Neutron production from Li^7, Be^9, $B^{10,11}$, C^{12}, O^{16}, F^{19}, $Mg^{24,25,26}$, Al^{27}, $Ca^{40,44}$, Cu, $Sn^{116,124}$, Ta^{181}, and Pb nuclei at proton energies of 1 GeV

V. N. Baturin, V.P. Koptev, E.M. Maev, M.M. Makarov, V. V. Nelyubin, V. V. Sulimov, A. V. Khanzadeev, and G. V. Shcherbakov

B. P. Konstantinov Institute of Nuclear Physics, USSR Academy of Sciences

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High-energy ($T_n > 400$ MeV) neutron production cross sections have been measured for the first time for 18 nuclei from Li to Pb at angles of 4, 7.5, and 11.3°. The dependences of cross sections of quasi-elastic and inelastic neutron production on nucleon target composition are obtained.

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The study of neutrons produced in the interaction between nuclei and protons is important for understanding the mechanism for the interaction between high energy particles and nuclei, and in the study of nuclear structure. However, there is extremely little experimental data[1] on the process of high-energy neutron production, and the data mainly pertain to a neutron angle of 0°. In most of the work information concerning the neutron energy spectra was obtained by additional scattering of the resulting neutrons by a hydrogen target. In this work neutron energies were measured by the time-of-flight technique using the time microstructure of the accelerator beam.[2] The use of this technique was made possible due to good time-dependent parameters of the LIYaF synchrocyclotron beam, and permitted a significant increase in the rate for gathering statistics in comparison with the double scattering technique. We first carried out systematic studies of neutron production at several angles for a large collection of nuclei with $7 \leqslant A \leqslant 208$.

The setup and technique have been described in Ref. 3. Figure 1 shows the two differential neutron production cross sections from B^{11} and Ta^{181} nuclei. Analogous spectra are observed for other nuclei as well. All of the spectra show two clearly defined peaks. The peak in the higher energy region is related to quasi-elastic neutron production. Its position (T_{qe}) differs somewhat from the energy T_{kin} corresponding to the kinematics of elastic *pn*-scattering. The ΔE dependence which characterizes the average neutron emission energy in a given process is shown in Fig. 2. According to Fig. 2, ΔE is nearly constant for nuclei heavier than carbon. The quasi-elastic production cross section $(d\sigma/d\Omega)^{qe}$ was obtained by integrating the energy spectra in the region of the quasi-elastic peak according to the procedure given in Ref. 3. The dependence of $(d\sigma/d\Omega)^{qe}$ on the target nucleus atomic number has the following properties:

1) for symmetrical ($Z = N$) nuclei $(d\sigma/d\Omega)^{qe}$ is proportional to $A^{1/3}$;

2) for nuclei heavier than Cu ($N > Z$) the $(d\sigma/d\Omega)^{qe}$ dependence changes its nature and becomes close to $A^{2/3}$;

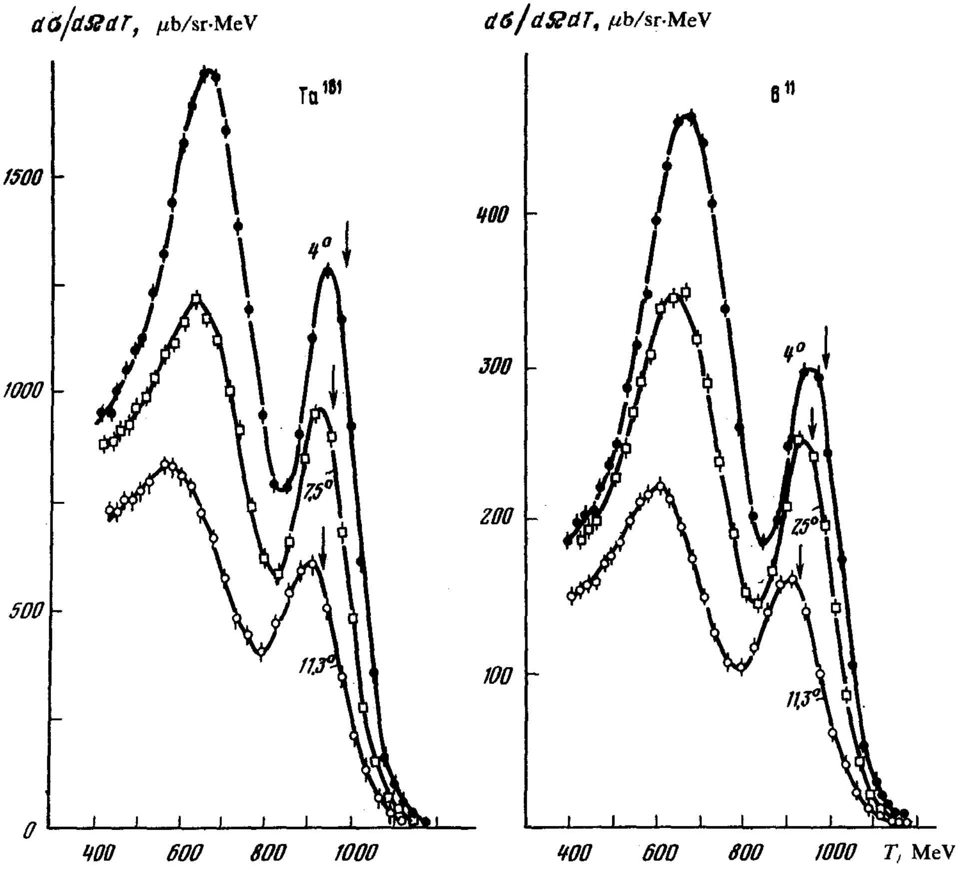

FIG. 1. Neutron spectra for B^{11} and Ta^{181} at angle of 4, 7.5, and 11.3°. Arrows indicate neutron energies corresponding to *pn*-scattering.

3) for all measured isotopes of B, Mg, Ca, and Sn, a significant increase in the cross section is observed with an increase in the number of neutrons.

The properties noted above may be described to within an accuracy of 10% by a simple phenomenological relationship: $(d\sigma/d\Omega)^{qe} = C_{qe}(\theta)N/ZA^{1/3}$, where $C_{qe}(\theta)$ is a normalized coefficient for angles 4, 7.5, and 11.3° and is equal to 18.5, 14.8, and 10.5 mb/sr, respectively. The broad maximum observed in the energy spectrum about 300 MeV away from the quasi-elastic peak is primarily related to neutron production in inelastic reactions with the production of π-mesons.

The dependence of the cross section for inelastic production of neutrons with $T_n > 400$ MeV on A is well approximated by the equation $(d\sigma/d\Omega)^{n_{inel}} = C_{inel}(\theta)A^{1/2}$, where $C_{inel}(\theta)$ is a normalized coefficient for the angles 4, 7.5, and 11.3° and is equal to 51.3, 36.8, and 25.1 mb/sr, respectively. It is interesting to note that for all three angles the $C_{qe}(\theta)$ and $C_{inel}(\theta)$ turned out to be close in magnitude to the correspond-

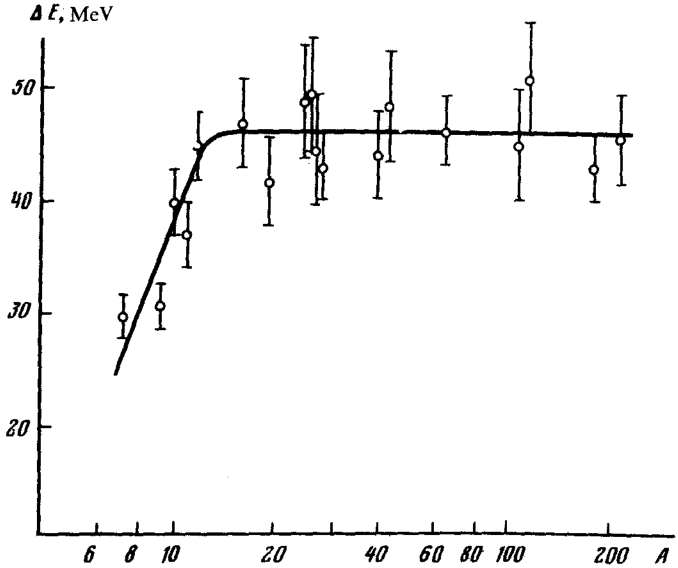

FIG. 2. Mean separation energies for neutrons during a quasi-elastic ejection process. Curve is drawn in by hand.

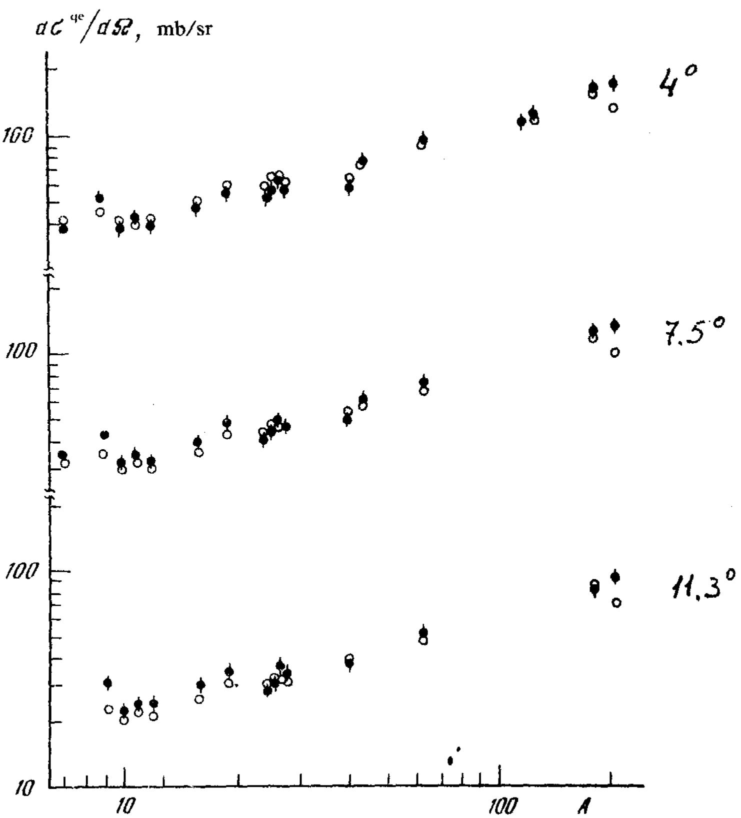

FIG. 3. Dependence of experimental (filled circles) and calculated (opened circles) cross sections for quasi-elastic neutron ejection on atomic number.

ing values of the cross sections for the quasi-elastic and inelastic production of neutrons from deuterium which were measured in the same experiment.

The cross section for the quasi-elastic production of neutrons was computed within the framework of the Glauber diffraction theory, taking into account the effects of scattering and absorption of the incident proton beam and of the produced neutrons.[4] The distribution of protons and neutrons for light nuclei with $A \leqslant 16$ was chosen in a form corresponding to a harmonic oscillator potential, and for heavy nuclei in the form of a two-parameter Fermi distribution. Figure 3 shows the results of the calculation under the assumption of a single distribution of protons and neutrons in nuclei. From Fig. 3, the agreement between experiment and theory is satisfactory for all nuclei except Be^9 and Pb. The significant excess of the experimental values of $(d\sigma/d\Omega)^{qe}$ at all three angles over the calculated values for Be and Pb may serve to indicate the difference in the neutron and proton distributions in these nuclei. An analysis of the experimental data and a detailed discussion of the computational scheme will be published later. The quasi-elastic neutron production process may be used to obtain information about the neutron distribution in the nucleus.

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