Geometrical Acceptances of the Detector Setup at LEGS

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Abstract

The geometry of the detector setup in the LEGS facility at Brookhaven National Laboratory was simulated using the GEANT package from CERN. Several experiments will be done at LEGS, including ^{3}He($\vec{\gamma}$,*pp*) *and* ^{3}He($\vec{\gamma}$,*pn*)*, so the characteristics of outgoing nucleons were studied. Geometrical acceptance for the scintillating bars was calculated and compared with the results from the GEANT simulation.*

Introduction

Calculations of the geometrical acceptance of the detector setup at the LEGS (Laser Electron Gamma Source) facility of Brookhaven National Laboratory (figures 1 and 2) were made and compared to a computer simulation of the detector setup using the program package GEANT. The experiment is being undertaken by a large collaboration including the University of Virginia, Rensselaer Polytechnic Institute, Tel Aviv University, Brookhaven National Laboratory, Institute of Physics in Rome, and the University of South Carolina. The goal of the experiment is to study the multi-nucleon emission in the photon absorption reaction by the ^{3}He nucleus. The photon-induced nuclear reactions could be measured at intermediate

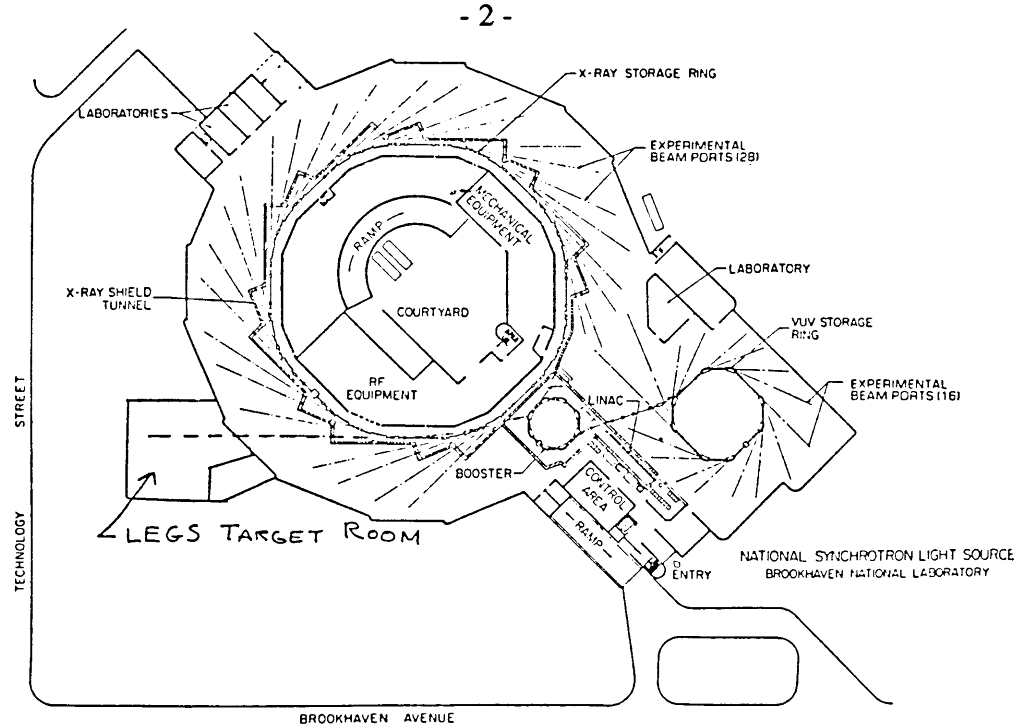

Figure 1: *Plan view of the NSLS facility from the NSLS 1986 annual report. The new LEGS target room has been added.*

energies where the Δ(1232) resonance plays a major role.

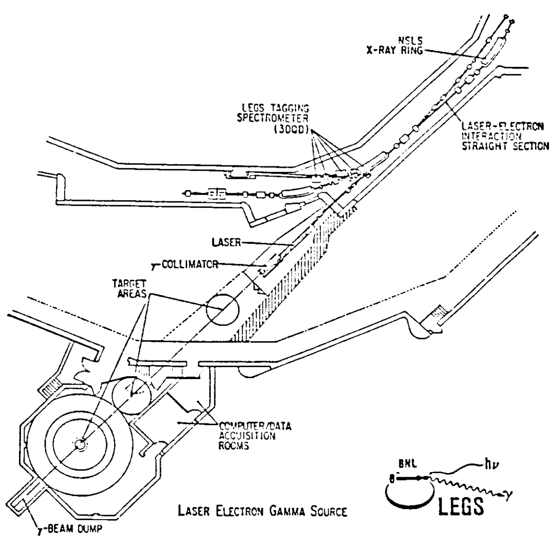

Figure 2: *Layout of the LEGS facility showing the three target areas and the computer acquisition rooms.*

The National Synchrotron Light Source (NSLS), of which the LEGS facility is a part, provides synchrotron radiation for experiments in a variety of fields from Nuclear Physics to Biology. This particular experiment utilizes a 170—300 MeV polarized photon beam. The LEGS facility uses Compton back scattering to produce polarized photons. Ultraviolet laser light with an energy of 3.5 eV collides at 180° with 2.5 GeV electrons traveling in a storage ring 27 meters in radius. The energy, E, of the γ-rays produced at an angle θ between the incoming laser photons and the outgoing photons is:

$$E = \frac{4\gamma^2 L}{1 + \frac{4\gamma L}{mc^2} + \theta^2\gamma^2}$$

where L is the energy of the laser photon, mc^2 is the electron beam energy and γ is the Lorentz factor. A useful beam is obtained by collimating the outgoing photons within an angular range of about 10^{-4} radians. γ for 2.5 GeV electrons is 4.9×10^3; thus the range of γ ray energies that reach the target is 270—335 MeV. The final beam passing through the target has an intensity of 5.2×10^6 photons per second which gives a power of 2.5×10^{-4} Watts.

The UV photons produced by the laser are polarized either linearly or circularly (nearly 100%) by filters before being aimed at the electron ring with mirrors. The UV photon, after colliding with an electron and recoiling back at 180°, retains its polarization and passes through the UV positioning mirror into the target area. The γ-rays are polarized so that the spin assymetry, or analyzing power, of the reaction can be determined by measuring the cross-section from photons polarized in one direction and compared to the cross-section from photons polarized in the opposite direction using the relation $A = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$, where σ stands for the cross-section.

In the ^{3}He target, several reactions will occur. A comprehensive study is planned at LEGS for reactions such as $^3\mathrm{He}(\vec{\gamma},d)p$, $^3\mathrm{He}(\vec{\gamma},p)^2\mathrm{H}$, $^3\mathrm{He}(\vec{\gamma},pn)p$, and $^3\mathrm{He}(\vec{\gamma},pp)n$. Particles leaving the nucleus will have a combined energy of almost 300 MeV since the nucleon binding energy is only about 8 MeV per nucleon in ^{3}He. 20 cm of scintillating material can stop protons of energies up to 175 MeV which will be adequate for these experiments. Neutron detection efficiency is expected to be about 20%.

There are two arrays of detectors that will be used in the experiment: one below and one above the target. Below the target is a set of Phoswich detectors which will detect outgoing protons. These detectors were already set up in the experimental room and have been used in other experiments. The faces of the Phoswich detectors are at a radius of 58.21 cm from the target center, and are grouped in threes, spaced every 20° from –20° to –140° from the horizontal target plane.

The detector above the target consists of 32 Bicron model BC-408 scintillating bars of dimensions 10×10×160 cm and 16 veto paddles of the same material of dimensions 1×11×160 cm. These bars and paddles are arranged cylindrically around the target at a radius of one meter and are grouped as shown in figure Lb every 8° between 20° and 140°from the horizontal plane of the target. The veto paddles are an important part of the detector because they will provide ΔE particle identification, allowing the detector to distinguish between charged particles and neutrons. Neutrons lose their energy in the scintillators all at once by reacting via scattering with hydrogen nuclei in the H-C-H chains of the scintillating plastic, while charged particles gradually lose their energy mainly by ionizing the atoms in the carbon chains. Therefore, nearly all of the neutrons will pass through the paddles undetected, while the protons will lose energy and create a signal in the phototubes attached to the veto paddles.

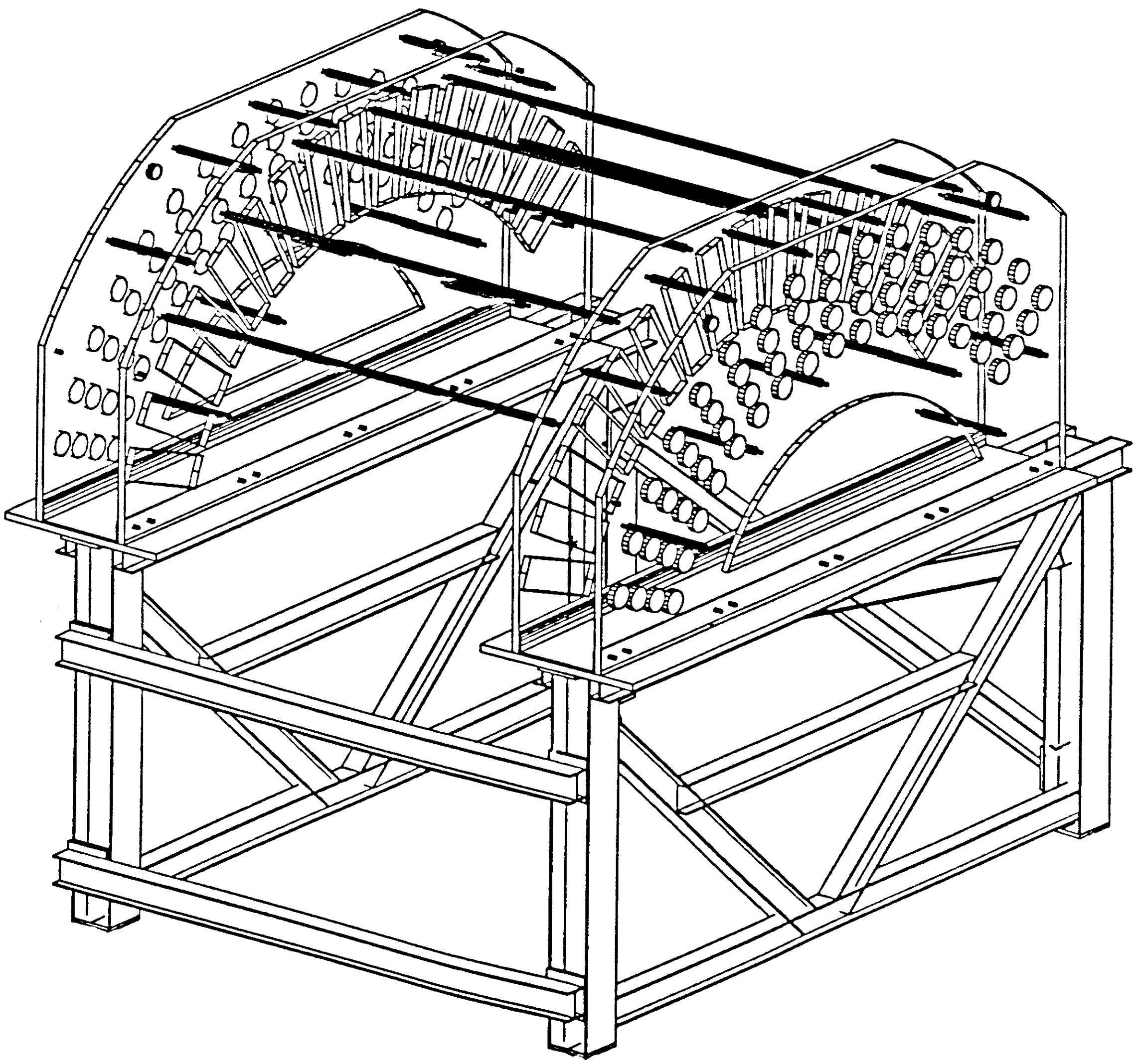

Figure 3: *Rendition of the support stand for the neutron bars in three dimensions by AutoCAD v.10.*

Monte Carlo Calculations

The geometrical acceptances of the detector setup at LEGS was calculated and compared to computer-simulated results using the computer program package GEANT3. GEANT has two main applications: tracking particles through experimental setups for acceptance studies or simulation of detector response, and graphical representation of the setup and of the particle trajectories. Experimental setups are represented by a structure of geometrical volumes of specific materials. Each volume is given a medium number by the user, and each medium is defined by a set of parameters which include reference to the material filling the volume.

GEANT generates Monte Carlo events and controls the transport of particles through various regions of the setup, recording particle trajectories and responses from the sensitive detectors which can be displayed visually on the screen. It is the responsibility of the user to provide the appropriate FORTRAN program segments to describe the geometry of the detector and the physics of the reaction. For the detector setup at LEGS, The geometry-related subroutines were provided by Chris Ruth of Rensselaer Polytechnic Institute. Figure 4 shows a three-dimensional view of the detector and target setup as simulated by GEANT.

In the GEANT simulations, particles are traced from the target to the detectors using two angles as defined in Figure 5. The positive z-axis is in the direction of the γ-beam, and the negative y-axis is pointing upward. The angle θ is measured on the yz plane with $\theta=0°$ on the positive z-axis, and the angle ϕ is measured on the xy plane, where $\phi=0°$ is on the positive x-axis.

Several variables in the GEANT code were adjusted for the simulations. The type of particle shot from the target is stored in the

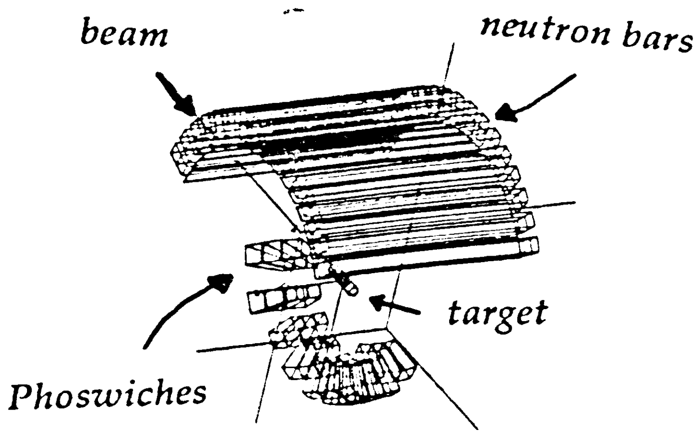

Figure 4: *3D view of detectors and target in GEANT.*

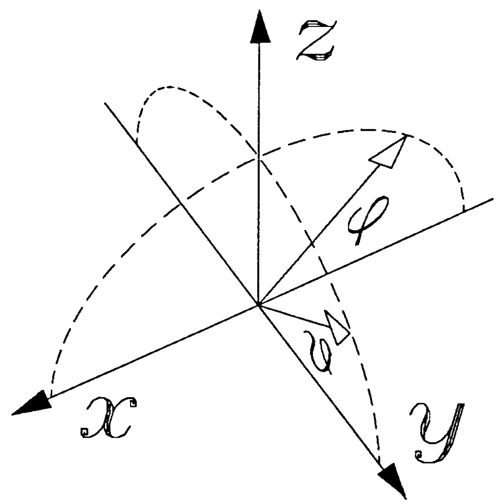

Figure 5: *Definition of angles.*

variable ITYPE in the subroutine GUKINE. For example, a neutron's ITYPE equals 13, and a neutrino's ITYPE is 4. Table 1 shows the ITYPE for particles in GEANT.

Another variable is the momentum of the outgoing particle used in the subroutine MOMDIST. To calculate the geometrical acceptance of the neutron

Table 1: *GEANT* ITYPE *variable.*

1	γ	13	n	25	$\bar{n}$	37	D^0
2	e^+	14	p	26	$\bar{\Lambda}$	38	$\bar{D}^0$
3	e^-	15	$\bar{p}$	27	$\bar{\Sigma}^-$	39	F^+
4	ν	16	K^0 short	28	$\bar{\Sigma}^0$	40	F^-
5	μ^+	17	η	29	$\bar{\Sigma}^+$	41	Λ_c^+
6	μ^-	18	Λ	30	$\bar{\Xi}^0$	42	W^+
7	π^0	19	Σ^+	31	$\bar{\Xi}^+$	43	W^-
8	π^+	20	Σ^0	32	$\bar{\omega}^+$	44	Z^0
9	π^-	21	Σ^-	33	τ^+	45	deuteron
10	K^0 long	22	Ξ^0	34	τ^-	46	tritium
11	K^+	23	Ξ^-	35	D^+	47	α
12	K^-	24	ω	36	D^-	48	*geantino*

detectors for some simulations, the particles' momentum were set at a different values. Neutrons have a momentum cutoff of 43.5 MeV — the lowest momentum which allows the neutron to pass through the target window and the air and enter the face of the neutron bars. The cutoff for protons is 265 MeV according to GEANT simulations.

The angular range of the outgoing particles are controlled in the subroutine MOMDIST. A random flat distribution of events is necessary for finding the simulated acceptances of the detectors, so a subroutine was written to allow an arbitrary angular range between 0° and 360° for ϕ and θ which has a flat distribution of events on any spherical region.

The origin of the particles can be specified in the array VERTEX, which contains the x, y, and z coordinates of the particle's origin. For a point source, the VERTEX was set to (0,0,0), while for an extended target, a random point in the target where the beam passes was chosen. For the extended target, x ranges between –0.787 and 0.787 cm; y between –0.223 and 0.223 cm; and z from –5.0 to 5.0 cm.

Other parameters include the choice of interactions allowed and the medium assignments. To find the solid angle of the neutron bars for some of the simulations, multiple scattering (MULS) and energy loss (LOSS) of the particles were turned off. To turn off the hadronic scattering (HADR) for some of the runs, the outgoing particle was made a neutrino. The effect of intervening air between the target and the detectors on the acceptance was studied by changing the air to a vacuum and comparing the results.

Solid Angle of Neutron Bars.

There are 16 sets of neutron bars and veto paddles in the LEGS detector setup as shown in Figure 9. Each set contains one veto paddle and two bars stacked on top of each other. The first set of bars is centered at a forward angle of 20° and extend in a cylindrical array around the target origin to 140°. This translates to an angular range in θ of 220° to 340° in the GEANT definition of coordinates.

For neutron particles, the first simulation was done for ϕ=90° and varying θ from 180° to 360°. For ϕ=90°, the θ anglular range of the neutron bars can be easily found. The exact θ range is necessary for looking at edge effects and for determining the number of particles deflected or stopped before they can enter the detectors. Figure 6 show a sample graphical output of the GEANT program where the target is in the center, the detectors are encircling the target, and the broken lines are neutrons. This view is the *xy* plane, but the setup can be seen from any direction. Using the following formula, the angular range of each set of bars at ϕ=90° was calculated:

$$\theta = 2\tan^{-1}\frac{w}{2r} = 5.436^\circ$$

where w=10 cm is the width of the neutron bar and r=105.315 cm is the distance from the target origin to the face of the neutron bar. Table 2 shows the expected angular range of each bar in the GEANT setup. The expected edges of the neutron bars are exactly positioned in the GEANT simulation. Looking at different runs, the border between misses and hits lie on the predicted edge of the neutron bars.

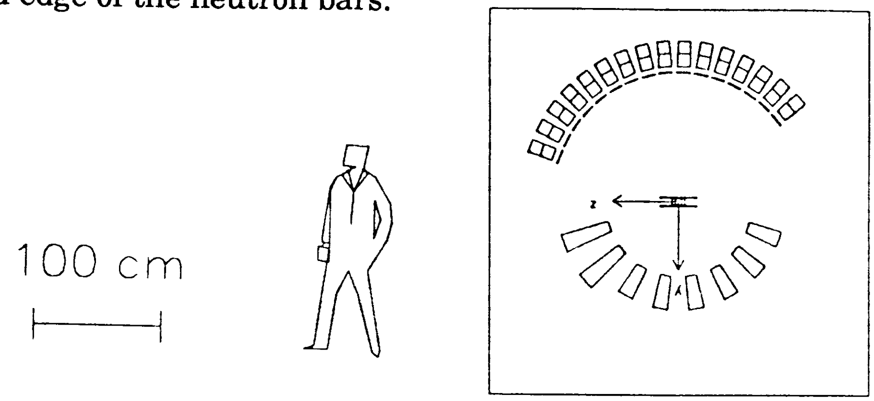

Figure 6: *yz-plane view of detectors and target in GEANT.*

Table 2: *Range in θ of each neutron bar at φ=90° using a distance to the target of 105.315 cm.*

Bar	central angle	minimum	maximum
1	220	217.28181	222.71817
2	228	225.28181	230.71817
3	236	233.28181	238.71817
4	244	241.28181	246.71817
5	252	249.28181	254.71817
6	260	257.28181	262.71817
7	268	265.28181	270.71817
8	276	273.28181	278.71817
9	284	281.28181	286.71817
10	292	289.28181	294.71817
11	300	297.28181	302.71817
12	308	305.28181	310.71817
13	316	313.28181	318.71817
14	324	321.28181	326.71817
15	332	329.28181	334.71817
16	340	337.28181	342.71817

For the theoretical acceptance of the neutron bars, the solid angle spanned by the side of one bar facing the target was calculated. The dimensions of the surface area of each bar on the side facing the target is 10×160 cm, and in GEANT the distance from the center of the target to the face of the first neutron bar is 105.315 cm. This distance is really 105.000 cm, but calculations were made using the value as it is found in the LEGS GEANT subroutine NBARP in the variable RN1. The veto paddle, whose face is 100 cm from the target center was ignored in calculating the acceptance of the detectors.

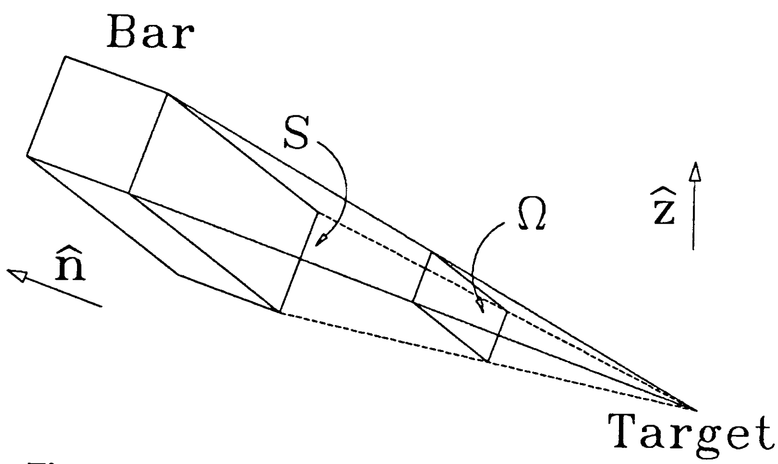

Figure 7: *Solid angle for each scintillating bar.*

By the divergence theorem, the solid angle (figure 7) of each bar is the double integral:

$$\Omega = \iint \frac{d\bar{S}\cdot\hat{n}}{r^2} = \int_{-b}^{b}\int_{-a}^{a} \frac{z}{(x^2+y^2+z^2)^{3/2}}\,dx\,dy$$

where a and b are each 1/2 of the width and length of the neutron bar. This function is symmetric in x and y so the limits of each variable are interchangeable. Evaluating with respect to x gives

$$\Omega = az\int_{-b}^{b}\frac{dy}{(y^2+z^2)\sqrt{y^2+a^2+z^2}}$$

This integral is elliptical and has been solved numerically using the computer program given in Appendix A. The solid angle of each neutron bar at 105.315 cm from the target origin was found to be 114.76 ms. This theoretical solid angle calculation does not include multiple scattering, energy loss and hadronic interactions. In addition, rays from the target origin do not always pass completely through the two neutron bars as can be seen in figure 9. The true solid angle depends on the effective distance of the neutron bar from the target origin. See Figure 8 for this dependence.

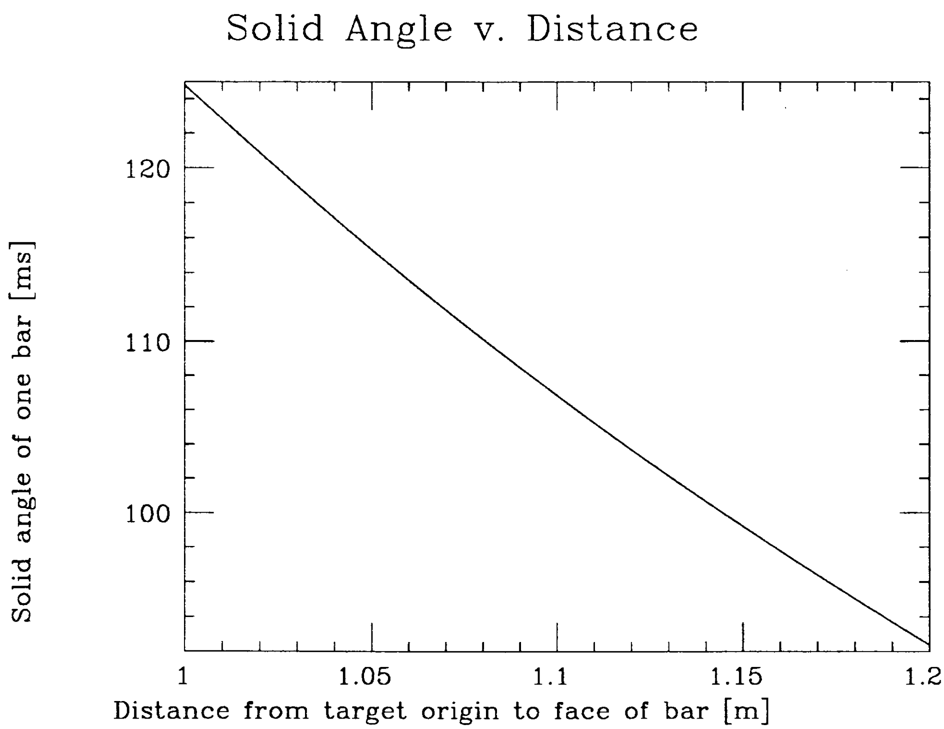

Figure 8: *Solid angle dependence on distance.*

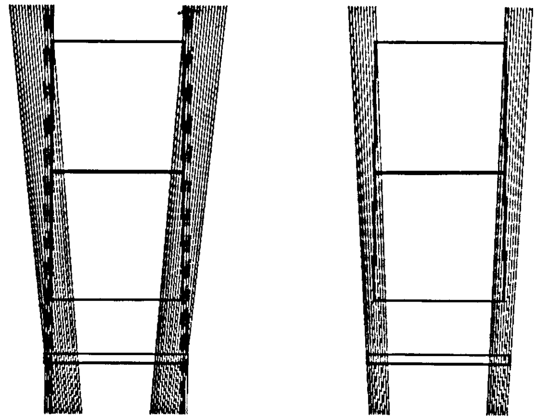

Figure 9: *Extreme rays from the extended target and point target.*

To compare the solid angle of the neutron bars in the GEANT setup with the theoretical solid angle from above, neutrinos, instead of neutrons, were shot into the hemisphere of the neutron bars to avoid the effects of multiple scattering, energy loss and hadronic interactions. The neutrinos were shot from a point source in random directions between θ=180° to 360° and ϕ=0° to 180°. The scatter plot in Figure 10 shows the angular distribution of neutrinos from the target hitting the scintillating bars. Out of 14,544 events, 4,335 hits occured. Dividing the number of hits by the total number of events then dividing by the sets of bars (16) and multiplying by 2π gives an acceptance of 117.05 ms for each neutron bar, which is 2% higher than calculated. Using an extended target 10 cm in length, a solid angle of 133 ms was simulated on the GEANT setup.

Neutrons and Protons in the Scintillating Bars.

To study the effect of air on the particles, the same simulations were repeated with a vacuum replacing the air. The vacuum initially had a deflection rate of 15% at 445 MeV momentum as opposed to 2% for air, which is too high since a vacuum should deflect or stop particles less than air. The parameters for the air in the subroutine UGEOM were substituted in the

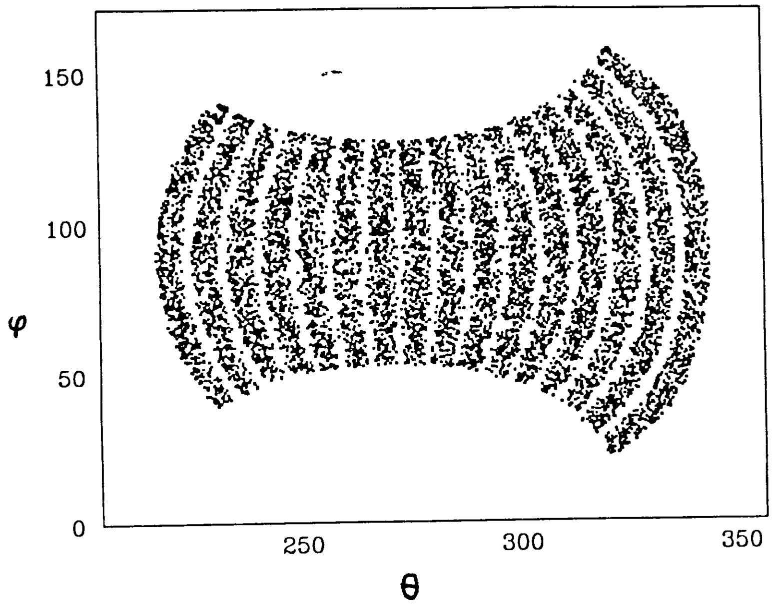

Figure 10: *Angular distribution of neutrinos hitting the scintillating bars.*

vacuum's parameter list, giving a better deflection rate of 3.37%, though this is still higher than the deflection of 2.16% in air. Here are the function calls for the medium surrounding the detectors in the GEANT setup:

air: `CALL GSTMED(4, 'AIR$',15,1,0,0.,0.,.1,.1,.2,.1,0,0)`
vacuum: `CALL GSTMED(4,'VACUUM$',16,1,0,0.,0.,2.,2.,2.,.1,0,0)`
vacuum, air params: `CALL GSTMED(4,'VACUUM$',16,1,0,0.,0.,.1,.1,.2,.1,0,0)`

The 8th, 9th and 10th parameters which differ between air and vacuum are the variables DMAXMS, DEEMAX, and EPSIL. DMAXMS is the maximum displacement for multiple scattering in one step (in cm), DEEMAX is the maximum fractional energy loss in one step, and EPSIL is the tracking precision (in cm).

The GEANT simulations for neutrons involved all physical process except the scintillating-bar neutron detection efficiency and was done for a range of momenta. Figure 11 shows the fraction of neutrons that successfully reach the neutron bar detector face. This function scales the effective solid angle for neutrons, with a fraction of 1.0 being a solid angle of 114.76 ms. The loss of neutrons is due to multiple scattering and hadronic interactions in the target cell, target windows, air and scintillators. The cutoff for protons in the neutron bars is a momentum of 43.5 MeV, or a kinetic energy of 10 keV.

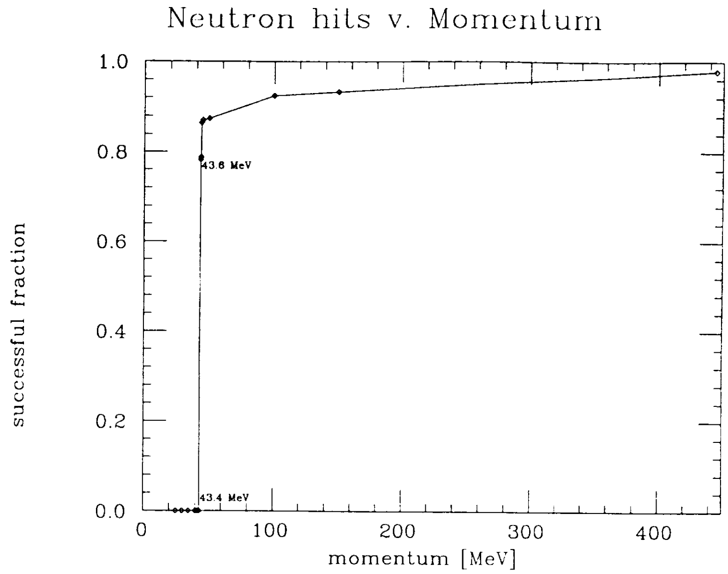

Figure 11: *Neutrons that reach the neutron bar face as a function of momentum.*

The GEANT simulations for protons involved all physical process except the detection efficiency and was done for a range of momenta. Figure 12 shows the fraction of protons that successfully reach the neutron bar detector face. This function scales the effective solid angle for protons, with a fraction of 1.0 being a solid angle of 114.76 ms. The loss of protons is due to coulomb interactins, multiple scattering and hadronic interactions in the target cell, target windows, air and scintillators. The cutoff for protons in the neutron bars is a momentum of 265 MeV, or a kinetic energy of 37 MeV.

{*Phoswich Detector Acceptances.*}

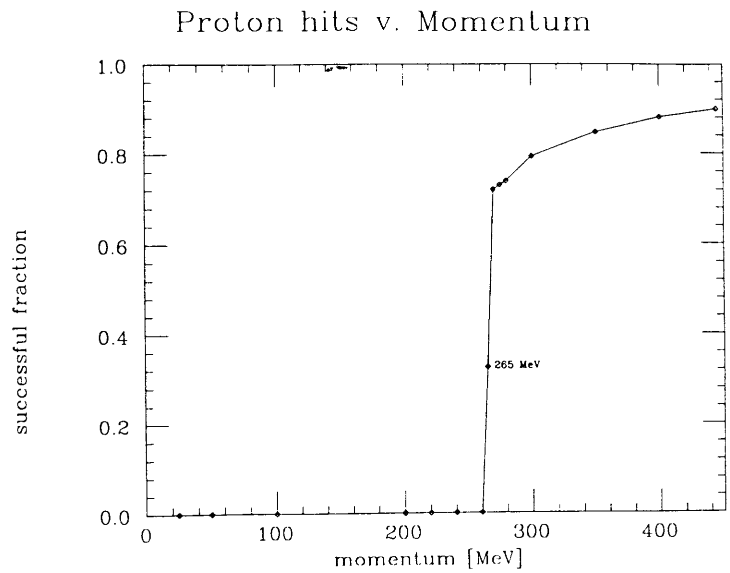

Figure 12: *Protons that reach the neutron bar face as a function of momentum.*