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Radioactive Foil Analysis Of 1.5 Gev Proton Bombardment Of A Hg Target

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ABSTRACT

The number of reactant nuclei in a series of foils surrounding a container of Hg that has been bombarded by 1.5 GeV protons is calculated and compared to experimental measurements. This is done to aid in the validation of the Hg cross sections used in the design studies of the Spallation Neutron Source (SNS). It was found that the calculations match the measurements to within the uncertainties inherent in the analysis.

I. INTRODUCTION

The conceptual design of the Spallation Neutron Source (SNS) facility has been completed [1]. This device will produce high-intensity, low-energy (<1 eV) neutron fluxes for experiments by utilizing the spallation process occurring when 1 GeV protons impinge on a mercury (Hg) target. For a variety of reasons, including target heat removal and thermal shock issues, it was necessary to use Hg as the target. However, no spallation sources have been built which use a Hg target. Thus, a particularly urgent requirement for the advanced design is the validation of the performance of the Hg cross sections used in the Monte Carlo neutronic calculations [2, 3] and the validation of the calculational procedures themselves. A substantial step in this direction was taken in June of 1997 when a series of experiments were performed at the AGS facility at Brookhaven National Laboratory (BNL) to study the effects of proton bombardment on a container of Hg. One of the experiments consisted of placing foil samples around the outside of the Hg container and determining via gamma ray spectroscopy nuclides formed through activation by neutrons liberated from the Hg target. Protons with energies of 1.5-, 7.0-, and 24.0- GeV were used for the experiments. Since the proton energy of SNS will be 1.0 GeV, the 1.5 GeV AGS data was given the highest priority for neutronics analysis. A particularly useful guide in evaluating the comparison between the calculations and the experimental results was the work in Ref. 4 where a comparable comparison was made in a similar energy range for proton bombardment of tungsten at 0.895 and 1.21 GeV. Tungsten is: 1) a nuclide for which the cross sections are much better known, 2) a nuclide reasonably near to Hg in both A and Z, and 3) a material which is commonly used for spallation neutron sources. The work in Ref. 4 would therefore be a useful benchmark, and it would be expected that, if the cross sections employed in the calculations are performing well, the comparison should be comparable to that seen in Ref. 4.

II. CALCULATIONAL DETAILS

The LCS computer code system [5] was used for these calculations. The LCS code package uses HETC [5] to perform the high-energy transport and MCNP [6] to transport neutrons produced in HETC with energies below 20 MeV. The MCNP code was used to calculate the neutron flux at the foil locations via the track length method. The model geometry is shown in Fig. 1. Only

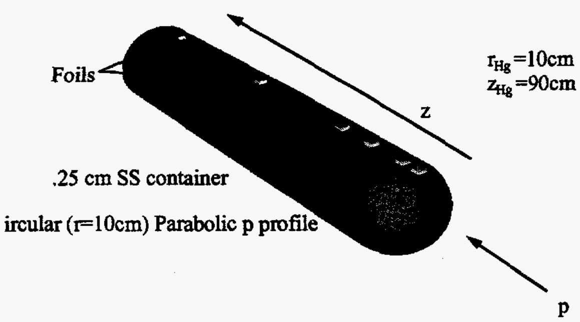

Fig. 1. AGS model used for calculations.

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one series of foils, all of which have the same azimuthal angle, is included in the geometry. The foils had dimensions of 20 × 20 × 1 mm. In the experiment many other foils were included at the same and at different azimuthal angles but they would not be expected to have a large effect on the results shown here. For all but one of the reactions studied, no additional features were included in the model. For the (n,γ) reaction, in which low-energy neutrons are important, other structures in the experimental area can play a significant role. As will be discussed below, a concrete wall was needed to understand this reaction.

For the analysis, two measurements independent of the foil data were needed. The first was the proton injection profile and the second was the total number of protons (N_p). The profile adopted for the calculations was a circular parabolic profile with a radius of 10 cm. This closely approximated the measured profile in Ref. 7. The total number of protons was taken from Ref. 8. Their activation method however, gave N_p values about a factor of two lower than that found by the other methods described. A complete discussion of the methods is given in Ref. 8. For this analysis the data was compared to the calculated values found when the largest and the smallest measured values for N_p were used. Experimentally, approximately 5000 data points were obtained for foils of Cu, Co, Fe, Ni, Bi, Nb, and Au. Only reactions and foils which allowed an interpretation in terms of simple processes were considered for this analysis since a verification of the calculated neutron flux appropriate to SNS rather than a detailed understanding of the nuclear physics was desired. This restriction reduced the data considered to that shown in Table 1. In all cases the foils consisted of naturally

Table 1. Foils and reactions considered.

Foil	Reactions			
Co	$^{59}Co_{27}(n,\gamma)^{60}Co_{27}$	$^{59}Co_{27}(n,p)^{59}Fe_{26}$	$^{59}Co_{27}(n,\alpha)^{56}Mn_{25}$	$^{59}Co_{27}(n,2n)^{58}Co_{27}$
Fe	$^{56}Fe_{26}(n,p)^{56}Mn_{25}$	$^{56}Fe_{26}(n,t)^{54}Mn_{25}$		
Ni	$^{58}Ni_{28}(n,p)^{58}Co_{27}$	$^{58}Ni_{28}(n,d)^{57}Co_{27}$	$^{58}Ni_{28}(n,t)^{56}Co_{27}$	

occurring elements. Only the single largest isotope listed in the table was used for the calculations. This simplified the study considerably and would be expected to yield sufficient accuracy for present purposes.

III. RESULTS

The neutron cross sections for one of the foil materials ($^{59}Co_{27}$) are shown in Fig. 2 for neutron energies below 20 MeV. In order for there to be a significant test of the neutron flux, the reactions considered should be sensitive to a wide range of energies. Sensitivity to a neutron flux in a narrow

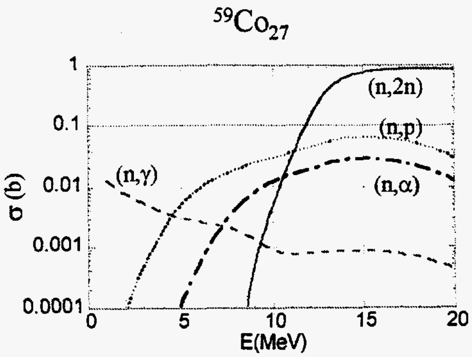

Fig. 2. Co cross sections.

energy range could result in agreement which was largely accidental since neutrons with energies above and below this narrow range could be inaccurate by significant amounts. As may be seen, the series of reactions studied for $^{59}Co_{27}$ has a sensitivity to neutrons throughout the energy range shown. This implies that the magnitude of the neutron flux throughout this energy range is being tested.

The measured number of various radioactive nuclei (N_0) produced in the Co sample is shown in Fig. 3 as a function of distance along the side of the container (See

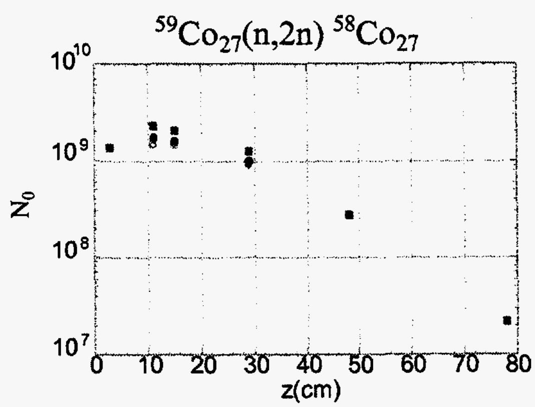

Fig. 3. Number of nuclei found in irradiated foils for the $^{59}Co_{27}$ (n,2n) $^{58}Co_{27}$ reaction at various azimuthal locations. The multiple points at single values of z are from foils with the same value of z but differing azimuthal locations.

Fig. 1). For the second, third, and fourth points (counting from the front of the target), results from foils located as in Fig. 1 are shown (the largest value in each case) together with results from foils located at different

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azimuthal angles. As may be seen, the azimuthal asymmetries are small. In the results shown later, a comparison is made between the number of reactant nuclei calculated and the number measured in foils located as shown in Fig. 1. The measured data from the foils located as in Fig. 1 will be labeled "1on". Also shown will be measured data averaged over foils from differing azimuthal angles (and the same z). This data will be labeled "azimuthal average". The variation in these measurements at different angles as seen in Fig. 3 is typical.

In Fig. 4 comparisons for three of the Co reactions are given. As discussed above, calculated results were

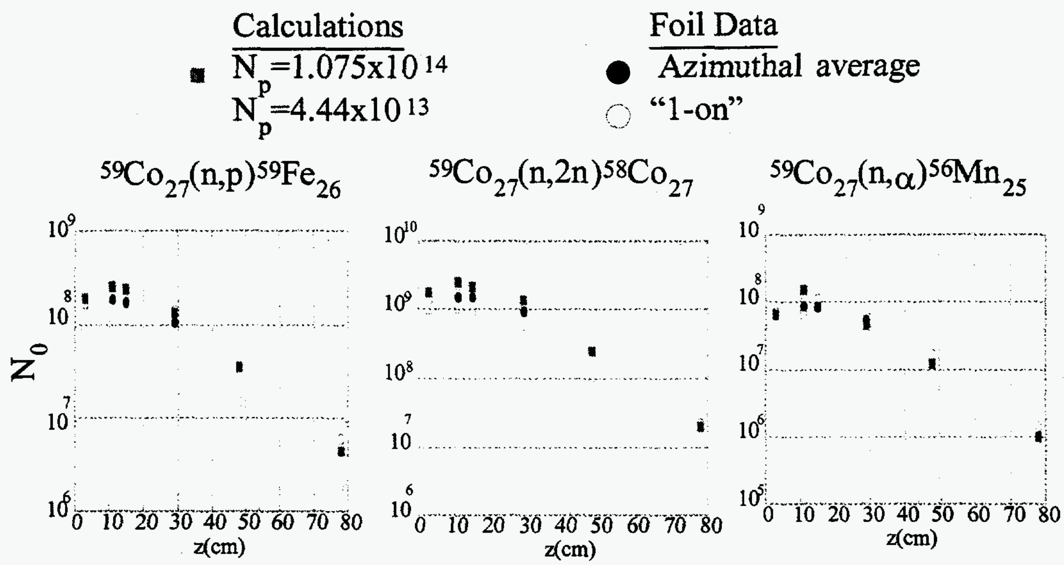

Fig. 4. Comparison between the number of foil nuclei measured and calculated for $^{59}Co_{27}$ reaction.

found using the largest and smallest measurements for the number of incident protons. As may be seen, the experimental results are between the calculated values found using these two values for N_p.

The comparison for the (n,γ) reaction is given in Fig. 5. For one of the calculations a room with a concrete wall and inside dimensions 2 × 2 × 2 m^3 was included. The thickness of the concrete wall was 0.5 m. The center of the room was at the front center of the Hg container. The calculated results, without accounting for the room, underestimated the measured data by approximately an order of magnitude at the peak and fell off too rapidly with depth relative to the measured foil activities. The slow fall off in the measured data with depth would indicate a neutron flux contribution from other than the spallation process. With the addition of the room in the model, the peak value and the axial distribution were in much better agreement. As may be seen in Fig. 2, the (n,γ) cross section peaks at low energies where many neutrons are generated by collisions with the wall. The addition of the wall had a negligible effect on the comparisons for the other reactions since these are threshold (a few MeV) reactions (See Fig. 2). In order to

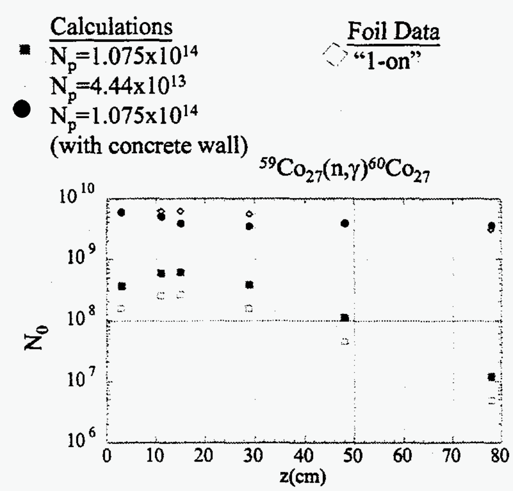

Fig. 5. Calculated number of nuclei (with and without a concrete wall) in irradiated foils compared to the measured.

get a better comparison, one would need to include a more detailed description of other features surrounding the experiment. A more complete calculational geometry was beyond the scope of this initial study.

As noted in Table 1, comparisons were also done for Fe foils and for Ni foils. Results were very similar to those given.

IV. DISCUSSION AND CONCLUSIONS

In all the results presented above, the calculated and the measured results are consistent within the uncertainties inherent in the analysis. The general agreement is also judged to be comparable to that found for tungsten in Ref. 4. This increases the confidence in both 1) the calculational procedures used to make predictions and to design the SNS and 2) the Hg cross sections. An analysis of the higher-energy activation data is planned in order to establish confidence in the energy deposition profiles that are used in the Hg thermal shock and fluid studies.

ACKNOWLEDGMENTS

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