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SPECTRAL MEASUREMENTS OF NEUTRONS FROM Pb, W, AND Na TARGETS IRRADIATED BY 0.8 AND 1.6 GEV PROTONS

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Abstract

Preliminary results of neutron spectra measurements from Pb, W, and Na targets irradiated by 0.8 and 1.6 GeV protons are presented. Measurements have been carried out using the proton beam extracted from the ITEP synchrotron and the TOF technique. Neutron registration has been carried out using BICRON MAB-511 liquid scintillation counters. Spectra measured at angles of 30°, 60°, 90°, 120°, and 150° have been compared with results of their simulation using the LAHET code system and the code CEM2k. The results are of interest both from data gathering viewpoint and as a benchmark of the up-to-the-date predictive powers of codes applied to design the hybrid Accelerator Driven Systems (ADS) using lead or lead-bismuth targets and sodium-cooled targets.

Foreword

Data on neutrons and charged particles generated from proton beam interactions with targets and structure materials are necessary when designing the present-day ADS facilities with proton beam energy of ~1-2 GeV [1, 2]. Requirements to the data accuracy are rather strict because such data determine the external source term of the ADS. Besides, the neutron and proton data determine the calculation accuracy requirements of such principal ADS blanket parameters as the $k_{eff}$, safety control system efficiency, energy deposition of the fuel assembly, and
the minor actinide transmutation rates. These data are also important in calculating radiation resistance of structure materials exposed to high-energy particles.

What is said above determines the necessity for further experimental investigations of particle generation cross sections and conducting more accurate measurements of these cross sections at energies of bombarding protons up to several GeV. Such results are important, first, as nuclear constants by themselves and, second, in verifying the computational codes used in practice to calculate the parameters of ADS facilities.

All known experiments in measuring double differential cross sections of neutrons generated as a result of interaction of protons of intermediate energies with thin and thick targets made of different materials are tabulated in Table 1.

An analysis of the data presented in these works shows that double differential cross sections of neutrons for lead measured at proton energy of 0.8 GeV at LANL, KEK, and SATURNE agree well with each other. They agree rather well with results of calculations performed with different codes. The agreement is worse for targets with small mass numbers where discrepancy may reach 100%. With incident proton energy increased to several GeV, the discrepancy between experimental and calculation data increases too.

Additional measurements of neutron spectra and yields in the proton energy range up to 2 GeV for different materials are necessary to study causes of mentioned discrepancies and improve further the available models and codes. Such experiments for measuring neutron double differential cross sections from Pb(p,xn), W(p,xn), and Na(p,xn) reactions in thick targets bombarded by protons with energies of 0.8 and 1.6 GeV were performed at the Institute of Theoretical and Experimental Physics (ITEP), Moscow. Measurements were made by the time-of-flight (TOF) techniques, neutron spectra were measured at angles of 30°, 60°, 90°, 120°, and 150° in the laboratory frame of reference.

The data obtained were compared with results of calculations by the LAHET code system [17] and the code CEM2k [18].

**Description of the experiment**

The experiment has been carried out using the time-of-flight (TOF) technique, the TOF spectrometers were located in the 512nd beam of the ITEP proton synchrotron with a maximum energy of 10 GeV. Detectors were located at a distance of 2.5 m from the floor and more than 5 m from the ceiling and walls. The beam intensity was of approximately $10^5$ protons per pulse. The beam was focused at the center of the investigated targets, its profile was close to an ellipse with axes of 2 cm $\times$ 2.5 cm. The distance between the target and neutron detectors changes from 1.5 m to 3 m and is not evacuated. The target materials and sizes are listed in Table 2. The contents of impurities in tungsten and sodium were less than 0.2% and 0.02%, respectively. Sodium was placed in a cylindrical steel container with 0.4-mm thick walls. The experimental facility layout is shown in Fig. 1, where PB is the proton beam, M2 is the bending magnet, Tg is the target under investigation, F3.0 and F3.1 are plastic scintillators.

A 12-m distance was selected to minimize the effect of the great mass of large magnet M2 on the measurement results. The targets under investigation were located in the second focus of the beam at 80 m from the accelerator internal target.

The particles leaving the target are recorded by three detector assemblies (N1, N2, N3).
Table 1: Neutron spectra experiments at proton energies above 100 MeV

| $E_{inc}$, MeV | Target nuclei | Neutron energy, MeV | Laboratory angle, degrees | Institute / Year | Refs. |
|---------------|---------------|---------------------|--------------------------|------------------|-------|
| 585           | C, Al, Fe, Nb, In, Ta, Pb, U | $0.9 - E_{max}$    | 30, 90, 150               | PSI / 87         | 3     |
| 120, 160      | Al, Zr, Pb    | $\geq 30$           | 0 – 145                  | IUCF / 90        | 4     |
| 113           | Be, C, O, Al, Fe, W, Pb, U | $0.5 - E_{max}$    | 7.5 – 150                | LANL / 89        | 5     |
| 256           | Be, C, O, Al, Fe, Pb, U | $0.5 - E_{max}$    | 7.5 – 150                | LANL / 92        | 6     |
| 256, 800      | Li, Al, Zr, Pb | $20 - E_{max}$     | 7.5 – 150                | LANL / 93        | 7     |
| 318, 800      | Al, Pb, U     | $5 - E_{max}$      | 7.5, 30                  | LANL / 86        | 8     |
| 597           | Be, B, C, N, O, Al, Fe, Pb, U | $0.5 - E_{max}$    | 30 – 150                 | LANL / 93        | 9     |
| 800           | Be, B, C, N, O, Al, Fe, Cd, W, Pb | $0.3 - E_{max}$    | 30 – 150                 | LANL / 92        | 10    |
| 800, 1500, 3000| C, Al, Fe, In, Pb | $1 - E_{max}$      | 15 – 150                 | KEK / 97         | 11    |
| 2200          | Cu            | 3.3 - 200           | 60                       | KEK / 83         | 12    |
| 500, 1500     | Pb            | $1 - E_{max}$      | 15 – 150                 | KEK / 95         | 13    |
| 800, 200, 1600| C, Fe, Zr, Pb, Th | $2 - E_{max}$     | 0 – 160                  | SATURNE/98       | 14    |
| 600 - 1600    | Al, Cu, Zr, Pb | 3 – 200             | 30 – 150                 | ITEP / 96        | 15    |
| 750, 1280, 2200| Cu, Pb, U    | 7.5 – 70            | 119                      | ITEP / 83        | 16    |
Table 2: The target materials and sizes

| Target material | Proton energy, GeV | Target size, cm |
|-----------------|--------------------|----------------|
| Pb              | 0.8                | $\varnothing$ 6.0 $\times$ 2.0 |
| Pb              | 1.6                | $15 \times 15 \times 20$ |
| W               | 0.8, 1.6           | $\varnothing$ 5.0 $\times$ 3.0 |
| Na              | 0.8, 1.6           | $\varnothing$ 6.0 $\times$ 20 |

Figure 1: The experimental facility layout.

Each of the assemblies consists of a 1 cm x 19 cm x 19 cm plastic scintillator (AN1, AN2, AN3) placed in the immediate proximity to, and ahead, a BICRON MAB-511 $\varnothing$ 12.7 cm $\times$ 15.2 cm liquid neutron detector. There was no protection of the neutron detectors. Scintillators were turn on for coincidence with neutron detectors in charged particles spectra measurements and for anti-coincidence, in neutron spectra measurements.

Separation of neutrons and gammas have been performed with an amplitude-amplitude analysis of the registered particle pulse ($A$(full charge) $-$ $A$(tail charge)) within the recoil proton energy range of 2.5 $-$ $\sim$10 MeV and an amplitude-time ($A$(full charge) $-$ T(pulse duration)) analysis within the recoil proton energy range of $\sim$ 10 $-$ 300 MeV. The first method provides reliable separation of the small amplitude pulses. This is shown in Fig. 2. The second method separates large amplitude pulses (Fig. 3), where the quality of the amplitude-amplitude separation is lost.

Fig. 3 demonstrates the branch behavior of the amplitude-time separation technique. From Fig. 3, one can see that with increasing the pulse amplitude the branches that corresponds to neutrons and gammas diverge and the quality of separation increases accordingly.

Thus, an acceptable quality of separation was achieved in the range of small pulse amplitudes by appropriate matching the parameters, and in the range of large pulse amplitudes, by using the amplitude-time separation technique.

The neutron counter efficiency was calculated using the SCINFUL \cite{19} and CECIL \cite{20} codes. Because the SCINFUL code application is limited to 80 MeV and the CECIL code gives reliable results up to energies of several hundred of MeV, the results of calculation with the SCINFUL code were used for energies below 80 MeV and the results of calculation with the
Figure 2: Separation of neutrons and gammas with the amplitude-amplitude analysis.

CECIL code were used for higher energies. The results of calculation using the CECIL code at 80 MeV and above were renormalized for matching with the results of the SCINFUL code at 80 MeV (see Fig. 3). The error in determining the efficiency is estimated to be equal to 10% at energies below 80 MeV and 15% at higher energies.

Simulation of neutron spectra

Because targets used in the present experiment can not be regarded as thin, simulations of neutron spectra by LAHET have included not only neutron generation from the proton-nucleus interactions, but also multiple scattering of primary protons together with the low energy (below 20 MeV) neutron transport by the HMCNP code. In the cases of lead and tungsten, elastic scattering of neutrons with energy above 20 MeV was taken into consideration as well.

Results

The measured neutron spectra from lead, tungsten, and sodium for proton energies of 0.8 and 1.6 GeV at angles of 30°, 60°, 90°, 120°, and 150° are shown in Figs. 5-7. The experimental data from other works ([10] and [11], for Pb at 0.8 GeV; [14], for Pb at 1.6 GeV; [10], for W 0.8 GeV) and calculations by LAHET are shown in the figures as well.

Comparison of experimental and calculation results shows a satisfactory agreement for the heavy nuclei targets, W and Pb (Fig. 3), at both proton energies. Exceptions may be seen for neutrons with energy above 100 MeV at angles 60°, 90°, and 120° for $T_p = 1.6$ GeV and for energetic neutrons at 90°, 120°, and 150° for $T_p = 0.8$ GeV. The agreement of calculated results with the data is worsen with transfer to sodium. Traditionally, this is explained by problems for
Figure 3: Separation of neutrons and gammas with the amplitude-time analysis.

Figure 4: Efficiency of the BC511 detector used for neutron registration (detector size $d_{5''} \times L_{6''}$). Calculation has been performed using the SCINFUL and CECIL codes at threshold corresponding to $^{137}$Cs.
Figure 5: Double differential neutron spectra from $^{nat}$Pb at proton energies of 0.8 and 1.6 GeV measured in the present work ($\circ$), in previous works ([10] and [11], for 0.8 GeV and [14], for 1.6 GeV), together with the results of calculation by LAHET.

the most of theoretical models to describe high-energy hadron interactions with nuclei of low masses.

As an example, for the lightest element measured, Na, where the thickness of target should be of the least importance for the measured neutrons, we show also calculations with the last version of the Improved Cascade-Exciton Model code, CEM2k [18], simulating pure proton-nucleus reactions, without taking into account any internuclear interactions (Fig. 5). One can see that for neutron energies above several MeV, where the thickness of target no longer affects significantly the measured spectra, CEM2k agrees with the data quite well, though some discrepancies in the very tails of the spectra still remain to be understood. Calculations with LAHET (both ISABEL and Bertini options) take into account the thickness of targets, therefore agree somewhere better than CEM2k with this data. Nevertheless, some disagreements between LAHET results and the data at the high-energy tails of most spectra and around $\sim$ 20 MeV at forward angles for Na have yet to be understood. At a glance, it looks like we got with both LAHET and CEM2k too many preequilibrium neutrons at forward angles and too few high-energy neutrons at backward angles; the last could be an indication that the local Fermi distribution for intranuclear nucleons used by all models may be a too rough approximation. But these points need a further, more detailed investigation.

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Figure 6: Double differential neutron spectra from $^{nat}$W at proton energies of 0.8 and 1.6 GeV measured in the present work (o), in previous a work ([10], for 0.8 GeV), together with calculations by LAHET.

Figure 7: Double differential neutron spectra from Na at proton energies of 0.8 and 1.6 GeV measured in the present work (o) together with the result of calculations by LAHET and CEM2k codes.
Figure 8: Calculation-to-Experimental data ratios of neutron spectra at 30° and 150° from Pb, W, and Na, as indicated.

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