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COMPARISON OF EVALUATION AND EXPERIMENT FOR NUCLEAR CASCADE INDUCED BY 650 MeV PROTONS IN THICK LEAD TARGET OF A SUBCRITICAL ASSEMBLY

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2. EXPERIMENT AND CALCULATIONS

The experimental investigations of the integral and differential characteristics of the hadron field around the thick cylindrical target of natural lead (50 cm long and 8.2 cm in diameter) irradiated by protons with energy 650 MeV have been done at the JINR phasotron. Neutron spectra have been measured at angles 45^0, 75^0 and 105^0 to the beam direction by a multisphere Bonner spectrometer (BSS) with LiI detector. The angular distributions of specific activities of threshold activation detectors arranged around the target as well as spatial distributions of the same values on the target surface have been evaluated experimentally. The experimental techniques and the experimental conditions are discussed in detail in [3, 4].

The numerical evaluations of neutron spectra from the target taking into account the detailed experimental conditions have been done in two ways.

The first one was a combination of the LAHET Code System [5] – for the nuclear cascade calculation at energies above 20 MeV and the MCNP4B code [6] – for the neutron transport evaluation below this energy threshold. The full information about neutrons ending their processing in the LAHET (falling below 20 MeV) has been then used for description of the neutron source for subsequent calculations with the MCNP4B code. The output data from the LAHET code have been transformed to the necessary format and transmitted in parts to the MCNP4B as the input data. The MCNP4B used the ENDF-B/VI cross-section library.

In the second way the calculations of neutron spectra has been performed with the use of MCNPX code [7] that also contains the LAHET code for high-energy calculations.

In both cases the Bertini model [8] for simulation of inelastic interactions of high-energy hadrons with nuclei has been used.

The monodirectional proton beam (energy 650 MeV) with the Gaussian shape of density distribution (σ = 4.5 mm) profile has been assumed for the calculations. A 1.5 mm thick cylindrical layer of stainless steel covered the target on its side. The calculated neutron spectra are energy dependent neutron fluences averaged over a sphere with 30.48 cm diameter placed at 277 cm distance (radius) from the target centre at the different angles. This volume corresponds to the volume of 12″ spherical moderator of the BSS. In fact the BSS readings were averaged over a set of volumes for diameters starting from the 12″ down to the smallest one 2″. However, this assumption should not bring a significant discrepancy between the experiment and the calculations owing to the weak angular dependence of neutron flux within the solid angle of such sphere as seen from the target.

The experimental geometry simulated in the codes input files is shown in Fig. 1.

3. RESULTS AND DISCUSSION

The results of comparison of the calculated and experimental spectra at three angles with regard to the beam are presented in the Figs. 2-4. The results are normalized to one beam proton. In addition to the Bertini intranuclear cascade model the other accessible options – SEM and ISABEL models have been also tested in the calculations of neutron spectra. All of them produced very similar spectra shapes and are not shown in the graphs.

The relative statistical errors of the calculation results in the most important energy range amount to 2÷3%. As a whole, the agreement of absolute values and the shapes of the experimental and calculated spectra are relatively satisfactory. The largest discrepancies have occurred in the high-energy regions of the spectra and in the 5÷20 MeV energy range. They can be explained by the following reasons of both the experimental and the calculation nature.

First of all, the BSS response functions in high-energy regions weakly depend on the neutron energy. As a result, the ability of the BSS technique of spectrum unfolding is poor in this range due to the information deficit. It is an inherent imperfection of the method while an improvement of the spectra unfolding in the high-energy range would require well precise knowledge of the BSS response functions, experimentally verified at neutron energies above 20 MeV. The use of a shadow bar between the BSS and the target for the background subtraction also caused a certain underestimation of the experimental spectra at high energies due to the insufficient thickness of the bar. The use of a priori information about the smoothed spectrum shape at the unfolding has brought a light correction in this shape too. However, the discrepancy at high energies is not so important in practice because the contribution of neutrons with energies above 30 MeV in the total fluence has not exceeded 5 %.

On the other hand there is a light underestimation in the results of fast neutron calculations because of imperfect modelling of the evaporation process (neglect of the neutron generation by protons with energies below 20 MeV) and due to the neglect of photoneutrons. A consideration of the contribution of these processes might correct the spectrum shape in the interval from 0.5 to 20 MeV.

The experimental and calculated fluences (neutron·cm^{-2} per initial proton) in the energy range from $3\cdot10^{-2}$ to 650 MeV at the 277 cm distance from the target centre are presented in Table. In our case a presentation of the differential data in terms of a radiation source (neutron per sr) is not strict since the target cannot be considered as punctual in the given measurement geometry.

The angular distributions of specific activities (measured in the experiment) of activation detectors around the target have been simulated with the MCNPX code. The specific activity of the detector is $A^{\infty}/(M_d{\cdot}I)$, where A^{∞} – the detector's activity extrapolated to the infinite time of the irradiation (s^{-1}), M_d – the total amount of ^{12}C atoms in the detector volume, I – the average beam intensity during the irradiation time (proton·s^{-1}). For the specific activities verification the energy depending neutron fluences of secondary hadrons (neutrons and protons) averaged over the detector's volumes at 1 m distance from the target centre have been calculated for every 15^0. These spectra at every angle have been then separately convoluted with the corresponding cross-sections of the ^{27}Al(h, x)^{18}F, ^{12}C(h, x)^{11}C and ^{27}Al(h, x)^{24}Na reactions with energy thresholds about 40, 20 and 6 MeV respectively. The total activities of the ^{12}C and ^{27}Al detectors induced by hadrons were obtained as the sum of two reaction channels. The uncertainty of the experimental reaction cross-section data determines mainly the errors of the evaluated activities. The experimental errors were estimates from 6 % in maximums of the distributions to 15 % in minimums of the distributions [4]. The adopted cross-sections of the above reactions have been taken from [9-11] and are shown in Figs. 5 and 6. The detector activation due to gammas and π-mesons did not take into account at calculations because of their reaction cross-sections negligibility.

The experimental and the calculated angular distributions of specific activities are compared in Figs. 7 and 8. It is obvious that the contributions to the detectors activity from neutrons and protons strongly differ depending on the angle except of the $^{27}Al(h, x)^{24}Na$ reaction distinct by a very small proton cross-section as compared to the neutron one. The statistics of calculations at 0^0 have been insufficient (particularly for protons), thus these data are not indicated in the graphs. As a whole, the calculated and the experimental angular distributions show fair agreement with the exception of the back angle 165^0 where the estimation of low energy albedo protons from the target may be understated.

In the same way the longitudinal distributions of specific activities of the aluminium foil and of the polyethylene film wrapped around the target has been calculated. The reactions $^{12}C(h, x)^{11}C$, $^{27}Al(h, x)^{24}Na$ and $^{12}C(h, spall)^{7}Be$ (energy threshold about 30 MeV) were considered. The spectra of hadrons coming out from the target have been averaged over each eighth part of its surface and on the front and back ends of the target. The experimental longitudinal distributions and the calculated ones are presented in Figs. 9 and 10. The calculations correctly describe the experimental distributions of the specific activities of irradiated detectors. The quantitative differences in the activities remain within the limits of total uncertainty of the comparison. It can be seen in the graphs that the proton contributions to the activities grow with the energy decrease that results in flattening of the distribution in that region.

The results of the present detailed study confirm a sufficient reliability of both aforementioned codes for the estimation of the physico-technical characteristics of subcritical assemblies driven by a high-energy (here 650 MeV) proton beam.

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Table. Comparison of experimental and calculated neutron fluences at the different angles

Angle	45^0	75^0	105^0
Experiment	$(1.40\pm0.05)\cdot10^{-5}$	$(1.42\pm0.06)\cdot10^{-5}$	$(1.26\pm0.07)\cdot10^{-5}$
Calculation by:			
MCNPX	$(9.647\pm0.019)\cdot10^{-6}$	$(1.070\pm0.002)\cdot10^{-5}$	$(1.013\pm0.002)\cdot10^{-5}$
LAHET + MCNP4B	$(9.391\pm0.193)\cdot10^{-6}$	$(1.046\pm0.022)\cdot10^{-5}$	$(1.053\pm0.276)\cdot10^{-5}$

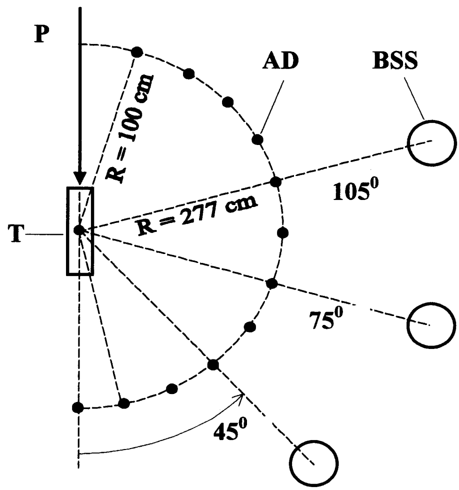

Fig.1. Sketch of the experiment geometry. T – the target, BSS – the multisphere spectrometer, AD – the C- and Al-activation detectors.

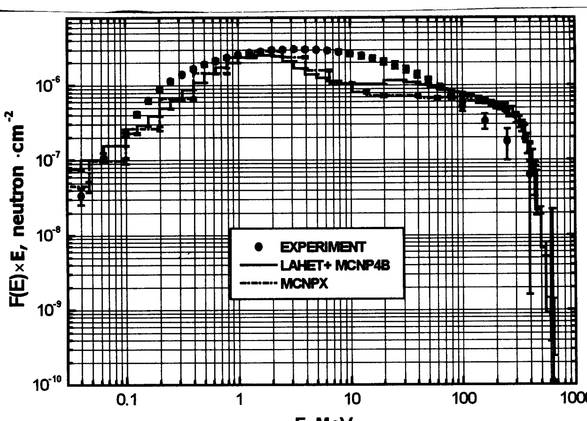

Fig.2. The calculated and experimental neutron spectra at 45^0.

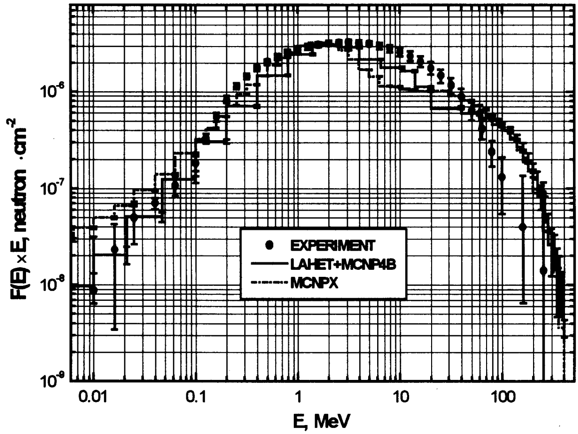

Fig.3. The calculated and experimental neutron spectra at 75^0.

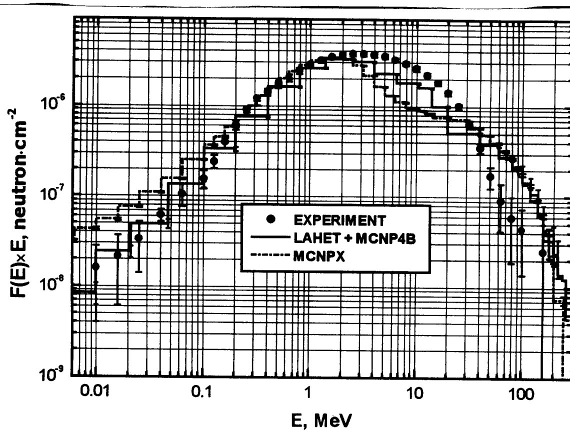

Fig.4. The calculated and experimental neutron spectra at 105^0.

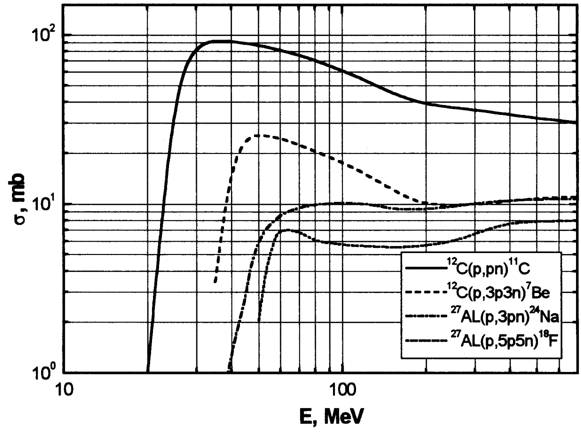

Fig.5. The proton cross-sections for AD.

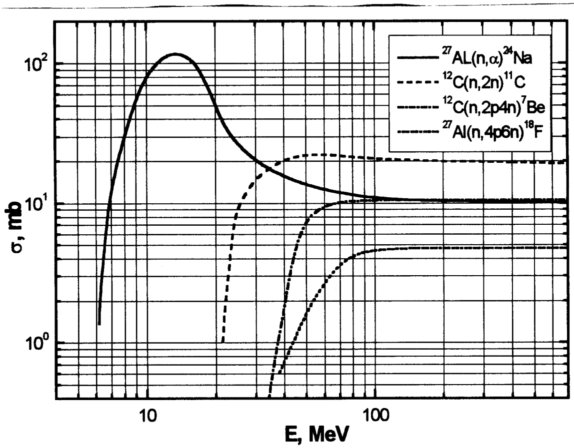

Fig.6. The neutron cross-sections for AD.

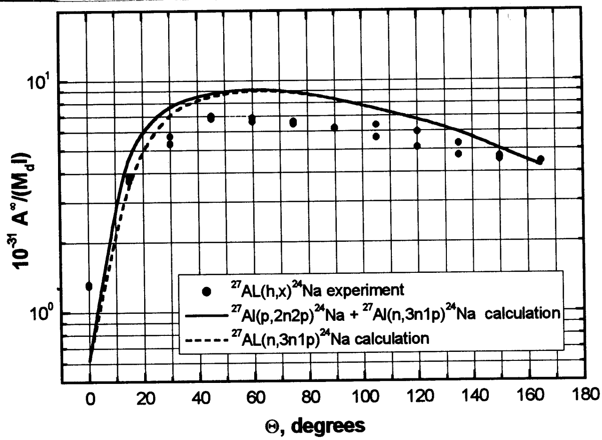

Fig.7. The angular distributions of the specific activities of the Al-detectors caused by the $^{27}Al(h,x)^{24}Na$ reactions.

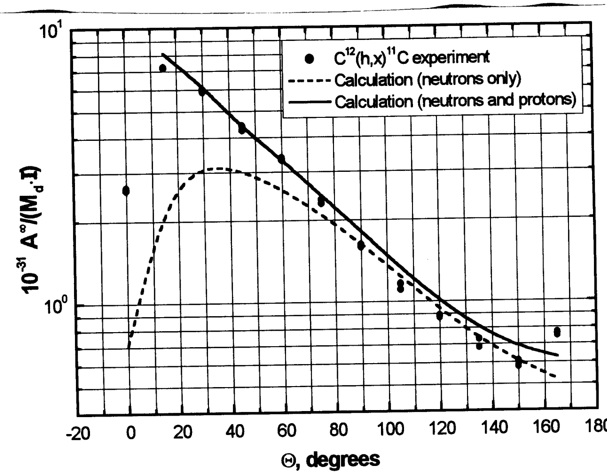

Fig.8. The angular distributions of the specific activities of the C-detectors caused by the $^{12}C(h,x)^{11}C$ reactions.

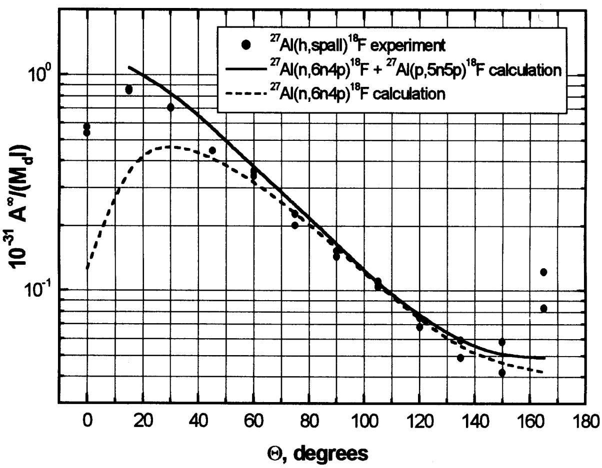

Fig.9 The angular distributions of the specific activities of the Al-detectors caused by the ^{27}Al(h, spall)^{18}F reactions.

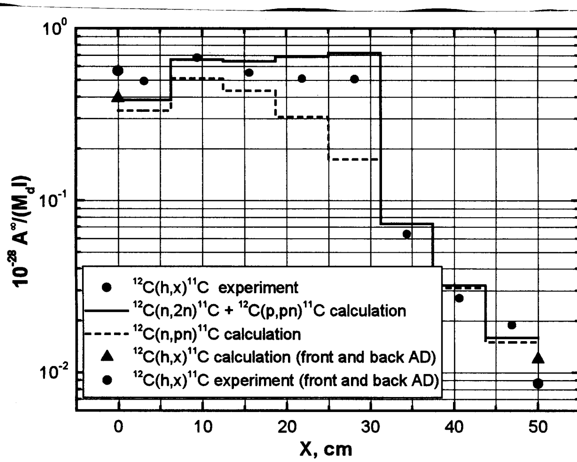

Fig.10. The spatial distributions of the specific activities of the C-detectors caused by the ^{12}C(h, x)^{11}C reactions.

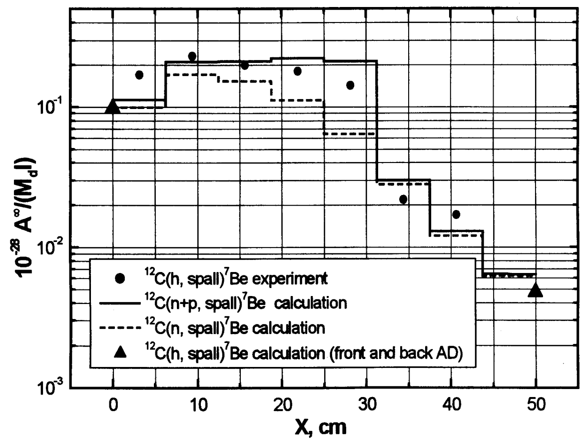

Fig.11. The spatial distributions of the specific activities of the C-detectors caused by the $^{12}C(h, spall)^{7}Be$ reactions.

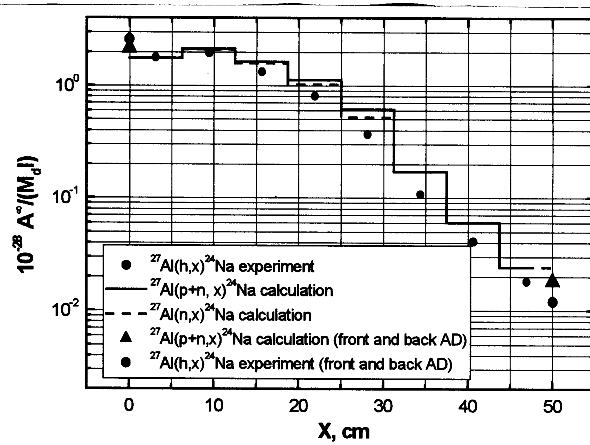

Fig.12. The spatial distributions of the specific activities of the Al-detectors caused by the $^{27}Al\ (h, x)^{24}Na$ reactions.

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Бамблевский В. П. и др. E3-2002-273
Сравнение расчетов с экспериментальными данными по развитию ядерного каскада, индуцированного протонами с энергией 650 МэВ, в толстой свинцовой мишени подкритической сборки

Описаны расчеты межъядерного каскада, развивающегося в толстой свинцовой мишени, облучаемой пучком протонов с энергией 650 МэВ. Данная работа выполнена в рамках проекта SAD (создание управляемой протонным ускорителем подкритической сборки на основе металлооксидного уран-плутониевого топлива). Результаты расчетов по различным программам спектрально-угловых потоков нейтронов из мишени в широком диапазоне энергий, а также угловых и пространственных распределений вторичных адронов сравнивались с результатами экспериментов, проведенных на пучке протонов фазотрона ЛЯП ОИЯИ. Получено хорошее согласие расчетных и экспериментальных данных.

Работа выполнена в Отделении радиационных и радиобиологических исследований ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2002

Bamblevski V. P. et al. E3-2002-273
Comparison of Evaluation and Experiment for Nuclear Cascade Induced by 650 MeV Protons in Thick Lead Target of a Subcritical Assembly

The evaluations of nuclear cascade generated within a thick lead target irradiated with the 650 MeV proton beam are described. The experiments have been performed at the proton accelerator of the Joint Institute for Nuclear Research within the framework of the project SAD (MOX fuelled Subcritical Assembly in Dubna). The calculated (with differnt codes) neutron spectra in a wide energy range as well as the angular and spatial distributions of secondary hadrons from the target are verified by the respective measurements. The agreement between the calculated and experimental data proved quite satisfactorily.

The investigation has been performed at the Division of Radiation and Radiobiological Research, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2002

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