about 25% more than used above. The neutron capture efficiency on chlorine is about 80% with an additional 3% on deuterium. Can the PVC option be improved, to approach more closely the dissolved NaCℓ option, without too much effect on the Cerenkov light?

An obvious thing to try is to increase the mass of Cℓ to that of the NaCℓ option, and fractionate it more. Table 1 gives a list of the calculations for PVC carried out by D. Patterson. It is seen that with a 45 cm lattice spacing and 2.3 cm diameter rods, the efficiency of n-capture on the chlorine is 64%, with an additional 8% on the deuterium. The n-capture on the chlorine is probably slightly high, because there will be about a 3% capture on the hydrogen in PVC. Estimating 62% on chlorine and 8% on the deuterium, this option is between 78% and 84% of the dissolved NaCℓ option neutron-capture efficiency. The 50 cm lattice with 2.5 cm diameter rods is only slightly worse.

Neutron capture efficiency is only half of the story. It is necessary also to detect the captures by the Cerenkov radiation they produce. If PVC was as transparent to optical photons as heavy water, and had the same index of refraction, then the proposed method would have the same Cerenkov detection efficiency as the dissolved salt option. However, the index of refraction is 1.54, and I shall consider that first.

4. Index of Refraction Effects

Table 1 shows the fraction of the detected photons which intercept a plastic rod. For the best case, from the point of view of neutron capture efficiency, the fraction of detected photons intercepting a PVC rod is 33%. Let us see what the effect is.

For simplicity, consider parallel light incident on a PVC cylinder normal to the central axis. Light which makes an incident angle θ_i relative to the normal to the surface of the cylinder is deviated by an angle

$$\theta_D = 2(\theta_i - \theta_r) \quad .$$

where θ_r is the refracted angle at the surface, given by $\sin\theta_r = \frac{n_i}{n_r}\sin\theta_i$,

and n_i and n_r are the indices of refraction of water (1.33) and PVC (1.54) (fig. 1). Light which makes an angle smaller than 90° with the cylinder axis, and has a scattering plane which is in the plane of a diameter of the cylinder will emerge parallel to the incident direction, but shifted.

Considering the extreme case of uniform, parallel light at normal incidence (fig. 1) (or alternatively, uniform impact parameter) the angular distribution of the deviation angle θ_D is given by

$$n(\theta_D) = \frac{\cos\theta_i}{2\left(1 - \frac{n_i}{n_r}\frac{\cos\theta_i}{\cos\theta_r}\right)}$$

and is shown in fig. 2 as a function of θ_D. However, there is also some reflection at the entrance and exit interfaces, and then the transmission depends on the impact parameter. Fig. 3 shows the transmission, as a function of deflection angle θ_D, for light polarized parallel to the plane of incidence. This feature sharpens up slightly the deviation angle distribution, which is shown in fig. 4. The rms angular spread, weighted by transmission, is about 18° for this most extreme case, compared to 6° for the spread due to the scattering of the Cerenkov-radiating electron.

Roughly 2% of the photons are reflected from the first interface. These will tend to scatter forward of 160° relative to the incident direction, because the reflection coefficient is only significant for large angles of incidence and therefore large impact parameters. The 2% which are reflected internally at the second interface will tend more to come out between 100° and 120° with respect to the incident direction.

Thus, for a Cerenkov event for which 100 Cerenkov photons are detected when no PVC rods are in place, the presence of the PVC rods of perfect transparency will result in 33 photons scattering in the rods, and about 10 of these scattering twice. The rms angular spread is probably somewhat less than 18° from single scatters, and 25° from double scatters. About 4 photons scatter at weird angles. If we treat them as lost, then the threshold shifts by about 4%, which would be a shift of the background wall by perhaps 0.1 MeV, relatively insignificant. More serious is the question of light transparency of clear PVC.

5. Light Transparency

Light transmission through several samples of PVC has been measured using a Beckman spectrophotometer, primarily to find the short wavelength cut-off. Fig. 5 shows the transmission for a half-cylinder of PVC (Simona) of 1 cm radius and 2 mm wall thickness. Most of the transmission losses in the range 400-500 nm is due to reflection from the surfaces, and there may be some effect from the fact that the sample was curved. A crude estimate of the attenuation coefficient at about 410 nm is 0.015/mm. Now the average path length for light through a PVC cylinder of index refraction 1.54 in water is about 1.74 times the radius. Therefore the average transmission at 410 nm through the 2.3 cm diameter PVC rods is about 74%.

Fig. 6 shows the transmission through PVC transparent film (Darvic), one with and one without UV absorber. Because of the thinness of these films (about 6 thou) it is difficult to make an absorption measurement. However, comparison of the shapes with the Simona sample in Fig. 5 suggests that the Simona sample had UV absorber in it and thus might be improved.

If we assume that PVC rods completely absorb light below 400 nm, and are perfectly transparent above (except for reflections discussed previously), then judging from fig. 6 of a report by A. Hallin (Calibration Issues & Plan) about 50% of the detectable photons incident on a rod would be absorbed. Therefore, in the example given in the last section, about 18 detectable photons will be lost by single and double interactions with the PVC tubes, that is, an 18% drop in photons. This would move the threshold wall up about 0.5 MeV (P. Skensved, B. Robertson, SNO-STR-91-27, 1991).

Part of the absorption of light observed in PVC may be due to the small amount of crystallinity in it. The crystals presumably scatter the light in somewhat random directions, but the light is not truly absorbed. If photons observed at strange angles are included in the energy estimate of the signal, the threshold wall shift due to the presence of the rods might be reduced. Nevertheless, finding or manufacturing PVC with better transmission properties would improve matters substantially.

6. Split-Vessel Design

One feature of the PVC design that is particularly advantageous relative to dissolved salt is that the PVC tubes could be hung in only one-half of the vessel, say the upper half, achieving a "split-vessel" design. This has the obvious advantage that both the NC-reaction and CC-reaction are continuously being measured, and simultaneous subtraction of the CC-events in the lower half of the vessel from the NC + CC events in the upper half of the vessel can be carried out, unlike in the dissolved salt option. The NC detectors are also always available in the event of a supernova in the Galaxy.

The split vessel has a slight improvement in neutron-capture efficiency per unit mass of PVC tubes. Wilhelmy (SNO-STR-94-051) shows that the efficiency per unit mass increases by about 9% relative to the full vessel value, so that in the 45 cm lattice design of section 3 we expect about 34% n-capture efficiency on chlorine in the PVC. This is to be compared with the time-averaged efficiency of 40% for the dissolved-salt option.

Additionally, there will also be less Cerenkov light lost or scattered. As a rough average, we might guess that the amount of light lost will be about the same as for a full vessel at $\sqrt{2}$ times the lattice spacing, and same diameter rods. Scaling from the case of 2.6 cm diameter PVDC rods at 70.7 cm lattice spacing (table 1), one would estimate the number of photons intercepting detectors as $(16.6\%) \times \left(\frac{2.3}{2.6}\right) \times \left(\frac{70.7}{63.6}\right) = 16.3\%$. Thus the light loss due to light attenuation in the PVC tubes is on average only one-half the full-vessel value. Of course, the light loss is position and direction dependent (this is also true in the case of the full-vessel option and the ^{3}He-detector option), but it can also be somewhat self-calibrating. For example, high energy events in the lower half of the vessel which are radiating downward have no light loss from the PVC tubes whereas those radiating upward will have light loss. However, it might be possible to fit the distribution shapes of the high energy events for these two situations and determine experimentally the light loss effects. This would serve primarily to check calibration results which will be very important for a split-vessel design.

One additional feature of the split-vessel option is that the PVC rods filling the upper half could be installed immediately and rather easily after the upper half of the acrylic vessel was assembled. A tethering system could be implemented which would allow the rods to be easily removed through the neck when the vessel was full of D_2O and when the ^{3}He tubes were ready to be installed, for example, or for any other reason. A further advantage is that the detector would be in the NC-mode from the beginning.

7. Radioactivity

All materials which are put into the D_2O have to be exceptionally free of radioactivity primarily because high-energy γ rays will photodisintegrate the deuteron, producing a signal indistinguishable from the NC-signal. For the PVC of the present option a level of 1 ppt thorium in equilibrium with its daughters will be equivalent to ~2.5 x 10^{-15} parts of thorium in the heavy water. A difficulty with PVC is that we will not be able to use neutron activation to determine the thorium and uranium levels because of the presence of chlorine. Techniques such as thermal ionization mass spectrometry which were developed for acrylic (N.L. Elliott, SNO-STR-92-059) would have to be developed.

8. Conclusions

This paper proposes the use of transparent PVC rods in a split-vessel design to replace dissolved salt for detecting the NC-reaction in the SNO detector. Using 2.5 cm rods on a 45-cm lattice in the upper-half of the acrylic vessel, a neutron detection efficiency of about 85% of the time-averaged dissolved salt option is achieved, with a relatively small increase in threshold. The advantages of this option is that

1) there is simultaneous NC and CC detection in separate parts of the vessel
2) it possibly could be implemented from the initial start-up, thus achieving NC determination immediately
3) supernova NC-detection is always active
4) the complication of adding and removing salt, with its attendant water-monitoring aspects, is avoided.

This performance can only be achieved with fairly good transparency for the PVC; presently commercially available PVC seems close to the minimum needed, and it might be possible to improve upon this with specially-prepared PVC rods. It is almost certain that specially-prepared PVC would be needed for radioactivity reasons.

I am especially grateful to B. Knox, D. Patterson, J. Wilhelmy for assistance during the preparation of this report, and to many discussions with the Guelph SNO group.

Table 1

Neutron Capture Fractions

Material	Rod Diameter (cm)	Lattice Spacing (cm)	% Capture on Rods	Deuterons	Photon-Rod Interceptions	Ref.
PVDC	3.7	100	37.8	17.4	12.6	P
	2.6	100	31.6	19.3	9.0	P
	2.6	70.7	47.7	13.6	16.6	P
	4.0	100	39.6			W
	3.0	100	35.9			W
	2.0	100	30.6			W
PVC	4.6	100	41.4	16.1	15.6	P
	2.3	50	59.4	10.1	28.5	P
	2.3	45	64.2	8.4	32.9	P
	2.5	50	61.2	9.5	30.4	P
	2.0	50	55.4	11.2	25.5	P

P = D. Patterson, private communication

W = J. Wilhelmy, SNO-STR-94-051

Figure Captions

1. Scattering geometry from a right-circular cylinder.
2. Angular distribution of the deviation angle θ_D.
3. Transmission through a cylinder for light polarized in the plane of incidence.
4. Angular distribution of the deviation angle θ_D, including transmission probability.
5. Light transmission through 2 mm thick half-cylinder of Simona PVC.
6. Light transmission through Darvic PVC film with and without UV absorber in the film.

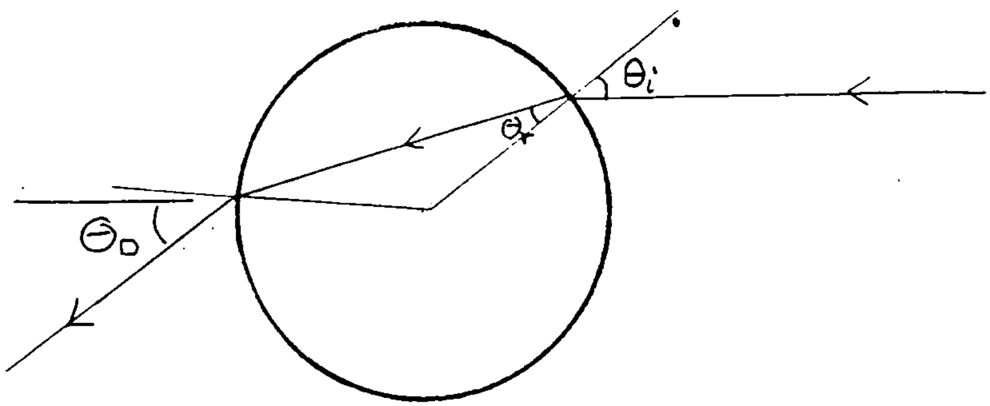
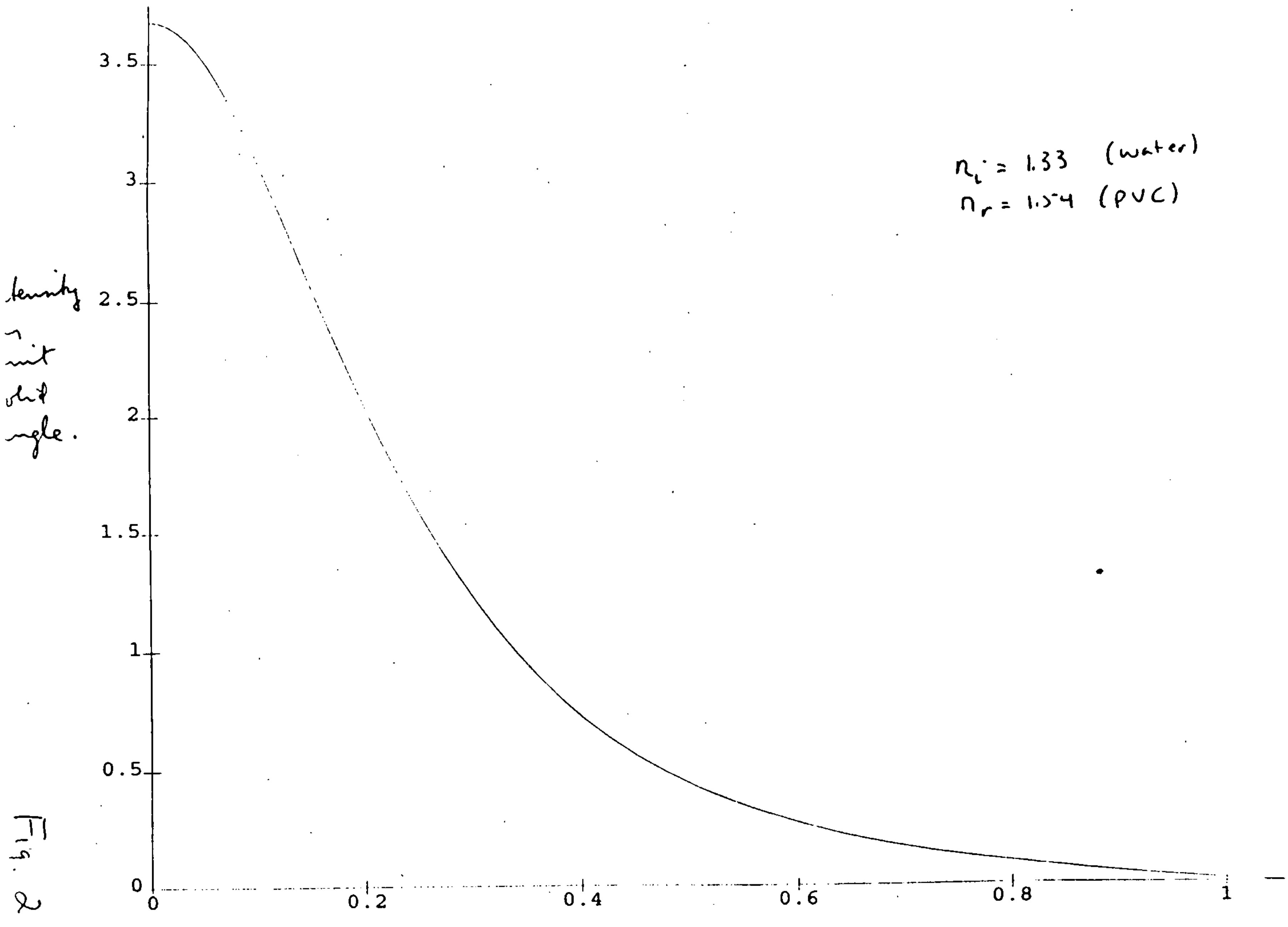


Fig. 1



3.5
3
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
$n_i = 1.33$ (water)
$n_r = 1.54$ (PVC)
$\Theta_{Deflection}$ (radians)

Fig. 2

transmission polariza on perpendicular
parallel

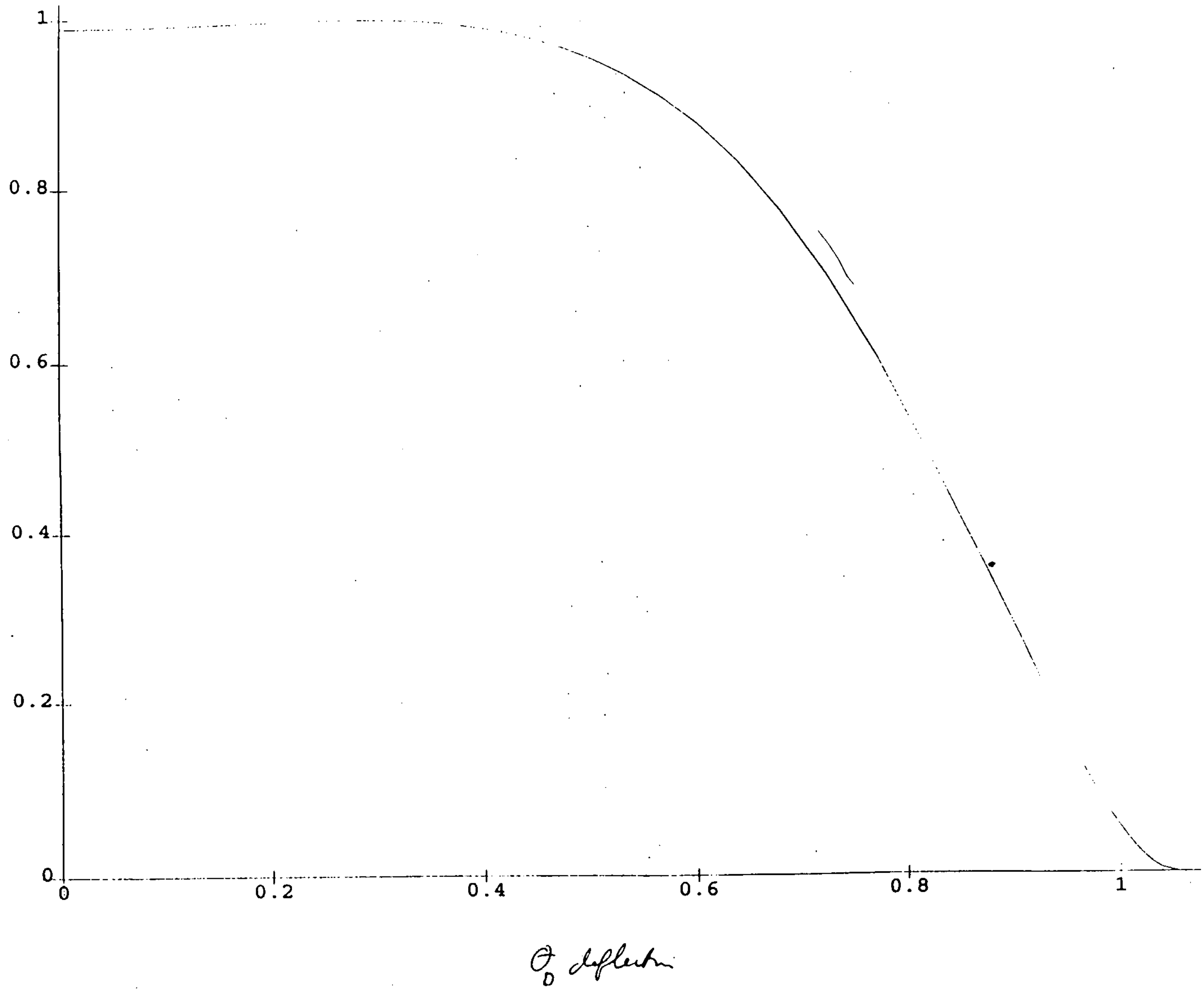


Fig 3

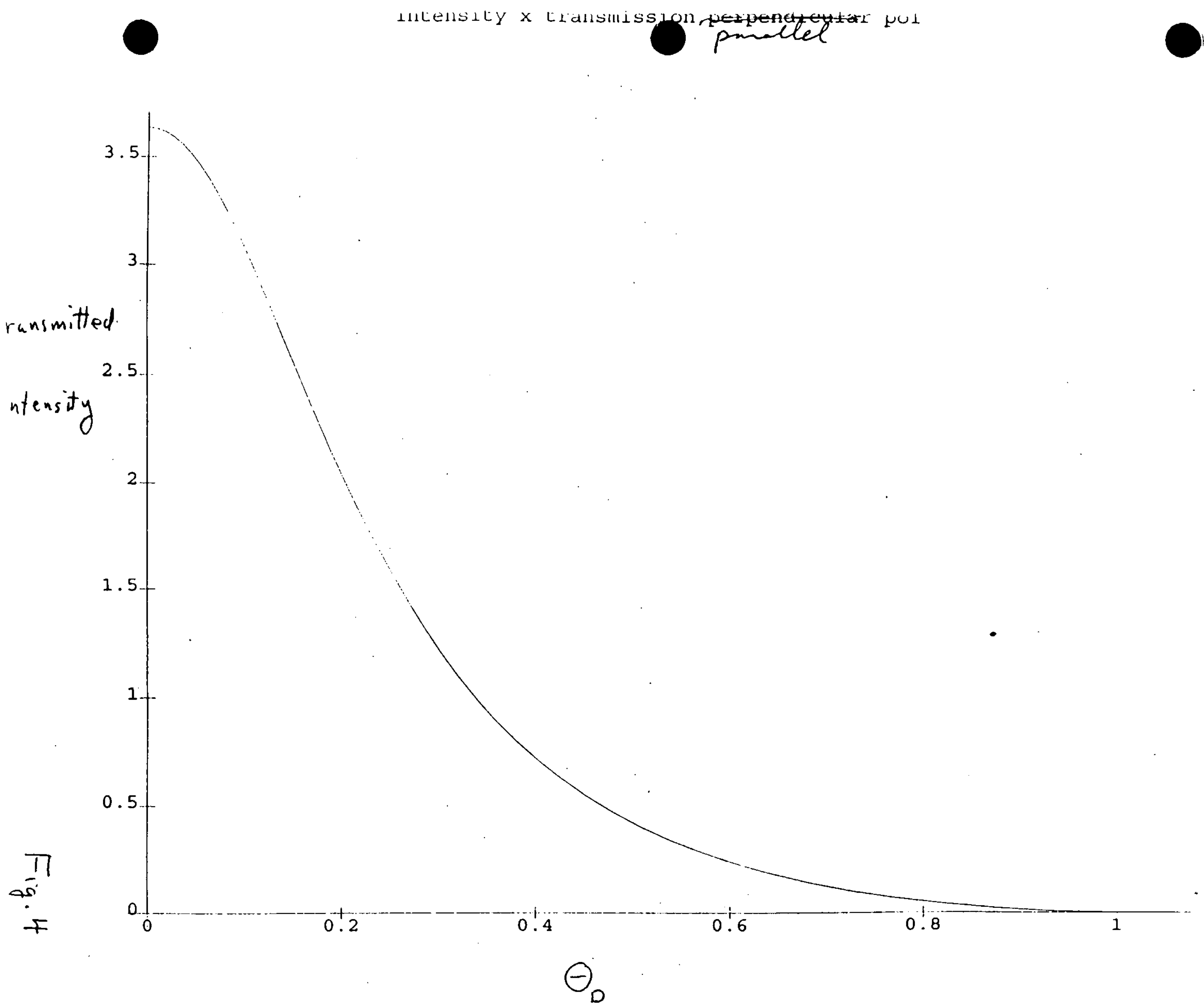

intensity x transmission ~~perpendicular~~ parallel pol
ransmitted intensity
3.5
3
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
Θ_D

Fig. 4

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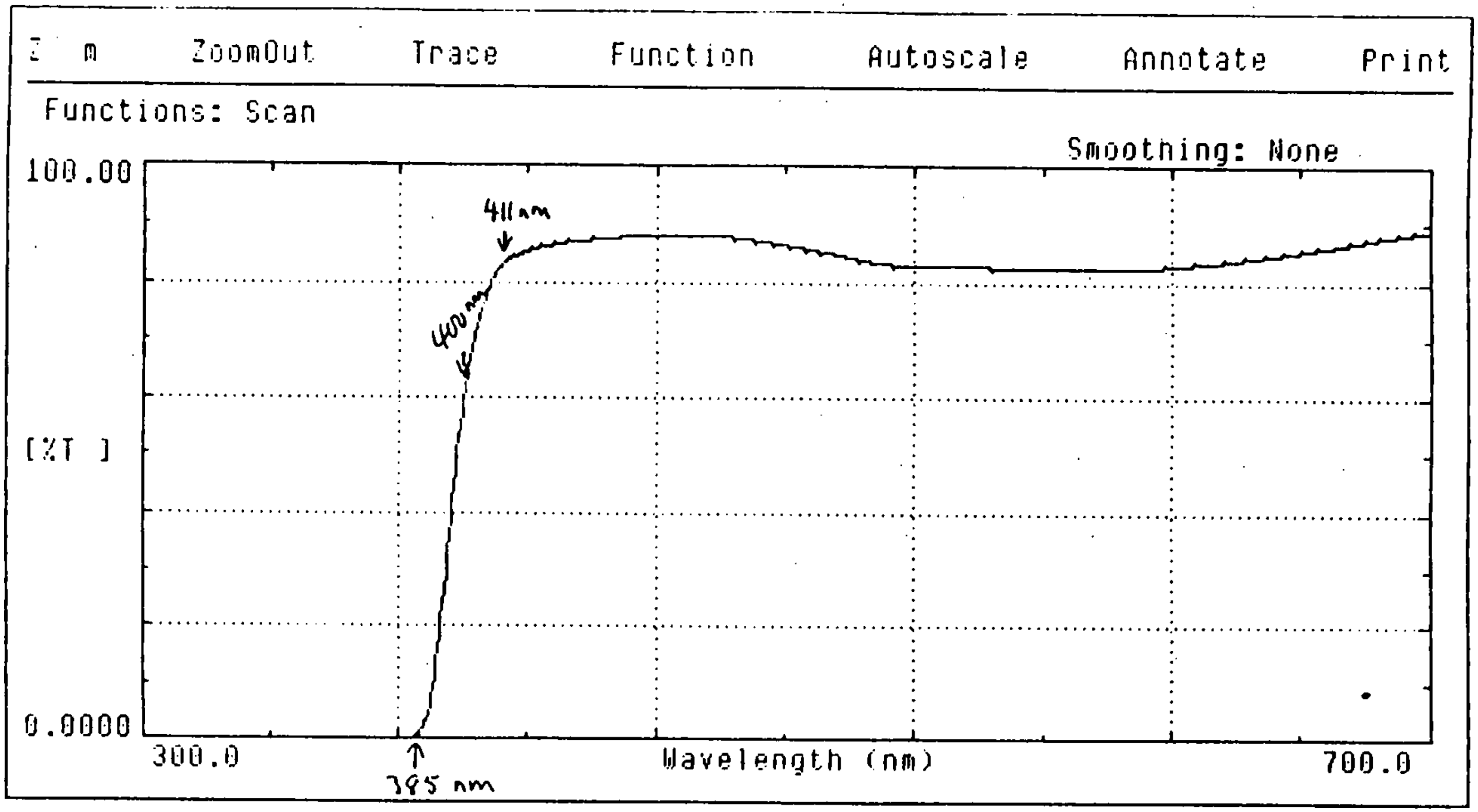

PVC tube (Simona)

2 mm thick

Fig. 5

Darvic

6 thou

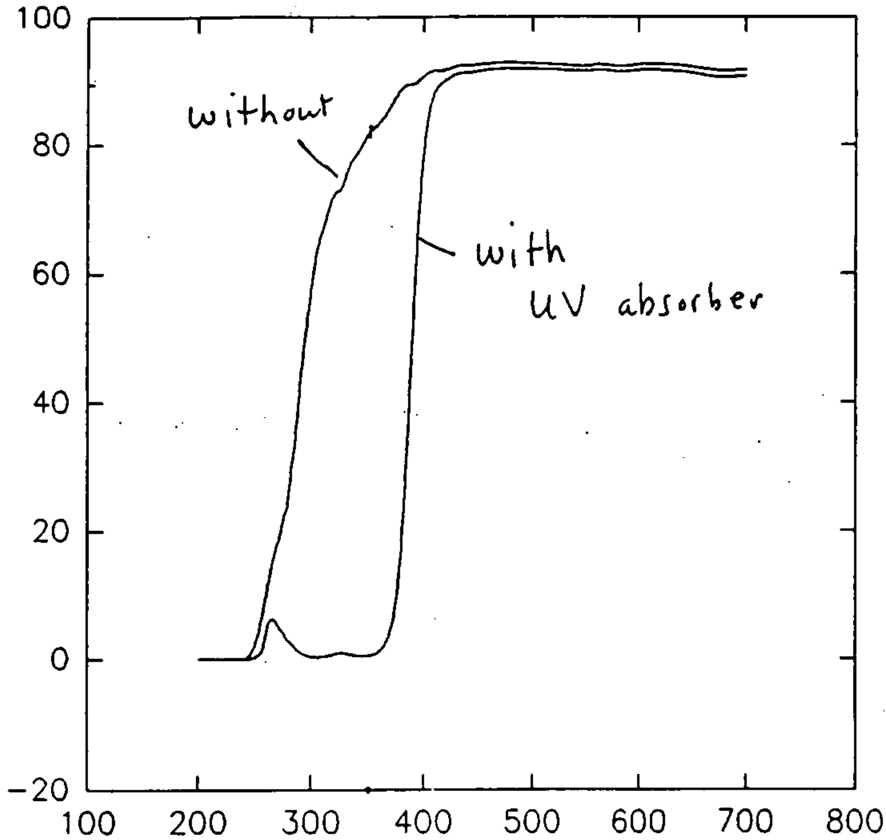

Fig. 6