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THRESHOLD REACTION RATES INSIDE AND ON THE SURFACE OF THICK W-Na TARGET IRRADIATED WITH 0.8 GEV PROTONS

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Abstract

The preliminary results are presented of the experimental determination of threshold reaction rates in experimental samples made of Al, Co, Bi, In, Au, to name but a few, placed both inside and on the surface of extended thick W-Na target irradiated with 0.8 GeV protons. The target consists of 26 alternating discs each 150 mm in diameter: 6 tungsten discs are 20 mm thick, 7 tungsten discs are 40 mm thick, and 13 sodium discs are 40 mm thick. The relative position of discs is matched with the aim of flattening the neutron field along the target surface. The comparison is made of the measured rates with results of their simulation using the LAHET and KASKAD-S codes, and the ENDF/B6, MENDL2, MENDL2P, SADKO-2, and ABBN-93 databases. The results are of interest both in terms of integral data collection and to test the up-to-the-date predictive power of the codes applied in designing of hybrid Accelerator Driven System (ADS) systems that use tungsten targets cooled with sodium.

Foreword

Quantitative information on interaction of accelerated protons with different targets is necessary to design ADS. Application of hadron-nucleus process simulations should be tested by
special experiments in which irradiation conditions, target material composition and location approximate the design type to the limit. There are several projects, [1, 2], for example, where tungsten cooled by sodium is considered to be used as target material. This served as the basis for conducting experiments with micromodels of such targets. Comparison of experimental data obtained on such micromodels with corresponding calculated values will give us valuable information both for modifications of codes and databases and for assessment the calculation accuracy of the target part of the relevant ADS facility designs.

**Experiment plan**

The target with alternating adherent tungsten and sodium discs was designed in our micromodel. The location of these discs, which was specially chosen, facilitates the maximum flattening of the neutron field along the target. Experimental samples made of Al, Co, In, Au, Bi, $^{63}$Cu, $^{65}$Cu, $^{98}$Nb, $^{64}$Zn, $^{19}$F (CF$_2$), $^{12}$C, Ta, and Tm manufactured by punching the corresponding foils or by molding fine powders, 10.5 mm in diameter and 0.1–0.3 mm thick, were placed inside the target and on its surface.

The layout of tungsten and sodium discs is shown in Fig. 1. All discs are 150 mm in diameter, disc thickness and sequence is listed in Table 1. The tungsten discs have special design providing insertion of special bars with round recesses for experimental samples to be placed inside the target. The discs are located on a special adjustment table which provides alignment of target and proton beam axes with an accuracy of the order of 1 mm. The proton beam size examination has been performed by using in tentative exposures to radiation aluminum cut foils and Polaroid film.

W (97.5%), Ni (1.75%), Fe (0.75%), and less than 0.2 % of impurities are incorporated in tungsten discs. The average density of the tungsten discs is of 18.6 g/cm$^3$. Sodium discs represent metallic sodium placed into a steel container with 0.4 mm thick walls. Impurities content in Na is less than 0.02%.

Target irradiation was performed with 0.8 GeV protons over a period of 10 hrs at an average intensity equal to 4.8·10$^{10}$ p/cm$^2$·pulse using the ITEP synchrotron. Pulse repetition rate is of 15 pulses per minute. Changes in the proton beam intensity over the irradiation period is presented in Fig. 2. After a short decay lag, experimental samples were extracted from the target’s surface and inside volume and packaged into labeled polyethylene packages. Subsequent gamma spectra measurements were made using several spectrometers. The absolute value for different threshold reaction rates were determined using the PCNUDAT decay database after gamma-spectra processing with the GENIE2000 code (see Table 2).

**Simulation of reaction rates**

To simulate the measured reaction rates, the LAHET Code System (LCS) [3] was used which involves the LAHET code for simulating hadron-nuclei interactions, the HMCNP code for simulating neutron transport at energies below 20 MeV, and the PHT code for simulating hard photon transport. Both neutron and proton spectra were calculated in all points where experimental samples are located.

Another code system applied to simulate the experiment is the KASKAD-S code [4] which
Figure 1: Layout of W and Na discs and experimental samples.

Figure 2: Changes in the proton beam intensity over the period of irradiation.
Table 1: Disc sequence, thickness, and experimental samples layout

| Disc number | Material | Thickness, mm | Samples                        | Samples                        |
|-------------|----------|---------------|--------------------------------|--------------------------------|
| W1          | W        | 20            | 5Al*, Co                       | Al, In, Bi, Au, Ta             |
| Na1         | Na       | 3*40=120      |                                |                                |
| W2          | W        | 20            | 5Al, Co                        | Al, In, Bi, Au, 169Tm, 65Cu, Ta, 65Cu, 93Nb, 64Zn, 19F, 12C, Co |
| Na2         | Na       | 2*40=80       |                                |                                |
| W3          | W        | 20            | 5Al, Co                        | Al, In, Bi, Au, Ta             |
| Na3         | Na       | 2*40=80       |                                |                                |
| W4          | W        | 20            | 5Al, Co                        | Al, In, Bi, Au, Ta             |
| Na4         | Na       | 40            |                                |                                |
| W5          | W        | 40            | 5Al, Co                        | Al, In, Bi, Au, Ta             |
| Na5         | Na       | 40            |                                |                                |
| W6          | W        | 40            | 5Al, Co                        | Al, In, Bi, Au, Ta             |
| Na6         | Na       | 40            |                                |                                |
| W7          | W        | 40            | 5Al, Co                        | Al, In, Bi, Au, Ta             |
| Na7         | Na       | 40            |                                |                                |
| W8          | W        | 40            | 5Al, Co                        | Al, In, Bi, Au, Ta             |
| Na8         | Na       | 40            |                                |                                |
| W9          | W        | 40+20=60      | 5Al, Co                        | Al, In, Bi, Au, Ta             |
| Na9         | Na       | 40            |                                |                                |
| W10         | W        | 2*40=80       | 5Al, Co                        | Al, In, Bi, Au, Ta             |
| Total       | W: 380   | 50 Al, 10 Co  | 10 Al, 10 In, 10 Bi, 10 Au, 10 Ta, 169Tm, 63u, 65Cu, 93Nb, 64Zn, 19F, 12C, Co |
|             | Na: 520  |               |                                 | 900                            |

*) “Al” designates a single Al sample; “5Al” designates five Al samples, etc.

**) There are samples (made of Al) beside those specified in Table 1, for measuring the proton beam density distribution across the front (Al) surface and to control the neutron field uniformity along discs that form the target.

uses a discrete ordinate algorithm for coupled charges/neutral particle transport calculations in 2D-pencil beam problems. The multigroup cross-section library SADKO-2 for nucleon-meson cascade calculations coupled with the CONSYST/ABBN-93 neutron and gamma-ray cross-section libraries below 20 MeV is used.

Reaction cross sections for neutrons with energies up to 100 MeV and protons with energies up to 200 MeV were taken from MENDL2  and MENDL2P  libraries, respectively. Reaction rates are obtained via integral product of spectra and cross sections \( R = \int \phi(E)\sigma(E)dE \). The discrepancy between calculated and experimental results was estimated using the root-mean-square discrepancy factor, <F>, defined in [8].
Table 2: Thresholds and main parameters of products for reaction rates being measured

| Reaction          | $E_{th}$ (MeV) | Product  | $T_{1/2}$ | $E_{\gamma}$ (keV) | $Y_{\gamma}$ (%) |
|-------------------|----------------|----------|-----------|--------------------|------------------|
| $^{115}$In(n,n')  | 0.335          | $^{115m}$In | 4.49h     | 336.2              | 45.8             |
| $^{27}$Al(n,p)    | 1.89           | $^{24}$Mg | 9.46m     | 843.7              | 71.8             |
| $^{64}$Zn(n,p)    | 2.1            | $^{64}$Cu | 12.70h    | 511.0              | 35.8             |
| $^{59}$Co(n,p)    | 2.6            | $^{59}$Fe | 44.50d    | 1099.3             | 56.5             |
| $^{27}$Al(n,\alpha)| 3.26         | $^{23}$Na | 15.02h    | 1368.5             | 100              |
| $^{197}$Au(n,2n)  | 8.5            | $^{196}$Au| 6.18d     | 355.7              | 86.9             |
| $^{115}$In(n,p)   | 9              | $^{115}$Cd| 2.23d     | 527.9              | 27.5             |
| $^{115}$In(n,2n)  | 9              | $^{114}$In| 49.51d    | 191.6              | 16              |
| $^{65}$Cu(n,2n)   | 10.1           | $^{64}$Cu| 12.70h    | 511.0              | 35.8             |
| $^{63}$Cu(n,3n)   | ~15            | $^{64}$Cu| 3.408h    | 656.0              | 10.7             |
| $^{59}$Co(n,2n)   | 11             | $^{58}$Co| 70.92d    | 810.8              | 99.4             |
| $^{19}$F(n,2n)    | 11.1           | $^{18}$F | 1.83h     | 511.0              | 194              |
| $^{64}$Zn(n,2n)   | 12.4           | $^{63}$Zn| 38.1m     | 669.6              | 84.0             |
| $^{12}$C(n,2n)    | ~20            | $^{11}$C | 20.38m    | 511.0              | 162              |
| $^{209}$Bi(n,4n)  | 22.6           | $^{206}$Bi| 6.24d     | 803.1              | 98.9             |
| $^{197}$Au(n,4n)  | 23             | $^{194}$Au| 39.5m     | 328.4              | 63               |
| $^{169}$Tm(n,4n)  | 25.5           | $^{166}$Tm| 7.7h      | 778.8              | 19.9             |
| $^{209}$Bi(n,5n)  | 29.6           | $^{205}$Bi| 15.31d    | 1764.3             | 32.5             |
| $^{93}$Nb(n,4n)   | 31             | $^{90}$Nb | 14.6h     | 1129.2             | 92.7             |
| $^{115}$In(n,5n)  | 35             | $^{111}$In| 2.83d     | 245.4              | 94               |
| $^{209}$Bi(n,6n)  | 38             | $^{204}$Bi| 11.22h    | 899.2              | 98.5             |
| $^{209}$Bi(n,7n)  | 45.3           | $^{203}$Bi| 11.76h    | 820.2              | 29.6             |

Results

The preliminary processing of gamma spectra from Al samples placed on the target outside surface and in the target center makes it possible to estimate the generation rates of $^{24}$Na and $^{27}$Mg. Experimental and calculated values obtained using the LAHET code are presented in Fig. 3. Measurements of gamma-spectra for all the samples irradiated are still being in progress and all the reaction rates listed in Table 2 are expected to be determined after the completion of gamma-spectra processing.

Convergence of calculated and experimental values

The rates for $^{24}$Na in Al foils predicted by LAHET are in satisfactory agreement with experimental values (except the first and last points on the surface), as shown in Fig. 3. Whereas, the predicted rates for $^{27}$Mg generation on the target surface are systematically overestimated compared to the measured values (by a factor of 1.6, on average), except the first point. At the same time, the $^{27}$Mg production rates predicted by KASKAD-S are underestimated on the average by a factor of 1.6. The observed discrepancies would be better understood only after
Figure 3: Reaction rates of $^{27}\text{Al}(p,x+n,x)^{24}\text{Na}$ and $^{27}\text{Al}(n,p)^{27}\text{Mg}$ at the target axis and on the surface (top plot). Calculations by LAHET and KASKAD-S are shown by solid and dashed lines, respectively. The ratios of reaction rate calculated values to the measured data are shown on the bottom plot.

the complete processing of gamma spectra for the rest of samples and determining both $(n,p)$ – purely “neutron” and $(p,n)$ – purely “proton” reactions.

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