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COMPUTATION METHODS FOR NEUTRON, HEAT AND RADIATION DAMAGE PROPERTIES OF PULSED NEUTRON SOURCES

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ABSTRACT

The results of calculations of neutron yield, heat and nuclei-products distributions for heavy extended targets (natural W, Pb, and depleted U cylindrical targets; D=20 cm, L=60 cm) irradiated with proton beam of energy up to 100 GeV are presented as well as the radiation damage cross sections for thin layers of structure materials. The calculations were made with Monte Carlo method on the base of exclusive high energy hadron transport code SHIELD. The comparison with available experimental data is given. An expediency of elaboration of spallation neutron source based on high-energy accelerator is briefly discussed.[1]

1 .Introduction

Process of neutrons generation in heavy extended target (W, Pb, U) under proton beam irradiation is a background for a number of important trends in nuclear physics and technics. These are, primarily, the pulsed neutron sources, conception of electro-nuclear breeding and connected with it problem of neutron transmutation of the power plant radioactive wastes which became especially actual during last years as well as some more special problems. In fact we are dealing with industrial production of neutrons. At that the questions of a total neutron yield from the target and a neutron energetic cost are very essential and even critical for some conceptions. Parameters of an energy release and nuclei-products distributions over a target volume are very essential also as well as the radiation damage of structure materials ones because of real constraining of beam power and consequently of the neutron yield. For these reasons a series of corresponding experimental and theoretical investigations has been undertaken since the fifties.

However a large-scale measurements with an extended target are very labor consuming and methodical sophisticated. Therefore only a limited number of measurements of total neutron yield from the target were made up to now. Results of early experiments in incident energy range near 1 GeV are presented, for example, in reviews [1]. In recent years the data have been produced in energy range 1 - 8 GeV for lead target [2] and at 70 GeV for tungsten target

[1] Keywords: Target, Neutron yield, Energy deposition, Monte Carlo

[3]. The calorimetric measurements of energy release in targets are presented in a few works only [4,5]. The situation is somewhat better for nuclei-products distributions over a target volume (see e.g. [6,7] and cited therein).

Thus the development of computation methods and computer codes for simulation of beam-target interaction process is necessary condition of a progress in the field under consideration. There are now several modifications of well-known transport code HETC [8] (LAHET-LANL, HERMES-KFA, NMTC-JAERI et al.) which provide mainly the adequate description of spallation-process in the target at proton beam energy up to several GeV. On the other hand presence of theoretical data for much more wide energy range would enable one to discuss some alternative conceptions of nuclear facilities.

Therefore the main objective of this work is systematic computational investigation of the total neutron yield from lead target under irradiation with protons of 0.1 to 100 GeV as well as the computation of energy deposition and nuclide production distributions in heavy targets and comparison with measured data. Question of structure materials radiation damage is briefly considered. The calculations were performed using the universal Monte Carlo hadron transport code SHIELD [9]. It is very close on its power to the HETC code in energy area up to several GeV. At the same time the SHIELD code is applicable for using up to 100 GeV and above.

2. Hadron transport code SHIELD

The SHIELD code is dedicated to the Monte Carlo simulation of hadron cascades in complex macroscopic targets of arbitrary geometric configuration and chemical composition. One can calculate a nucleon, pion, kaon, antinucleon, and muon transfer in energy range up to 100 GeV. The ionization loss of energy for charged particles and straggling are taken into account. At transporting of pions and kaons the main modes of 2- and 3-particles decays are simulated.

The capabilities and quality of a hadron transport code depends substantially on a hadron-nucleus (hA) generator used. hA-generator of the SHIELD code includes known Russian models of nuclear reactions: Dubna version of the intranuclear cascades model detailed in monograph [10]; for more high energies - the hadron-nucleus and nucleus-nucleus generator based on an independent quark-gluon string model [11]; a combined nuclear deexcitation model [12,13] considering the multifragmentation of highly excited nuclei, equilibrium particle emission involving evaporation/fission competition for heavy nuclei and Fermi break-up for light nuclei. The pre-equilibrium emission is taken into account recently. hA-generator of the SHIELD code provides an exclusive description of the nuclear reactions over entire energy range and nuclei-targets mass area.

During a hadron tree generation in target the source of the "evaporated" neutrons is formed as well as the sources of the mesons decay products: γ-rays, e^-/e^+, and neutrinos. Subsequent neutron transport is simulated with the original neutron code LOENT based on 26-group neutron data system BNAB [14]. The electromagnetic (EM) showers are simulated by means of the well-known EGS4 code which is connected to the SHIELD with a special interface.

Each hadron cascade tree is stored without any loss of physical information during its simulation, allowing to divide completely modeling and registrating parts of the code as well as to repeat tree processing and visualize the tree. The SHIELD code's open architecture presumes its modification and improvement.

Some parameters of hadron cascade which are computed with the SHIELD code can be used for further calculations. In particular the individual parameters of residual nuclei in a target (i.e. PKA - primary knocked-out atoms) were used in this work for calculation of the radiation damage cross sections of structure materials.

3. Results of calculations

In our calculations the targets are the cylinders of 20 cm diameter and 60 cm in length from W and Pb of natural isotope composition and from depleted U (0.3% U^{235}). Such dimension guarantees nearly complete absorption of hadron cascade charged component and are the accepted standard for topic in question. Pencil proton beam impinges on center of target along cylinder axis.

Fig.1 shows the yield of neutrons with energies below 10.5 MeV from the whole surface of Pb target in two different manners: while Fig.1a gives the yield in units neutron/proton, Fig.1b demonstrates the specific neutron yield, i.e. the number of escaped neutrons per incident proton and divided by the incident energy (neutron/proton GeV). The specific yield let us to emphasize the energetic optimum of spallation process (curve maximum corresponds to minimal energy cost of one neutron). The value 10.5 MeV is nothing more than upper limit of the 1-st BNAB energy group; the main bulk of the neutron yield is in this low energy region. The experimental data mentioned above are depicted here also. At 70 GeV the experimental neutron yield value [3] is given being recounted from tungsten to lead target according to the relationship $[Y(Pb)/Y(W)]_{exp}=[Y(Pb)/Y(W)]_{theor}$, where theoretical values of yield are obtained using the SHIELD code.

Fig.2 gives fractions of the beam energy expended in W target for

- forming of a source of neutrons with kinetic energies below 10.5 MeV (this fraction includes kinetic and binding energies),
- energy deposition in the target,
- energy leakage from the target during hadron and electromagnetic cascade development

as a percentage of beam energy. In turn the energy deposition is decomposed in its components. Taking the total deposited energy as 100% it is pictured what a fraction was released because of

- direct ionization loss of charged hadrons,
- heating due to EM showers induced by π^0 decays,
- kinetic energy of recoil/product nuclei,
- residual excitation of nuclei-products after particle emission from nucleus is exhausted (this excitation can be removed with γ-transitions only).

As one can see the fraction of the energy pumped from hadron to EM cascades via π^0 -decays exceeds direct ionization loss beginning from incident energies ~10 GeV. The share of residual nuclei in energy deposition is less than several percent in W target at all incident energies. Let us notice that for fissile target a contribution of kinetic energy of nuclei-products (fission fragments) into energy release can become determinative.

Fig.3 demonstrates the distributions of energy deposition along target axis for incident beam energies of 1, 10, and 30 GeV (the curves are result of histograms smoothing). Dotted lines give a variant of computation without simulation of EM showers: it was assumed that EM energy is deposed locally in π^0-decay point. Evidently last approximation is justified below 1 GeV only while the correct account of energy transfer by electron-photon showers becomes essential for forming of the proper energy deposition profile (including maximum location) as beam energy increases. At 1 GeV the comparison of SHIELD calculations of energy deposition profile with calorimetric measurements [5] for Pb and depleted U targets is presented. One can see a good accordance for both cases. As our calculations have demonstrated the contribution of kinetic energy of fission fragments into complete energy deposition in the target achieves about 70% for this fissile composition.

Fig.4 illustrates the charge distribution of nuclei-products formed during hadron cascade development in Pb target for beam energies of 1, 10, and 30 GeV. The contribution of different nuclear processes is easily observable. The area near Z of the target (Z=~60-83) is determined by deep disintegration (spallation) process. The responsibility for mediate Z area is on both fast fission and multifragmentation of highly excited nuclei processes. The small Z area is determined with the multifragmentation. As would be expected the role of this process increases with incident energy. In Fig.4b the depth distribution of the production rate (nucleus/proton) of radionuclide Pb^{201} is displayed together with measured one from [7] at incident proton energy of 1 GeV just as an example.

The radiation damage cross sections (barn*keV/proton) for structure materials with different Z (Al, Fe, Cu, Mo, W) are presented in Fig.5. Pencil proton beam of 600 MeV impinges normally on a thin material layer. The individual values (A_p,Z_p) for each nucleus-product and its kinetic energy E_0, as these are computed by the SHIELD code, were further used for radiation damage calculations with the RADDAM code [15]. These values (A_p,Z_p,E_0) enable one to calculate the damage energy E_d which, having been convoluted with the residual nucleus production cross section, give us the desired damage cross section. The details of E_d calculation procedure based on the works of J.Lindhard et al (1963) and of M.J.Norgett et al (1975) are described in [15]. The stopping power of the recoil ions in the material was treated in two ways: on the basis of Thomas-Fermi model or using some tabulated empirical data. The contributions into the cross sections were summarized over the whole nuclei-product ensemble. Degree of agreement of different variants between them is clear from the figure. It is difficult to make definite conclusion on the advantage of some variant as the radiation damage cross section defies to a direct measurement and some details of the HETC-calculation are omitted in corresponding articles (see [15] for greater detail).

4. Discussion

Thus the SHIELD code provides the adequate description of varied processes in extended targets at incident energies up to 100 GeV in exclusive (eventual) approach. In other words the code enables one to simulate any individual characteristics (including correlation ones) for each separate event but not just to get the averages on a whole ensemble (e.g. inclusive particle spectra). The SHIELD code is applicable for more high incident energies (up to 0.5 TeV at present time). However we didn't perform some systematic calculations above 100 GeV up to now. Moreover there are no available measured data suitable for comparison in this energy range.

At last let us discuss, using the obtained results, a possibility of designing a neutron source based on a high energy accelerator. As one can see in Fig.1b, the maximal specific neutron yield is observed at incident proton energy near 1.2 GeV. A fall in yield at lower energies is determined by direct ionization loss of primary protons energy while at more high energies - by energy transfer into electron-photon showers due to generation and decay of neutral pions (see Fig.2). Therefore the optimal energy for generation of neutrons (with respect to the energy cost of one neutron) is approximately 1.2 GeV. However an application of high-current proton beams of such energy is joined with some difficulties at beam forming and injection into a target which are connected, at first, with losses during beam acceleration and transport and, moreover, with radiation damages of materials and high density of energy deposition in target areas near its first wall.

On the other hand although the specific neutron yield decreases with incident proton energy, the total neutron yield is very high in tens GeV region and continues substantially increase (Fig.1a). For example at 70 GeV near 650 neutrons per proton are generated as compared to 24 neutrons at 1 GeV. Therefore one can discuss the possibility of neutron generation by means of 30 - 100 GeV proton beam but at beam intensity on one and a half - two orders below as compared to 1 GeV proton beam. This point of view was for the first time expressed in report [16] as applied to pulsed neutron source on a base of a 30 - 40 GeV energy proton accelerator ("kaon factory"). Decreasing of specific neutron yield by a factor of 2 - 3 in tens GeV region may be compensated by a significant softening of the "first wall" and target cooling problems (as the maximum of energy deposition is shifted inside target and becomes more smooth with incident energy, see Fig.3). Both these factors are very significant in point of realization of neutron generators on a base of the spallation process. It is not improbable that going up more on the incident energy one could generate record neutron fluxes using some existing by the time or building up superhigh energy accelerators [17].

5. References

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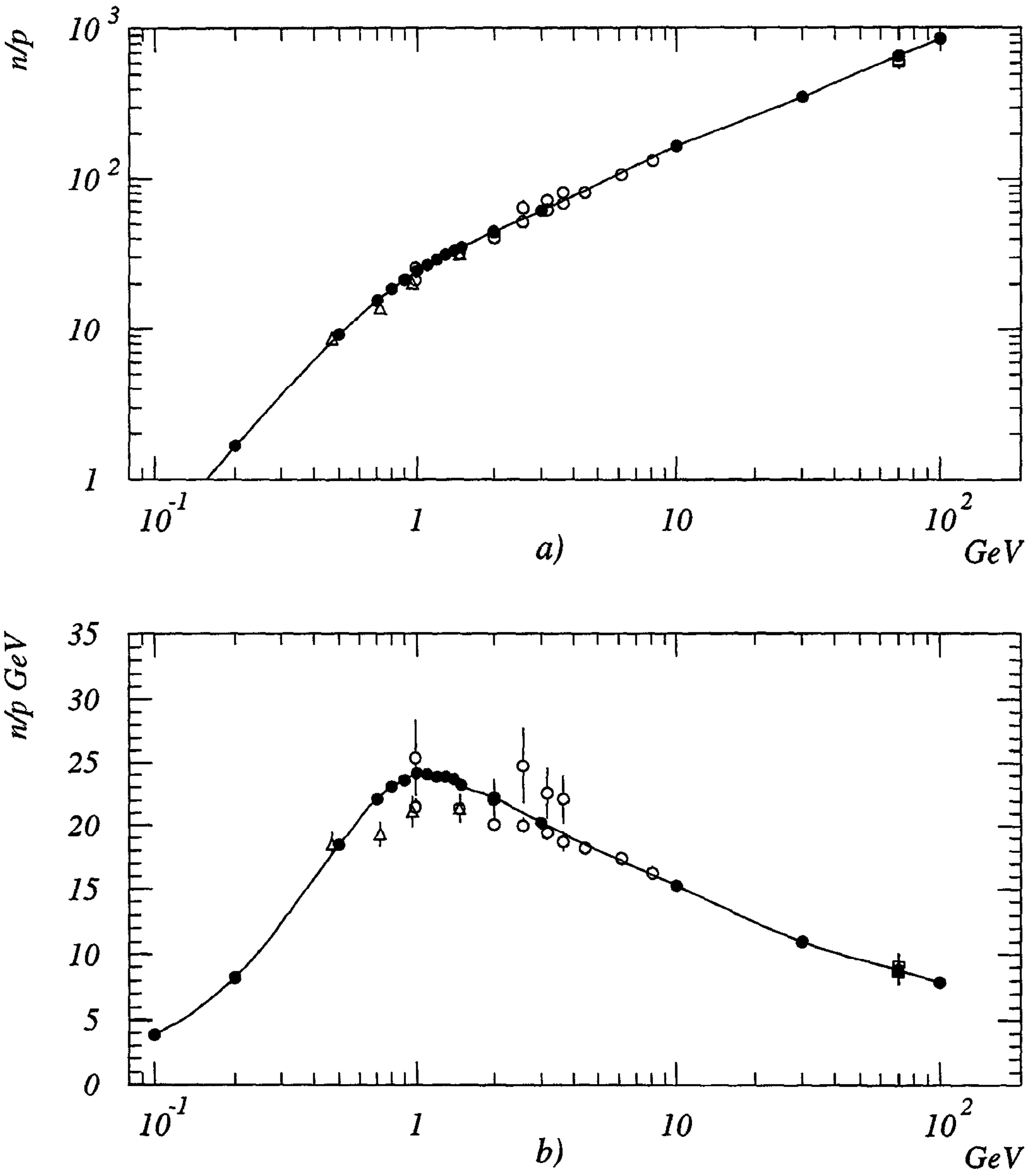

Figure 1: Neutron yield (a) and specific neutron yield (b) from a whole surface of Pb target (E_n <10.5 MeV). Curves approximate the results of SHIELD calculations. Experimental points are taken from works: △ – R.P.Trunnicliffe et al (extracted from [1]); ○ – [2]; □ – [3].

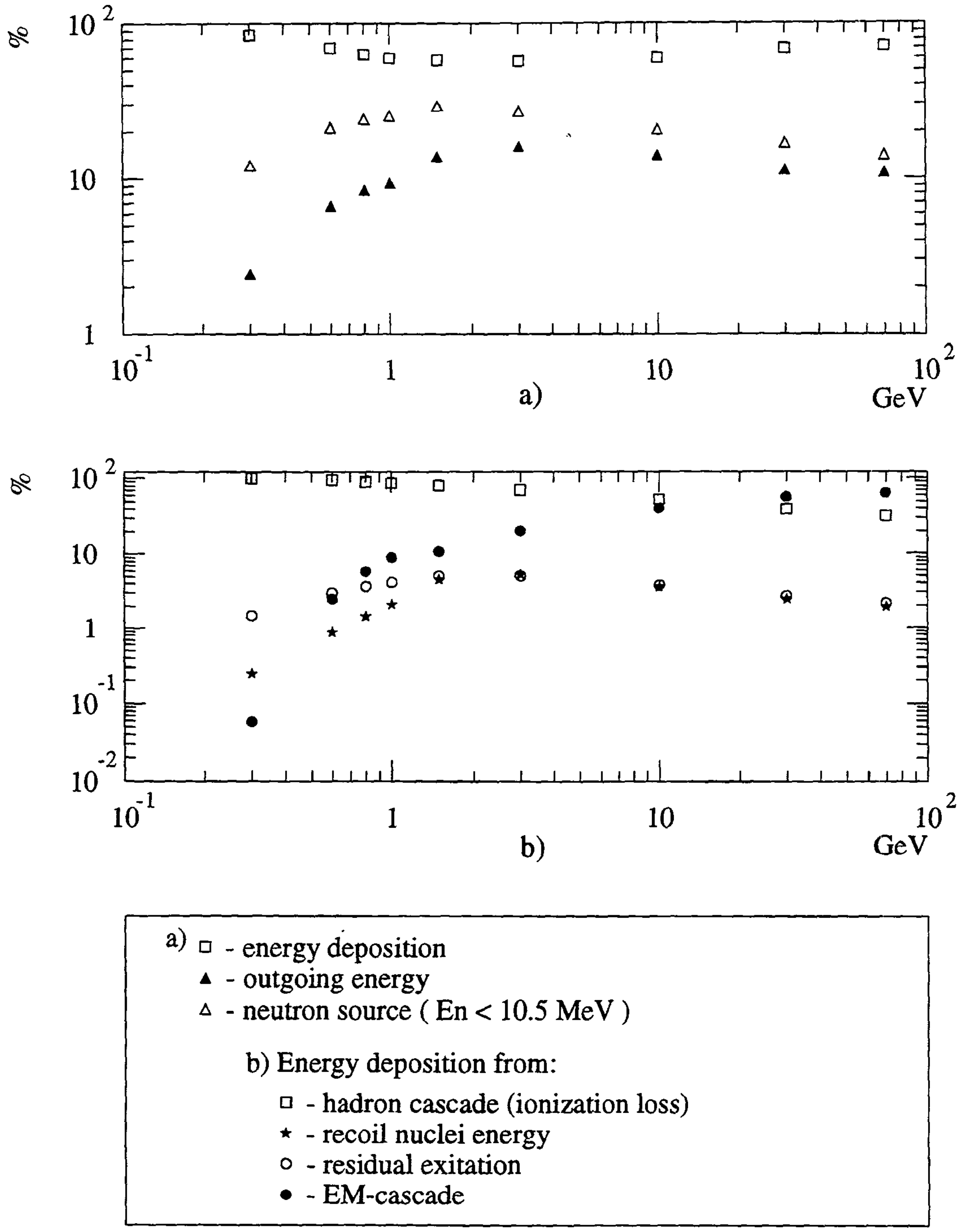

Figure 2: **W target: (a) fraction of proton beam energy (in %) have been spent on neutron source forming, target warming and removed from target (by hadron and electromagnetic cascades); (b) structure of heat release in dependence of primary proton energy (100 % – total energy deposition from both hadron and EM cascades).**

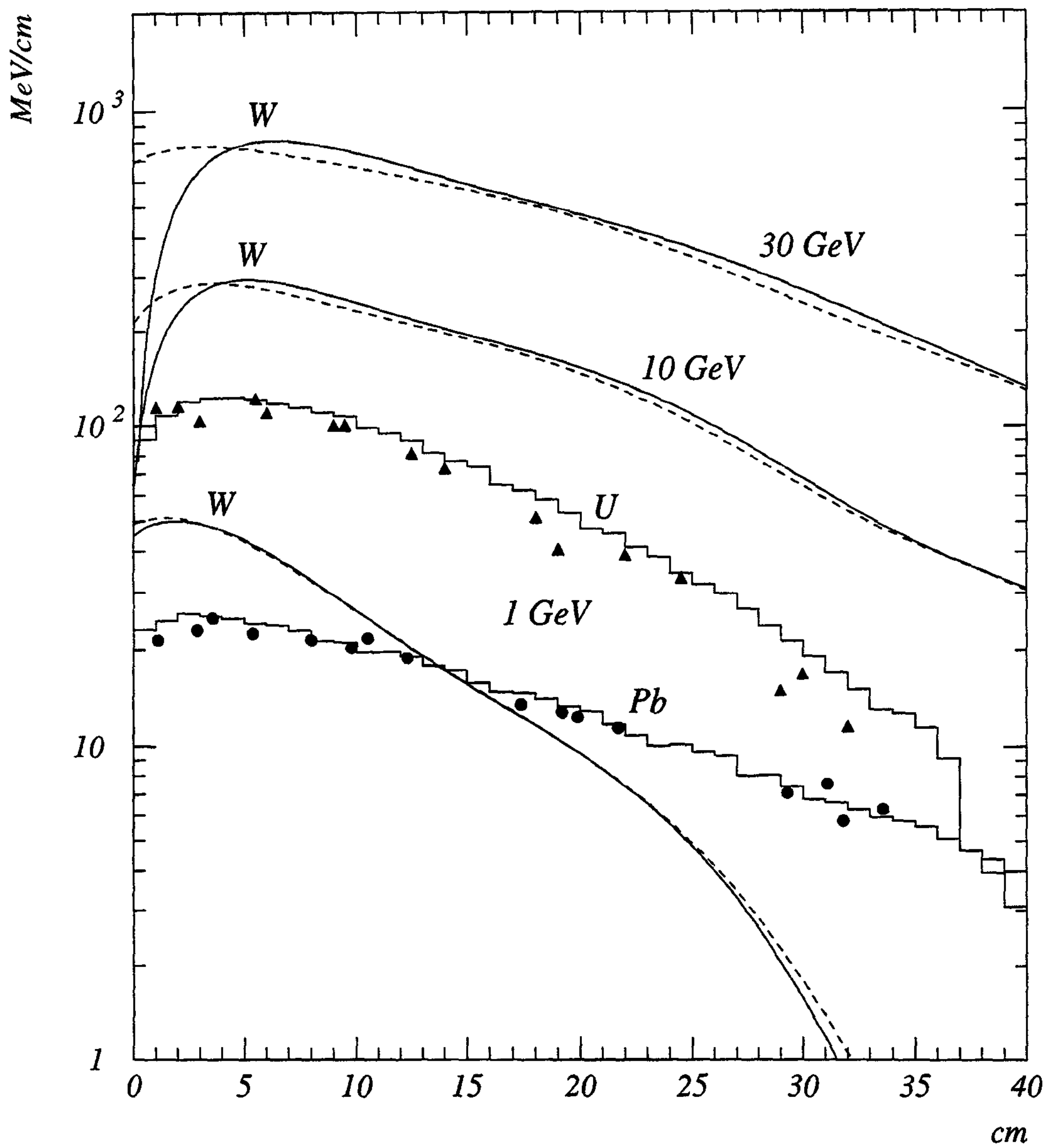

Figure 3: **Distribution of energy deposition in Pb, W, and depleted U targets along target axis. Solid line – calculation with consideration of EM showers (EGS4), dashed ones – calculation in assumption of local energy release at point of π^0 decay. Incident proton energy and target material are indicated near curves. Points show the calorimetric mesurements [5].**

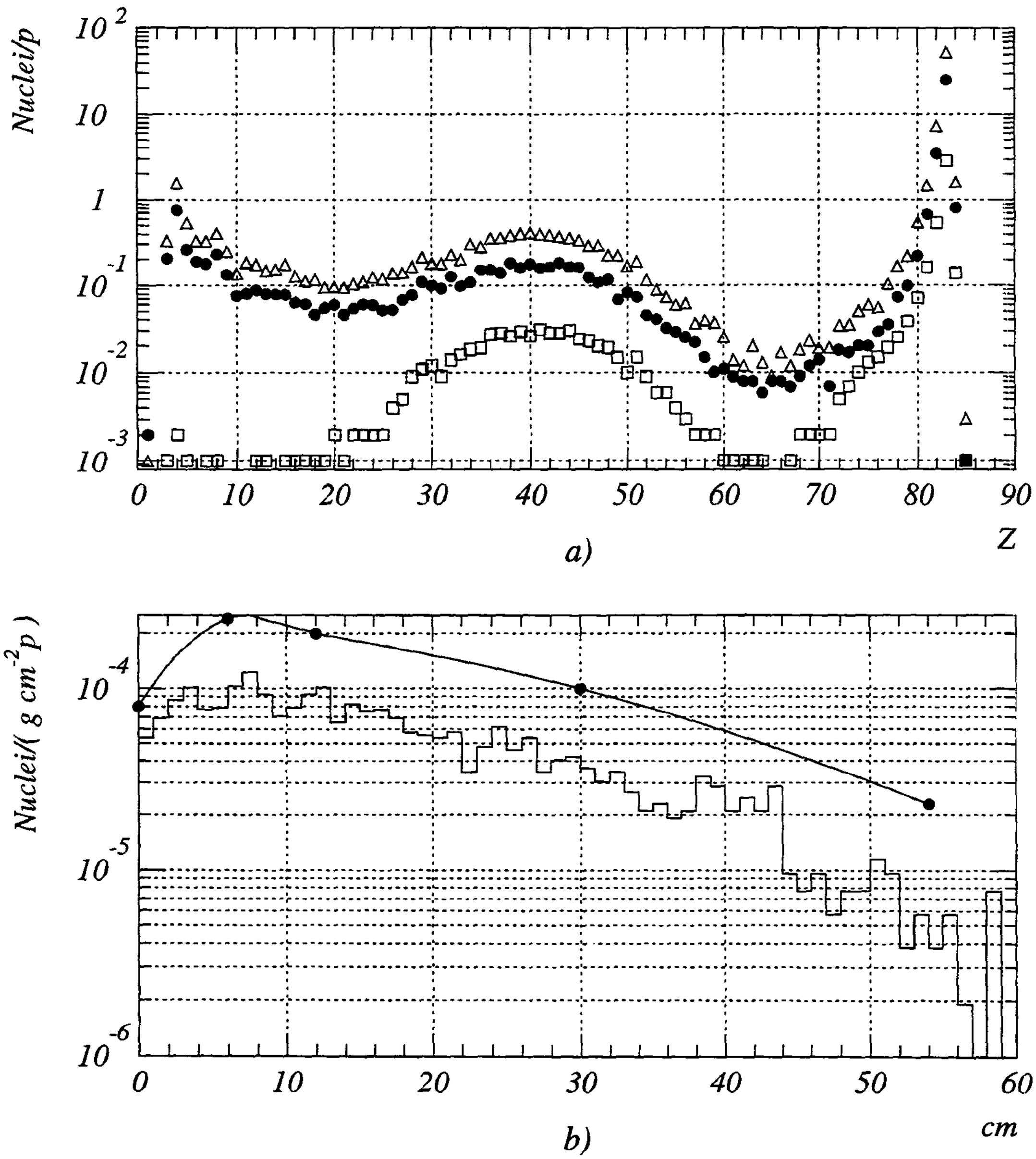

Figure 4: Nuclei-products charge distribution (a) over a whole Pb target at incident proton energies of: 1 GeV – □, 10 GeV - •, and 30 GeV - Δ. Distribution of product ^{201}Pb along Pb target axis (b) at icident proton energy 1 GeV as compared with measurement [7] - •.

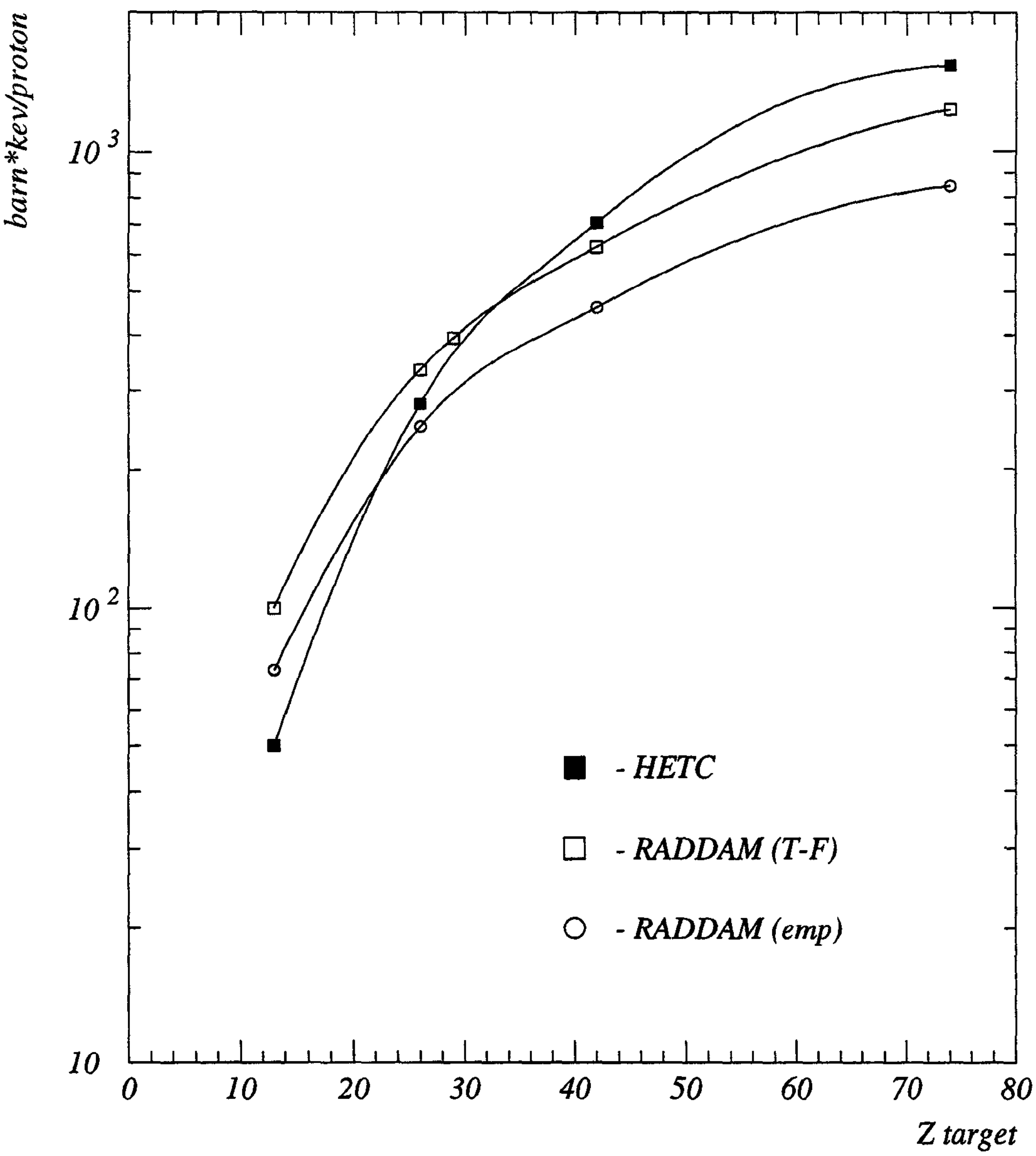

Figure 5: **Radiation damage cross section for thin metallic target of Al, Fe, Cu, Mo, and W under 600 MeV proton irradiation.**