Spallation Neutron Production Measurements

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Abstract. Measurements of neutron production by the proton bombardment of range-thick targets of lead (Pb) and of tungsten (W) at energies of 0.8, 1.0, 1.2, and 1.4 GeV were made for comparison with calculations based on the computer codes LAHET for neutrons with $E_n > 20$ MeV and MCNP for $E_n \leq 20$ MeV and also to compare with each of two prior experiments dating from about 1965.¹

The high-energy transport codes have consistently tended to over-predict n production from range-thick targets by an amount significantly greater than supposed experimental uncertainties.¹ Spallation target (and the ancillary accelerator) design relies on high-energy transport code calculations. The projected capital and operating costs for spallation neutron accelerator installations are large enough that it is necessary to gauge the precision of such calculations, and to have an incentive for code improvement and basis for comparison.

A first trial of a benchmark experiment reported here used the heavy-ion acceleration capability of the BNL AGS, rather than a (primary) proton beam, in order to minimize background (Fig. 1). A primary beam of Au ions bombarded a Be target and the reaction products, including the desired protons, were momentum selected to form a (secondary) particle beam which passed through a time-of-flight (TOF) path for particle identification, and then impacted the target material under study, either a Pb cylinder identical in dimensions (10.2 cm D by 61 cm L) to those used in both earlier experiments (under AECL and AERE auspices) to facilitate comparison of the experimental results, or a W cylinder (10.2 cm D by 40 cm L). Both targets were effectively range-thick at the proton bombarding energies.

Fig. 1. Schematic of Experiment

The neutron production target (nPT) was surrounded by a detector in the form of a coaxial hollow cylinder of moderator material (high density polyethylene) containing 32 ³He proportional counters (Fig. 2), each part of an independent channel (consisting of the proportional counter, preamplifier, amplifier, and discriminator) providing a fast (50 ns) pulse

for each detected n. The effective dead-time of the counter due to the $\approx 10 \mu\text{s}$ proportional counter pulse width is thus approximately $1/32$ of that width or about $0.3 \mu\text{s}$. The pulses representing neutron detections are combined into one pulse stream by an OR circuit and are the input to a multi-channel scaler (MCS) (with 64 channels, each $2 \mu\text{s}$ wide) gated by coincidence with the TOF condition.

dimensions in inches
1 inch = 2.54 mm

Fig. 2. Basic Mechanical Drawing of Detector

The neutrons (produced by a particle impacting the nPT) that entered the detector were moderated, and then captured by the ^3He in the proportional counters at an exponentially decreasing average rate determined by the detector "die-away time" (the lifetime of a neutron in the detector before it diffuses or scatters out of the detector or is captured in a proportional counter or other material the detector is made of). The pulse height spectrum of each proportional counter, typified by that shown in Fig. 3, allowed a discriminator setting clearly above the noise level but below the smallest proportional counter pulse, resulting in a 1:1 correspondence between $^3\text{He}(n,p)t$ events and output pulses. Each neutron detection from each spallation event was labelled with its detection time and recorded in computer memory with TOF information for particle identification and other relevant information in an event-by-event fashion. The pooled die-away time data for the detector (Fig. 4) exhibits classic behavior: an initial rapid increase corresponding to the neutron thermalization time, followed by a relatively slow simple exponential decrease back down to a (flat) random background due to various neutron loss mechanisms. This background was determined by fitting the exponentially decreasing part of the die-away curve with an exponential, plus a constant representing the background. (In more recent experiments, random background was also measured by inserting delays into the timing. The two methods are in complete agreement.) Establishing the die-away curve for the detector enabled accurate determination of the correction for neutrons from a given event that were not counted because they occurred after the end the $128 \mu\text{s}$ time scan acceptance window of the MCS.

The die-away data for a particular incident particle and incident energy constituted the basic data of this experiment (which is similar to the "Rossi- α " technique used in reactor physics). Correcting this data for the finite MCS time window and the random background as mentioned above, and the efficiency of the detector for detecting neutrons, which is discussed below, yielded the number of neutrons per incident particle. (Alternately, the process may be viewed

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as the codes being used to predict the average number of neutrons detected per incident proton, which number is then compared with the actual number, obtained by correcting the observed die-away data for the finite time window.)

Fig. 3. ^3He Proportional Counter Pulse-Height Spectrum

Fig. 4. Neutron Capture by He^3 vs. Time, Pb Target (Fit: Two Exponentials Plus a Constant)

The detector efficiency was calculated, using the combination of LAHET and MCNP. The calculation took into account neutrons produced in the detector body by (n, xn) and (p, xn) reactions caused by energetic neutrons or protons from the target, and the effect of the target material on the thermal flux. LAHET was used to calculate the initial production of neutrons and protons, their initial transportation, and the production of secondaries. Any neutrons and protons that reached 20 MeV and below were used to create a source file for the lower energy code MCNP, which continued to follow them until they either reacted with ^3He resulting in an electrical pulse, or are eliminated by other processes. This use of the codes to calculate efficiency (defined as the number of neutrons detected divided by the number leaving the target) might seem suspect since it is the high-energy transport code (LAHET) that is being tested, in particular, its ability to predict the average number of spallation neutrons generated by a proton, but can be justified by the following facts and discussion. MCNP is a code designed for neutron energies ≤ 20 MeV which has already been proven by bench testing, and for well-defined and characterized systems of simple geometry, such as this detector, is

considered accurate to about 0.5%. Code calculated values of the neutron energy spectrum shown in Fig. 5 (for 1 GeV protons on Pb) indicate that while in principle the spallation process can produce neutrons of up to the incident proton energy, about 85% of the neutrons actually are ≤ 20 MeV in energy and so are within the scope of MCNP. (Note also that $\approx 95\%$ of the neutrons are ≤ 100 MeV, and so are only a few scatterings away from becoming < 20 MeV; the extent that the lower energy neutrons predominate may seem surprising.) Two factors involved in the detector efficiency calculation are the proportion of neutrons of energy > 20 MeV to those ≤ 20 MeV that are predicted to leave the target, and the fraction of each of those neutron groups that reacts with the ^3He . Note that the number of neutrons leaving the target, which is what is being tested, is not needed in the efficiency calculation. If, as we believe, calculations involving MCNP can be performed with an accuracy of, say 0.5% for the 85% of neutrons that are ≤ 20 MeV, and that part of the calculation requiring LAHET involving 15% of the neutrons can only be done with an accuracy which is 20 times worse, or about 10%, then assuming the resulting uncertainties propagate in quadrature, the efficiency determination will have an uncertainty of the order of 1.6%. Calculation may be the most accurate way of establishing the detector efficiency.

Fig. 5. Cumulative Energy Distribution of Neutrons
1 GeV protons: Pb, 61 cm L x 10.2 cm D

The present BNL results are in excellent agreement with those of the earlier AECL and AERE measurements.¹ In this energy region the neutron production as a function of bombardment energy is accurately linear; the three sets of experimental values for Pb can be fit with the same straight line, which has a correlation parameter $R^2 = 0.99+$ (Fig. 6a). All three experiments were made by different experimental groups, accelerators, and measurement techniques. With such agreement, it seems quite unlikely that systematic errors are appreciable. Uncertainties calculated for the Pb data are typically about 1.3% at the 2σ level; the W results (for which there are no other experimental results for comparison) are less precise, about 2.5% at 1σ . The experimental values were compared with calculations made using LAHET², (see Fig. 6b for the Pb data), with the result that, e.g., at 1.0 GeV, the calculated (n/p) ratio is 14% higher for Pb and 17% higher for W than was measured. LAHET does agree better with the data than does the older code HETC.

The codes can also be used to compute the tritium generated by the $n(^3\text{He},p)t$ reaction in the proportional counters. Since the basis for sponsoring these experiments was interest in the accelerator production of tritium, the number of reactions observed, each one corresponding to the production of a triton, was compared with the prediction by the computer codes. The

triton per incident proton (t/p) production is shown in Fig. 7. The measurements of (n/p) and (t/p) are compared to the code predictions in Table 1.

Fig. 6a. (n/p), Experiment Compared to Code Pb, 10.2 cm D x 61 cm L

Fig. 6b. Code-Calculated vs. Experimental Data for Pb (61 cm L x 10.2 cm D)
95% Confidence Limits Shown

Fig. 7. (t/p) Ratio for Pb and W
10.2 cm D x 61 cm L (Pb), x 40 cm L (W)

Table 1 Summary of BNL Results for (n/p) and (t/p) Compared to Code Calculations

Target	E_p (GeV)	(n/p) Expt.	(n/p) Code	(t/p) Expt.	(t/p) Code
Pb	0.80	13.60	14.96	4.228	4.794
	1.00	17.38	19.82	5.409	6.357
	1.20	22.31	24.25	6.932	7.742
	1.40	26.21	28.26	8.113	9.046
W	0.80	15.11	17.47	4.230	4.965
	1.00	20.40	23.22	5.705	6.579
	1.20		28.81		8.113
	1.40	28.46	33.67	7.935	9.425

The high-energy transport code version (LAHET) used can be characterized as an "intranuclear cascade based on the Bertini model, followed by the pre-equilibrium model and then by the Rutherford-Appleton Lab evaporation fission model, with the Gilbert-Cameron-Cook-Ignatyuk model giving the level density." Table 2 summarizes the AECL, AERE and present BNL data for Pb and gives the least-squares fit to all the data considered as a single statistical population.

Table 2 Summary of AECL, AER and BNL Experimental (n/p) Data for Pb

E_p (GeV)	AECL	AERE	BNL	L.S. Fit	Uncertainty*
0.54	7.96			7.993	0.322
0.72	11.76			11.717	0.246
0.96	16.64			16.683	0.224
1.47	26.40			27.235	0.457
0.3167		3.130		3.372	0.446
0.5024		7.091		7.215	0.341
0.6600		10.614		10.475	0.268
0.8287		14.252		13.996	0.222
0.9899		17.288		17.301	0.230
0.9978		17.104		17.465	0.232
0.80			13.600	13.372	0.226
1.00			17.380	17.510	0.233
1.20			22.310	21.648	0.308
1.40			26.210	25.787	0.415

*The random uncertainty; to be interpreted as the 95% confidence limit of the mean value of a series of measurements made at the corresponding proton energy.

Table 3 summarizes the BNL (n/p) data for W, and Table 4 summarizes (t/p) data for Pb and W targets, with experimental uncertainties, and compares experimentally derived values with code calculations.

Table 3 Summary of (n/p) for W Target

E_p (GeV)	Exptl.	Exptl. L.S. Fit	Exptl. Uncert. (1σ)	Code Calc.
0.8	15.11	15.47	0.40	17.47
1.0	20.40	19.86	0.51	23.22
1.2	-----	-----	-----	28.81
1.4	28.46	28.64	0.74	33.67

Table 4 The (t/p) Ratio, Experiment in Comparison with Code

	E_p	Exptl.	Exptl. Uncert. (1σ)	Code Calc.
Pb	0.8	4.228	0.077	4.864
	1.0	5.409	0.100	6.278
	1.2	6.932	0.122	7.692
	1.4	8.113	0.145	9.508
W	0.8	4.230	0.110	5.033
	1.0	5.705	0.148	6.525
	1.2	-----	-----	8.016
	1.4	7.935	0.206	9.508

The basic conclusions are that there is excellent agreement between all three experimental groups for the number of neutrons per proton for the one element studied by all three groups (Pb), and that a recent recommended version of a high-energy transport code (LAHET) predicts production of neutrons and tritons for both Pb and W targets greater than the experimental yields by amounts distinctly greater than the uncertainties that can be assigned, a situation not too different from the comparison between the earlier experiments and the high-energy transport codes then available.

Seven measurements (4 Pb, 3 W) took just 3 days of running time. Data on n production by particles other than protons (mesons, deuterons, tritons, and alphas) are gathered simultaneously. Except for the mesons, the number of such events is much less than those involving protons. Such data have not been analyzed yet. Present plans are to extend the measurements to 3.6 GeV, and to other candidate nPT materials. Since the BNL AGS facility may soon be the only available in this energy range, collaboration with other groups interested in spallation research is therefore invited.

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