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Shielding in Expt. 93-026 - G_E^n

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I. INTRODUCTION

During the first data taking period of Expt. 93-026 (June 1998 to October 1998), various shields were used to reduce the background at the neutron detector. A detailed description of the shield configurations is given in fig. 2 in the form of a table. The information in this table is entirely based on the hclog Hall C electronic log book entries. The relevant entries have been collected in a compressed PostScript document G_E^n *shielding*, available on the G_E^n Web page. The configurations can be summarized as follows:

• Shield in front of the neutron detector scintillators:

It consisted initially of three layers of lead sheets, probably 7/64" (= 2.78 mm) thick each (described in the log book either as being between 2.5 and 3 mm, or as ~ 2.5 mm). The sheets cover the entire surface of the detector facing the target.* Later additions were a 1" plastic layer (which cover most, but not all, of the detector face) followed by a 1/4" aluminum layer, and a fourth Pb layer (also 7/64"). These additions were at different times each. The final configuration consisted of the installation of two additional Pb layers of the same thickness as the first four, for a total of 6 layers, 16.7mm total thickness, and the simultaneous removal of the Al layer, leaving only the Pb and plastic.

• Shield around the target:

A wall of lead bricks, 8" thick was built around and downstream of the target. A diagram of the brick arrangements is shown in Fig. 1.

• Other shields. At different times several additional shields, some of them temporary, were introduced:

a) Three sheets of lead covering both the left and right phototubes and bases of the detector were added on 09/08/1998. Each sheet was 7/64" thick.

b) A hanging lead shield was installed in front of the HMS deck, resulting in minimal background reduction. Presumably it was removed after testing.

c) The direct view of the target was blocked off to investigated background sources. The conclusions on this test in the log book entries 7922 and 7934 are that most of the neutron detector counting rate does not originate in the target but elsewhere. I disagree with those conclusions as I detail below.

II. EFFECTIVENESS OF THE SHIELDS

In the absence of a detailed re-analysis of data runs with well defined detector and beam configurations spanning periods before and after the different shields were introduced, I have reviewed the conclusions of on-line tests of shield effectiveness entered in hclog. The relevant information is summarized in the table of fig. 2, and it consists of phototube anode currents and detector rates for data before and after a new shield configuration was tried.

A. Addition of 1" plastic layer to the initial 8.3 mm Pb.

This addition had a very significant effect, reducing the PMT currents of the two veto layers by a factor of two and the current of the first bar layer by 35%. The second and higher layers did not show significant changes, as it would be expected, since the first bar layer acts as a 10 cm thick shield. These conclusions are based on data taken with a 100 nA beam as measured by BCM1 on the CH_2 target.

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*The neutron detector consists of two layers of thin scintillators followed by five layers of thick ("bar") scintillators, with a surface of 1.3 m× 2 m (H×V).

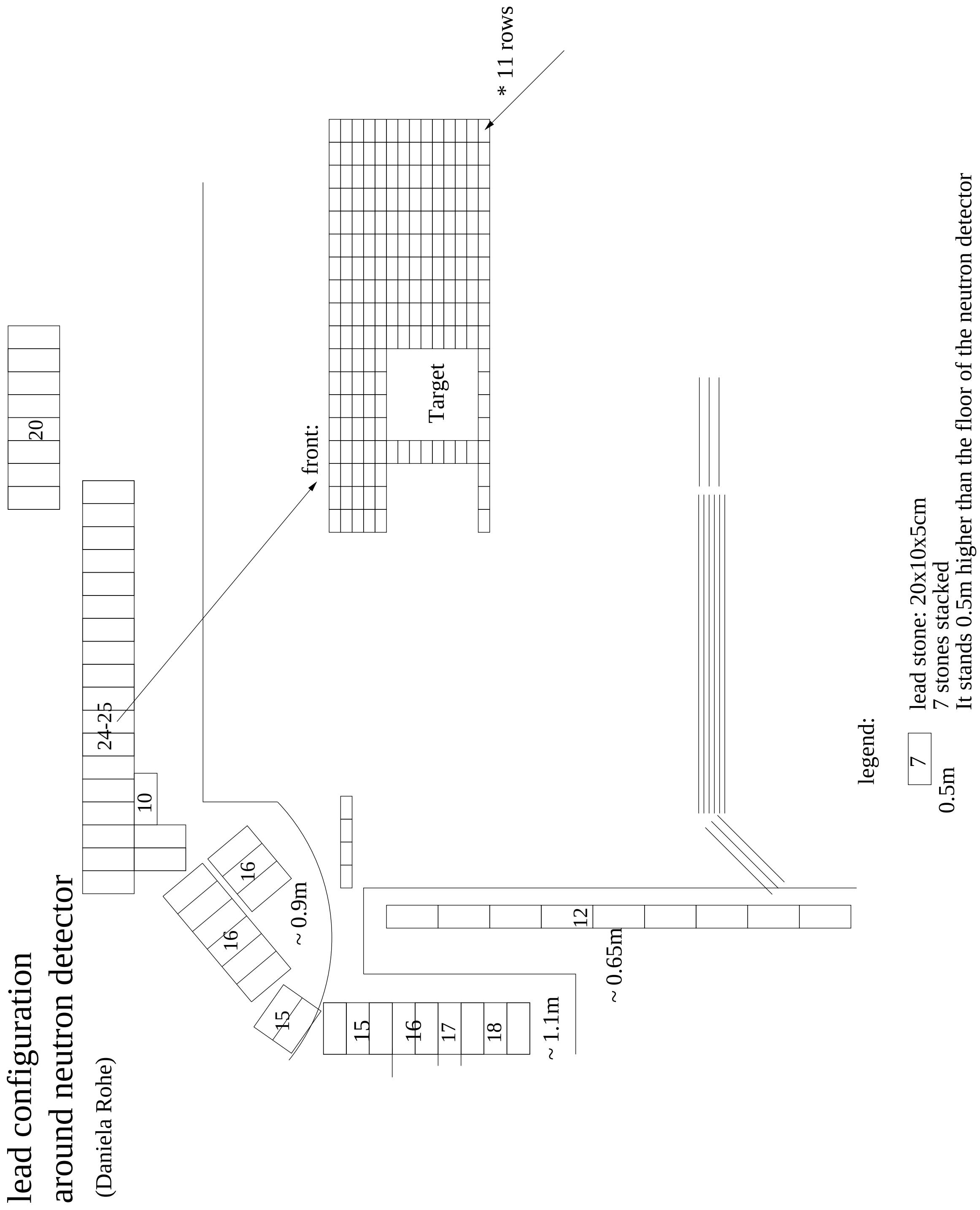

FIG. 1. Shield around and downstream of target. Top view. A side view of one section is shown (labelled 'front'). The target location in this diagram is directly above this section.

B. Direct view of target blocked.

Data were taken with and without a shield blocking the direct view of the target from the neutron detector. The data of entry 7922 (Table I) indicate that the shield attenuated the incident flux on the neutron detector by about 30%. However enough flux penetrated the shield to produce a 440 kHz (72 kHz) single hits/paddle(bar) rate on the front paddles (front bars), when a 75 nA current was incident on the ND_3 target. The rate dropped to 158 kHz

(24 kHz) for the "hole"target, at the same beam current. The ratios of the ammonia (ND_3) to "hole" rates (2.8 for paddles, 3 for bars) are entirely consistent with the ratio of target thickness's 2.7 = 2.36 g cm^{-2} for ND_3 / 0.86 g cm^{-2} for the "hole" (which actually consists of 3 cm LHe at 1 K, plus windows and extra LHe outside the nominal 3 cm cell length)†. The attenuated rates are almost entirely correlated with target thickness.

Assuming the direct view shield was thick enough‡ to attenuate most of the direct flux, it is difficult to conceive of a mechanism of secondary particles somehow generating a back flux into the neutron detector at a rate almost three times as high as the net direct rate (= total direct rate - attenuated rate (kHz) = 592 - 440 = 152 for paddles; 104 - 72 = 34 for bars). This implies that the luminosity of the source of the background is 3 times that of the combined ND_3 target plus 75 nA beam. Moreover, the back flux particles would have to penetrate the shield downstream of the target (shown in Fig. 1) before getting to the neutron detector front shield. The 20 cm lead in the downstream shield represent a minimum attenuation factor of 10^6 for gamma rays energies between 1 and 10 MeV, and an even higher factor for more energetic gammas.

As a first step in understanding these observations, I estimated the total expected rate (no direct view shield). I used the EPC code [1] modified to compute the single arm $A(e-[p,n,\pi^+,\pi^-$ or $\pi^0])$ cross sections for a range of pion momenta or angles. The dominant contribution is from neutrons. Assuming that the plastic and lead in front of the detector absorb neutrons below ~1 MeV, we get

- Integrated cross section $\sigma(43$ MeV/c $\leq \mathbf{p}_n \leq 1600$ MeV/c, $55° \leq \theta_n \leq 65°) = 750$ μb/sr
- ^{15}N luminosity at 75 nA $\mathcal{L} = 26 \times 10^{33}$ Hz cm^{-2}.
- Paddle solid angle (at 0.5 GeV^2) $\Delta\Omega_n \sim 0.01$ sr

Rate = $2^*\mathcal{L}\sigma\Delta\Omega_n = 390$ kHz,

where the factor 2 accounts for the contributions from deuterium, He and windows. The contributions from charged pions add 125 μb/sr for pions with momenta $\mathbf{p}_\pi > 120$ MeV/c, that can penetrate the 4 Pb layers. This represents an additional 65 kHz rate. The π^0 cross section is 103 μb/sr, for all momenta up to 900 MeV/c . It is not simple to estimate the resulting gamma rate, but a crude approximation is to take one detected gamma per produced pion, which implies another 51 kHz. The total rate from neutrons and pions is 506 kHz, and the remaining $\sim$ 90 kHz rate is reasonably explained by contributions from protons and electrons.

A possible explanation of the origin of the rate observed with the direct shield in place is pion and neutron production at the target in the direction of the neutron detector. Charged pions with momenta > 200 MeV/c can penetrate 2" of lead [2]. This flux and the electromagnetic showers produced by the charged pions and the gammas from π^0 decay, could account for a significant fraction of the observed rate. A crude estimate of only charged pion rate gives $\sim$ 45 kHz. A 35 kHz rate of gamma's from π^0's that penetrate the shield has to be added.

The neutron rate has also been estimated. The half-value thickness for neutron attenuation in concrete (density 2.4 g cm^{-3}) from ref. [3] can be reasonably approximated by two values: $t_{1/2}$ = 4" for neutron kinetic energy $T_n \leq 150$ MeV, and $t_{1/2}$ = 18" for $T_n > 150$ MeV. For low energy neutrons ("fast neutrons", $T_n \sim 20$ MeV) the attenuation length in lead and concrete is about the same [4], and we assume that the equality holds up to 150 MeV. Above this energy, the $(e-n)$ cross section at 60° is much smaller than that at low energy, so the rate is dominated by the low energy neutrons. Integrating the cross section in two ranges of neutron momenta corresponding to the respective kinetic energy regions, the product of total cross section times attenuation in the shield is 524 μb/sr for the low energy region and $\sim$ 8 μb/sr for the high energy region. The associated neutron rate, from all target materials is 272 kHz, which combined with the pion and gamma rate (80 kHz) accounts for about 80% of the observed rate with shield, neglecting the contribution from showers generated in the 9-radiation lengths thick shield itself (an EGS4 simulation of this component is in preparation). The calculated/measured rates for the flux with and without direct shield are 0.80 and 0.85, respectively.

Also, if the LHe in the target insert had been boiled off, then a meaningful "almost no target" measurement could have been done.

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†By the way, this is a quick way of estimating the packing fraction (pf). The ratio is 2.74 for pf=0.55, 2.9 for pf = 0.6 and 2.6 for pf = 0.5

‡There are no hclog entries stating this thickness, but D. Day points out it was at least 2" thick, i.e. single file lead bricks sitting on their narrow faces.

C. Fourth Pb layer in front of neutron detector.

The hclog entries suffer from inconsistent references to instrument readings (quite often beam currents are given without stating the BCM they were read on), detector rates or currents are listed without their associated high voltages or threshold settings, etc. These deficiencies severely limit any attempt at comparing conditions before and after a change, unless an extensive research program is done. Explicit rules for making hclog entries are a must for any future data taking periods. Nevertheless, some useful information can still be extracted, making some reasonable assumptions.

For example, entry 7109 lists the left/right PMT average paddle rate for paddle P14 as 560kHz, with 60 nA (BCM1) incident on the "Empty" target. The shield configuration was 3 Pb layers, Al and plastic. Entry 7922 shows a 158 kHz rate for the same paddle, for 75 nA (BCM not given) on the "hole" target, after the addition of the 4th. layer of Pb to the neutron detector shield, and with the direct view shield in place. We know that the latter shield attenuates the flux by $\sim 35\%$ (from the data taken with the ND3 target), so we can estimate the expected no direct shield paddle rate to be 213 kHz for the "hole" target, after the 4th. Pb layer was added.

Next, we try to identify the BCM used to read the 75 nA. From entry 7993 we see that the rate for the same paddle was 560 kHz, for 62 nA (BCM1) on ND_3, very similar to the 592 kHz rate of entry 7922 for the same target and 75 nA. Both readings were done with the same shield configuration. This indicates that the 75 nA was probably read on BMC2 (which reads 75 nA when BCM1 reads 60 nA, according to entry 8040). Therefore, the paddle rate measured after addition of the 4th. layer is less than one half the rate before the addition. The error in this estimate is given by the spread of readings for paddle P14, with the notation Rate - entry No.: 592kHz - 7922; 560 kHz - 7993; 498 kHz - 8040, (all for 60 nA on BCM1 and ND_3 and identical shields, and presumably discriminator thresholds and PMT HV's too), or about +/- 12%.

This is the only measurement of the effectiveness of the 4th. layer that can be extracted from the hclog. Since one goal of the paddle rate measurements and the hclog entries is to provide on-line information for making decisions during the run, the experiment would benefit substantially from more detailed entries that could be promptly evaluated and interpreted by a core group of experimenters who are free to concentrate on planning rather than doing routine shift work.

D. Final configuration

There are no hclog entries that could be used to evaluate the effectiveness of the final configuration.

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[1] J.W. Lightbody, Jr. and J.S. O'Connell, Comp. Phys., May/June 1998, p. 57.
[2] Particle Data Group, Phys. Lett. **B**204,1 (1988).
[3] Jerry B. Marion and F.C. Young, *Nuclear reaction analysis. Graphs and tables*, Amsterdam, North-Holland Pub. Co., 1968, p. 103.
[4] Harold Etherington, *Handbook of Nuclear Engineering*, New York, McGraw-Hill, 1955.

Date	hclog	Shield in front of neutron detector						Target shield	Other shield	PMT	currents					Rates				Target	Beam current	Run No	Notes
	entry	Layers	Thickness		Thickness		Thickness	Pb	Pb	Veto	PMT L	PMT R	Bars	PMT L	PMT R	Paddles		Bars			nA		
		Pb	mm	CH2	mm	Al	mm	mm		Layer	uA	uA	Layer	Current		Layer	kHz	Layer	kHz		BCM1		
06/27/98	6063	3	8.3	0	0	0	0			1	50		1	70						CH2	100		
										2	45		2	50									
													3	25									
													4	25									
													5	15									
06/27/98	6062	3	8.3	1	25.4	0	0																
06/27/98	6079	3	8.3	1	25.4	0	0			1	28	37	1	45	56					CH2	100		
										2	24	25	2	49	55								
													3	21	22								
													4	18	34								
													5	11	16								
06/27/98	6082	3	8.3	1	25.4	0	0			1	28		1	45									
										2	22												
07/19/98	6728	3	8.3	1	25.4	1	6.35			1		26	1		33					CH2	100		HV < 1650
										2		20.5	2		17								
													3		15								
													4		24								
													5		10								
07/19/98	6729	3	8.3	1	25.4	1	6.35									1	10000	1	1100	CH2	100		HV < 1650
																2	5500	2	540				
																		3	500				
																		4	380				
																		5	170				
07/23/98	6837	3	8.3	1	25.4	1	6.35																Proton energy losses
07/26/98	7026	3	8.3	1	25.4	1	6.35	203.2															
07/27/98	7040	3	8.3	1	25.4	1	6.35	203.2															All rates reduced 50%
07/31/98	7109	3	8.3	1	25.4	1	6.35	203.2		1	?	60	1	45	45	1	560	1	127	Empty	60		
08/11/98	7694	4	11.1	1	25.4	1	6.35	203.2		1		55	1		34					C	50		HV > ~1700
										2		27	2		23								
													3		17								
													4		13								
													5		11.5								
										1		42	1		47.5								New counters
08/11/98	7696	4	11.1	1	25.4	1	6.35	203.2								1(?)	360	1	105	C	50		
08/18/98	7922	4	11.1	1	25.4	1	6.35	203.2								1	592	1	104.5	ND3	75	21371	BCM2 ?
									Block target							1	440.5	1	72	ND3	75	21397	BCM2 ?
									Block target							1	157.5	1	24	hole	75	21398	BCM2 ?
08/20/98	7993	4	11.1	1	25.4	1	6.35	203.2								1	560.5			ND3	62	21311	Threshold 30 mV
08/20/98	8022	4	11.1	1	25.4	1	6.35	203.2	HMS deck									Events Hz	180	ND3	75		BCM2
									HMS deck										40	hole	75		BCM2
08/20/98	8023	4	11.1	1	25.4	1	6.35	203.2	HMS deck									Events Hz	170	ND3	75		BCM2?
									HMS deck										40	hole	75		BCM2?
08/20/98	8033	4	11.1	1	25.4	1	6.35	203.2										Normaliz. Hz	1	ND3	84	21386	
									HMS deck										0.95	ND3	62	21472	
08/20/98	8040	4	11.1	1	25.4	1	6.35	203.2								1	498			ND3	60		= 75 nA BCM2
08/29/98	8354	6	16.7	1	25.4	0	0	203.2															
09/08/98	8805	6	16.7	1	25.4	0	0	203.2	ndet PMTs														3 Pb layers ea.2.5mm
10/01/98	9517	6	16.7	1	25.4	0	0	203.2															Proton energy losses

FIG. 2. Summary of hclog entries related to shielding during exp. 93-026.