NEUTRON SPECTRAL AND ANGULAR DISTRIBUTION MEASUREMENTS FOR 113 AND 256 MeV PROTONS ON RANGE-THICK Al AND U-238 TARGETS USING THE FOIL ACTIVATION TECHNIQUE

by

L. R. GREENWOOD AND A. INTASORN

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Targets Using the Foil Activation Technique

L. R. Greenwood and A. Intasorn*

Chemical Technology Division
Argonne National Laboratory
Argonne, Illinois 60439

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Kirtland Air Force Base, New Mexico
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*IAEA Fellow; Permanent Address Department of Physics
Srinakharinwirot University, Bangkok, Thailand

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Neutron Spectral and Angular Distribution Measurements for 113 and 256 MeV Protons on Range-Thick Al and ^{238}U Targets Using the Foil Activation Technique

L. R. Greenwood and A. Intasorn
Argonne National Laboratory

Abstract

Secondary neutron yields, energy spectra, and angular distributions have been measured at seven angles from 0 to 150° for 113 and 256 MeV protons stopped in range-thick targets of aluminum and depleted uranium (^{238}U). Thin foil stacks of ten different materials were activated by secondary neutrons at distances of 20-30 cm from the targets. Following each irradiation, 30-40 different activation products were measured by gamma-ray spectroscopy. These activation rates were then used to adjust neutron energy spectra calculated by the HETC computer code. Activation cross sections were taken from ENDF/B-V below 20 MeV, from literature values tested in $\text{Be}(d,n)$ fields up to 50 MeV, and from proton spallation data and calculations from 50-250 MeV. Spectral adjustments were made with the STAY'SL computer code using a least-squares technique to minimize χ^2 for a covariance matrix determined from uncertainties in the measured activities, cross sections, and calculated flux spectra. Neutron scattering effects were estimated from foil packets irradiated at different distances from the target. Proton effects were measured with (p,n) reactions. Systematic differences were found between the adjusted and calculated neutron spectra, namely, that HETC underpredicts the neutron flux at back angles by a factor of 2-3 and slightly overpredicts the flux at forward angles.

Introduction

The measurement of neutron flux spectra by the multiple foil activation technique is well established for fission reactor applications where high radiation fields and space restrictions preclude the use of active detectors.¹ The method consists of activating a small packet of foil or wire materials, measuring the activation products, and then using computer codes to solve a series of integral equations to adjust the neutron spectrum to give the best fit to the data. We have spent considerable effort in trying to extend this technique to higher neutron energies. The main problem is that activation cross sections are generally only known up to 20 MeV in data evaluations such as ENDF/B-V.² Hence, we have made numerous differential and integral measurements to provide a data base for accelerator-based neutron sources.³⁻⁵ Whenever possible, we have tested the data and procedures in well-characterized neutron fields measured by time-of-flight techniques. The foil technique has been applied at spallation neutron sources primarily to determine the spectrum and radiation damage rates close to the target for materials irradiations.⁶⁻⁸

There are many advantages in using the foil activation technique to determine neutron yields for defense applications. Foils are relatively

inexpensive and small packets can be placed in virtually any location, including the inside of complex assemblies. Sensitivities can be adjusted by changing the size of the foil and length of irradiation and measurements have been made in neutron fluxes from 10^4 up to 10^{16} n/cm²-s. No requirements need be placed on accelerator operations regarding either pulsing or beam currents and using high currents allows measurements to be completed rapidly, a distinct advantage when accelerator time is charged by the hour. It is rather easy to achieve precisions of 1-2% for integral activation rates which, by themselves, can be quite useful in determining relative neutron yields from different targets, incident particles, or beam energies.

Naturally, there are also disadvantages to the technique. Since individual activation cross sections tend to respond over a range of neutron energies, many overlapping reactions are needed to define a neutron spectrum. Even so, the energy resolution is at best only about 10-20%. Consequently, the technique is best suited for determining broad-group neutron fluxes and is simply not very sensitive to narrow peaks and valleys. Since foils are generally irradiated in close geometries, neutron scattering effects may be difficult to determine. However, this can be a distinct advantage for measurements inside of complex targets where knowledge of the complete environment is needed and time-of-flight or other active techniques cannot be used. It may also be difficult to distinguish between protons and neutrons. However, we have developed techniques for measuring unique proton-induced activation products which determine the proton flux levels. The accuracy of the technique is limited at present by uncertainties in the activation cross sections, especially above 50 MeV. However, this situation can be improved enormously by performing integral tests in well-measured neutron fields. Furthermore, the technique can be tested by direct comparison with time-of-flight measurements.

The purpose of the present measurements is to demonstrate the foil activation technique for 113 and 256 MeV protons stopped in range-thick targets of Al and ²³⁸U. These energies were chosen to coincide with time-of-flight measurements now in progress at Los Alamos National Laboratory. In this way our results can be compared directly with the inherently more accurate time-of-flight technique. Furthermore, this comparison can be used to adjust poorly known activation cross sections to improve the accuracy of the method. Other measurements are currently in progress for 50 MeV protons on Al and ²³⁸U and for 100 MeV deuterons on Al. Having demonstrated the utility of the foil technique, we then propose that it provides a cheap and rapid way to survey neutron yields and energy spectra for defense applications from a wide range of target materials for either protons or deuterons at any incident energy of interest.

Foil Irradiations at IPNS

The irradiations were performed in the beam dump area of the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory. Figure 1 shows an overall layout of the facility. The IPNS is designed primarily for neutron scattering measurements and was built around the Zero Gradient Synchrotron (ZGS) facility which was decommissioned in 1979. The Neutral

Particle Beam Test Stand (NPBTS),⁹ which uses the 50 MeV H⁻ Linac beam, was constructed in the unused ring room of the older ZGS, labelled NPBTS Areas A and B on the figure. In the present case we used the IPNS beam dump located in the main proton transport tunnel for IPNS. This area is labelled Lethality Test Area D on the figure since large samples could be irradiated in this location with beam energies between 50 and 500 MeV with beam currents up to about 15 microamps. Larger samples could be irradiated in the main proton tunnel itself, as shown on the figure as Component Test Area E. The beam has a pulse width of about 120 nanoseconds and a repetition rate from 1 to 30 hertz (3×10^{12} H⁺/pulse). This time structure is not suitable for neutron time-of-flight measurements, although proposals have been submitted to shorten the pulse width to 20 nanoseconds. Deuterons can also be accelerated by the linac to 25 MeV; however, changes must be made in the Rapid Cycling Synchrotron to accelerate deuterons up to 260 MeV. A Discrimination Test Area C could then be set up as shown in the figure for time-of-flight measurements with either protons or deuterons.

Detailed drawings of the foil irradiation geometries are shown in Figs. 2 and 3. The proton beam enters the beam dump through a 5 mil Ti window and then passes through the air until it is stopped in our target. With no target in place, the beam is stopped in a Faraday cup. Since we are stopping the beam in the target, we used aluminum foils in front of the target to determine both the absolute fluence and spatial distribution of the protons. A beam toroid upstream was also used to monitor the beam. Foil packets were mounted on a thin aluminum spider suspended over the top of the target. Since the beam dump gap measures only about 1 meter square in the horizontal plane but is nearly 3 meters in height, this vertical foil configuration was chosen to minimize neutron scattering effects. Furthermore, this design allowed the entire foil assembly to be rapidly inserted and removed to minimize personnel exposure after each irradiation.

Following each irradiation, the aluminum beam foils were autoradiographed by placing the 10 cm x 10 cm square foils directly on top of polaroid film. Exposures of about 1 minute were adequate for showing a clear distribution of the beam particles on the exposed film. In all cases the beam was centered within 1 cm and had a nearly circular distribution with a width of about 2 to 4 cm. Three 0.13 mm thick aluminum foils were irradiated in the proton beam, the front and rear foils being used to correct for the recoil of activated atoms from the central foil. The middle foil was then segmented and gamma counted for ⁷Be, ²²Na, and ²⁴Na. Cross sections for the production of these isotopes were measured previously at the IPNS using the Faraday cup in the beam dump to obtain absolute beam currents to about 5%.¹⁰ Table 1 compares our activation data with the beam toroid measurements to determine the proton currents for each irradiation. As can be seen, the two independent measurements of the beam current agree within 8%.

The foil materials and principal activation reactions and products are listed in Table 2. All foils were high-purity materials (99.99% or better) since trace impurities could cause undesired activities, especially in the case of weakly produced spallation products. Each foil was cut into a 2.5 cm diameter disk, scribed with an identification label, cleaned, and weighed. The disks were then stacked up and wrapped in thin aluminum foil to form a packet for irradiation. Foil thicknesses varied from 0.025 to 0.5 mm thick,

with thicker foils being used at backward angles to enhance the activity. The total foil packets measured 2.3 mm thick for forward angles and 3.4 mm thick for angles beyond 90° .

The foil packets were taped onto thin aluminum discs attached to each arm of an aluminum spider at angles of 0° , 7.5° , 30° , 60° , 90° , 120° , and 150° . The spider arms formed an arc of 22 cm radius for the U runs at both 113 and 256 MeV and for the Al run at 113 MeV. A larger radius of 32 cm was used for the 256 MeV Al target due to the longer length of the target (20 cm). Distances and angles were carefully checked prior to insertion of the foil holder over the targets. Two foil packets were also placed further from the target in each case in order to investigate neutron scattering effects at forward and backward angles. One was placed at 30° at about 30 cm from the center of the target and the other was at about 150° at 30 cm (37 cm for the 256 MeV Al run).

All of the cylindrical targets measured 10 cm in diameter and were 2.5 cm and 5.0 cm thick for U at 113 and 256 MeV, respectively, and 5 cm and 20 cm thick for the corresponding energies in Al. In all cases, the thicknesses were more than needed to completely stop the proton beam. The depleted uranium targets were identical to those used as primary IPNS targets consisting of 10 cm diameter by 2.5 cm thick cylinders with a 1.5 mm thick zircalloy cladding. At 256 MeV, two of these targets were mounted back-to-back. In all cases, the targets were mounted on aluminum holders about 7.6 cm above a 3.2 mm thick steel platform which was in turn mounted on a steel column about 1 meter from the floor. In order to assure good thermal contact between the target and mount, a thin stainless steel clamp attached to the mount was tightened around the target. In the case of the uranium targets, the mount was further cooled by water lines connected to the bottom of the mount about 7.6 cm below the target. This allowed us to run more beam current; however, we could only run about 1/4 the current used for the aluminum targets due to the relatively poor heat conduction in uranium. Increasing the water cooling, for example with water lines around the target, would certainly have allowed us to run more beam current and hence enhance the neutron output. However, we were concerned that the water would moderate the neutrons, thereby clouding the interpretation of our results. Hence, we tried to minimize the water near the target. Furthermore, the water lines were run directly below the target whereas the foils were on top of the target. Hence, neutrons which scattered from the water would have to pass back through the thick targets before they could reach the foils.

The aluminum target irradiations were conducted on December 10, 1987; the 113 MeV U run was on January 27, 1988; and the 256 MeV U run was on February 24, 1988. The irradiation times varied from 60 to 90 minutes. Time-averaged beam currents were approximately 1 microamp for the U and 4 microamps for the Al targets. The beam actually was pulsed at 30 pulses per second with a pulse width of about 50 microseconds, so that the peak current was about 0.5 to 2.0 milliamps. The proton current was limited by a facility requirement that the target temperature not exceed 300°C . Thermocouples were attached to the periphery and in a well drilled near the center of each target to monitor the temperatures. The beam currents were then slowly increased until the temperature neared 300°C . There was never any problem in controlling the target temperatures since it took 5-10 minutes to reach

equilibrium for a given setting of the beam current. Furthermore, the temperature could be dropped very rapidly by simply reducing or shutting off the beam current, as needed. In each case, the irradiation histories were rather flat showing some increase in beam current prior to reaching equilibrium, then a nearly flat run for 60-90 minutes, and an abrupt cutoff. Following each run, targets were allowed to cool for at least 30 minutes. We then entered the beam transport tunnel and were able to retrieve the foil holder in a matter of minutes. Residual target activities were at least 20 R/hr at 1 foot at this time; however, they further decayed to less than 100 mR/hr on contact after a few weeks. The foil packets at each angle were relatively easy to handle since the activity levels were always less than 100 mR/hr on contact; hence, we were able to disassemble the foils for gamma counting within an hour after the end of irradiation without undue radiation exposure.

Gamma Activity Measurements

Since we were able to start gamma counting of the foils within an hour of the exposure, we were able to analyze relatively short-lived activities, such as ^{56}Mn (2.5 hr) and $^{116\text{m}}\text{In}$ (54 m). In all cases, each foil was counted several times. This was usually needed in order to see both short and long-lived activities in the same sample. Furthermore, it helped to identify some activities by following the decay curve and was needed to follow the growth of some decay chains. In some cases, such as the production of both ^{57}Ni and ^{57}Co from Ni, we could easily follow the buildup of ^{57}Co and identify separate yields for each isotope. However, in other cases we can only report a chain yield, an important point to remember in subsequent calculations of spallation product yields. The gamma activities were then converted to saturated activation rates correcting for decay during and after irradiation, sample weight, gamma self-absorption, detector efficiency and geometry, and coincidence summing. Due to the large number of foils used in these irradiations, seven different Ge detectors were used in the analysis. Each detector was separately calibrated with standard sources traceable to the National Bureau of Standards. Cross comparisons were made between the detectors and we also tried to count the same sample on different detectors at different decay times in order to minimize detector biases. Geometry effects due to counting the relatively large foil discs close to the detectors were determined experimentally by counting some of the more active samples at various distances. Coincidence summing effects were calculated using summing coefficients from the nuclear decay schemes and experimental measurements of the peak and total efficiencies. Nuclear decay data were taken from reference 11. The activities have an overall uncertainty of about 2%. The counting statistics were generally better than 1%, except where indicated, and the detector efficiencies are accurate to about 1.5%. Geometry and coincidence summing corrections were only needed for the weaker activities and varied from 1-10%.

The corrected activation rates and their uncertainties are listed in Tables 3-6 and illustrated in Fig. 4. As can be seen, reactions which are sensitive to thermal neutrons or which have low-energy thresholds tend to be nearly isotropic. This would be expected from compound nuclear effects and

the effect may be enhanced by neutron scattering both from the large targets and from the walls of the beam dump (typically 0.6 to 1.0 meter from the target or foils). Higher threshold reactions decline more rapidly with angle, as expected, since the high-energy neutrons are preferentially emitted in the forward direction.

Neutron Energy Spectrum Adjustments with STAY'SL

The activation rates in Tables 3-6 represent integrals of the energy-dependent reaction cross sections times the flux spectrum. We thus have to solve a system of integral equations for the neutron flux spectrum where the cross sections and integral values are known. The STAY'SL¹² computer code solves this problem by the least-squares technique. The input data consists of the measured activities, reaction cross sections, and calculated flux spectrum, with uncertainties and their covariances for each quantity. A matrix inversion procedure then determines the most likely solution (minimum χ^2). It is important to note that all input data is adjusted according to the prescribed uncertainties and covariances. The activation rates have already been presented. A description of the reaction cross sections and input flux spectrum calculations is given below.

Activation cross sections have been measured and tested for many years in order to establish a data base for fission reactor dosimetry. This effort has resulted in the evaluated library ENDF/B-V,² which also includes recommended uncertainties and covariances. Unfortunately, this file only extends to 20 MeV. As mentioned previously, we have extended these cross sections to about 50 MeV using data from the literature and calculations which were then tested and adjusted in neutron fields produced at accelerators by the Be(d,n) reaction at deuteron energies of 7, 16, 30, and 40 MeV.³⁻⁵ These neutron fields were characterized by time-of-flight spectroscopy. The STAY'SL computer code was then used to adjust the cross sections.

At energies above 50 MeV, differential neutron activation data is not generally available since it is usually not possible to perform such measurements. However, there have been numerous measurements of proton-induced activation^{10,13-15} and computer codes have been developed to calculate spallation yields,^{16,17} primarily for astrophysical applications. At sufficiently high energies, nucleon-induced reaction cross sections are believed to be charge independent. Hence, we generally expect that spallation yields will be identical for neutrons and protons above some poorly-defined energy which we have taken to be about 100 MeV. This approximation appears to work very well for high-threshold reactions such as the production of Sc isotopes from Fe, Ni, or Cu, where the thresholds are well above 100 MeV. However, we certainly expect significant differences between protons and neutrons for more direct reactions where the isotope produced is close in mass to the target. Hence, considerable care must be used in selection of proton activation data. We also have the problem of extrapolating neutron cross sections which are well-known below 50 MeV to higher energies. In many cases it can be shown that these extrapolations are not very important. For example, we estimate that for the neutron spectrum produced at 30° by 256 MeV protons stopped in uranium, less than 5% of the

^{58}Co activity from the $^{58}\text{Ni}(n,p)$ reaction will be produced by neutrons above 24 MeV, including spallation yields from ^{60}Ni . On the other hand, in the same spectrum, we estimate that about half of the ^{54}Mn activity from iron will be produced by neutrons from 50-100 MeV, primarily due to the relatively low abundance of ^{54}Fe (5.8%) compared to ^{56}Fe . Integral tests in well-defined neutron spectra (TOF) are needed to assess the accuracy of these cross sections.

Some of the neutron activation cross sections used in this work are shown in Fig. 5. As can be seen, the cross sections are rather smooth and generally decrease at higher energies as the total reaction cross section declines and more reaction channels become available. The energy responses of selected reactions are illustrated in Fig. 6. The lines for each reaction indicate where 90% of the activity is generated for the neutron spectrum shown (p + U at 30° at 256 MeV). The reactions were chosen to illustrate both that they cover the entire energy range and that they are highly overlapping. The capture (n,γ) reactions were not shown since they are sensitive primarily below 0.1 keV. Since we were able to use 25-35 reactions for each spectral calculation, it is easy to see that our flux values at each energy group depend on many different reactions and that nearby flux groups are very strongly correlated.

The input neutron spectra were calculated by Lt. Dave Ek (AFWL) using the High Energy Transport Code (HETC).¹⁸ Only statistical uncertainties were available for these calculations; however, model-dependent uncertainties are known to be quite large, especially at back angles.^{19,20} This creates a problem since we need to specify flux uncertainties as input to STAY'SL. However, sensitivity tests show that as we steadily increase the value of the flux variances, we rapidly reach a point where no changes are found in the output flux solutions. Hence, it is only necessary to input sufficiently large uncertainties (30-50%) that we do not unduly restrict the range of acceptable flux solutions. It was also necessary to extrapolate the spectral calculations down to thermal energies, since they generally stopped at about 10^{-3} MeV, and up to the kinematic limits, since poor statistics limited some of the calculations. It is necessary to have a non-zero flux input to STAY'SL; otherwise, no flux solutions are allowed. In these regions, the input uncertainties were increased to about 200%. Covariances between the flux group uncertainties are completely unknown. One school of thought recommends setting the covariance terms to zero in this case. However, this has the practical disadvantage that physically unreasonable solutions may result. In particular, it is possible that sharp dips or valleys may be created even though we know that the technique has inherently poor energy resolution. This is a particular problem near cross section resonances. Physics considerations would argue that the flux groups are indeed strongly correlated since we expect to find rather smooth energy spectra based on previous measurements and calculations. Hence, we used a Gaussian correlation function with a 5 group half-width and a 3% long-range correlation between all groups. Although these values are arbitrary, sensitivity tests show that they have little effect on the flux solutions. Such effects only show up in the fine group structure solutions (e.g., - 100 groups). However, if we collapse the solutions to smaller group sizes, then we find virtually no effects caused by the Gaussian correlation parameters.

Input uncertainties for the activation rates are given in Tables 3-6. Since samples were counted on seven different detectors and results were averaged, cross-correlations are believed to be quite small. A constant covariance term of 0.5% was thus assumed. Uncertainties for the activation cross sections were taken from ENDF/B-V below 20 MeV and values typically vary between 1-20%, depending on energy. Uncertainties at higher energies were taken from proton activation data in the literature or were estimated. The variances tended to increase with energy and ranged from 10-30%. Cross section covariances are not well-known; however, physics considerations suggest that there should be strong correlations between nearby groups. Hence, we have also assumed a Gaussian covariance function with a half-width of 7 groups and a long-range correlation of 3%.

Results of Neutron Spectral Adjustments

An example of a typical flux adjustment by STAY'SL is shown in Table 7. The second column gives the measured activation rates (times 10^{24}) along with their uncertainties. The column labelled "before" gives the calculated activity using the input neutron flux spectrum. The column labelled "after" gives the calculated activity after the flux spectrum has been adjusted. In each case, % differences are given for each reaction and the overall standard deviations are listed at the bottom. As can be seen, the differences generally improved markedly and the standard deviation decreased from 25 to 14%. In this example, the value of χ^2 was 0.99, showing that the fit is as good as can be expected given the stated input uncertainties. The last two columns indicate the energy range covered by each reaction, where 5% of the activity is produced by neutrons above and below these energy limits. As can be seen, each reaction is sensitive in only a small part of the energy spectrum and we have good foil coverage over the whole spectrum.

The main conclusion to be drawn from the STAY'SL fits to the foil activation data is that acceptable flux solutions ($\chi^2 < 2$) were achieved for 20 to 35 different reactions for every target, proton energy, and angle which we measured. The standard deviations in the activity calculations were less than 20% in all cases. This demonstrates that our foil activation technique produces self-consistent flux solutions, although we cannot rule out the possibility of biases, especially at higher neutron energies where the reaction cross sections are not well-known.

The adjusted neutron spectra from STAY'SL are presented in Tables 8-11 and shown in Figs. 7-10. The adjustments were performed in a 100 point energy grid. Typical flux uncertainties for each group are shown in Fig. 11. However, this is only part of the story since the output uncertainties are highly correlated. If we consider broader group fluxes, then the uncertainties are substantially lower. This is demonstrated in Table 12 where the output fluxes and uncertainties have been collapsed to 10 groups. The relative covariance matrix is also shown. As can be seen, the flux uncertainties for this broader group structure are less than 20% between 1 and 200 MeV. Below 1 MeV we have only a few capture gamma reactions and cannot distinguish between thermal and epithermal effects. For the highest energy group (200-256 MeV) the uncertainty increases due to poor foil coverage and high cross section uncertainties.

Neutron Scattering and Proton Activation Corrections

One of the pitfalls of foil activation measurements close to the target is that we have no direct way to determine either neutron scattering effects or foil activation caused by protons rather than neutrons. Neutron scattering effects will show up primarily at lower neutron energies. Neutrons lose energy every time they scatter and this energy loss will be substantial in our application since the scattering is primarily from low- z materials. Furthermore, scattering effects are minimized in our geometry where the foils are much closer to the target than to potential scattering materials. An effort was made to minimize extraneous material near the target and foils were irradiated from 22-32 cm from the target whereas the concrete walls were at 60-90 cm away in the horizontal directions and 2-3 meters vertically. Hence, we expect the flux of scattered neutrons to be much less than the direct flux from the target and the mean energy of the scattered neutrons to be less than 10 MeV. In the case of neutron capture gamma reactions, which are sensitive to thermal neutrons, our data suggests that the neutron flux below 1 MeV is nearly isotropic in the beam dump cavity, as is apparent in Tables 3-6 and Fig. 4.

In order to assess the influence of scattered neutrons on our foil activations, foil packages were placed further from the target in both the forward and backward directions at angles of approximately 30 and 150°. We can then make a direct comparison of the adjusted flux spectra from STAY'SL as a function of distance from the target on the assumption that scattering effects above 1 MeV will increase steadily as we move away from the target and closer to the scattering surfaces. Figures 12-15 compare spectra measured at 30 and 150° at the two different distances from the target. As can be seen, differences are generally small at 30°, especially at lower neutron energies. The 150° comparisons also show very little effect below about 40 MeV. At higher energies for 150°, the spectral comparisons are difficult due to the larger uncertainties in the data measured farther from the target, especially at 113 MeV where the fluxes are rather low. It should also be pointed out that at 150° at 113 MeV the flux above 40 MeV is less than 1% of the total neutron flux above 1 MeV and hence is rather unimportant. Consequently, we estimate that neutron scattering effects are not very important (10-20%) from about 1 to 40 MeV. Since we have no way to directly determine the scattering correction, we did not attempt to correct the data. Neutronics calculations could be used to make a better estimate of scattering effects. However, the effects could be reduced substantially by performing the irradiations in a more open geometry. Unfortunately, this was not possible in the present case since we lacked funding required to modify the IPNS beam transport lines to permit foil irradiations in the main beam line (Component Test Area E on Fig. 1) rather than in the more confined beam dump area. If this modification was accomplished, then scattering effects would be minimal since the target and foils would be at 2-3 meters from all major scattering materials and there would be space to use shadow bar techniques, as is done routinely in TOF measurements.

Proton activation of the foils is possible from three distinct sources. Protons in the beam will be directly scattered by the Ti beam exit foils as well as our Al beam monitor foils. As shown in Figs. 2 and 3, these protons can hit our foils directly at all angles larger than 30°. This source of

protons is unique in that the proton energies at our foil positions can be nearly as high as the beam energy. Protons are also made in the targets with fluxes comparable to the neutron fluxes. However, since protons lose energy before escaping the target, the target-generated protons will be severely degraded in energy before they reach our foils. In fact, it is easy to show from energy loss calculations that no target protons, or protons from the Ti or Al beam foils, can reach our foils at 0 or 7.5°. The final possibility is that protons from the first two sources will be scattered by extraneous materials surrounding our experiment. Due to energy loss and kinematic considerations, we expect that such scattered protons will be severely degraded in energy by the time they reach our foil packages.

Fortunately, we have a way to directly measure the presence of protons in our foils since we can detect radioisotopes which cannot be made by neutrons. In particular, we detected ^{55}Co and ^{56}Co from the $(p,2n)$ and (p,n) reactions with ^{56}Fe , and ^{62}Zn and ^{65}Zn from the $^{63}\text{Cu}(p,2n)$ and $^{65}\text{Cu}(p,n)$ reactions. We can rule out the possibility that these activities can be made from neutron reactions on impurities in our foils since we would then expect to see other activities, such as ^{57}Co or ^{58}Co from a Co impurity in Fe or ^{69}Zn from a Zn impurity in Cu. None of these activities were present in the data. Proton activation cross sections have been measured for the above reactions.¹³⁻¹⁵ Table 13 lists measured proton activities in our Fe and Cu foils.

Unfortunately, it is difficult to quantitatively determine proton fluxes from our measurements. In principle, one could unfold proton fluxes just as we do neutrons. However, we face a unique problem since all other proton-induced reaction products are also made equally well by neutrons. (In fact, we rely on this assumption that the very high energy spallation cross sections are identical for both protons and neutrons.) We can easily determine an upper limit for the proton fluxes if we assume that the protons all have the highest possible energies and hence the lowest possible activation cross sections. This calculation results in proton fluxes of about 10^{-6} p/p-cm² for the 113 MeV data and for the U target at 256 MeV, and about 10^{-5} for Al at 256 MeV. In this case, proton activation can account for less than 10% of our measured results for most reactions except those having the very highest thresholds in which case the effect can be as large as 30%. However, the Al data at 256 MeV is not consistent with this assumption since we would then predict more proton activation than our measurements for many of our reactions! This assumption, that most of the protons have energies near the beam energy, can also be ruled out since we see significant proton activity at 0 and 7.5° where it is physically impossible for protons to penetrate through the targets to reach the foil packages. Consequently, we must conclude that the protons have substantially less energy than the beam energy and hence that the fluxes are much lower since the proton activation cross sections decline by about two orders of magnitude from 250 to 10 MeV.

We then attempted to place limits on the permissible proton energies and hence on the proton fluxes. However, detailed analysis of the data in Table 13 is very difficult. For example, why should the proton fluxes for the case of 256 MeV protons on Al be nearly an order of magnitude higher than the

other three combinations of beam energy and target material? (This difference also suggests that the beam foils are not the direct source of protons since we would then expect proton effects to be target independent.) This aluminum target data at 256 MeV clearly indicates that the target itself strongly influences the proton flux. However, the target is probably not the major source of protons since it is not possible to emit protons at forward angles due to energy loss effects. The aluminum target at 256 MeV is much larger (20 cm long) than any of the other targets (2.5-5.0 cm long). Hence, we expect that there is a significant amount of proton scattering from the target. All of the data is then consistent with the assumption that protons from both the beam foils and those emitted at back angles from the target undergo multiple scattering with the walls and target materials prior to hitting our foils. This would explain how we can get proton activation at forward angles and why the Al values are so high at 256 MeV (more scattering material). The large variations in the proton activation values also suggest that the average proton energies must be rather low, since, in this case, the observed variations may be due to variations in the cross sections with energy rather than due to differences in flux levels. At very low energies (<50 MeV), energy loss in the foil packages themselves also becomes significant and even the angle of incidence becomes important in the calculation.

Although we do not have enough data to quantify the proton fluxes, the above arguments strongly suggest that the average proton energies are less than 50 MeV. In this case, the activation cross sections are much higher (factor of 10-100) than at the beam energy and hence the proton fluxes are more in the range of 10^{-8} to 10^{-7} p/p-cm². We can then calculate the level of proton-induced activation for each of our neutron reactions. In all cases, we find that protons produce less than 10% of the activity seen in our foils. For lower energy reactions, such as $^{58}\text{Ni}(n,p)^{58}\text{Co}$, proton effects are less than 1%. Since the data is insufficient to make exact corrections, no corrections were performed for protons. As is the case for neutron scattering, these effects would be much lower in a better designed facility where we are further away from potential sources of proton scattering, especially the beam exit foils and wall surfaces.

Comparison with HETC Calculations

Figures 16-19 compare the adjusted neutron spectra with the HETC calculations at 30 and 120° for each combination of proton energy and target. Examination of the differences shows that HETC consistently underpredicts the neutron flux at back angles and slightly overpredicts the flux at forward angles. Such differences have also been noted in previous studies,¹⁹ indicating that there are fundamental problems with the nuclear reaction models used by HETC. Work is now in progress at other laboratories to revise the HETC calculations to improve the fit to experimental data. Figures 20-23 show the ratio of our measured integral fluxes to those calculated by HETC. As can be seen, the calculations become steadily worse as the angle increases. Generally, HETC underpredicts the flux beyond 120° by a factor of 2-3, although in some cases the differences are nearly an order of magnitude. These differences tend to be similar for both Al and U and for both 113 and

256 MeV. In light of the significant discrepancies in the calculations, it is clear that we cannot rely on HETC at present to predict neutron yields and angular distributions for defense applications.

Future Work

As mentioned previously, one of the motivations of this work was to compare our foil results with time-of-flight measurements now in progress at LANL. When these data become available, a detailed comparison with our results is appropriate. The purpose of such a comparison is twofold. First of all, we hope to demonstrate that the foil technique gives acceptable results for neutron yields, energy spectra, and angular distributions. In this case, more confidence can be placed in the technique. Secondly, the comparison can be used to improve the foil technique by pointing out discrepant cross sections and allowing us to adjust poorly-known cross sections.

Foil measurements have also been performed for 50 MeV protons on aluminum and depleted uranium at IPNS and for 100 MeV deuterons on aluminum at Michigan State University, in collaboration with the Air Force Weapons Laboratory. Gamma analysis and preliminary STAY'SL calculations have been completed and we hope to issue separate reports on these measurements in the near future. In the case of the deuteron measurements, it was found that the HETC calculations incorrectly limited the neutron energies to about half of the incident deuteron energy. This caused a serious discrepancy with our foil results since STAY'SL cannot adjust an input zero flux value. We hope to receive improved calculations for the deuteron case. In the case of the 50 MeV data, we have found that the proton flux was unusually high due to the close proximity of the beam exit foils. We are attempting to estimate these corrections prior to adjusting the neutron spectra; however, further measurements may be needed to correctly interpret the data.

Conclusions

The present measurements demonstrate that the foil activation technique represents a relatively cost-effective way to obtain neutron yields and energy spectra from a wide variety of targets over a large range of neutron energies. Although the results do not provide either the accuracy or fine spectral details possible with the time-of-flight method, foil measurements can be done at any accelerator facility with brief exposures at high beam currents. Foil results are especially useful and reliable for broad-group or integral fluxes (e.g., - flux >10 MeV), where uncertainties are in the 10-20% range. Foil techniques are also highly reliable for comparing yields between targets or incident particles (e.g., - protons vs. deuterons). Foils should be used to complement time-of-flight or other techniques since they can be used at any angle and geometry and are sensitive at low energies (below TOF thresholds) and very high energies (where TOF timing resolution is poor). It should be pointed out that the foil measurements can be directly combined with the TOF data using the STAY'SL computer code. If the TOF data and uncertainties are used as input, then STAY'SL will use the foil data to adjust and improve the neutron spectrum, especially at low and high neutron

energies. Foils are also an invaluable monitor for beam currents and particle distributions and can be used to determine secondary proton effects. Finally, foils can be used at very high flux levels and in complex targets where active detectors cannot operate.

The accuracy of foil techniques can be improved enormously by a twofold program of measuring and calculating proton spallation yields at higher energies combined with integral testing in well-characterized (TOF) neutron fields. By improving our knowledge of activation cross sections, we can substantially reduce the uncertainties in the adjusted flux spectra. Furthermore, we can begin to use more reactions, such as some of those listed in Tables 2-6 for which cross sections are unknown. This type of bootstrapping procedure has been used very successfully at lower neutron energies and will allow us to tap the full potential of the foil technique for a variety of defense applications.

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References

1. Standard Method for Determining Neutron Flux, Fluence, and Spectra by Radioactivation Techniques, ASTM Standard Method E261-77, Vol. 12.02, pp. 56-64, 1988.
2. Evaluated Neutron Data File, Version V, Part B, National Neutron Data Center, Brookhaven National Laboratory, 1979.
3. L. R. Greenwood, Recent Research in Neutron Dosimetry and Damage Analysis for Materials Irradiations, ASTM-STP 956, pp. 743-749, 1987.
4. L. R. Greenwood, R. R. Heinrich, R. J. Kennerley, and R. Medrzychowski, Development and Testing of Neutron Dosimetry Techniques for Accelerator-Based Irradiation Facilities, Nucl. Technol. 41, pp. 109-128, 1978.
5. L. R. Greenwood, R. R. Heinrich, M. J. Saltmarsh, and C. B. Fulmer, Integral Tests of Neutron Activation Cross Sections in a $^9\text{Be}(d,n)$ Field at $E_d = 40$ MeV, Nucl. Sci. Eng. 72, pp. 175-190, 1979.
6. M. A. Kirk, R. C. Birtcher, T. H. Blewitt, L. F. Greenwood, R. J. Popek, and R. R. Heinrich, Measurement of Neutron Spectra and Fluxes at Spallation-Neutron Sources and Their Application to Radiation Effects Research, Jou. Nucl. Mater. 96, pp. 37-50, 1981.

7. D. R. Davidson, L. R. Greenwood, R. C. Reedy, and W. F. Sommer, Measured Radiation Environment at the Clinton P. Anderson LAMPF Irradiation Facility, ASTM-STP 870, pp. 1199-1208, 1985.
8. M. S. Wechsler, D. R. Davidson, L. R. Greenwood, and W. F. Sommer, Calculation of Displacement and Helium Production at the Clinton P. Anderson LAMPF Irradiation Facility, ASTM-STP 870, pp. 1189-1198, 1985.
9. Neutral Particle Beam Test Stand FY1988 Program Plan, ANL/NPBTS-RPT-020, Sept. 1988.
10. L. R. Greenwood and R. K. Smither, Measurement of Al Spallation Cross Sections at IPNS, Damage Analysis and Fundamental Studies Quarterly Progress Report, DOE/ER-0046/14, pp. 19-24, August 1983.
11. D. C. Kocher, Radioactive Decay Data Tables, DOE/TIC- 11026, 1981.
12. F. G. Perey, Least-Squares Dosimetry Unfolding: The Program STAY'SL, ORNL/TM-6062, 1977.
13. L. R. Greenwood and R. K. Smither, Measurement of Cu Spallation Cross Sections at IPNS, Damage Analysis and Fundamental Studies Quarterly Progress Report, DOE/ER-0046/18, pp. 11-17, August 1984.
14. R. Michel, G. Brinkmann, H. Weigel, and W. Herr, Measurement and Hybrid-Model Analysis of Proton-Induced Reactions with V, Fe, and Co, Nuclear Phy. A322, pp. 40-60, 1979.
15. R. L. Brodzinski, L. A. Rancitelli, J. A. Cooper, and N. A. Wogman, High- Energy Proton Spallation of Titanium, Phys. Rev. 4C, pp. 1250-1265, 1971.
16. G. Rudstam, Z. Naturforsch. 21A, 1027, 1966.
17. R. Silberberg and C. H. Tsao, Astrophysical Jour. Supp. 25, pp. 315-367, 1973; parameters updated in succeeding International Cosmic Ray Conference Proceedings.
18. T. W. Armstrong and K. C. Chandler, HETC - A High Energy Transport Code, Nucl. Sci. Eng. 49, 110, 1972.
19. See for example the Summary of the Meeting of the Medium Energy Nuclear Data Working Group, Brookhaven National Laboratory, S. Pearlstein, BNL-NCS-38404, 1986.

Table 1: Proton Beam Current Measurements
 (Values are $\times 10^{16}$ protons on target)
 (Al foil values $\pm 6\%$; Toroid $\pm 10\%$)

Experiment	Foil	Toroid	Ratio (toroid/foil)
Al 113 MeV	8.35	9.05	1.084
Al 256 MeV	8.29	8.94	1.078
U 113 MeV	6.58	6.63	1.008
U 256 MeV	4.35	4.50	1.036

Table 2: Foil Materials and Radioisotopes

Al - ^7Be , ^{22}Na , ^{24}Na

Au - $^{194,195,196,198}\text{Au}$

Co - $^{55,56,57,58,60}\text{Co}$; $^{52,54,56}\text{Mn}$; ^{59}Fe

Cu - $^{61,64}\text{Cu}$; $^{55,56,57,58,60}\text{Co}$; $^{52,54,56}\text{Mn}$; $^{47,48}\text{Sc}$

Fe - $^{52,59}\text{Fe}$; $^{52,54,56}\text{Mn}$; ^{51}Cr ; $^{46,47,48}\text{Sc}$; ^{48}V

In - $^{111,114m,115m,116m}\text{In}$

Nb - $^{90,92,93m}\text{Nb}$; $^{86,88,89}\text{Zr}$; $^{86,87,88}\text{Y}$

Ni - $^{56,57}\text{Ni}$; $^{55,56,57,58}\text{Co}$; $^{52,54}\text{Mn}$; ^{51}Cr

Ti - $^{44m,46,47,48}\text{Sc}$; $^{42,43}\text{K}$; ^{47}Ca

Zr - $^{86,88,89,95,97}\text{Zr}$; $^{90,92,95}\text{Nb}$; $^{86,87,88}\text{Y}$

Table 3: Activation Rates for 113 MeV p + Al
(activity in atom/p-sr followed by % error)

Reaction	0°		7.5°		30°		60°		90°		120°		150°	
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	3.81E-26	2.1	3.79E-26	2.1	3.77E-26	2.1	3.68E-26	2.1	3.66E-26	2.1	2.06E-26	2.1	2.02E-26	2.1
$^{59}\text{Co}(n,\gamma)^{60}\text{Co}$	4.33E-27	3.9	4.50E-27	2.9	4.45E-27	3.4	4.47E-27	3.4	4.22E-27	3.4	3.60E-27	2.7	3.64E-27	2.7
$\text{Cu}(n,x)^{64}\text{Cu}$	1.69E-27	4.4	1.58E-27	5.6	1.16E-27	6.4	6.74E-28	8.6	5.68E-28	8.6	3.93E-28	9.4	4.85E-28	7.9
$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$	3.52E-26	2.3	3.50E-26	2.3	3.52E-26	2.4	3.45E-26	2.2	3.58E-26	2.2	3.12E-26	2.6	3.27E-26	2.6
$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	2.60E-27	2.6	2.56E-27	2.4	2.31E-27	2.4	1.46E-27	2.4	1.29E-27	2.4	1.25E-27	2.4	1.25E-27	9.0
$^{197}\text{Au}(n,2n)^{196}\text{Au}$	6.89E-27	2.8	6.85E-27	2.1	4.77E-27	2.6	2.39E-27	2.6	1.39E-27	2.6	1.05E-27	2.6	1.04E-27	2.6
$^{197}\text{Au}(n,3n)^{195}\text{Au}$	1.20E-26	7.0	9.47E-27	7.2	5.10E-27	7.0	2.21E-27	7.0	1.07E-27	7.0	5.53E-28	4.9	4.95E-28	8.0
$^{197}\text{Au}(n,4n)^{194}\text{Au}$	4.85E-27	2.7	4.43E-27	2.1	2.58E-27	2.7	8.12E-28	3.4	2.58E-28	3.7	1.18E-28	3.4	1.08E-28	2.8
$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	4.47E-28	2.1	4.54E-28	2.3	3.16E-28	2.1	1.54E-28	2.2	9.74E-29	2.6	7.14E-29	2.3	7.01E-29	2.3
$\text{Ti}(n,x)^{46}\text{Sc}$	1.41E-26	2.4	1.37E-26	2.4	7.20E-27	2.6	2.39E-27	3.8	8.93E-28	5.2	5.99E-28	6.5	5.64E-28	6.5
$\text{Ti}(n,x)^{47}\text{Sc}$	1.75E-26	2.2	1.73E-26	2.2	9.20E-27	2.2	3.46E-27	2.2	1.46E-27	2.2	8.14E-28	2.2	7.72E-28	2.2
$^{48}\text{Ti}(n,p)^{48}\text{Sc}$	3.85E-28	2.6	3.64E-28	2.6	2.42E-28	2.6	1.03E-28	3.1	5.60E-29	2.4	4.04E-29	2.2	3.97E-29	2.9
$\text{Ti}(n,x)^{44\text{m}}\text{Sc}$	8.05E-29	2.7	7.87E-29	2.7	3.93E-29	2.7	1.00E-29	3.0	2.98E-30	4.2	1.48E-30	5.7	1.62E-30	5.7
$\text{Cu}(n,x)^{58}\text{Co}$	3.62E-28	3.2	3.60E-28	4.1	1.89E-28	4.5	5.85E-29	9.7	1.48E-29	17.1	7.66E-30	16.1	8.05E-30	16.1
$^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$	1.58E-27	3.0	1.58E-27	2.2	1.10E-27	3.1	5.39E-28	2.1	3.04E-28	2.1	2.08E-28	3.1	2.02E-28	3.1
$^{90}\text{Zr}(n,2n)^{89}\text{Zr}$	6.72E-27	2.2	6.58E-27	2.2	4.29E-27	2.2	1.68E-27	2.2	8.14E-28	2.2	4.64E-28	2.2	4.39E-28	2.2
$^{59}\text{Co}(n,p)^{59}\text{Fe}$	2.89E-28	5.1	2.66E-28	5.1	1.93E-28	3.9	1.12E-28	8.1	6.99E-29	10.2	4.77E-29	7.9	4.08E-29	8.6
$^{59}\text{Co}(n,\alpha)^{56}\text{Mn}$	2.08E-28	2.3	2.10E-28	2.5	1.16E-28	3.0	4.87E-29	3.0	2.54E-29	5.5	1.77E-29	3.0	1.77E-29	3.0
$^{59}\text{Co}(n,2n)^{58}\text{Co}$	3.70E-27	2.5	3.73E-27	2.5	2.62E-27	2.5	1.11E-27	3.3	5.95E-28	4.3	3.87E-28	3.5	3.60E-28	3.5
$^{59}\text{Co}(n,3n)^{57}\text{Co}$	1.58E-27	2.7	1.61E-27	2.7	9.32E-28	2.6	3.23E-28	4.4	1.17E-28	6.0	6.12E-29	6.3	6.39E-29	5.9
$^{54}\text{Fe}(n,p)^{54}\text{Mn}$	2.93E-26	2.5	2.94E-26	2.5	1.70E-26	2.5	5.58E-27	2.8			1.49E-27	3.4	1.38E-27	7.7
$^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$	7.33E-27	2.4	7.28E-27	2.7	3.79E-27	2.4	1.12E-27	3.4			1.92E-28	6.2	2.10E-28	15.1
$^{56}\text{Fe}(n,p)^{56}\text{Mn}$	4.56E-28	2.3	4.77E-28	2.3	3.31E-28	2.3	1.68E-28	2.5	1.01E-28	2.5	7.47E-29	2.4	9.47E-29	2.8
$\text{Fe}(n,x)^{52}\text{Mn}$	1.33E-28	3.0	1.31E-28	3.0	6.60E-29	3.0	1.50E-29	3.0	6.45E-30	13.2	2.54E-30	2.9	2.85E-30	5.7
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	4.04E-27	2.5	3.91E-27	2.3	3.04E-27	2.4	1.69E-27	2.4	1.27E-27	2.6	1.08E-27	2.4	1.18E-27	2.4
$^{58}\text{Ni}(n,2n)^{57}\text{Ni}$	5.91E-28	2.5	5.89E-28	2.5	3.85E-28	2.5	1.45E-28	2.5	6.89E-29	2.8	4.83E-29	2.5	4.52E-29	2.5
$\text{Ni}(n,x)^{52}\text{Mn}$	8.87E-29	2.7	8.41E-29	2.7	4.33E-29	3.9	8.97E-30	6.3	2.75E-30	8.1	1.68E-30	10.0	2.04E-30	5.0
$^{58}\text{Ni}(n,x)^{57}\text{Co}$	5.33E-27	2.4	5.22E-27	2.4	2.94E-27	2.6	1.27E-27	2.6	6.43E-28	2.6	3.91E-28	2.6	3.81E-28	2.6
$\text{Ni}(n,x)^{56}\text{Co}$	9.47E-28	3.0	8.37E-28	3.8	5.08E-28	5.9	1.58E-28	4.4	5.08E-29	8.8	3.75E-29	5.9	3.35E-29	5.9

Table 4: Activation Rates for 113 MeV p + U
(Activity in atom/p-sr followed by % error)

Reaction	0°		7.5°		30°		60°		90°		120°		150°	
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	4.08E-25	2.1	4.30E-25	2.1	4.15E-25	2.4	4.18E-25	2.4	4.23E-25	2.1	2.34E-25	2.1	2.48E-25	2.1
$^{59}\text{Co}(n,\gamma)^{60}\text{Co}$	3.89E-26	2.3	4.24E-26	2.3	4.02E-26	2.3	4.09E-26	2.3	4.05E-26	2.3	3.40E-26	2.3	3.64E-26	2.3
$\text{Cu}(n,x)^{64}\text{Cu}$	4.59E-27	5.1	4.83E-27	2.8	4.16E-27	5.1	3.94E-27	5.4	3.43E-27	6.1	3.16E-27	6.6	3.72E-27	5.0
$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$	2.37E-25	2.7			2.48E-25	2.2					2.35E-25	2.8		
$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	1.31E-26	2.4			1.21E-26	2.4					1.31E-26	2.4		
$^{115}\text{In}(n,2n)^{114\text{m}}\text{In}$	7.80E-27	2.3			7.21E-27	2.5					5.58E-27	2.3		
$^{113}\text{In}(n,3n)^{111}\text{In}$	2.03E-26	2.2			1.26E-26	2.3					7.16E-28	2.6		
$^{197}\text{Au}(n,2n)^{196}\text{Au}$	6.18E-27	2.5	6.57E-27	2.5	5.09E-27	2.5	2.64E-27	2.8	1.51E-27	3.8	2.11E-27	2.5	2.05E-27	2.5
$^{197}\text{Au}(n,3n)^{195}\text{Au}$	6.37E-27	10.0	6.97E-27	2.7	4.67E-27	5.6	1.85E-27	5.9	1.14E-27	5.1	9.14E-28	2.8	8.30E-28	4.0
$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	4.16E-28	2.1	4.32E-28	2.2	3.48E-28	2.2	1.78E-28	2.3	1.15E-28	2.4	1.72E-28	2.4	1.68E-28	2.4
$\text{Ti}(n,x)^{46}\text{Sc}$	9.53E-27	2.4	9.73E-27	2.6	6.22E-27	2.4	2.36E-27	3.1	1.21E-27	2.4	1.66E-27	2.4	1.55E-27	2.4
$\text{Ti}(n,x)^{47}\text{Sc}$	1.28E-26	5.0	1.28E-26	2.2	8.65E-27	5.0	3.45E-27	5.0	1.75E-27	5.0	2.42E-27	5.0	2.22E-27	5.0
$^{48}\text{Ti}(n,p)^{48}\text{Sc}$	2.95E-28	2.1	3.23E-28	2.2	2.37E-28	2.3	1.09E-28	2.4	6.37E-29	2.4	8.89E-29	2.1	7.95E-29	2.1
$\text{Ti}(n,x)^{44\text{m}}\text{Sc}$	4.77E-29	2.4	4.74E-29	2.4	3.14E-29	2.4	6.92E-30	4.0	2.94E-30	3.9	1.81E-30	3.6	2.14E-30	2.9
$\text{Ti}(n,x)^{42}\text{K}$	4.05E-29	5.0	3.90E-29	5.0	2.39E-29	6.7	4.24E-30	15.1	1.67E-30	15.1				
$\text{Cu}(n,x)^{58}\text{Co}$	2.29E-28	2.2	2.31E-28	2.4	1.54E-28	2.4	4.17E-29	2.4	1.64E-29	3.9	9.53E-30	3.1	1.05E-29	2.7
$^{63}\text{Cu}(n,3n)^{61}\text{Cu}$	5.43E-28	3.0	5.43E-28	2.9	3.65E-28	2.9	1.17E-28	4.5	5.48E-29	21.1	3.86E-29	8.9	3.76E-29	8.1
$^{59}\text{Co}(n,p)^{59}\text{Fe}$	3.38E-28	3.2	3.28E-28	2.5	2.76E-28	2.6	1.47E-28	3.2	1.01E-28	2.8	1.81E-28	2.4	1.74E-28	2.4
$^{59}\text{Co}(n,\alpha)^{56}\text{Mn}$	1.63E-28	2.3	1.59E-28	2.3	1.10E-28	2.3	4.72E-29	2.3	2.90E-29	2.4	4.26E-29	2.5	4.09E-29	2.5
$^{59}\text{Co}(n,2n)^{58}\text{Co}$	3.01E-27	2.2	2.94E-27	2.2	2.35E-27	2.2	9.88E-28	2.2	5.48E-28	2.2	6.42E-28	2.2	5.78E-28	2.2
$^{59}\text{Co}(n,3n)^{57}\text{Co}$	8.79E-28	2.2	9.34E-28	2.2	6.92E-28	2.2	2.17E-28	2.4	1.13E-28	2.7	7.95E-29	2.2	7.95E-29	2.2
$^{59}\text{Co}(n,4n)^{56}\text{Co}$	1.15E-28	4.4	1.20E-28	3.5	8.50E-29	5.0	2.03E-29	8.2	1.24E-29	17.1	6.32E-30	7.1	1.38E-29	7.5
$^{54}\text{Fe}(n,p)^{54}\text{Mn}$	2.40E-26	2.2	2.48E-26	2.7	1.67E-26	2.4	7.31E-27	2.4	4.26E-27	3.1	6.82E-27	2.5	7.16E-27	2.3
$^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$	4.41E-27	2.4	4.60E-27	3.6	3.10E-27	3.9	8.20E-28	3.7	3.95E-28	6.4	3.19E-28	9.7	3.28E-28	4.4
$^{54}\text{Fe}(n,3n)^{52}\text{Fe}$	3.21E-29	2.5	3.12E-29	3.3	3.76E-29	6.3	7.21E-30	5.5	2.49E-30	21.1	1.70E-30	24.1	2.64E-30	7.4
$^{56}\text{Fe}(n,p)^{56}\text{Mn}$	4.81E-28	2.3	4.86E-28	2.3	3.88E-28	2.3	2.02E-28	2.3	1.35E-28	2.3	2.07E-28	2.3	1.99E-28	2.3
$\text{Fe}(n,x)^{52}\text{Mn}$	7.16E-29	20.0	7.81E-29	3.7	5.09E-29	2.1	1.21E-29	2.4	4.99E-30	3.1	3.00E-30	2.8	4.12E-30	3.0
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	9.39E-27	2.3	1.02E-26	2.3	8.89E-27	2.3	5.63E-27	2.3	4.12E-27	2.3	8.64E-27	2.3	8.40E-27	2.3
$^{58}\text{Ni}(n,2n)^{57}\text{Ni}$	3.85E-28	2.5	4.09E-28	2.5	3.19E-28	2.5	1.20E-28	2.5	6.87E-29	2.5	6.13E-29	2.5	6.03E-29	2.2
$\text{Ni}(n,x)^{52}\text{Mn}$	4.59E-29	2.7	4.99E-29	3.4	3.14E-29	3.5	6.87E-30	6.6	2.46E-30	11.2	1.58E-30	3.2	2.43E-30	2.4
$^{58}\text{Ni}(n,x)^{57}\text{Co}$	3.52E-27	2.4	3.43E-27	2.4	2.56E-27	2.4	1.06E-27	2.5	5.09E-28	2.7	6.32E-28	2.4	6.08E-28	2.4
$\text{Ni}(n,x)^{56}\text{Co}$	5.43E-28	3.0	5.63E-28	2.3	3.72E-28	3.4	1.11E-28	3.8	4.54E-29	9.1	3.66E-29	2.7	4.45E-29	2.7
$\text{Ni}(n,x)^{55}\text{Co}$	5.29E-29	2.7	5.19E-29	2.3	3.72E-29	4.5	9.68E-30	4.6	4.02E-30	3.5	3.41E-30	3.7	5.38E-30	2.6
$^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$	1.41E-27	2.3	1.35E-27	2.3	1.10E-27	2.3	4.99E-28	2.3	2.97E-28	2.5	3.67E-28	2.3	3.42E-28	2.3
$^{93}\text{Nb}(n,4n)^{90}\text{Nb}$	8.94E-28	3.9	8.60E-28	2.1	5.68E-28	2.3	1.42E-28	2.3	5.38E-29	2.2	3.10E-29	2.2	3.33E-29	2.2
$^{90}\text{Zr}(n,2n)^{89}\text{Zr}$	4.82E-27	2.2	4.88E-27	2.2	3.61E-27	2.2	1.42E-27	2.4	7.36E-28	2.2	6.87E-28	2.5	6.32E-28	2.5
$^{90}\text{Zr}(n,3n)^{88}\text{Zr}$	2.01E-27	2.3	2.09E-27	2.4	1.36E-27	2.6	4.01E-28	3.1	1.67E-28	4.5	1.08E-28	5.2	1.05E-28	6.8

Table 5: Activation Rates for 256 MeV p + Al
(Activity in atom/p-sr followed by % error)

Reaction	0°		7.5°		30°		60°		90°		120°		150°	
$^{59}\text{Co}(n,\gamma)^{60}\text{Co}$	4.27E-26	2.3	4.31E-26	2.2	4.24E-26	2.3	4.24E-26	2.3	4.20E-26	2.6	3.41E-26	2.3	3.33E-26	2.3
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	3.62E-25	2.1	3.61E-25	2.1	3.66E-25	2.1	3.56E-25	2.1	3.45E-25	2.1	1.98E-25	2.1	1.93E-25	2.1
$\text{Cu}(n,x)^{64}\text{Cu}$	7.49E-27	3.0	7.20E-27	4.3	6.81E-27	5.6	5.68E-27	4.8	4.74E-27	5.3	3.69E-27	4.7	3.39E-27	4.7
$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$	3.49E-25	3.0	3.19E-25	2.1	3.35E-25	2.7	3.20E-25	2.7	3.23E-25	2.7	3.03E-25	2.7	3.02E-25	2.7
$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	9.41E-27	2.3	8.44E-27	2.2	7.82E-27	2.5	7.20E-27	2.3	6.88E-27	2.5	6.30E-27	2.6	5.90E-27	2.5
$^{197}\text{Au}(n,2n)^{196}\text{Au}$	2.17E-26	2.5	2.13E-26	2.1	1.66E-26	2.5	1.14E-26	2.5	7.96E-27	2.5	5.76E-27	2.5	4.53E-27	2.5
$^{197}\text{Au}(n,3n)^{195}\text{Au}$	2.35E-26	4.3	2.18E-26	2.6	1.81E-26	3.4	1.02E-26	3.4	5.86E-27	5.4	3.20E-27	2.6	2.12E-27	4.7
$^{197}\text{Au}(n,4n)^{194}\text{Au}$	1.58E-26	6.2	1.52E-26	2.1	1.03E-26	2.5	5.54E-27	2.6	2.61E-27	2.8	1.12E-27	2.8	5.58E-28	2.7
$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	1.97E-27	2.1	1.89E-27	2.0	1.34E-27	2.3	1.04E-27	2.0	5.32E-28	2.3	3.80E-28	2.3	3.03E-28	2.3
$\text{Cu}(n,x)^{58}\text{Co}$	2.74E-27	2.5	2.60E-27	2.5	1.70E-27	3.0	6.77E-28	3.5	2.19E-28	5.7	7.78E-29	7.1	3.48E-29	11.2
$^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$	5.18E-27	2.5	5.03E-27	2.1	4.27E-27	3.9	2.69E-27	2.2	1.74E-27	2.7	1.22E-27	3.9	9.30E-28	3.9
$^{90}\text{Zr}(n,p)^{89}\text{Zr}$	2.38E-26	2.1	2.31E-26	2.1	1.80E-26	2.1	1.09E-26	2.1	5.50E-27	2.2	3.14E-27	2.1	2.15E-27	2.1
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	1.38E-26	2.2	1.37E-26	2.2	1.09E-26	2.2	9.01E-27	2.2	7.31E-27	2.2	6.08E-27	2.2	5.43E-27	2.2
$^{58}\text{Ni}(n,2n)^{57}\text{Ni}$	2.70E-27	3.0	2.62E-27	3.0	2.40E-27	5.0	1.17E-27	5.0	4.89E-28	5.0	2.45E-28	4.0	1.70E-28	4.0
$^{58}\text{Ni}(n,x)^{57}\text{Co}$	1.98E-26	3.0	1.84E-26	3.0	1.23E-26	5.0	6.84E-27	5.0	3.76E-27	5.0	2.29E-27	2.5	1.62E-27	2.5
$\text{Ni}(n,x)^{56}\text{Co}$	4.49E-27	4.3	4.49E-27	2.6	3.22E-27	3.0	1.49E-27	2.2	5.58E-28	3.4	2.34E-28	3.0	1.17E-28	3.0
$\text{Ni}(n,x)^{52}\text{Mn}$	8.80E-28	2.2	8.47E-28	2.2	5.65E-28	2.5	1.86E-28	2.5	4.71E-29	3.9	1.27E-29	6.0	5.21E-30	8.3
$\text{Ti}(n,x)^{46}\text{Sc}$	6.23E-26	2.4	5.90E-26	2.2	3.95E-26	2.4	1.78E-26	2.4	8.18E-27	2.8	4.53E-27	6.3	2.41E-27	4.1
$\text{Ti}(n,x)^{47}\text{Sc}$	6.73E-26	5.0	6.41E-26	2.0	4.09E-26	5.0	2.02E-26	5.0	1.16E-26	5.0	5.18E-27	4.0	3.34E-27	4.0
$^{48}\text{Ti}(n,p)^{48}\text{Sc}$	1.53E-27	2.2	1.45E-27	2.0	9.88E-28	2.2	5.83E-28	2.2	3.80E-28	2.4	2.40E-28	2.2	1.80E-28	2.2
$\text{Ti}(n,x)^{44\text{m}}\text{Sc}$	5.76E-28	2.2	9.52E-28	2.1	3.95E-28	2.4	1.62E-28	2.5	6.26E-29	5.9	1.25E-29	5.9	6.48E-30	8.5
$^{54}\text{Fe}(n,p)^{54}\text{Mn}$	1.33E-25	2.5	1.26E-25	2.5	9.01E-26	2.5	4.38E-26	2.5	2.01E-26	2.6	1.03E-26	2.5	7.28E-27	2.5
$^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$	6.01E-26	2.4	5.65E-26	2.4	3.69E-26	2.7	1.39E-26	2.7	4.34E-27	3.0	1.64E-27	2.7	8.69E-28	3.9
$\text{Fe}(n,x)^{52}\text{Mn}$	1.05E-27	2.5	1.01E-27	2.5	7.17E-28	2.5	2.66E-28	2.5	7.35E-29	2.5	2.18E-29	2.5	9.27E-30	2.5
$^{56}\text{Fe}(n,p)^{56}\text{Mn}$	1.56E-27	2.2	1.47E-27	2.2	1.10E-27	2.2	7.93E-28	2.2	5.68E-28	2.2	4.20E-28	2.2	3.26E-28	2.2
$^{59}\text{Co}(n,p)^{59}\text{Fe}$	7.93E-28	4.5	8.04E-28	4.9	5.86E-28	3.9	4.16E-28	5.9	3.33E-28	3.9	2.47E-28	3.4	2.33E-28	5.2
$^{59}\text{Co}(n,\alpha)^{56}\text{Mn}$	1.11E-27	3.0	1.05E-27	3.0	7.13E-28	2.5	3.35E-28	2.5	1.25E-28	2.9	1.12E-28	2.7	8.00E-29	2.5
$^{59}\text{Co}(n,2n)^{58}\text{Co}$	1.22E-26	2.3	1.19E-26	2.3	9.45E-27	2.3	6.05E-27	2.3	3.66E-27	2.3	2.31E-27	2.3	1.65E-27	2.3
$^{59}\text{Co}(n,3n)^{57}\text{Co}$	5.79E-27	2.5	5.68E-27	2.5	4.63E-27	2.5	2.43E-27	2.6	1.03E-27	2.5	4.82E-28	2.5	2.78E-28	3.4
$\text{Co}(n,x)^{52}\text{Mn}$	4.02E-28	3.0	3.98E-28	3.9	2.59E-28	3.0	7.96E-29	5.0	1.55E-29	6.7				

Table 6: Activation Rates for 256 MeV p + U
(Activity in atom/p-sr followed by % error)

Reaction	0°		7.5°		30°		60°		90°		120°		150°	
$^{59}\text{Co}(n,\gamma)^{60}\text{Co}$	1.92E-25	2.2	1.80E-25	2.2	1.63E-25	2.2	1.75E-25	2.3	1.75E-25	2.2	1.52E-25	2.4	1.71E-25	2.4
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	1.53E-24	2.1	1.56E-24	2.2	1.50E-24	2.1	1.52E-24	2.1	1.52E-24	2.1	1.00E-24	2.1	1.09E-24	2.1
$\text{Cu}(n,x)^{64}\text{Cu}$	1.95E-26	3.0	2.01E-26	3.0	1.93E-26	3.1	1.76E-26	3.1	1.71E-26	3.1	1.67E-26	3.6	1.71E-26	3.6
$^{115}\text{In}(n,\gamma)^{116\text{m}}\text{In}$					1.38E-24	2.6					1.05E-24	2.6		
$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$					4.56E-26	2.3					4.83E-26	2.3		
$^{197}\text{Au}(n,2n)^{196}\text{Au}$	2.22E-26	2.3	2.24E-26	2.8	2.04E-26	2.3	1.31E-26	2.8	1.09E-26	2.3	1.09E-26	2.5	1.17E-26	2.5
$^{197}\text{Au}(n,3n)^{195}\text{Au}$	1.75E-26	3.0	1.82E-26	3.0	1.41E-26	3.0	8.45E-27	3.0	6.09E-27	3.0	4.34E-27	3.3	3.88E-27	3.0
$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	1.92E-27	2.2	1.90E-27	2.2	1.58E-27	2.2	9.96E-28	2.2	8.15E-28	2.2	8.70E-28	2.2	9.86E-28	2.2
$^{59}\text{Co}(n,p)^{59}\text{Fe}$	1.21E-27	2.5	1.19E-27	2.5	1.11E-27	2.5	7.70E-28	2.5	7.19E-28	2.5	7.95E-28	2.8	9.00E-28	2.8
$^{59}\text{Co}(n,\alpha)^{56}\text{Mn}$	8.80E-28	2.1	8.25E-28	2.1	5.93E-28	2.1	3.24E-28	2.1	2.24E-28	2.1	2.19E-28	2.1	2.35E-28	2.1
$^{59}\text{Co}(n,2n)^{58}\text{Co}$	1.07E-26	2.2	1.07E-26	2.2	8.90E-27	2.2	5.48E-27	2.2	4.12E-27	2.2	3.54E-27	2.2	3.38E-27	2.2
$^{59}\text{Co}(n,3n)^{57}\text{Co}$	3.68E-27	2.3	3.52E-27	2.3	3.15E-27	2.3	1.52E-27	2.3	8.80E-28	2.5	6.34E-28	2.5	4.67E-28	2.7
$^{59}\text{Co}(n,4n)^{56}\text{Co}$	6.64E-28	6.3	6.34E-28	5.1	4.21E-28	4.8	1.86E-28	3.7	9.31E-29	5.4	3.98E-29	12.1	3.39E-29	14.1
$\text{Co}(n,x)^{52}\text{Mn}$	2.52E-28	2.5	2.41E-28	2.5	1.20E-28	3.2	3.32E-29	3.2	1.00E-29	4.6	5.23E-30	18.2	4.43E-30	7.8
$\text{Co}(n,x)^{54}\text{Mn}$	1.88E-27	4.3	1.90E-27	4.3	1.11E-27	3.6	4.28E-28	6.5	2.46E-28	11.2	1.15E-28	19.1	5.99E-29	32.0
$^{63}\text{Cu}(n,x)^{60}\text{Co}$	1.90E-27	4.0	1.89E-27	4.6	1.26E-27	3.0	6.49E-28	4.3	4.46E-28	3.5	4.26E-28	3.0	4.92E-28	3.0
$\text{Cu}(n,x)^{52}\text{Mn}$	5.63E-29	2.4	5.13E-29	2.4	1.92E-29	2.4	3.62E-30	6.1	7.90E-31	11.0				
$\text{Cu}(n,x)^{54}\text{Mn}$	3.85E-28	2.6	3.60E-28	2.6	1.57E-28	2.8	3.87E-29	7.3	9.46E-30	10.1	3.92E-30	21.0	2.64E-30	23.0
$\text{Cu}(n,x)^{58}\text{Co}$					1.04E-27	2.4	4.17E-28	2.4	1.82E-28	2.4	1.01E-28	2.5	7.54E-29	2.5
$^{54}\text{Fe}(n,p)^{54}\text{Mn}$	1.03E-25	2.5	1.11E-25	2.5	7.90E-26	2.5	4.47E-26	2.5	3.16E-26	2.5	3.12E-26	2.5	3.38E-26	2.5
$^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$	3.65E-26	3.0	3.66E-26	2.5	2.04E-26	2.6	7.95E-27	2.6	3.69E-27	2.6	2.32E-27	2.8	2.01E-27	2.9
$^{56}\text{Fe}(n,p)^{56}\text{Mn}$	1.78E-27	2.2	1.78E-27	2.2	1.51E-27	2.2	1.04E-27	2.2	9.10E-28	2.2	1.03E-27	2.2	1.13E-27	2.5
$\text{Fe}(n,x)^{52}\text{Mn}$	6.39E-28	2.5	6.44E-28	2.8	3.63E-28	2.5	1.33E-28	2.5	5.18E-29	2.3	2.66E-29	2.5	2.10E-29	2.6
$^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$	4.91E-27	2.4	5.08E-27	2.4	4.34E-27	2.4	2.71E-27	2.4	2.11E-27	2.4	2.11E-27	2.4	2.18E-27	2.4
$^{90}\text{Zr}(n,2n)^{89}\text{Zr}$	1.85E-26	2.3	1.79E-26	2.5	1.45E-26	2.3	8.35E-27	2.3	5.53E-27	2.3	4.49E-27	2.3	3.99E-27	2.3
$\text{Ti}(n,x)^{46}\text{Sc}$	4.76E-26	2.4	4.60E-26	2.5	3.34E-26	2.5	1.65E-26	2.5	1.02E-26	2.5	8.80E-27	2.7	8.90E-27	2.7
$\text{Ti}(n,x)^{47}\text{Sc}$	5.68E-26	2.3	5.58E-26	2.3	4.09E-26	2.3	2.18E-26	2.3	1.41E-26	2.3	1.20E-26	2.3	1.17E-26	2.3
$^{48}\text{Ti}(n,p)^{48}\text{Sc}$	1.32E-27	2.4	1.32E-27	2.4	1.05E-27	2.5	6.59E-28	2.4	4.84E-28	2.5	4.74E-28	2.5	4.96E-28	2.5
$\text{Ti}(n,x)^{44\text{m}}\text{Sc}$	4.13E-28	2.6	3.97E-28	2.6	2.43E-28	3.0	9.21E-29	2.4	3.70E-29	3.0	1.89E-29	4.5	1.56E-29	5.4
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	3.50E-26	2.2	3.67E-26	2.2	3.49E-26	2.2	2.69E-26	2.2	2.50E-26	2.2	3.14E-26	2.2	3.96E-26	2.2
$^{58}\text{Ni}(n,2n)^{57}\text{Ni}$	1.89E-27	2.3	1.85E-27	2.3	1.35E-27	2.3	7.59E-28	2.3	4.55E-28	2.4	3.69E-28	2.5	3.30E-28	2.5
$^{58}\text{Ni}(n,x)^{57}\text{Co}$					1.18E-26	2.4	6.84E-27	2.4	4.34E-27	2.4	3.90E-27	2.4	3.72E-27	2.4
$\text{Ni}(n,x)^{52}\text{Mn}$	5.28E-28	2.4	5.23E-28	2.4	2.85E-28	2.4	9.71E-29	2.9	3.61E-29	3.4	1.69E-29	4.6	1.25E-29	5.6
$\text{Ni}(n,x)^{56}\text{Co}$	2.86E-27	3.5	2.70E-27	2.4	1.87E-27	2.2	8.65E-28	2.3	4.73E-28	3.9	2.78E-28	3.0	2.12E-28	3.2

Table 7: STAY'SL Spectral Adjustment for P + U, 256 MEV, 30⁰

DOSIMETRY ACTIVITIES						$\chi^2 = 0.99$			
REACTION	MEASURED	+OR- %	BEFORE	DIFF %	AFTER	DIFF %	CHI	90 %	ENERGY LIMITS
C059(N, γ)C060	3.240E+09	2.20	2.660E+09	-17.89	3.133E+09	-3.29	0.621	1.00E-10	1.00E-04
IN115(N, γ)IN116	2.750E+10	2.60	2.221E+10	-19.24	2.756E+10	0.22	-0.231	1.00E-10	6.30E-06
AU197(N, γ)AU1978	2.990E+10	2.10	2.206E+10	-26.24	2.981E+10	-0.32	0.419	1.00E-10	1.35E-05
CU(N,*)CU64	3.840E+08	3.10	3.383E+08	-11.90	3.870E+08	0.79	-0.394	1.00E-10	18.
IN115(N,N')IN115M	9.070E+08	2.30	5.765E+08	-36.44	8.856E+08	-2.36	1.176	1.	10.
AU197(N,2N)AU196	4.050E+08	2.30	4.095E+08	1.11	4.150E+08	2.46	0.014	9.	68.
AU197(N,3N)AU195	2.810E+08	3.00	2.767E+08	-1.52	3.364E+08	19.72	-0.090	18.	100.
AL27(N,*)NA24	3.140E+07	2.20	3.218E+07	2.49	3.338E+07	6.30	0.206	7.	92.
C059(N,P)FE59	2.210E+07	2.50	1.679E+07	-24.02	2.026E+07	-8.31	1.159	3.	20.
C059(N, α)MN56	1.180E+07	2.10	1.279E+07	8.42	1.267E+07	7.41	0.727	7.	130.
C059(N,2N)C058	1.770E+08	2.20	1.596E+08	-9.82	1.804E+08	1.92	-0.212	12.	40.
C059(N,3N)C057	6.270E+07	2.30	4.563E+07	-27.23	5.749E+07	-8.31	0.370	20.	56.
C059(N,4N)C056	8.360E+06	4.80	9.162E+06	9.60	1.030E+07	23.24	0.142	32.	72.
C059(N,*)MN52	2.380E+06	3.20	2.617E+06	9.97	2.222E+06	-6.66	-0.110	44.	160.
C059(N,*)MN54	2.210E+07	3.60	2.048E+07	-7.32	1.954E+07	-11.57	0.509	32.	150.
C059(N,*)C058	2.510E+07	3.00	2.197E+07	-12.46	2.195E+07	-12.55	1.648	6.	140.
CU(N,*)MN52	3.810E+05	2.40	6.510E+05	70.87	4.872E+05	27.88	2.482	80.	190.
CU(N,*)MN54	3.120E+06	2.80	2.703E+06	-13.38	2.129E+06	-31.75	2.489	52.	180.
CU(N,*)C058	2.070E+07	2.40	2.463E+07	19.00	2.436E+07	17.69	1.615	28.	150.
CU(N,*)V48	8.480E+04	4.00	1.446E+05	70.49	9.795E+04	15.51	1.756	100.	200.
FE(N,*)MN54	1.570E+09	2.50	1.190E+09	-24.18	1.412E+09	-10.04	4.825	3.	110.
FE(N,*)CR51	4.060E+08	2.60	5.527E+08	36.12	5.003E+08	23.22	4.448	20.	150.
FE56(N,P)MN56	3.010E+07	2.20	2.769E+07	-8.01	3.027E+07	0.55	-0.226	6.	140.
FE(N,*)MN52	7.210E+06	2.50	9.121E+06	26.51	8.442E+06	17.09	0.405	32.	150.
NB93(N,2N)NB92M	8.620E+07	2.40	8.121E+07	-5.79	8.312E+07	-3.58	0.179	10.	20.
ZR290(N,2N)ZR89	2.890E+08	2.30	2.434E+08	-15.78	2.849E+08	-1.41	0.137	14.	72.
TI46(N,X)SC46	6.640E+08	2.50	5.014E+08	-24.50	5.594E+08	-15.76	2.622	5.	120.
TI47(N,*)SC47	8.140E+08	2.30	5.217E+08	-35.91	6.263E+08	-23.06	7.470	3.	100.
TI48(N,*)SC48	2.090E+07	2.50	1.799E+07	-13.93	1.967E+07	-5.89	0.605	7.	60.
TI(N,*)SC44M	4.830E+06	3.00	5.771E+06	19.49	5.228E+06	8.24	0.224	32.	150.
NI58(N,*)C058	6.940E+08	2.20	4.879E+08	-29.69	7.077E+08	1.98	-1.658	2.	24.
NI58(N,*)NI57	2.690E+07	2.30	2.346E+07	-12.81	2.640E+07	-1.84	0.128	16.	110.
NI58(N,*)C057	2.340E+08	2.40	2.258E+08	-3.48	2.521E+08	7.75	-0.118	10.	92.
NI(N,*)MN52	5.660E+06	2.40	5.180E+06	-8.48	4.510E+06	-20.32	0.226	28.	170.
NI(N,*)56CO	3.720E+07	2.20	3.815E+07	2.55	4.287E+07	15.25	0.128	28.	110.
STD. DEV. =				25.33	13.73				

Table 8: Neutron Fluxes for $^{113}\text{p} + \text{Al}$
(Flux/proton-sr-MeV)

Lower Energy (MeV)	0°	7.5°	30°	60°	90°	120°	150°
1.00E-10	3.48E+03	3.53E+03	3.83E+03	3.79E+03	1.74E+03	1.69E+03	2.89E+03
1.00E-09	1.56E+03	1.58E+03	1.65E+03	1.58E+03	1.04E+03	8.37E+02	1.28E+03
1.00E-08	8.44E+02	8.53E+02	8.63E+02	7.91E+02	6.88E+02	4.97E+02	6.91E+02
2.30E-08	5.70E+02	5.74E+02	5.73E+02	5.34E+02	5.66E+02	3.88E+02	4.93E+02
5.00E-08	3.08E+02	3.10E+02	3.14E+02	2.99E+02	3.47E+02	2.38E+02	2.81E+02
1.15E-07	1.61E+02	1.61E+02	1.65E+02	1.59E+02	1.94E+02	1.38E+02	1.52E+02
2.55E-07	8.49E+01	8.48E+01	8.64E+01	8.45E+01	1.04E+02	7.94E+01	8.23E+01
5.50E-07	4.38E+01	4.37E+01	4.40E+01	4.35E+01	5.20E+01	4.39E+01	4.29E+01
1.28E-06	2.18E+01	2.17E+01	2.17E+01	2.17E+01	2.41E+01	2.30E+01	2.12E+01
2.80E-06	1.10E+01	1.09E+01	1.11E+01	1.09E+01	1.10E+01	1.20E+01	1.04E+01
6.30E-06	5.08E+00	5.06E+00	5.14E+00	4.96E+00	4.65E+00	5.92E+00	4.83E+00
1.35E-05	1.80E+00	1.79E+00	1.71E+00	1.58E+00	1.70E+00	2.67E+00	1.97E+00
3.00E-05	4.51E-01	4.41E-01	3.49E-01	3.09E-01	5.11E-01	1.05E+00	6.75E-01
6.90E-05	1.35E-01	1.30E-01	8.54E-02	7.24E-02	1.78E-01	4.72E-01	2.71E-01
1.00E-04	7.68E-02	7.19E-02	3.82E-02	3.10E-02	9.49E-02	2.06E-01	1.21E-01
2.80E-04	5.12E-02	4.66E-02	1.38E-02	1.06E-02	5.60E-02	3.94E-02	2.83E-02
5.75E-04	3.69E-02	3.26E-02	6.23E-03	4.65E-03	3.52E-02	1.08E-02	9.31E-03
1.28E-03	2.78E-02	2.39E-02	2.97E-03	2.16E-03	2.41E-02	3.11E-03	3.28E-03
2.00E-03	2.24E-02	1.87E-02	1.77E-03	1.27E-03	1.90E-02	1.43E-03	1.93E-03
3.40E-03	1.76E-02	1.43E-02	1.01E-03	7.12E-04	1.64E-02	8.02E-04	1.55E-03
5.50E-03	1.28E-02	1.01E-02	6.01E-04	4.70E-04	1.14E-02	7.11E-04	1.60E-03
9.20E-03	8.76E-03	6.68E-03	4.09E-04	4.16E-04	5.09E-03	9.70E-04	1.85E-03
1.20E-02	4.49E-03	3.30E-03	8.67E-04	8.32E-04	2.27E-03	1.59E-03	2.92E-03
5.25E-02	1.90E-03	1.35E-03	1.42E-03	1.43E-03	1.55E-03	2.61E-03	3.86E-03
1.00E-01	2.02E-03	1.43E-03	1.65E-03	1.68E-03	2.23E-03	3.05E-03	3.34E-03
2.00E-01	1.73E-03	1.28E-03	1.70E-03	1.54E-03	1.88E-03	2.41E-03	2.23E-03
5.00E-01	1.63E-03	1.29E-03	1.50E-03	1.31E-03	1.51E-03	1.76E-03	1.51E-03
1.00E+00	1.22E-03	1.02E-03	1.22E-03	1.13E-03	1.21E-03	1.32E-03	1.08E-03
2.00E+00	8.86E-04	7.76E-04	9.28E-04	8.16E-04	7.88E-04	8.15E-04	6.91E-04
3.00E+00	1.00E-03	9.10E-04	8.29E-04	6.15E-04	5.57E-04	5.13E-04	4.94E-04
4.00E+00	9.49E-04	8.92E-04	7.33E-04	4.84E-04	4.40E-04	3.77E-04	3.80E-04
5.00E+00	7.52E-04	7.29E-04	6.10E-04	3.74E-04	3.21E-04	2.81E-04	2.98E-04
6.00E+00	5.36E-04	5.35E-04	5.30E-04	2.97E-04	2.38E-04	2.12E-04	2.42E-04
7.00E+00	4.17E-04	4.28E-04	4.35E-04	2.33E-04	1.85E-04	1.64E-04	1.97E-04
8.00E+00	2.95E-04	3.10E-04	3.49E-04	2.09E-04	1.43E-04	1.25E-04	1.59E-04
9.00E+00	3.09E-04	3.33E-04	2.82E-04	1.94E-04	1.38E-04	1.10E-04	1.25E-04
1.00E+01	3.49E-04	3.83E-04	2.27E-04	1.57E-04	1.22E-04	9.05E-05	1.14E-04

Table 8: Neutron Fluxes for 113 MeV p + Al, Cont.

Lower Energy (MeV)	0°	7.5°	30°	60°	90°	120°	150°
1.10E+01	2.99E-04	3.33E-04	2.12E-04	1.35E-04	8.72E-05	6.62E-05	8.57E-05
1.20E+01	2.45E-04	2.74E-04	2.00E-04	1.28E-04	7.46E-05	5.42E-05	6.53E-05
1.30E+01	2.12E-04	2.34E-04	1.66E-04	1.02E-04	5.60E-05	4.04E-05	4.91E-05
1.40E+01	1.36E-04	1.47E-04	1.72E-04	7.72E-05	4.51E-05	3.32E-05	2.99E-05
1.50E+01	1.47E-04	1.54E-04	1.95E-04	7.76E-05	4.52E-05	3.38E-05	2.74E-05
1.60E+01	2.97E-04	3.01E-04	1.90E-04	8.68E-05	3.88E-05	3.06E-05	2.84E-05
1.70E+01	4.38E-04	4.31E-04	2.05E-04	9.57E-05	4.88E-05	3.63E-05	2.92E-05
1.80E+01	5.19E-04	5.01E-04	2.19E-04	1.02E-04	5.77E-05	3.97E-05	2.96E-05
1.90E+01	4.74E-04	4.50E-04	2.30E-04	1.03E-04	6.08E-05	3.86E-05	2.92E-05
2.00E+01	3.40E-04	3.19E-04	2.24E-04	9.44E-05	5.38E-05	3.11E-05	2.66E-05
2.40E+01	2.28E-04	2.12E-04	1.98E-04	7.75E-05	4.13E-05	2.14E-05	2.14E-05
2.80E+01	2.78E-04	2.58E-04	1.77E-04	6.20E-05	2.74E-05	1.37E-05	1.39E-05
3.20E+01	3.29E-04	3.06E-04	1.56E-04	4.89E-05	1.49E-05	7.76E-06	7.36E-06
3.60E+01	2.75E-04	2.58E-04	1.26E-04	3.96E-05	1.04E-05	5.30E-06	4.28E-06
4.00E+01	1.97E-04	1.86E-04	1.05E-04	3.55E-05	7.09E-06	4.37E-06	2.94E-06
4.40E+01	1.58E-04	1.52E-04	9.20E-05	3.26E-05	5.55E-06	3.97E-06	2.24E-06
4.80E+01	1.56E-04	1.53E-04	8.42E-05	2.85E-05	5.50E-06	3.69E-06	1.86E-06
5.20E+01	1.53E-04	1.55E-04	7.96E-05	2.50E-05	5.56E-06	3.27E-06	1.72E-06
5.60E+01	1.36E-04	1.43E-04	7.28E-05	2.19E-05	4.86E-06	2.56E-06	1.75E-06
6.00E+01	1.13E-04	1.24E-04	6.42E-05	1.81E-05	3.70E-06	1.77E-06	1.88E-06
6.40E+01	9.46E-05	1.08E-04	5.76E-05	1.41E-05	2.81E-06	1.19E-06	2.04E-06
6.80E+01	7.93E-05	9.25E-05	4.89E-05	9.84E-06	2.07E-06	8.12E-07	2.07E-06
7.20E+01	6.60E-05	7.64E-05	3.69E-05	5.48E-06	1.44E-06	5.76E-07	1.83E-06
7.60E+01	5.65E-05	6.26E-05	2.59E-05	2.63E-06	9.68E-07	3.91E-07	1.49E-06
8.00E+01	5.09E-05	5.23E-05	1.83E-05	1.27E-06	6.42E-07	2.29E-07	1.20E-06
8.40E+01	4.80E-05	4.50E-05	1.30E-05	6.15E-07	4.23E-07	9.86E-08	9.59E-07
8.80E+01	4.52E-05	3.87E-05	9.58E-06	3.23E-07	2.68E-07	2.09E-08	7.65E-07
9.20E+01	4.01E-05	3.20E-05	7.47E-06	2.06E-07	1.44E-07	0.00E+00	6.03E-07
9.60E+01	3.27E-05	2.49E-05	5.77E-06	1.39E-07	4.21E-08	0.00E+00	4.49E-07
1.00E+02	1.50E-05	1.14E-05	2.93E-06	6.22E-08	0.00E+00	0.00E+00	1.86E-07

Table 9: Neutron Fluxes for 113 MeV p + U
(Flux/proton-sr-MeV)

Lower Energy (MeV)	0°	7.5°	30°	60°	90°	120°	150°
1.00E-10	2.96E+03	1.72E+03	5.95E+04	2.89E+04	1.30E+04	9.18E+03	2.59E+04
1.00E-09	5.20E+03	3.45E+03	1.94E+04	1.24E+04	7.21E+03	5.27E+03	8.60E+03
1.00E-08	6.48E+03	5.32E+03	6.46E+03	6.38E+03	4.55E+03	3.42E+03	3.53E+03
2.30E-08	6.08E+03	6.89E+03	2.05E+03	4.64E+03	3.56E+03	2.66E+03	2.34E+03
5.00E-08	3.19E+03	5.77E+03	5.06E+02	3.05E+03	2.50E+03	1.82E+03	1.54E+03
1.15E-07	8.74E+02	2.86E+03	2.06E+02	1.74E+03	1.53E+03	1.05E+03	9.82E+02
2.55E-07	2.93E+02	1.42E+03	1.22E+02	9.93E+02	9.13E+02	6.34E+02	6.39E+02
5.50E-07	1.98E+02	6.87E+02	1.97E+02	5.53E+02	5.24E+02	4.00E+02	4.17E+02
1.28E-06	1.72E+02	3.14E+02	2.10E+02	3.03E+02	2.96E+02	2.66E+02	2.75E+02
2.80E-06	1.29E+02	1.35E+02	1.36E+02	1.35E+02	1.42E+02	1.57E+02	1.58E+02
6.30E-06	7.23E+01	5.02E+01	4.74E+01	3.61E+01	5.03E+01	6.58E+01	6.57E+01
1.35E-05	3.65E+01	1.89E+01	1.51E+01	1.04E+01	2.02E+01	2.83E+01	2.85E+01
3.00E-05	1.61E+01	6.97E+00	4.06E+00	2.92E+00	8.38E+00	1.13E+01	1.19E+01
6.90E-05	7.83E+00	3.12E+00	1.20E+00	9.78E-01	4.15E+00	5.13E+00	5.69E+00
1.00E-04	4.09E+00	1.66E+00	4.41E-01	4.17E-01	2.33E+00	2.61E+00	2.98E+00
2.80E-04	1.47E+00	6.55E-01	7.71E-02	9.16E-02	8.19E-01	7.79E-01	9.88E-01
5.75E-04	6.62E-01	3.30E-01	1.96E-02	2.82E-02	3.58E-01	2.96E-01	4.02E-01
1.28E-03	3.24E-01	1.79E-01	5.36E-03	9.18E-03	1.63E-01	1.17E-01	1.71E-01
2.00E-03	1.96E-01	1.18E-01	2.20E-03	4.22E-03	9.32E-02	6.05E-02	8.97E-02
3.40E-03	1.15E-01	7.42E-02	8.78E-04	1.86E-03	5.03E-02	2.98E-02	4.45E-02
5.50E-03	6.96E-02	4.69E-02	8.00E-04	1.39E-03	2.62E-02	1.80E-02	2.84E-02
9.20E-03	4.65E-02	3.22E-02	1.81E-03	2.17E-03	1.35E-02	1.57E-02	2.69E-02
1.20E-02	3.02E-02	2.14E-02	6.40E-03	4.95E-03	8.82E-03	2.25E-02	4.38E-02
5.25E-02	2.41E-02	1.74E-02	1.47E-02	1.01E-02	7.77E-03	3.34E-02	6.24E-02
1.00E-01	3.51E-02	2.59E-02	2.27E-02	1.57E-02	9.89E-03	4.07E-02	6.28E-02
2.00E-01	3.74E-02	2.84E-02	2.87E-02	2.05E-02	1.46E-02	4.65E-02	5.49E-02
5.00E-01	2.91E-02	2.30E-02	2.83E-02	2.13E-02	1.63E-02	4.32E-02	4.11E-02
1.00E+00	1.89E-02	1.56E-02	1.92E-02	1.44E-02	1.11E-02	2.73E-02	2.34E-02
2.00E+00	9.97E-03	8.72E-03	1.01E-02	7.05E-03	5.58E-03	1.29E-02	1.12E-02
3.00E+00	5.18E-03	4.80E-03	5.81E-03	4.15E-03	3.08E-03	6.64E-03	6.05E-03
4.00E+00	2.74E-03	2.70E-03	3.45E-03	2.37E-03	1.81E-03	3.52E-03	3.59E-03
5.00E+00	1.77E-03	1.85E-03	2.13E-03	1.37E-03	1.03E-03	1.81E-03	2.17E-03
6.00E+00	2.82E-03	3.10E-03	1.40E-03	8.07E-04	5.98E-04	9.61E-04	1.42E-03
7.00E+00	1.79E-03	2.05E-03	9.42E-04	5.51E-04	4.35E-04	7.34E-04	8.21E-04
8.00E+00	5.30E-04	6.15E-04	6.98E-04	4.21E-04	3.28E-04	7.98E-04	4.46E-04
9.00E+00	6.74E-04	7.60E-04	5.14E-04	2.78E-04	1.77E-04	4.58E-04	3.11E-04
1.00E+01	4.38E-04	4.57E-04	3.89E-04	1.68E-04	1.25E-04	1.24E-04	2.33E-04

Table 9: Neutron Fluxes for 113 MeV p + U, Cont.

Lower Energy (MeV)	0°	7.5°	30°	60°	90°	120°	150°
1.10E+01	1.91E-04	1.79E-04	2.63E-04	1.13E-04	1.07E-04	1.08E-04	1.32E-04
1.20E+01	2.00E-04	1.72E-04	1.85E-04	1.73E-04	7.07E-05	8.62E-05	6.46E-05
1.30E+01	2.10E-04	1.73E-04	1.35E-04	1.40E-04	5.47E-05	8.04E-05	6.52E-05
1.40E+01	1.89E-04	1.57E-04	1.19E-04	5.65E-05	4.34E-05	7.79E-05	6.68E-05
1.50E+01	1.41E-04	1.20E-04	1.31E-04	5.11E-05	3.31E-05	6.56E-05	4.68E-05
1.60E+01	1.07E-04	9.55E-05	1.46E-04	5.77E-05	4.11E-05	6.71E-05	5.04E-05
1.70E+01	2.16E-04	2.02E-04	1.73E-04	6.85E-05	5.31E-05	6.69E-05	5.23E-05
1.80E+01	3.08E-04	3.01E-04	2.03E-04	8.00E-05	6.12E-05	6.19E-05	5.28E-05
1.90E+01	3.15E-04	3.20E-04	2.25E-04	9.09E-05	5.97E-05	5.17E-05	5.05E-05
2.00E+01	2.75E-04	2.87E-04	2.22E-04	9.12E-05	4.71E-05	3.56E-05	4.10E-05
2.40E+01	2.41E-04	2.57E-04	1.94E-04	7.39E-05	3.36E-05	2.29E-05	2.94E-05
2.80E+01	1.97E-04	2.13E-04	1.51E-04	5.08E-05	2.74E-05	2.40E-05	2.18E-05
3.20E+01	1.44E-04	1.55E-04	1.13E-04	3.52E-05	1.84E-05	1.91E-05	1.15E-05
3.60E+01	1.23E-04	1.32E-04	8.74E-05	2.66E-05	9.72E-06	8.59E-06	4.77E-06
4.00E+01	1.17E-04	1.24E-04	6.10E-05	2.09E-05	5.76E-06	3.95E-06	3.83E-06
4.40E+01	1.08E-04	1.12E-04	4.08E-05	1.76E-05	4.46E-06	2.16E-06	4.34E-06
4.80E+01	9.35E-05	9.46E-05	3.20E-05	1.60E-05	4.67E-06	1.46E-06	4.45E-06
5.20E+01	7.84E-05	7.76E-05	3.31E-05	1.45E-05	4.86E-06	1.10E-06	4.03E-06
5.60E+01	6.45E-05	6.26E-05	3.93E-05	1.15E-05	3.97E-06	8.38E-07	3.27E-06
6.00E+01	5.30E-05	5.08E-05	4.64E-05	7.86E-06	2.57E-06	6.35E-07	2.42E-06
6.40E+01	4.46E-05	4.26E-05	5.18E-05	5.40E-06	1.65E-06	4.86E-07	1.70E-06
6.80E+01	3.89E-05	3.73E-05	5.11E-05	3.93E-06	1.17E-06	4.01E-07	1.21E-06
7.20E+01	3.52E-05	3.41E-05	4.22E-05	3.29E-06	1.05E-06	3.90E-07	9.59E-07
7.60E+01	3.32E-05	3.25E-05	3.13E-05	2.94E-06	1.06E-06	4.07E-07	8.56E-07
8.00E+01	3.24E-05	3.22E-05	2.27E-05	2.61E-06	1.05E-06	4.21E-07	8.33E-07
8.40E+01	3.27E-05	3.30E-05	1.63E-05	2.30E-06	1.04E-06	4.30E-07	8.49E-07
8.80E+01	3.27E-05	3.34E-05	1.19E-05	1.97E-06	9.61E-07	4.35E-07	8.65E-07
9.20E+01	3.05E-05	3.15E-05	9.07E-06	1.58E-06	7.88E-07	4.35E-07	8.55E-07
9.60E+01	2.63E-05	2.74E-05	6.75E-06	1.17E-06	5.75E-07	4.29E-07	8.08E-07
1.00E+02	1.50E-05	1.57E-05	3.27E-06	5.62E-07	2.68E-07	2.50E-07	4.54E-07
1.10E+02	2.75E-06	2.88E-06	5.07E-07	8.58E-08	3.90E-08	4.00E-08	7.03E-08

Table 10: Neutron Fluxes for 256 MeV p + Al
(Flux/proton-sr-MeV)

Lower Energy (MeV)	0°	7.5°	30°	60°	90°	120°	150°
1.00E-10	3.84E+04	4.04E+04	5.50E+04	5.35E+04	4.28E+04	2.68E+04	2.11E+04
1.00E-09	1.42E+04	1.42E+04	1.90E+04	1.86E+04	1.63E+04	1.13E+04	9.13E+03
1.00E-08	6.62E+03	6.13E+03	8.04E+03	7.86E+03	7.63E+03	5.74E+03	4.66E+03
2.30E-08	4.36E+03	3.72E+03	4.67E+03	4.53E+03	4.83E+03	3.93E+03	3.49E+03
5.00E-08	2.53E+03	2.03E+03	2.34E+03	2.23E+03	2.55E+03	2.28E+03	2.24E+03
1.15E-07	1.45E+03	1.14E+03	1.21E+03	1.13E+03	1.33E+03	1.25E+03	1.33E+03
2.55E-07	8.51E+02	6.88E+02	6.92E+02	6.45E+02	7.31E+02	7.09E+02	7.69E+02
5.50E-07	4.88E+02	4.20E+02	4.05E+02	3.82E+02	4.08E+02	4.04E+02	4.29E+02
1.28E-06	2.46E+02	2.29E+02	2.30E+02	2.20E+02	2.23E+02	2.29E+02	2.31E+02
2.80E-06	1.05E+02	1.05E+02	1.06E+02	1.03E+02	1.01E+02	1.16E+02	1.13E+02
6.30E-06	4.21E+01	4.60E+01	2.71E+01	2.67E+01	2.58E+01	4.21E+01	4.30E+01
1.35E-05	1.67E+01	1.97E+01	7.01E+00	6.94E+00	6.77E+00	1.57E+01	1.72E+01
3.00E-05	6.31E+00	7.85E+00	1.64E+00	1.61E+00	1.62E+00	5.45E+00	6.62E+00
6.90E-05	2.78E+00	3.59E+00	4.40E-01	4.28E-01	4.47E-01	2.18E+00	2.96E+00
1.00E-04	1.41E+00	1.82E+00	1.62E-01	1.55E-01	1.69E-01	1.02E+00	1.50E+00
2.80E-04	5.31E-01	6.56E-01	3.00E-02	2.78E-02	3.17E-02	2.76E-01	4.72E-01
5.75E-04	2.57E-01	3.01E-01	1.19E-02	1.01E-02	1.35E-02	9.82E-02	1.88E-01
1.28E-03	1.36E-01	1.51E-01	6.09E-03	3.84E-03	8.64E-03	3.70E-02	7.86E-02
2.00E-03	8.76E-02	9.33E-02	5.06E-03	2.57E-03	6.90E-03	1.86E-02	4.18E-02
3.40E-03	5.38E-02	5.54E-02	6.05E-03	3.07E-03	5.27E-03	8.94E-03	2.13E-02
5.50E-03	3.30E-02	3.31E-02	7.92E-03	3.57E-03	3.88E-03	4.82E-03	1.08E-02
9.20E-03	2.16E-02	2.12E-02	9.71E-03	3.44E-03	2.89E-03	3.30E-03	5.53E-03
1.20E-02	1.30E-02	1.25E-02	8.91E-03	6.07E-03	6.49E-03	5.95E-03	7.19E-03
5.25E-02	1.27E-02	1.20E-02	6.87E-03	8.76E-03	1.09E-02	1.03E-02	1.28E-02
1.00E-01	1.30E-02	1.20E-02	6.03E-03	8.42E-03	1.13E-02	1.15E-02	1.49E-02
2.00E-01	6.49E-03	5.94E-03	5.13E-03	7.44E-03	9.64E-03	9.78E-03	1.17E-02
5.00E-01	4.64E-03	4.24E-03	4.80E-03	6.52E-03	7.86E-03	7.84E-03	8.74E-03
1.00E+00	4.55E-03	4.18E-03	4.32E-03	5.19E-03	6.49E-03	6.18E-03	6.49E-03
2.00E+00	3.80E-03	3.54E-03	3.20E-03	3.57E-03	4.63E-03	4.25E-03	4.11E-03
3.00E+00	2.12E-03	2.00E-03	2.50E-03	2.79E-03	3.38E-03	3.11E-03	2.99E-03
4.00E+00	1.64E-03	1.57E-03	1.95E-03	2.26E-03	2.44E-03	2.16E-03	2.13E-03
5.00E+00	1.65E-03	1.60E-03	1.58E-03	1.79E-03	1.78E-03	1.50E-03	1.42E-03
6.00E+00	1.05E-03	1.03E-03	1.32E-03	1.41E-03	1.39E-03	1.19E-03	1.09E-03
7.00E+00	1.11E-03	1.08E-03	1.07E-03	1.26E-03	1.05E-03	9.18E-04	8.05E-04
8.00E+00	1.47E-03	1.43E-03	8.73E-04	1.08E-03	8.45E-04	7.31E-04	5.78E-04
9.00E+00	1.79E-03	1.73E-03	7.27E-04	8.45E-04	6.80E-04	5.85E-04	4.45E-04
1.00E+01	1.19E-03	1.14E-03	5.95E-04	6.37E-04	4.92E-04	4.47E-04	3.72E-04

Table 10: Neutron Fluxes for 256 MeV p + Al, Cont.
(Flux/proton-sr-MeV)

Lower Energy (MeV)	0°	7.5°	30°	60°	90°	120°	150°
1.10E+01	3.96E-04	3.79E-04	5.85E-04	5.02E-04	3.42E-04	3.35E-04	2.91E-04
1.20E+01	6.04E-04	5.81E-04	6.86E-04	4.59E-04	2.85E-04	2.95E-04	1.92E-04
1.30E+01	8.41E-04	8.12E-04	7.32E-04	4.60E-04	2.44E-04	2.54E-04	1.68E-04
1.40E+01	9.95E-04	9.67E-04	6.56E-04	4.61E-04	2.13E-04	2.17E-04	2.05E-04
1.50E+01	9.28E-04	9.06E-04	6.60E-04	4.58E-04	2.42E-04	2.19E-04	1.98E-04
1.60E+01	7.11E-04	6.95E-04	7.14E-04	4.65E-04	2.84E-04	2.13E-04	1.59E-04
1.70E+01	9.85E-04	9.60E-04	6.66E-04	4.92E-04	3.09E-04	2.02E-04	1.45E-04
1.80E+01	1.19E-03	1.15E-03	6.60E-04	5.12E-04	3.33E-04	1.96E-04	1.43E-04
1.90E+01	1.21E-03	1.16E-03	7.12E-04	5.14E-04	3.50E-04	1.92E-04	1.58E-04
2.00E+01	1.04E-03	9.89E-04	7.81E-04	4.83E-04	3.22E-04	1.69E-04	1.36E-04
2.40E+01	7.77E-04	7.34E-04	7.53E-04	4.34E-04	2.50E-04	1.27E-04	6.93E-05
2.80E+01	7.62E-04	7.15E-04	6.62E-04	3.82E-04	1.91E-04	9.29E-05	3.18E-05
3.20E+01	8.44E-04	7.90E-04	5.83E-04	3.25E-04	1.53E-04	7.03E-05	3.28E-05
3.60E+01	8.29E-04	7.75E-04	5.09E-04	2.80E-04	1.21E-04	5.34E-05	3.43E-05
4.00E+01	8.21E-04	7.71E-04	4.82E-04	2.43E-04	9.45E-05	3.97E-05	2.47E-05
4.40E+01	7.74E-04	7.33E-04	4.76E-04	2.18E-04	7.94E-05	3.01E-05	1.44E-05
4.80E+01	6.73E-04	6.45E-04	4.73E-04	2.04E-04	7.54E-05	2.36E-05	8.23E-06
5.20E+01	5.90E-04	5.74E-04	4.71E-04	1.94E-04	7.47E-05	1.90E-05	5.22E-06
5.60E+01	5.74E-04	5.69E-04	4.68E-04	1.80E-04	7.00E-05	1.52E-05	3.75E-06
6.00E+01	5.98E-04	6.05E-04	4.59E-04	1.64E-04	6.17E-05	1.20E-05	2.95E-06
6.40E+01	6.09E-04	6.30E-04	4.40E-04	1.51E-04	5.43E-05	9.61E-06	2.50E-06
6.80E+01	6.05E-04	6.40E-04	4.17E-04	1.39E-04	4.66E-05	7.88E-06	2.26E-06
7.20E+01	5.83E-04	6.32E-04	3.94E-04	1.28E-04	3.78E-05	6.66E-06	2.30E-06
7.60E+01	5.52E-04	6.10E-04	3.70E-04	1.19E-04	2.97E-05	5.86E-06	2.43E-06
8.00E+01	5.17E-04	5.79E-04	3.44E-04	1.12E-04	2.32E-05	5.35E-06	2.52E-06
8.40E+01	4.80E-04	5.42E-04	3.17E-04	1.07E-04	1.82E-05	5.01E-06	2.57E-06
8.80E+01	4.37E-04	4.93E-04	2.85E-04	1.00E-04	1.47E-05	4.76E-06	2.51E-06
9.20E+01	3.86E-04	4.30E-04	2.46E-04	9.19E-05	1.27E-05	4.58E-06	2.29E-06
9.60E+01	3.35E-04	3.64E-04	2.06E-04	8.29E-05	1.14E-05	4.39E-06	2.00E-06
1.00E+02	2.81E-04	2.95E-04	1.64E-04	6.93E-05	9.67E-06	3.83E-06	1.58E-06
1.10E+02	2.27E-04	2.27E-04	1.27E-04	5.12E-05	6.90E-06	2.98E-06	1.13E-06
1.20E+02	1.82E-04	1.70E-04	1.00E-04	3.62E-05	4.13E-06	2.28E-06	8.36E-07
1.30E+02	1.46E-04	1.26E-04	7.92E-05	2.53E-05	2.41E-06	1.69E-06	6.40E-07
1.40E+02	1.21E-04	9.47E-05	6.15E-05	1.68E-05	1.46E-06	1.13E-06	5.35E-07
1.50E+02	1.03E-04	7.26E-05	4.97E-05	1.07E-05	9.10E-07	6.91E-07	4.78E-07
1.60E+02	8.96E-05	5.75E-05	4.49E-05	6.94E-06	5.85E-07	4.29E-07	4.22E-07
1.70E+02	8.09E-05	5.14E-05	4.18E-05	4.25E-06	3.82E-07	2.57E-07	3.40E-07
1.80E+02	7.67E-05	4.90E-05	3.58E-05	2.18E-06	2.49E-07	1.37E-07	2.25E-07
1.90E+02	7.79E-05	5.14E-05	2.90E-05	1.00E-06	1.65E-07	6.79E-08	1.32E-07
2.00E+02	8.18E-05	5.94E-05	2.07E-05	4.04E-07	9.86E-08	2.98E-08	6.90E-08
2.20E+02	6.34E-05	5.05E-05	1.06E-05	1.05E-07	4.34E-08	8.99E-09	2.62E-08
2.40E+02	2.13E-05	1.83E-05	3.03E-06	2.35E-08	1.09E-08	2.04E-09	5.98E-09
2.60E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 11: Neutron Fluxes for 256 MeV p + U
(Flux/proton-sr-MeV)

Lower Energy (MeV)	0°	7.5°	30°	60°	90°	120°	150°
1.00E-10	2.30E+05	1.98E+05	2.67E+05	1.63E+05	1.38E+05	2.18E+05	3.46E+04
1.00E-09	5.19E+04	5.60E+04	6.89E+04	6.18E+04	5.74E+04	7.25E+04	2.15E+04
1.00E-08	1.52E+04	1.90E+04	2.21E+04	2.55E+04	2.55E+04	2.75E+04	1.58E+04
2.30E-08	9.38E+03	1.25E+04	1.35E+04	1.83E+04	1.93E+04	1.37E+04	1.47E+04
5.00E-08	5.83E+03	7.76E+03	7.83E+03	1.19E+04	1.29E+04	5.94E+03	1.32E+04
1.15E-07	3.65E+03	4.60E+03	4.39E+03	7.16E+03	7.85E+03	2.90E+03	1.11E+04
2.55E-07	2.41E+03	2.81E+03	2.62E+03	4.25E+03	4.61E+03	2.06E+03	8.83E+03
5.50E-07	1.60E+03	1.72E+03	1.70E+03	2.48E+03	2.61E+03	1.88E+03	6.58E+03
1.28E-06	9.34E+02	9.53E+02	9.86E+02	1.21E+03	1.24E+03	1.30E+03	2.99E+03
2.80E-06	4.52E+02	4.51E+02	4.25E+02	4.35E+02	4.36E+02	4.21E+02	4.19E+02
6.30E-06	2.03E+02	2.06E+02	1.69E+02	1.54E+02	1.57E+02	1.18E+02	5.64E+01
1.35E-05	8.95E+01	9.59E+01	6.54E+01	5.78E+01	6.06E+01	3.17E+01	8.75E+00
3.00E-05	3.81E+01	4.37E+01	2.37E+01	2.11E+01	2.26E+01	7.36E+00	1.30E+00
6.90E-05	1.89E+01	2.28E+01	1.01E+01	9.05E+00	9.75E+00	1.89E+00	2.29E-01
1.00E-04	1.00E+01	1.21E+01	4.84E+00	4.33E+00	4.73E+00	6.67E-01	7.37E-02
2.80E-04	3.77E+00	4.33E+00	1.47E+00	1.23E+00	1.35E+00	9.99E-02	9.24E-03
5.75E-04	1.69E+00	1.80E+00	5.69E-01	4.45E-01	4.97E-01	2.28E-02	6.96E-03
1.28E-03	8.30E-01	8.19E-01	2.39E-01	1.74E-01	1.97E-01	4.85E-03	9.08E-03
2.00E-03	5.06E-01	4.77E-01	1.31E-01	9.12E-02	1.04E-01	3.07E-03	1.20E-02
3.40E-03	3.08E-01	2.88E-01	7.03E-02	4.72E-02	5.36E-02	5.98E-03	1.43E-02
5.50E-03	1.93E-01	1.82E-01	3.91E-02	2.55E-02	2.86E-02	1.22E-02	2.17E-02
9.20E-03	1.31E-01	1.25E-01	2.39E-02	1.51E-02	1.67E-02	1.86E-02	3.58E-02
1.20E-02	8.03E-02	7.69E-02	3.39E-02	2.16E-02	2.21E-02	4.01E-02	8.13E-02
5.25E-02	6.30E-02	6.06E-02	5.70E-02	3.73E-02	3.53E-02	7.49E-02	1.42E-01
1.00E-01	8.73E-02	8.48E-02	7.20E-02	4.79E-02	4.53E-02	9.91E-02	1.65E-01
2.00E-01	9.60E-02	9.52E-02	8.85E-02	6.08E-02	6.01E-02	1.19E-01	1.72E-01
5.00E-01	8.66E-02	8.85E-02	9.11E-02	6.52E-02	6.57E-02	1.15E-01	1.50E-01
1.00E+00	5.56E-02	5.89E-02	6.26E-02	4.68E-02	4.73E-02	7.43E-02	9.24E-02
2.00E+00	3.02E-02	3.28E-02	3.60E-02	2.69E-02	2.71E-02	3.91E-02	4.80E-02
3.00E+00	2.01E-02	2.20E-02	2.39E-02	1.76E-02	1.78E-02	2.39E-02	2.83E-02
4.00E+00	1.34E-02	1.47E-02	1.46E-02	1.17E-02	1.12E-02	1.43E-02	1.75E-02
5.00E+00	9.61E-03	1.03E-02	8.71E-03	7.38E-03	7.01E-03	8.76E-03	1.08E-02
6.00E+00	6.32E-03	6.55E-03	5.53E-03	4.56E-03	4.86E-03	5.79E-03	6.76E-03
7.00E+00	3.87E-03	3.90E-03	3.66E-03	2.91E-03	2.97E-03	3.57E-03	4.38E-03
8.00E+00	2.49E-03	2.46E-03	2.58E-03	2.00E-03	1.77E-03	2.21E-03	2.80E-03
9.00E+00	2.03E-03	2.00E-03	1.77E-03	1.32E-03	1.18E-03	1.49E-03	1.81E-03
1.00E+01	1.68E-03	1.67E-03	1.32E-03	9.26E-04	8.24E-04	1.02E-03	1.14E-03

Table 11: Neutron Fluxes for 256 MeV p + U, Cont.
(Flux/proton-sr-MeV)

Lower Energy (MeV)	0°	7.5°	30°	60°	90°	120°	150°
1.10E+01	1.26E-03	1.27E-03	1.10E-03	7.48E-04	6.41E-04	7.59E-04	7.85E-04
1.20E+01	8.87E-04	8.95E-04	8.93E-04	6.01E-04	5.36E-04	6.01E-04	6.49E-04
1.30E+01	6.04E-04	6.06E-04	8.10E-04	4.70E-04	4.33E-04	4.62E-04	4.90E-04
1.40E+01	6.41E-04	6.35E-04	7.44E-04	4.67E-04	3.76E-04	3.83E-04	3.95E-04
1.50E+01	8.42E-04	8.27E-04	6.59E-04	4.86E-04	3.87E-04	3.63E-04	3.73E-04
1.60E+01	9.05E-04	8.92E-04	6.74E-04	4.42E-04	3.72E-04	3.29E-04	2.92E-04
1.70E+01	9.35E-04	9.31E-04	6.87E-04	4.16E-04	3.28E-04	2.99E-04	2.76E-04
1.80E+01	9.59E-04	9.64E-04	7.05E-04	4.13E-04	3.13E-04	2.82E-04	2.72E-04
1.90E+01	9.71E-04	9.80E-04	7.24E-04	4.33E-04	3.24E-04	2.75E-04	2.78E-04
2.00E+01	8.78E-04	8.80E-04	6.94E-04	4.34E-04	3.05E-04	2.42E-04	2.36E-04
2.40E+01	7.03E-04	6.96E-04	6.02E-04	3.79E-04	2.34E-04	1.78E-04	1.47E-04
2.80E+01	6.34E-04	6.20E-04	5.17E-04	2.99E-04	1.67E-04	1.27E-04	9.86E-05
3.20E+01	5.87E-04	5.69E-04	4.62E-04	2.32E-04	1.25E-04	9.18E-05	6.94E-05
3.60E+01	5.29E-04	5.13E-04	4.16E-04	1.86E-04	9.74E-05	6.43E-05	3.92E-05
4.00E+01	5.33E-04	5.20E-04	3.67E-04	1.67E-04	8.46E-05	4.49E-05	2.23E-05
4.40E+01	4.85E-04	4.78E-04	3.21E-04	1.56E-04	7.87E-05	3.16E-05	1.51E-05
4.80E+01	3.70E-04	3.69E-04	2.81E-04	1.44E-04	7.35E-05	2.28E-05	1.31E-05
5.20E+01	2.85E-04	2.87E-04	2.49E-04	1.32E-04	6.69E-05	1.78E-05	1.22E-05
5.60E+01	2.65E-04	2.70E-04	2.22E-04	1.18E-04	5.83E-05	1.42E-05	1.06E-05
6.00E+01	2.82E-04	2.90E-04	1.99E-04	1.03E-04	4.92E-05	1.13E-05	8.82E-06
6.40E+01	2.99E-04	3.10E-04	1.79E-04	8.94E-05	4.11E-05	9.32E-06	7.60E-06
6.80E+01	3.03E-04	3.16E-04	1.64E-04	7.65E-05	3.39E-05	8.13E-06	6.90E-06
7.20E+01	2.83E-04	2.98E-04	1.53E-04	6.47E-05	2.75E-05	7.96E-06	6.75E-06
7.60E+01	2.57E-04	2.71E-04	1.47E-04	5.56E-05	2.23E-05	8.13E-06	6.77E-06
8.00E+01	2.35E-04	2.48E-04	1.44E-04	4.93E-05	1.86E-05	8.09E-06	6.64E-06
8.40E+01	2.18E-04	2.29E-04	1.45E-04	4.51E-05	1.58E-05	7.89E-06	6.39E-06
8.80E+01	2.05E-04	2.14E-04	1.46E-04	4.21E-05	1.33E-05	7.57E-06	6.07E-06
9.20E+01	1.96E-04	2.04E-04	1.46E-04	3.96E-05	1.09E-05	7.19E-06	5.74E-06
9.60E+01	1.88E-04	1.95E-04	1.42E-04	3.76E-05	8.71E-06	6.79E-06	5.41E-06
1.00E+02	1.78E-04	1.83E-04	1.31E-04	3.36E-05	6.08E-06	6.22E-06	4.93E-06
1.10E+02	1.67E-04	1.68E-04	1.14E-04	2.68E-05	3.31E-06	4.69E-06	4.22E-06
1.20E+02	1.55E-04	1.52E-04	9.52E-05	2.03E-05	1.63E-06	2.72E-06	3.22E-06
1.30E+02	1.47E-04	1.39E-04	7.72E-05	1.49E-05	8.21E-07	1.54E-06	2.07E-06
1.40E+02	1.41E-04	1.30E-04	5.97E-05	9.92E-06	4.55E-07	1.03E-06	1.07E-06
1.50E+02	1.37E-04	1.24E-04	4.48E-05	5.99E-06	2.78E-07	8.00E-07	4.59E-07
1.60E+02	1.33E-04	1.19E-04	3.47E-05	3.69E-06	1.77E-07	6.31E-07	2.03E-07
1.70E+02	1.28E-04	1.14E-04	2.59E-05	2.21E-06	1.14E-07	4.79E-07	9.91E-08
1.80E+02	1.20E-04	1.07E-04	1.73E-05	1.19E-06	7.21E-08	3.27E-07	5.71E-08
1.90E+02	1.13E-04	1.01E-04	1.10E-05	6.04E-07	4.56E-08	2.11E-07	3.90E-08
2.00E+02	1.05E-04	9.48E-05	6.42E-06	2.69E-07	2.57E-08	1.22E-07	2.64E-08
2.20E+02	7.10E-05	6.56E-05	2.69E-06	8.08E-08	1.05E-08	5.14E-08	1.33E-08
2.40E+02	2.08E-05	1.97E-05	7.32E-07	1.86E-08	2.60E-09	1.27E-08	3.85E-09
2.60E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 12: Broad-Group STAY'SL Results for P + U, 256 MEV, 30⁰

LOWER ENERGY (MeV)	FLUX ^a (n/cm ² -s)	FLUX (n/sr-p)	Std. Dev. (%)
TOTAL	5.839E+09	2.937E-01	+/- 15.83
1.000E-10	6.777E+07	3.409E-03	+/- 40.27
5.500E-07	2.834E+08	1.426E-02	+/- 25.81
1.000E-01	1.577E+09	7.930E-02	+/- 38.80
1.000E+00	2.725E+09	1.371E-01	+/- 16.36
5.000E+00	4.422E+08	2.224E-02	+/- 17.36
1.000E+01	1.652E+08	8.310E-03	+/- 7.81
2.000E+01	2.140E+08	1.076E-02	+/- 15.34
4.000E+01	2.388E+08	1.201E-02	+/- 13.98
1.000E+02	1.216E+08	6.114E-03	+/- 20.37
2.000E+02	3.914E+06	1.969E-04	+/- 67.91
2.560E+02			

RELATIVE COVARIANCE MATRIX (10X10)^b

1000	-67	21	13	-1	15	-2	4	1	0
1000	367	66	-3	22	-5	7	0	2	
1000	486	-87	3	12	10	-3	2		
1000	-410	157	-6	2	8	0			
1000	-417	-43	-29	7	0				
1000	-361	76	-14	7					
1000	-432	96	-21						
1000	-675	183							
1000	-292								
1000									

^aNeutron flux at 22 cm for 1 A beam current^bRelative covariances between 10 groups listed above normalized 1000 on the diagonal; only half of matrix is shown since the matrix is symmetric. Negative values indicate anticorrelation.

Table 13 - Proton Activation Data
 ($\times 10^{-32}$ atom/atom-proton ($\pm\%$))

Angle,deg.	$^{56}\text{Fe}(\text{p,n})^{56}\text{Co}$	$^{65}\text{Cu}(\text{p,n})^{65}\text{Zn}$	$^{56}\text{Fe}(\text{p,n})^{56}\text{Co}$	$^{65}\text{Cu}(\text{p,n})^{65}\text{Zn}$
113 MeV	Uranium		Aluminum	
0	0.44 (15)	-	0.65 (10)	2.39 (13)
30	1.48 (6)	2.25 (19)	1.70 (4)	2.38 (13)
60	0.76 (10)	1.74 (19)	0.74 (12)	1.57 (20)
90	1.03 (10)	-	0.96 (4)	1.61 (15)
120	-	0.83 (25)	-	-
150	1.99 (6)	2.04 (11)	1.37 (5)	2.07 (10)
256 MeV	Uranium		Aluminum	
0	3.43 (9)	11.0 (7)	3.58 (5)	7.34 (12)
30	3.02 (6)	6.47 (12)	19.0 (3)	34.9 (4)
60	1.31 (7)	3.09 (20)	10.3 (3)	14.8 (10)
90	1.49 (7)	-	2.78 (6)	4.00 (11)
120	-	3.43 (18)	-	-
150	3.29 (3)	4.24 (15)	0.85 (6)	1.40 (13)

Fig 1. Layout of the Intense Pulsed Neutron Source Facility. Present experiments were conducted in the beam dump labelled Lethality Test Area D. The Neutral Particle Beam Test Stand Areas A and B are also shown as well as proposed areas C and E for neutron time-of-flight and lethality applications.

Fig. 2. Setup for foil irradiations at 113 MeV and for the uranium target at 256 MeV. Foil packets were suspended vertically above the target on a radius of 22 cm.

Fig. 3. Setup for foil irradiations at 256 MeV for the 20 cm long aluminum target. Foils were moved further back to a radius of 32 cm in this case.

Fig. 4. Angular dependence of measured activation rates for the aluminum target at 256 MeV. Note that thermal and low-energy reactions are nearly isotropic whereas high-threshold spallation products decline steeply with angle.

Fig. 5. Production cross sections for ^{58}Co and ^{57}Ni from ^{58}Ni ; ^{24}Na from ^{27}Al ; ^{52}Mn from Fe ; and ^{56}Co and ^{48}V from Cu . Note that each reaction peaks in a different energy region.

Fig. 6. The 90% energy sensitivity limits are shown for various reactions in the measured 30⁰ neutron spectrum from 256 MeV protons on U. Note the good, overlapping coverage across the entire spectrum.

Fig. 7. Adjusted neutron spectra from STAY'SL are shown as a function of angle for 113 MeV protons on a range-thick aluminum target.

Fig. 8. Adjusted neutron spectra from STAY'SL are shown as a function of angle for 113 MeV protons on a range-thick uranium target.

Fig. 9. Adjusted neutron spectra from STAY'SL are shown as a function of angle for 256 MeV protons on a range-thick aluminum target.

Fig. 10. Adjusted neutron spectra from STAY'SL are shown as a function of angle for 256 MeV protons on a range-thick uranium target.

Fig. 11. Sample of flux group uncertainty data from STAY'SL at 30° for 256 MeV protons on uranium. Note that the uncertainties are highly correlated so that broader-group uncertainties are much less than indicated.

Fig. 12. Comparison of neutron spectra measured at 30° and 150° at two distances from the target for 113 MeV protons on aluminum. The good agreement at 30° and below 40 MeV indicates that neutron scattering effects are not very significant.

Fig. 13. Comparison of neutron spectra measured at 30° and 150° at two distances from the target for 113 MeV protons on uranium.

Fig. 14. Comparison of neutron spectra measured at 30° and 150° at two distances from the target for 256 MeV protons on aluminum. Note that the back foils were at 133° rather than 150° in this case.

Fig. 15. Comparison of neutron spectra measured at 30° and 150° at two distances from the target for 256 MeV protons on uranium.

Fig. 16. Comparison of neutron spectra measured with foils and calculated by HETC at 30 and 120° for 113 MeV protons on aluminum.

Fig. 17. Comparison of neutron spectra measured with foils and calculated by HETC at 30 and 120° for 113 MeV protons on uranium.

Fig. 18. Comparison of neutron spectra measured with foils and calculated by HETC at 30 and 120° for 256 MeV protons on aluminum.

Fig. 19. Comparison of neutron spectra measured with foils and calculated by HETC at 30 and 120° for 256 MeV protons on uranium.

Fig. 20. Ratio of integral neutron fluxes measured with foils and calculated by HETC for 113 MeV protons on aluminum.

Fig. 21. Ratio of integral neutron fluxes measured with foils and calculated by HETC for 113 MeV protons on uranium.

Fig. 22. Ratio of integral neutron fluxes measured with foils and calculated by HETC for 256 MeV protons on aluminum.

Fig. 23. Ratio of integral neutron fluxes measured with foils and calculated by HETC for 256 MeV protons on uranium.

Distribution List for ANL/NPBTS-TR-023

Anthony Armstrong
SAIC
P. O. Box 2351
La Jolla, CA 82038

Ed Arthur
Los Alamos National Laboratory
MS B243
Los Alamos, NM 87545

George Auchampaugh
Los Alamos National Laboratory
P-DO, MS D408
Los Alamos, NM 87545

David Berwald
Grumman Aerospace Corp.
111 Stewart Ave.
Bethpage, NY 11714-3592

William Beyer
P7, MS B284
Los Alamos National Laboratory
Los Alamos, NM 87545

Robert C. Birtcher
Argonne National Laboratory
Materials Science Division, Bldg. 212
9700 S. Cass Ave.
Argonne, IL 60439

Mike Bozoian
Los Alamos National Laboratory
MS B243
Los Alamos, NM 87545

Scott Bradley
Kaman Sciences, Inc.
2560 Huntington Road
Alexandria, VA 22303

Bruce S. Brown
Argonne National Laboratory
PNS, Bldg. 360
9700 S. Cass Ave.
Argonne, IL 60439

Franklin R. Brumwell
Argonne National Laboratory
PNS, Bldg. 360
9700 S. Cass Ave.
Argonne, IL 60439

Melvin Buchwald
Los Alamos National Laboratory
P-DO, MS D408
Los Alamos, NM 87545

Al Bustamante
Sandia National Laboratories
Division 9142
P. O. Box 5800
Albuquerque, NM 87185

Roger Byrd
MS D456
Los Alamos National Laboratory
Los Alamos, NM 87545

John M. Carpenter
Argonne National Laboratory
PNS, Bldg. 360
9700 S. Cass Ave.
Argonne, IL 60439

R. B. Clare
Argonne National Laboratory
Engineering Physics Division
9700 S. Cass Ave., Bldg. 207
Argonne, IL 60439

Floyd N. Coppage
RDA
P. O. Box 9335
Albuquerque, NM 87119

S. Arthur Cox
Argonne National Laboratory
Engineering Division, Bldg. 207
9700 S. Cass Ave.
Argonne, IL 60439

Oakley H. Crawford
Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, TN 37831

Michael W. Curtin
1725 Jefferson-Davis Hwy.
Suite 1100
Arlington, VA 22202

Ted Debiak
Grumman Aerospace Corp.
111 Stewart Ave.
Bethpage, NY 11714-3592

Captain Thurman Deloney
SD/CNWD
P. O. Box 92960
Worldway Postal Center
Los Angeles, CA 90009

Daniel E. Driemeyer
M/S13-3
MDAC
5301 Bolsa Ave.
Huntington Beach, CA 92648

William L. Dunn
Applied Research Corp.
6404 Falls of Neuse Road
Suite 200
Raleigh, NC 27615

George Edlin
USA Strategic Defense Command
DASD-H-D
P. O. Box 500
Huntsville, AL 35807

Bill Feldman
ESS 8, MS D438
Los Alamos National Laboratory
Los Alamos, NM 87545

Charles L. Fink
Argonne National Laboratory
Engineering Physics Division
9700 S. Cass Ave., Bldg. 207
Argonne, IL 60439

Herbert Flicker
Nichols Research Corp.
8618 Westwood Center Drive
Suite 200
Vienna, VA 22180-2222

Captain Mark Franz
AFSTC/XLS
Kirtland AB, NM 87117-6008

John Generosa
PRI
4151 Montgomery Blvd., NE
Albuquerque, NM 87109

Pierre Grand
Brookhaven National Laboratory
Building 902C, Neutral Beam Division
Upton, NY 11973

Charles Goulding
Los Alamos National Laboratory
MS D436
Los Alamos, NM 87545

Larry R. Greenwood
Argonne National Laboratory
Chemical Technology Division
9700 S. Cass Ave., Bldg. 205
Argonne, IL 60439

Zaven Guiragossian
TRW MS 147/1040
One Space Park
Redondo Park, CA 90278

Lt. Kerry Habiger
AFWL/AWYW
Kirtland AFB, NM 87117-6008

C. Ross Harder
GA Technologies
P. O. Box 26708
San Diego, CA 92138

Col. James Head
USAFB/DFP
USAA, CO 80840

Howard L. Herdman
M/S13-3
MDAC
5301 Bolsa Ave.
Huntington Beach, CA 92648

Lt. Col. Ernest Herrera
AFWL/TA
Kirtland AFB, NM 87117-6008

Lee Hilbert
USA Strategic Defense Command
DASD-H-D
P. O. Box 500
Huntsville, AL 35807

Chuck Huddleston
ORI, Inc.
1375 Piccard Drive
Rockville, MD 20850

IEAE Fellowship Office - GR 440A (2)
Office of Scientific and
Engineering Personnel
National Research Council
2101 Constitution Ave.
Washington, D.C. 20418

Thomas Ingersoll
M/S13-3
MDAC
5301 Bolsa Ave.
Huntington Beach, CA 92648

Arune Intasorn (4)
Department of Physics
Faculty of Science
Srinakharinwirot University,
Prasarnmitr
Sukhumvit 23, Bangkok 10110
Thailand

Carl E. Johnson
Argonne National Laboratory
Chemical Technology Division
9700 S. Cass Ave., Bldg. 205
Argonne, IL 60439

Charles Johnson
General Research Corp.
635 Discovery Drive
Huntsville, AL 35806

Captain Brian Johnston
AFWL/AWYW
Kirtland AFB, NM 87118-6008

Howard Kerr
Oak Ridge National Laboratory
9201-3, MS8, Y12 Plant
Oak Ridge, TN 37830

Marquis A. Kirk, Jr.
Argonne National Laboratory
Materials Science Division
9700 S. Cass Ave., Bldg. 212
Argonne, IL 60439

Captain Rex Kiziah
USAFA/DFP
Colorado Springs, CO 80840-5701

Inara Kuck
HQ DNA/SPAS
6801 Telegraph Road
Alexandria, VA 33031

Burris D. Lamar
Argonne National Laboratory
Engineering Physics Division
9700 S. Cass Ave., Bldg. 207
Argonne, IL 60439

Jeffrey R. Lawrence
Organization Number 2126
Sandia National Laboratories
Albuquerque, NM 87185-5800

Leo G. LeSage
Argonne National Laboratory
Engineering Physics Division
9700 S. Cass Ave., Bldg. 207
Argonne, IL 60439

Henry Lichenstein
Los Alamos National Laboratory
MS B226
Los Alamos, NM 87545

Ron Lipinski
Organization Number 2126
Sandia National Laboratories
Albuquerque, NM 87185-5800

David Lukens
USA Strategic Defense Command
DASD-H-V
P. O. Box 1500
Huntsville, AL 35807

Duncan MacArthur
N2, MS J562
Los Alamos National Laboratory
Los Alamos, NM 87545

Richard G. Madonna
Grumman Aerospace Corp.
111 Steward Ave.
Bethpage, NY 11714-3592

Ann K. Mahoney
W. J. Shafer Associates
1901 N. Fort Meyer Dr.
Suite 800
Arlington, VA 22209

F. Mann
Battelle Pacific Northwest Laboratory
P. O. Box 1970
Richland, WA 99352

Mike Meier
Los Alamos National Laboratory
MS D436
Los Alamos, NM 87545

Maj. Daniel Mulder
PSC 2, Box 18025
AP San Francisco, CA 96311-0006

Paul A. Nelson
Argonne National Laboratory
Chemical Technology Division
9700 S. Cass Ave., Bldg. 205
Argonne, IL 60439

Basil Nichols
P7, MS B284
Los Alamos National Laboratory
Los Alamos, NM 87545

Captain Mark Owen
AFSTC/SWL
Kirtland AFB, NM 87117

R. Papsco
Grumman Aerospace Corp.
111 Steward Ave.
Bethpage, NY 11714-3592

Daniel Payton
EOS Technologies
Suite 1121
200 Lomas NW
Albuquerque, NM 87102

Robert Poll
JAYCOR
P. O. Box 1577
Santa Monica, CA 90406

S. Pruett
USA Strategic Defense Command
DASD-H-D
P. O. Box 500
Huntsville, AL 35807

Clifford R. Qualls
University of New Mexico
Albuquerque, NM 87131

Antanas V. Rauchas
Argonne National Laboratory
PNS Division, Bldg. 360
9700 S. Cass Ave.
Argonne, IL 60439

John Reed
Radiation Technologies
128 Rancho Del Rey
Escondido, CA 92025

Lt. Col. Peter Rensema
AFSTC/XLS
Kirtland AFB, NM 87117-6008

Jim Rice
Organization Number 1270
Sandia National Laboratories
Albuquerque, NM 87185-5800

Captain David Richards
AFSTC/XLS
Kirtland AFB, NM 87117-6008

Stuart Ridgway
RDA
P. O. Box 9695
Marina Del Rey, CA 90295

Don Rigali
Organization Number 9140
Sandia National Laboratories
Albuquerque, NM 87185-5800

Charles T. Roche
Argonne National Laboratory
Engineering Physics Division
9700 S. Cass Ave., Bldg. 207
Argonne, IL 60439

Stan Rudnick
Argonne National Laboratory
Engineering Physics Division
9700 S. Cass Ave., Bldg. 207
Argonne, IL 60439

George Safonov
R&D Associates
P. O. Box 9695
Marina Del Rey, CA 90291

Robert W. Scarlett
Los Alamos National Laboratory
MS B243
Los Alamos, NM 87545

Stanley Schneider
M/S13-3
MDAC
5301 Bolsa Ave.
Huntington Beach, CA 92648

Robert Schulte
Grumman Aerospace Corp.
111 Steward Ave.
Bethpage, NY 11714-3592

Robert Sepucha
Wally J. Shaeffer Assoc.
1901 North Ft. Myer Drive
Suite 800
Arlington, VA 22209

Donald L. Smith
Argonne National Laboratory
Engineering Physics Division
9700 S. Cass Ave., Bldg. 207
Argonne, IL 60439

C. Lewis Snead
Brookhaven National Laboratory
Building 902C, Neutral Beam Division
Upton, NY 11973

W. F. Sommer
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Allen Spencer
Delta Research Inc.
315 Wynn Drive
Huntsville, AL 35805

Martin J. Steindler
Argonne National Laboratory
Chemical Technology Division
9700 S. Cass Ave., Bldg. 205
Argonne, IL 60439

Larry Stewart
GA Technologies Inc.
P. O. Box 85608
San Diego, CA 92138

Dave Straw
W. J. Shaeffer Associates
Suite 202
1600 Randolph Court
Albuquerque, NM 87106

Daniel D. Strottman
Los Alamos National Laboratory
MS B243
Los Alamos, NM 87545

Scott Texter
TRW MS 147/1040
One Space Park
Redondo Park, CA 90278

Alan J. Toepfer
SAIC
2109 Air Park Road SE
Albuquerque, NM 87106

Juitien Tsai
The Aerospace Corp.
P. O. Box 92957
Los Angeles, CA 90009-2957

Robert J. Thibault
P. O. Box 8555
Philadelphia, PA 19101

Vlad Vanek
TRW Defense Systems Group
One Space Park, MS 134/8079
Redondo Beach, CA 90278

Charles Veseley
Grumman Aerospace Corp.
111 Steward Ave.
Bethpage, NY 11714-3592

Clark E. Wallace
TRW Defense Systems Group
One Space Park, MS 134/8079
Redondo Beach, CA 90278

Tom Ward
Brookhaven National Laboratory
Neutral Beam Division, Bldg. 902C
Upton, NY 11973

Clayton E. Watson
Los Alamos National Laboratory
MS B243
Los Alamos, NM 87545

Howard Weisberg
R&D Associates
P. O. Box 9695
Marina Del Rey, CA 90291

Ron Weitz
SAIC
2109 Air Park Road
Albuquerque, NM 87106

Dan Whitener
USA Strategic Defense Command
DASD-H-D
P. O. Box 500
Huntsville, AL 35807

Warren Wilson
AFWL/AWYW
Kirtland AFB, NM 87117-6008

Craig Wuest
Lawrence Livermore National Laboratory
P. O. Box 808 L-82
Livermore, CA 94550

Douglas C. Yoon
RDA
P. O. Box 9695
Marina Del Rey, CA 90295

Thomas J. Yule
Argonne National Laboratory
Engineering Physics Division
9700 S. Cass Ave., Bldg. 207
Argonne, IL 60439

Raymond Zazworsky
Sandia National Laboratories
P. O. Box 5800
Albuquerque, NM 87185-5800

M. S. Zucker
Brookhaven National Laboratory
Neutral Beam Division, Bldg. 902C
Upton, NY 11973

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