BONNER SPHERE MEASUREMENTS OF NEUTRONS FROM A THICK TARGET OF HEVIMET BOMBARDED BY ^{40}Ar AT 150 MeV/u AND PREDICTIONS FOR THE COUPLED CYCLOTRON FACILITY

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The proposed coupling of the K500 and K1200 cyclotrons will provide beam intensities up to one particle microampere for lighter ions, with beam energies to 200 MeV per nucleon. Beams with these characteristics will produce copious amounts of penetrating radiation, the most important being neutrons.

Few data are available for heavy ion beams irradiating thick targets that have this energy. Thus, reliable neutron production source terms for these beams are not readily available for shielding calculations. Previously, we published data [1] on neutrons produced from beams of ^{4}He, ^{12}C, and ^{16}O ions at 155 MeV/u, stopping in a thick target placed in the target region of the NSCL s A1200 beam analysis system. The yield from oxygen ions was found to be possibly slightly larger than the yield from carbon ions. We wished to repeat these measurements under more favorable conditions, i.e. less background from room scattering, and to extend them to an ion having a larger mass. We also made a measurement using ^{40}Ar ions at 150 MeV/u.

Our thick-target experiments were set up in the N4 vault, which is relatively free from background-producing scattering sources. The target was a solid cylinder of Hevimet [1], an alloy of tungsten, nickel, and copper. This material is used for many of the beam stops and Faraday cups at the NSCL. The target diameter was 5.08 cm and the length was 5.093 cm. For reference, the ranges of the He, C, and O ions in Hevimet are about 1.72 cm, 0.61 cm, and 0.46 cm, respectively. The ^{40}Ar ion range is about 0.20 cm. The target was pressed into a long copper pipe. Insulating rings were placed around this pipe, and the assembly was placed in the beam line, forming a Faraday cup for current integration.

The ^{4}He, ^{12}C, and ^{16}O ions were simultaneously produced in the NSCL s room temperature ECR ion source, from a mixture of He and CO_2 gases. The desired ion beam (the beams were charge-to-mass analogs) was selected by changing only the K1200 cyclotron frequency. The ^{40}Ar beam was produced in a separate experiment.

A commercial [2] Bonner-sphere spectrometer, having polyethylene spheres with diameters of 2, 3, 5, 8, 10, and 12 inches, was used for the neutron measurements. For the ^{40}Ar measurements, additionally a cylinder of polyethylene, having 18 inches in length and 17 inches in diameter, was used as an 18-inch pseudo-sphere. The detector-photomultiplier housing was constructed of low-carbon steel, for additional magnetic shielding, and can house a 10 mm diameter detector. We used the standard 4 mm detector described below. The spectrometer was placed one meter from the target. Measurements were made, using each ion beam, at angles of 0, 30, 60, 90, and 120 degrees with respect to the beam direction. In addition to using the moderating spheres, measurements were made with the bare detector, i.e., without using a sphere, and with the bare detector covered with cadmium foil. The detector was a cylinder (4 mm diameter, 4 mm length) crystal of LiI(Eu), enriched in ^{6}Li, mounted to a photomultiplier tube. A plastic scintillator, placed at approximately 2 meters from the target, and about 20 degrees from the beam direction, was used to monitor the beam position on the target.

Several additional measurements were made to assess the target thickness effect on the neutron yields. With the spectrometer at 90 degrees, measurements using the beam were made first with the target alone, then with additional Hevimet. Measurements were also made using a PuBe source (about 4.5 MeV average neutron energy), first with the target removed and then with the source behind the target. Both sets of measurements, using the data for the three largest spheres, gave an estimation of the average interaction length of about 1.27 cm. This only gives a rough estimate of the interaction length, because the interaction length is neutron-energy-dependent, and each sphere has its own energy response.

Room scattering was also measured. Using the beam, we placed a shadow bar, consisting of a solid cylinder of iron, having a diameter of 10.16 cm and a length of 30.48 cm, between the target and the spectrometer at 90 degrees. The shadow bar data contain contributions from room and target scattering into the detector. We also made an additional measurement, but using the PuBe source to give us a known neutron energy spectrum, with the spectrometer at zero degrees. Here, measurements were done with and without the target, and with the target and a shadow bar. The shadow bar, in this case, was a 27.94 cm-long, truncated cone of brass, tapered from 17.15 cm in diameter to 10.80 cm. The latter set of measurements will be compared with a measurement, using the PuBe source, made in a relatively open area of the NSCL, which simulated a scatter-free situation.

Figure 1 shows measured yield per beam ion for each ion as a function of angle, for ions of ^{4}He, ^{12}C, ^{16}O and ^{40}Ar stopping in the target of Hevimet. Table 1 shows the integrated yield per beam ion, and compares them to our earlier measurement. Qualitatively, there are fewer neutrons per beam ion for heavier ions, compared to He at a given energy per nucleon. In addition, as expected from many other studies, the number of neutrons per beam ion decreases for increasing detection angle. Quantitatively, these data are preliminary in that a more refined estimate of the target thickness contribution needs to be made, and the room scattering background must be considered. The corrected data will then be analyzed using the unfolding code BUNKIUT[3].

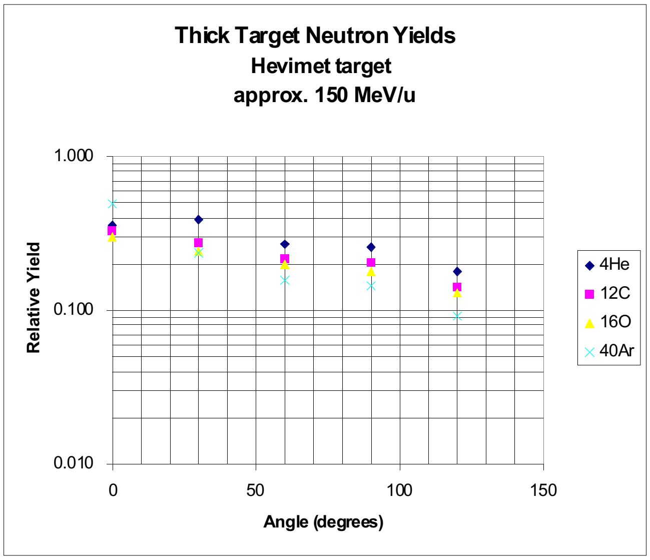

Figure 1. Measured neutron yield per beam ion as a function of angle, using a Bonner sphere spectrometer. The ion beams of ^{4}He, ^{12}C, and ^{16}O at 155 MeV/u, and 40Ar at 150 MeV/u, stopped in the target of Hevimet. Measurements were made using a bare detector, a Cd-covered bare detector, and using 2, 3, 5, 8, 10, and 12 inch-diameter moderating spheres, for ^{4}He, ^{12}C, and ^{16}O ions. Data were also taken with an 18-inch psuedosphere for ^{40}Ar ions. The spectrometer was at one meter from the target.

There are very few measured neutron yields from thick targets for ions heavier than ^{4}He. Indeed, thick-target neutron yields are not available for most of the expected coupled cyclotron ion beams. A plausible procedure must be worked out to predict them, for example to help ensure reasonable estimates for

Ion	Neutrons/ion E > 0 MeV	Ratio to He	Ratio to C	Neutrons/ion E > 4 MeV	Ratio to He	Ratio to C	Compare to Britvitch et al.	Ratio to He

^{4}He	3.1	1.00		1.0	1.0		4.9	1.00
^{12}C	2.4	0.78	1.00	0.79	0.8	1.00	1.56	0.32
^{16}O	2.2	0.69	0.89	0.72	0.7	0.90	1.74	0.36
^{40}Ar	1.6	0.52	0.67	0.46	0.5	0.59		

Table 1: Neutron yields from ion beams of ^{4}He, ^{12}C, ^{16}O at 155 MeV/u, and ^{40}Ar at 150 MeV/u. The number of neutrons per ion is shown for two different energy cuts, and is compared to other measurements.

shielding and other safety purposes. We used a scaling procedure suggested by Madey *et al.* [6], which successfully explained yields from different targets irradiated by the same ion beam.

In our procedure, we use a measured thick-target yield or neutron multiplicity for a given beam ion-target combination. Using the model by Madey *et al.* [6], the ratio of multiplicities, R, is related to the ratio of total reaction cross sections for the ion-target combination:

$$R = \frac{M\left(A_1, Z_1, A_t, Z_t, \frac{E}{A}\right)}{M\left(A_2, Z_2, A_t, Z_t, \frac{E}{A}\right)} = \frac{\sigma\left(A_1, Z_1, A_t, Z_t, \frac{E}{A}\right)}{\sigma\left(A_2, Z_2, A_t, Z_t, \frac{E}{A}\right)} \times \left(\frac{A_1^{1/3} + A_t^{1/3}}{A_2^{1/3} + A_t^{1/3}}\right)^5 .$$

The thick-target yield is the multiplicity times the number of interactions. The fraction of beam ions that interact in the target may be estimated from

$$Interaction\ fraction = -\frac{6.022 \times 10^{23}}{A_t} \times \int_0^E \frac{\sigma\left(A_i, Z_i, A_t, Z_t, \frac{E}{A}\right)}{\frac{dE}{d\rho x}} dE.$$

Therefore, from a known multiplicity or yield, and from the calculations of R and the number of interactions, the unknown yield may be estimated.

In the calculations of the cross sections we used total reaction cross sections parameterized by Kox *et al.* [8] and Townsend and Wilson [7]. We then made our yield estimates using the experimental data of Heilbronn *et al.*, which are shown in Table 2.

System (155 MeV/u)	Yield (Neutrons/ion)	Interaction Fraction	Multiplicity (Neutrons/interaction)
^{4}He + Al	0.348(13)	0.34	1.02(4)
^{12}C + Al	0.179(5)	0.18	0.99(3)

Table 2: Experimental results from Heilbronn *et al.* [1], for ^{4}He and ^{12}C at 155 MeV/u on a thick aluminum target.

Our yield predictions for beams that will be available from the coupled cyclotron facility are shown in Table 3. Yields from neutron rich ion beams may exceed yields from carbon beams at the same specific ion energy. Yields from neutron deficient ion beams may be lower than from carbon beams at the same specific ion energy. In particular, from Table 1, the ratio of measured yield from ^{40}Ar to the measured yield from ^{12}C is about 0.7. In Table 3, the calculated ratio of ^{36}Ar to ^{12}C is 0.8, which is in good agreement. In summary, the model by Madey *et al.* [6] appears to be useful for predictions of thick target neutron yields of heavy ions.

Ion	Reactions per Ion	Yield/Inc. Ion at 155 MeV/u	Ratio of Yields Compared to 12C
^{12}C	0.224	0.18	1.0
^{18}O	0.224	0.21	1.2
^{22}Ne	0.189	0.19	1.1
^{36}Ar	0.115	0.14	0.8
^{48}Ca	0.139	0.19	1.1
^{84}Kr	0.096	0.18	1.0

Table 3: Estimates of neutron yields from thick targets for beams available from the coupled cyclotron facility which are heavier than carbon.

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References

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