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THE SPECTRA OF NEUTRONS FROM THE n+^{209}Bi REACTION AT 14 MeV

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V.P. Lunev, A.A. Lychagin, S.P. Simakov,
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IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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THE SPECTRA OF NEUTRONS FROM THE n+^{209}Bi REACTION AT 14 MeV

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Bismuth is used as structural material in power reactors. For this reason the precision with which the secondary neutron spectra are required to be known is ~ 20% [1]. The available experimental data at 14 MeV do not yet satisfy this requirement, especially in the high-energy part of the spectrum. Moreover, ^{209}Bi is a neighbour of the twice magic nucleus of ^{208}Pb. This determines the comparatively simple structure of the excited states, offering additional possibilities for the theoretical interpretation of the inelastically scattered neutron spectra.

In view of the foregoing we carried out measurements and theoretical interpretation of the spectra of secondary neutrons generated after the interaction of 14 MeV neutrons with ^{209}Bi. In order to obtain a better energy resolution in the high-energy part, we supplemented the measurements on the small path length with those on a large path length in the experiment.

EXPERIMENT

The secondary neutron spectra were measured with a time-of-flight spectrometer based on the cascade pulse generator KG-0,3 [2]. The diagram of the experimental set-up is shown in Fig. 1.

A scintillation detector comprising an NE-218 (Ø 100 and height 50 mm) and a KhR-2041 photomultiplier was used for neutron recording. During the measurements at the small path length (L = 2.15 m) the detector was installed in a heavy shield, by moving which around the scatterer the spectra could be measured at different scattering angles. In order to obtain the large path length (L = 7.1 m), we placed the detector outside the experimental room's concrete wall, which had a collimation hole. The scattering angle was varied by moving the sample in relation to the target. When this was done,

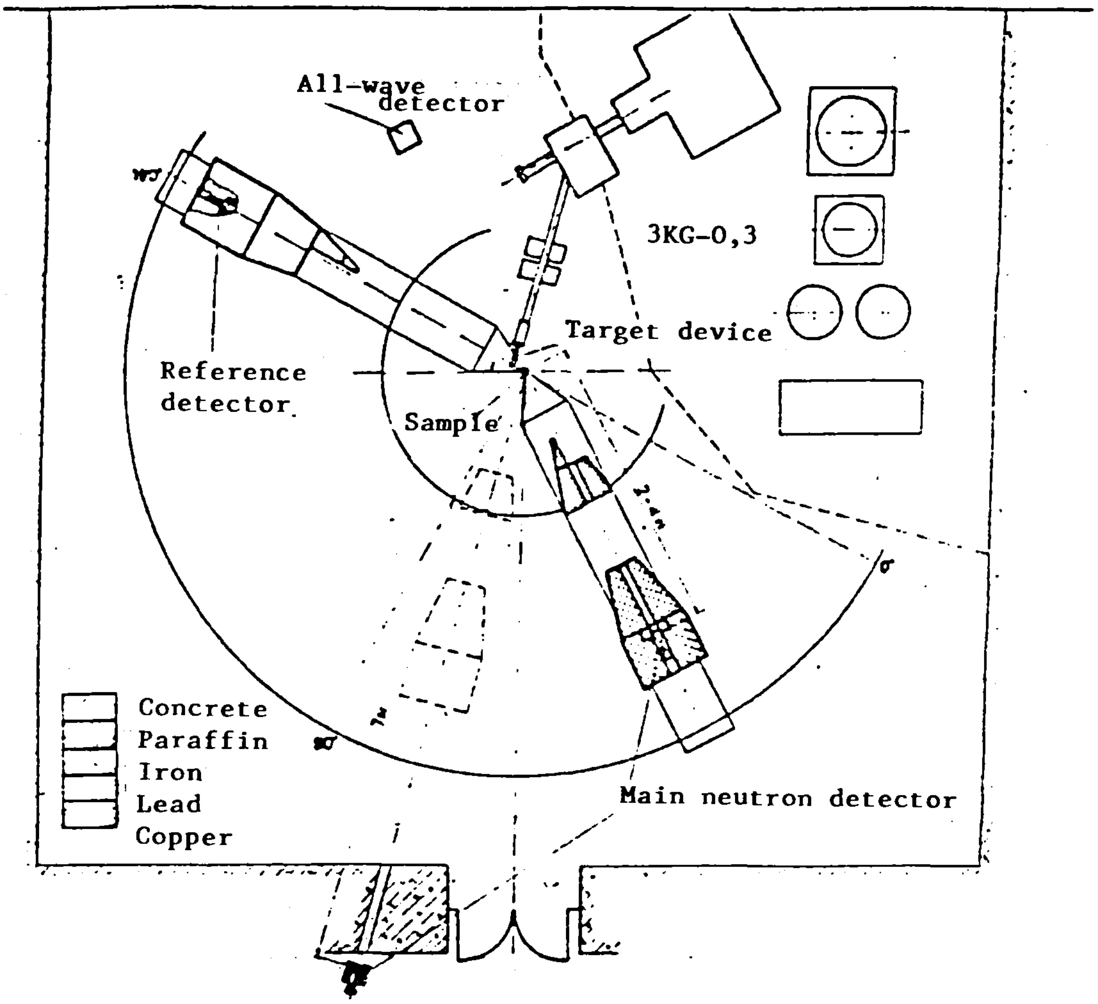

Fig. 1. Experimental set-up.

the energy E_0 of the neutrons incident on the sample also varied as a function of the scattering angle: 14.9 MeV (30°) to 13.3 MeV (150).

Since the repetition period of deuteron pulses on the target remained identical (T = 400 ns), a higher neutron detector threshold E_{thr} was set at the large path length to suppress the effect of cyclicity (Table 1). Table 1 also gives the spectrometer energy resolution ΔE for the neutron energy of 10 MeV, which was calculated from time resolution $\Delta t = 3$ ns. It will be seen that at the large path length the energy resolution is higher by a factor of 3.

The efficiency of the neutron detector was measured by two methods. In the first, a ^{252}Cf fission chamber was installed in place of the sample [3], and the fission neutron spectrum was measured by the time-of-flight

Table 1

Parameters of the spectrometer

L, m	E_0, MeV	E_{thr},MeV	ΔE, MeV
2,I5	I4,I	0,I6	0,37
7,I	I3,3-I4,9	I,3	0,I2

technique. Thereafter the efficiency was calculated from experimental data with the use of the standard ^{252}Cf fission neutron spectrum [4]. In the neutron energy region above 6-8 MeV, where the accuracy of efficiency determination with californium becomes low, we carried out calibration in relation to elastic neutron scattering by hydrogen [5]. For this purpose, a scintillation detector with a stilbene crystal 10 mm in diameter and 40 mm in height was installed in place of the sample. This detector served as scatterer at the same time and gave the stop signal for the time analysis since the accelerator was operated in the continuous mode in order to reduce the experiment time. The detector efficiency was found by averaging the results obtained by the two methods. The error of determination of efficiency was evaluated as 2-4%.

The sample under study had the shape of a hollow cylinder with an outer diameter of 50 mm, an inner diameter of 40 mm and a height of 50 mm. It weighed 429 g. The distance between the target and the scatterer for a scattering angle of 90° was 14 cm.

The measurement procedure for scattered neutron spectra included measurements with the sample (effect + background) and without the sample (background). In order to normalize these measurements, we used the readings of two monitors - all-wave counter and reference detector (Fig. 1). The latter was a scintillation detector measuring the spectrum of neutrons from the target by the time-of-flight technique. The absolute normalization of the measured scattered neutron spectra was performed with respect to the n-p scattering cross-section and by the Al-foil activation technique. Both methods give consistent results to within 5%.

The experimental data were corrected for beam attenuation and multiple neutron scattering in the sample. The correction was calculated by the BRAND program [6] with the NEDAM data package [7].

EXPERIMENTAL RESULTS

By carrying out measurements at two path lengths we obtained the secondary neutron spectra at five scattering angles (30°, 60°, 90°, 120° and 150°) in the scattered neutron energy regions of 0.6-10 MeV (measurements with L = 2.15 m) and 2-13 MeV (L = 7.1 m). The resulting file corresponding to the 0.6-13 MeV region and to the initial neutron energy of 14.1 MeV was compiled from these data. Here account was taken of the dependence of the initial neutron energy on angle in the measurements at the large path length. Considering that the (n, 2n) and (n,n') reaction cross-sections remain virtually unchanged in the 13.3-14.9 MeV region [8], the experimental spectra were reduced to one initial energy, namely 14.1 MeV.

The experimental data were compared with the results of Refs [9] and [10]. In Ref. [9] the experimental data of four original studies [11-14] were systematized and the evaluated spectrum of 14.1 MeV scattered neutrons by ^{209}Bi in the 0.25-12 MeV region was obtained. The difference between our data and those of Ref. [9] does not generally exceed 10%. An exception is the high-energy part of the spectrum, where the spectra in Refs [11-14] were measured with a lower energy resolution. The neutron spectrum was measured in Ref. [10] with a somewhat better resolution, and the disagreement with these data at some angles in the high-energy part of the spectrum reaches ~ 50%.

ANALYSIS OF EXPERIMENTAL DATA

The theoretical calculations of the secondary neutron spectra were carried out with allowance for the contribution of two mechanisms - equilibrium and direct. The statistical part of the cross-section was

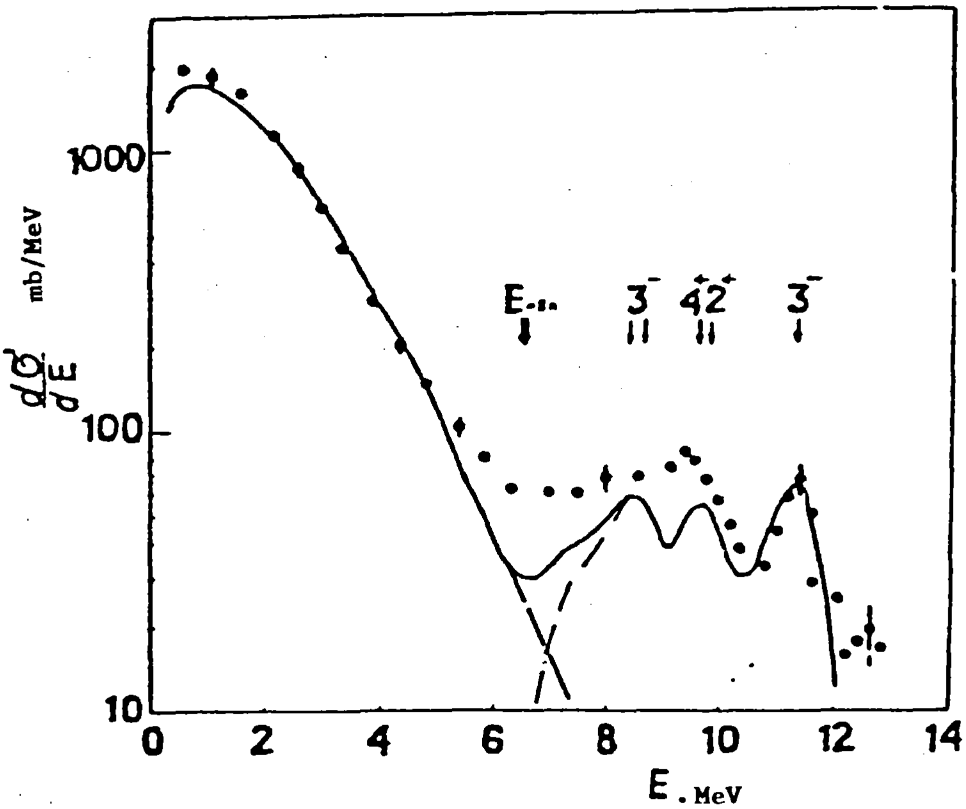

Fig. 2. Angle-integrated spectrum of secondary neutrons emitted during the interaction of 14 MeV neutrons with ^{209}Bi:
●◆ - Experimental data.
Calculation:
— — — - compound nucleus scattering,
—•— - direct scattering,
——— - their sum.
The arrows and numbers denote the position, spin and parity of the most strongly collectivized levels of ^{208}Pb. E_{n2n} is the maximum energy of neutrons from the ^{209}Bi(n,2n) reaction.

calculated within the framework of the Hauser-Feshbach formalism. In order to calculate the transmission coefficients, we took the optical potential parameters from Ref. [15]. We took into account the scheme of discrete states of the residual ^{209}Bi nucleus - 40 levels up to the excitation energy of 3.6 MeV. For higher energies we introduced the nuclear level density function within the framework of the phenomonological variant of the generalized superfluid model of the nucleus [16]. However, the density parameters were taken from Ref. [11], where they were obtained from the description of the neutron spectra of the (p,n) reaction with nuclei of the lead group.

The part of the cross-section corresponding to the direct process was calculated by the strong channel coupling method and in the Born approximation

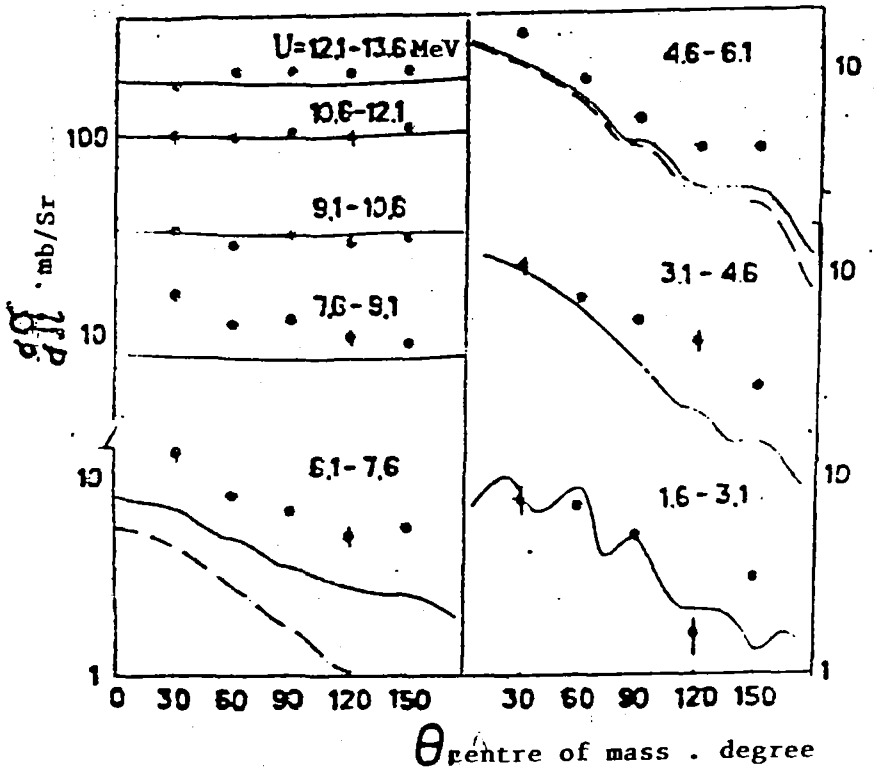

Fig. 3. Secondary neutron angular distributions integrated in the indicated ranges of excitation energy U. Notation as in Fig. 2.

of distorted waves. The structure of the excited states of the ^{209}Bi nucleus was modelled by approximation of the weak coupling of the odd proton in the $9/2^-$ shell with the vibrational states of the doubly magic ^{208}Pb core. Available experimental data [18, 19] confirm the validity of this assumption for the most strongly collectivized states. The spectroscopic data on the position, spin and parity of the vibrational phonons were taken from [19], where the experimental data on the ^{208}Pb reaction were analysed. The calculations were performed by the SMT 80 [20] and CCVIB [21] programs.

The calculation results and the experimental data are given in Figs 2 and 3. Comparison shows that they agree satisfactorily in the low-energy region of the spectrum ($E < 8$ MeV), where compound nucleus scattering predominates. In the high-energy part of the spectrum, as can be seen in Fig. 2, there appears a structure associated with direct excitation of the most strongly collectivized states of the ^{208}Pb core (in Fig. 2 their position, spin and parity are indicated by arrows).

In the intermediate energy region $5 < E < 10$, as we can see in Fig. 2, the theoretical calculations are lower in comparison with the experimental data. This is due, in our opinion, either to a gap in or to lack (in Ref. [19] data are available to an excitation energy of 7.4 MeV) of data on the parameters of the excited states in direct transitions. In order to fill this gap, we evaluated the contribution of the two-phonon states to this region within the framework of the harmonic oscillator model. The total contribution of the two-phonon states is ~ 2 mb/MeV in the 4-7 MeV region, which leads to an increase by less than 10% in the calculated cross-section in this region.

The "experimental" evaluation of the direct process contribution as the difference between the experimental spectrum and the spectrum calculated by the Hauser-Feshbach model is 351 mb, whereas the sum of the cross-sections of all the direct transitions considered is 181 mb. For an explanation of the remaining difference it is necessary, to all appearances, to apply the model of direct excitation of single-particle levels (simultaneously with description of the levels of the ^{209}Bi nucleus, which is more correct than the weak coupling model) or the mechanism of multistage direct and statistical transitions.

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