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IRRADIATED BY 0.8 AND 1.6 GeV PROTONS

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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

The preliminary results of the spectra measurements of neutrons generated in 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 ITEP synchrotron and the TOF technique. Neutron registration has been carried out using BICRON MAB511 liquid scintillation counters. Spectra measured at angles of 30°, 60°, 90°, 120° and 150° have been correlated with the results of their simulation using the LAHET code system. The results are of interest both from data gathering viewpoint and as a demonstration of up-to-the-date predictive power of codes applied in the design of hybrid Accelerator Driven Systems (ADS) using lead or lead-bismuth targets, and sodium-cooled targets [1, 2].

Foreword

Data on neutrons and charged particles generated during proton beam interaction with the target and structural materials are required for designing modern ADS facilities with proton beam energy of appr. 1-2 GeV. Requirements to the accuracy of these data are rather high because they determine the calculation accuracy of such ADS blanket main parameters as k_{eff} , control power security efficiency, power deposition of the fuel assembly, and minor actinides transmutation rates. These data are also important in calculating radiation resistance of structural 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. These results are of great value first as nuclear constants per se and, second, for verification of computation codes being used in practice to calculate the parameters of ADS facilities.

All known experiments in measuring double differential cross sections and spectra 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.

The analytical treatment of data presented in these works shows that the double differential cross sections of the neutron yield for lead measured at proton energy of 0.8 GeV in LANL, KEK, and SATURNE agree well between each other. They agree rather well with results of calculations performed using HETC code. The agreement is worse for targets with small mass numbers where dis-

crepancy can reach 100%. With incident proton energy increased to several GeV, the discrepancy between experimental and calculation data increases too.

What is said above determines the necessity for additional measurements of neutron cross sections and yields in the proton energy range up to 2 GeV for different materials with the aim of analyzing causes of the said discrepancies. Such experiments for measuring the neutron spectra and double differential cross sections in Pb(p,xn), W(p,xn), and Na(p,xn) reactions in thick targets bombarded by protons with energy of 0.8 and 1.6 GeV were performed in the Institute of Theoretical and Experimental Physics, ITEP. Measurements were taken by the time-of-flight (TOF) techniques, neutron yields were measured at angles of 30°, 60°, 90°, 120° и 150° in the laboratory frame of reference. The data obtained were compared with results of calculations performed using the LAHET code system [17].

Table 1. Neutron spectra experiments at proton energies above 100 MeV

N	E_{inc} , MeV	Target nuclei	Neutron energy, MeV	Laboratory angle, degrees	Institute	Refs.
1	585	C, Al, Fe, Nb, In, Ta, Pb, U	0.9- E_{max}	30, 90, 150	PSI	3
2	120, 160	Al, Zr, Pb	≥ 30	0 - 145	IUCF	4
3	113	Be, C, O, Al, Fe, W, Pb, U	0.5- E_{max}	7.5 - 150	LANL	5
4	256	Be, C, O, Al, Fe, Pb, U	0.5- E_{max}	7.5 - 150	LANL	6
5	256, 800	Li, Al, Zr, Pb	20 - E_{max}	7.5 - 150	LANL	7
6	318, 800	Al, Pb, U	5 - E_{max}	7.5, 30	LANL	8
7	597	Be, B, C, N, O, Al, Fe, Pb, U	0.5- E_{max}	30-150	LANL	9
8	800	Be, B, C, N, O, Al, Fe, Cd, W, Pb	0.3- E_{max}	30 - 150	LANL	10
9	800, 1500, 3000	C, Al, Fe, In, Pb	1 - E_{max}	15 - 150	KEK	11
10	2200	Cu	3.3 - 200	60	KEK	12
11	500, 1500	Pb	1 - E_{max}	15 - 150	KEK	13
12	800, 200, 1600	C, Fe, Zr, Pb, Th	2 - E_{max}	0 - 160	SAT-URNE	14
13	600 - 1600	Al, Cu, Zr, Pb	3 - 200	30 - 150	ITEP	15
14	750, 1280, 2200	Cu, Pb, U	7.5-70	119	ITEP	16

Description of the experiment.

The experiment has been carried out using the time-of-flight spectrometer, TOFS located in 512nd beam of the ITEP proton synchrotron with maximum energy of 10 GeV. Detectors were located at the distance of 2.5 m from the floor and more than 5 m from the ceiling and walls. The beam intensity was approximately 10^5 protons per pulse. The beam was focused at the centers of the investigated

targets, its cross section was close to an ellipse with axes of 2 cm x 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 и 0.02%, respectively. Sodium was placed in a cylindrical steel container with 0.4 mm thick walls.

Table 2. The target material and size

Target material	Proton energy, GeV	Target size, cm
Pb	0.8	$\varnothing 6.0 \times 2.0$
Pb	1.6	15x15x20
W	0.8, 1.6	$\varnothing 5.0 \times 3.0$
Na	0.8, 1.6	$\varnothing 6.0 \times 20$

The experimental facility layout is shown in Fig. 1 where Q are the quadrupole lenses, $M_{1,2}$ are magnets, TA are the accelerator internal target, T is the target under investigation, D_1 and D_2 are detectors (plastic scintillators with thickness of 5 and 10 mm) located at the interval of 10 m. Scintillators D_1 and D_2 are used to detect charged particles by the TOF technique and separate protons from pions and other particles being generated within the accelerator internal target. The time resolution of the separation circuit was 0.31 nanoseconds, and therefore protons have been almost totally separated from pions and deuterons. The target under investigation was located in beam the second focus (F_2) at the distance of 80 m from the accelerator internal target.

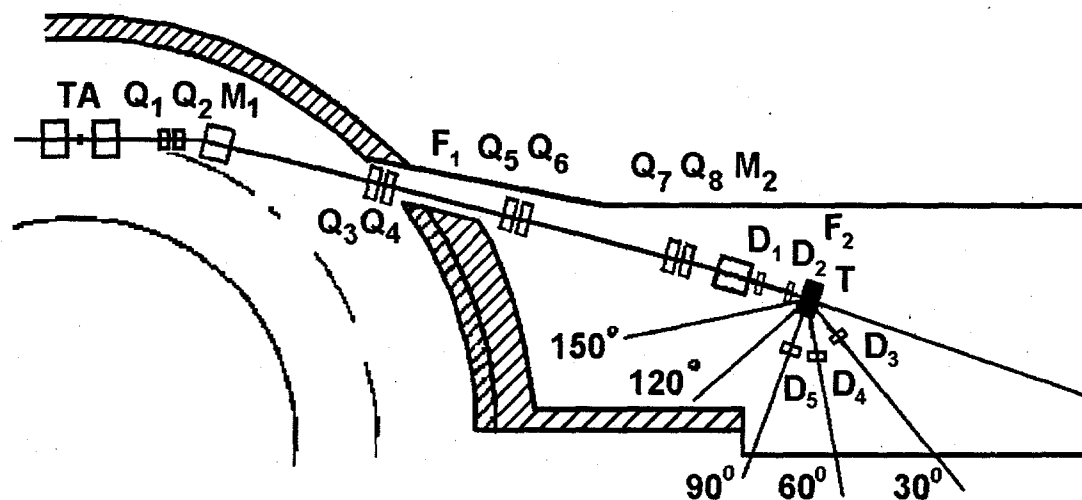


Fig. 1. The experimental facility layout

Particles leaving the investigated target have been registered by three detector assemblies each consisting of 1 cm x 1 cm x 19 cm plastic scintillator and the BICRON MAB-511 $\varnothing 12.7$ cm x 15.2 cm liquid neutron detector. The assemblies were located at angles of 30°, 60°, 90°, 120° и 150° to the beam axis. There were 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 amplitude-amplitude analysis of the registered particle pulse ($A(\text{total charge}) - A(\text{tail charge})$) within the recoil proton energy range of 2.5 - ~ 10 MeV and amplitude-time ($A(\text{total charge}) - T(\text{pulse duration})$) analysis within the recoil proton energy range of ~ 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.

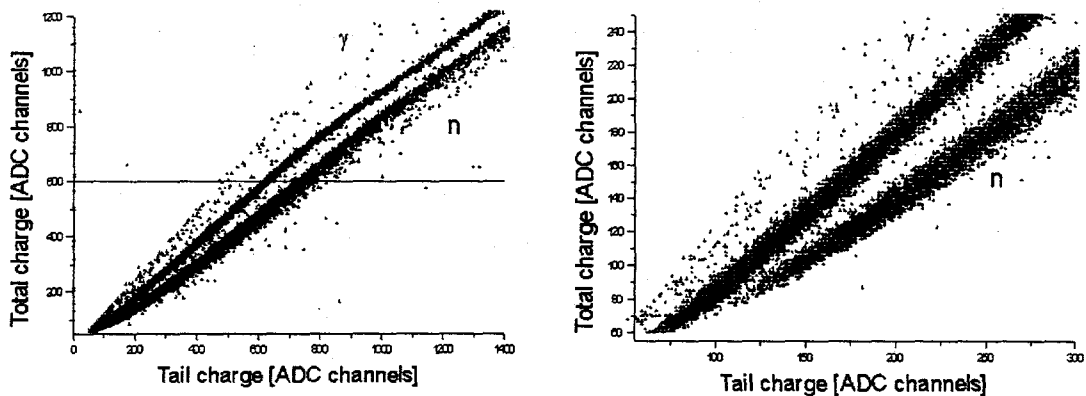


Fig. 2. Separation of neutrons and gammas with amplitude-amplitude analysis

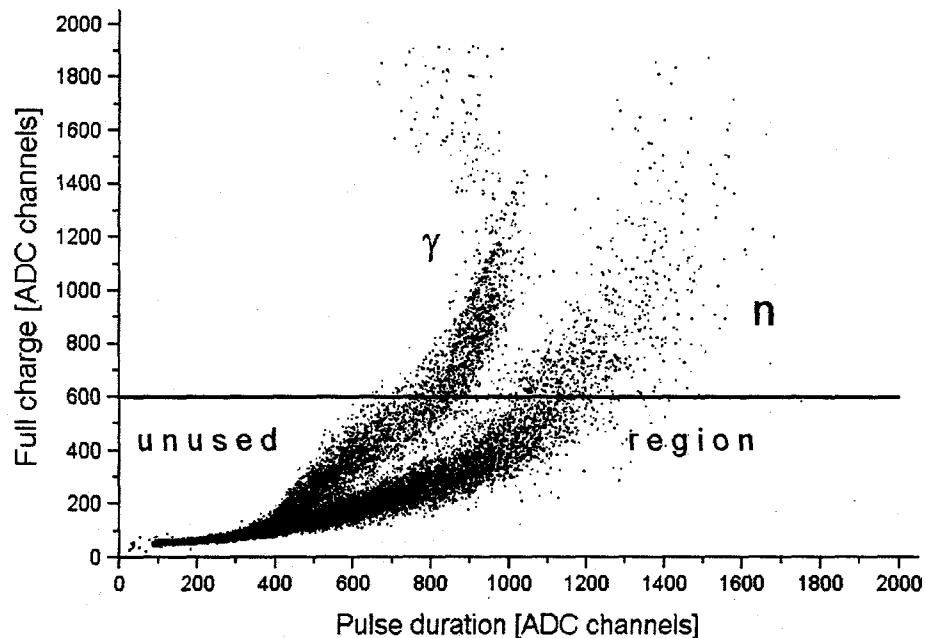


Fig. 3. Separation of neutrons and gammas with amplitude-time analysis

The plot presented in Fig. 3 demonstrates the branch behavior of the amplitude-time separation technique. With reference to Fig. 3, it can be seen that with increase in pulse amplitude the branches that corresponds to neutrons and gammas the branches diverge and the quality of separation increases accordingly.

Thus, the acceptable quality of separation is achieved both in the range of small pulses by means of appropriate parameter matching and in the range of small pulses by means of applying the amplitude-time separation technique.

The neutron counter efficiency is calculated using the SCINFUL [18] and the CECIL [19] codes. Because the SCINFUL code application is limited to 80 MeV and the CECIL code gives reliable results up to the energies of several hundred MeV, the results of calculation with the SCINFUL code were used for energies below 80 MeV and the results of calculation with the CECIL code were used for higher energies. The results of calculation using the CECIL code 80 MeV were renormalized for matching with the results of the SCINFUL code at 80 MeV energy (cf. Fig. 4). The error in determining the efficiency is estimated to be equal to 10% at energies below 80 MeV and 15% at higher energies.

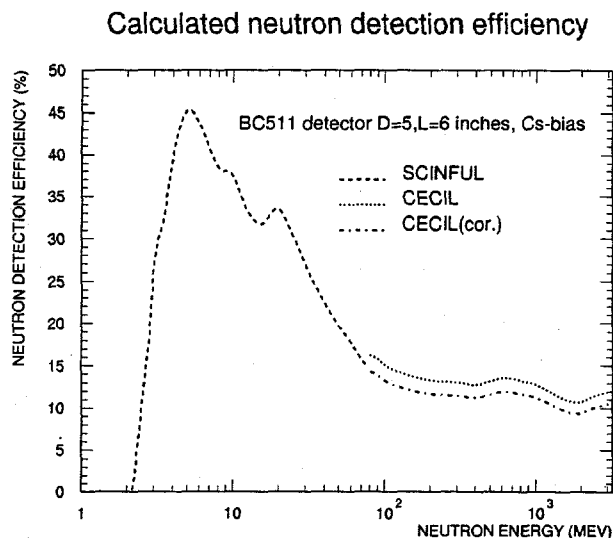


Fig. 4. Efficiency of the BC511 detector used for neutron registration (detector size d5"*L6"). Calculation has been performed using the SCINFUL and the CECIL codes at threshold corresponding to ^{137}Cs .

Simulation of neutron spectra

Because targets used in experiment can not be regarded as thin simulation of neutron spectra using LAHET code system included not only generation of the proton-nucleus interaction, but multiple scattering of primary protons together with the low energy (below 20 MeV) neutron transport using HMCNP code. In the case of lead and tungsten elastic scattering of neutrons with energy above 20 MeV was taken into consideration.

Results

The results of determining neutron spectra for lead, tungsten, and sodium under the induced by protons with energies of 0.8 and 1.6 GeV at angles of 30° , 60° , 90° , 120° и 150° are shown in Fig. 5, 6 и 7. The experimental data from other works ([10], [11] for Pb at 0.8 GeV, [14] for Pb at at 1.6 GeV, [10] for W 0.8 GeV) and calculation data using LAHET code are shown in the above figures too.

Comparison of experimental and calculation data presented show satisfactory convergence for heavy nuclei targets W and Pb (Fig. 8). Relatively high convergence has lead at both energy values. The exceptions are neutrons with energy above 200 MeV at angles of 30° , 60° , 90° , 120° и 150° (1.6 GeV). The convergence of calculation results with experimental data is worsen with transfer to sodium. Traditionally this is explained by the inadequacy of the theoretical models used in describing the high-energy hadron interaction with nuclei of low mass.

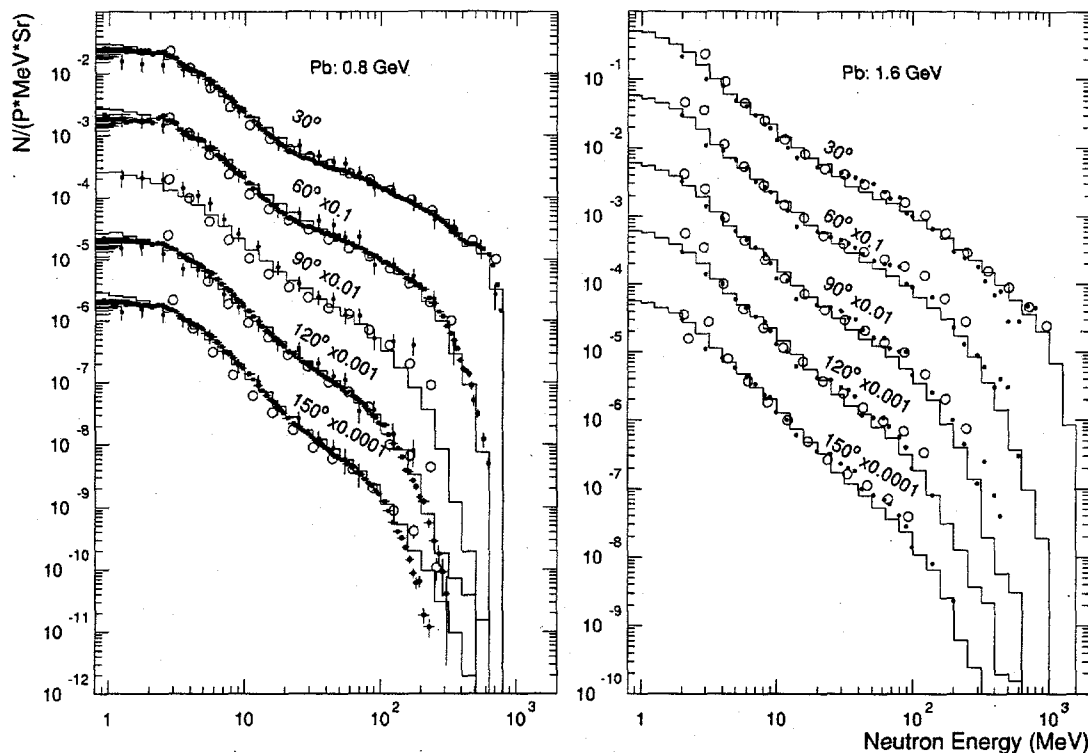


Fig. 5. The double differential neutron spectra from ^{208}Pb at proton energies of 0.8 and 1.6 GeV measured in the present work (\circ), in other works (\blacksquare : [10], [11] for Pb 0.8 GeV, [14] for Pb 1.6 GeV) together with the result of calculation using the LAHET code.

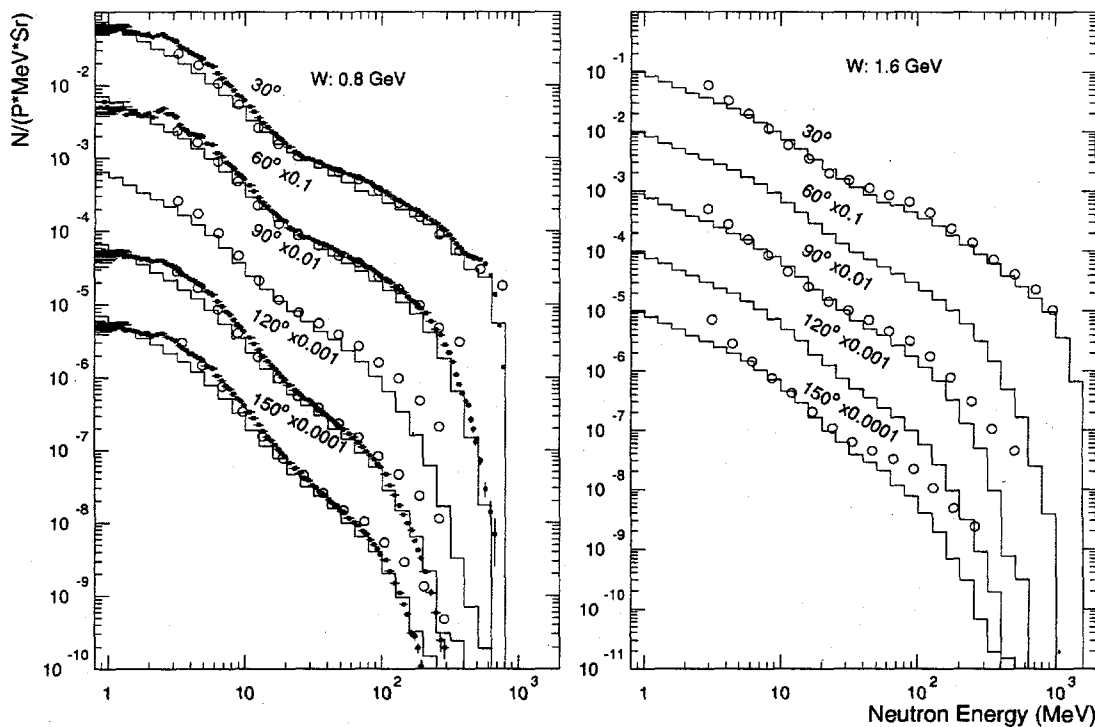


Fig. 6. The double differential neutron spectra from ^{187}W at energies of 0.8 and 1.6 GeV measured in the present work (\circ), in other works (\blacksquare : [10] for 0.8 GeV) together with the result of calculation using the LAHET code.

Neutron spectra from Na induced by 0.8 and 1.6 GeV protons

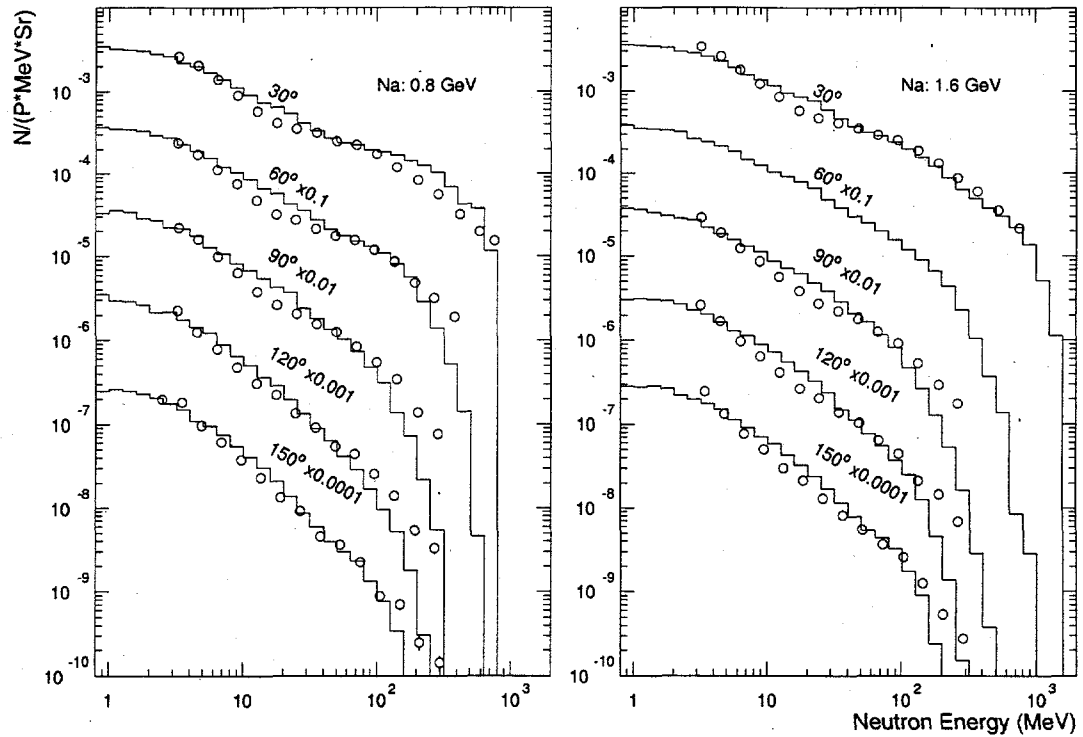


Fig. 7. The double differential neutron spectra from Na at energies of 0.8 and 1.6 GeV, measured in the present work (\circ), together with the result of calculation using LAHET code.

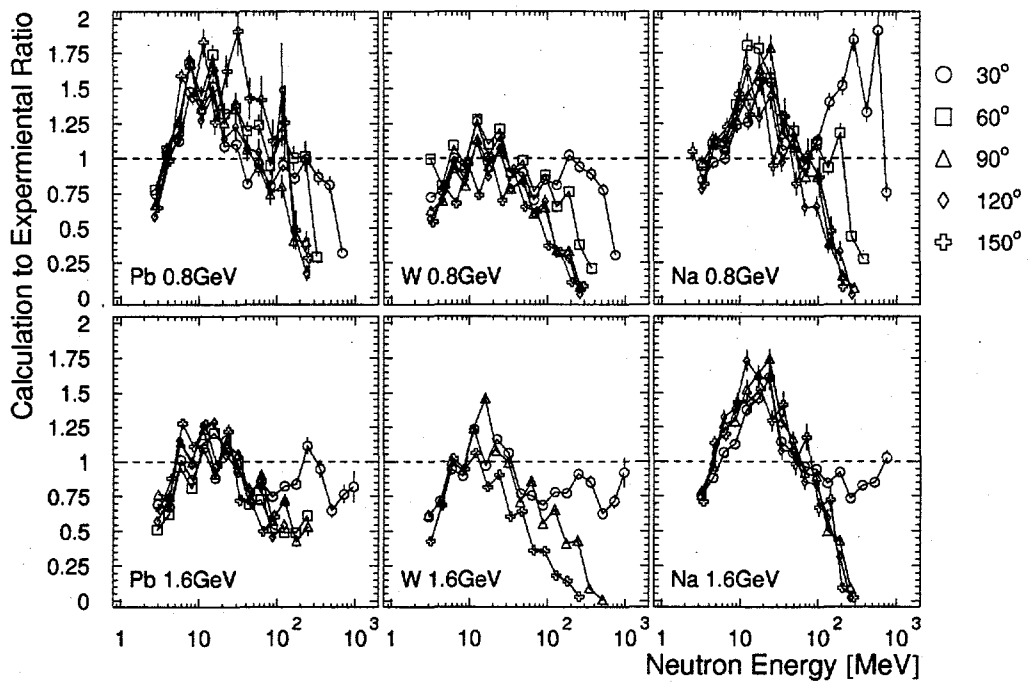


Fig. 8. Calculation-to-Experimental data ratios.

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