

CONCLUSIONS of
INTERNATIONAL CODE COMPARISON FOR
INTERMEDIATE ENERGY NUCLEAR DATA
Thick target benchmark for Lead and Tungsten
Report NSC/DOC(95)2

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1. Introduction

The present text concerns the problem of accelerator driven transmutation of nuclear wastes (ADT). To be more specific, the task of computer simulation of a proton beam interaction with heavy extended targets is considered.

This Conclusion is based on the Report NSC/DOC(95)2 which contains: (1) a formulation of the benchmark problem for codes comparison; (2) brief writes-up of the hadron transport codes under comparison; (3) results of the calculations presented by the participants.

The benchmark problem was formulated as follows: a pencil proton beam at energy 800 MeV impinges along axis on the cylindrical target of $D=20$ cm in diameter and of $L=60$ cm in height. The target material is Pb or W .

The participants of the benchmark calculations were asked to calculate, per one incident proton: (1) neutron yield, i.e. the number of neutrons which were created over a whole target volume and their energy spectrum; (2) neutron leakage, i.e. the number of neutrons which went out across a whole side surface of the target, their energy spectrum, and the leakage distribution along target axes; (3) spallation product yield distributions over A and Z in a whole target. The other details for setting up the benchmark problem one can find in the Report NSC/DOC(95)2.

An attempt is made in this Conclusion to analyze the results obtained, to formulate some deductions and to suggest a plan for further works on development of the hadron transport codes in the context of the ADT problem.

2. Contributing Authors and Laboratories

Altogether 12 Laboratories (Groups) took part in the intercomparison (see Table 1), two of them have performed two variants of calculation. Thus there are a total of 14 variants but some Groups have presented only a part of the values asked (see Table 2). It seems appropriate to classify the Groups according to the codes used (see Table 1).

Most of the Groups have used some version of the well-known High Energy Transport Code (HETC) in combination with one of the neutron transport codes: MORSE, MCNP, TWODANT, 05R (the ENEA, JAERI, LANL, KFAKfK, PSI Groups).

The INR Group has used an original transport code SHIELD which is ideologically similar to the HETC code. The SHIELD code is based on Russian models of intranuclear cascades and deexcitation. Neutron transport is simulated on the basis of 26-group neutron constant system BNAB.

Two Groups (CDF and INFN) performed calculations with GEANT, FLUKA, and GHEISHA packages which are employed usually at simulation of installations in high energy physics.

At last, two Groups (ANSALDO and JINR) have used approaches which don't involve a Monte Carlo simulation of the hadron-nucleus interactions. More details on the codes used one can find in the Report NSC/DOC(95)2.

3. Integral Characteristics of Neutron Yield and Leakage

Let us consider at first the integral characteristics of the neutron yield and leakage, i.e. the total number of neutrons created in the target and the total leakage from the target across its side surface per one incident proton. Both these values will be considered for a whole energy interval 0-800 MeV as well as separately for two areas $E_n > 20$ MeV and $E_n < 20$ MeV. In Table 3 the data for the lead target are presented while in Table 4 are the data for the tungsten one.

Pb-target. As one can see from Table 3, all calculations based on HETC codes give close enough results. Nevertheless there are some disagreements and contradictions.

The explicit contradiction can be observed in Table 3 (see also Fig. 1a, 1b, 1c). According to data of most Groups the neutron yield exceeds the leakage in the energy region $E_n > 20$ MeV. On the contrary, in the ENEA and PSI Groups' reports, the leakage exceeds essentially the neutron yield (i.e. number of neutrons created in the target) in this energy region. There are no physical reasons for reloading of neutrons into this upper energy interval in process of neutron transport. At the same time the data of the ENEA and PSI Groups for the leakage agree mainly with other authors.

The reason for this contradiction can consist in not unique interpretation of the notion "neutron yield". Indeed the neutron leakage, i.e. the number of neutrons which escape the target across its surface is a uniquely defined value. It can be measured experimentally. In contrast, the neutron yield, i.e. the number of neutrons generated inside the target can't be directly measured. It assumes some agreement about a procedure of the registration (counting) of them during the computation which can depend on an algorithm (e.g. how many generations of secondary neutrons should be taken into account?). Therefore the neutron leakage is more preferable value for code intercomparison.

In the ENEA case, contrary to all other Groups, the leakage from Pb-target exceeds the yield for the area $E_n < 20$ MeV also and, as a result, for total energy interval 0-800 MeV.

It engages one's attention that the PSI Group's data for the leakage depend noticeably on which neutron transport code was used - either 05R or TWODANT - though the neutron yield is the same in both cases.

Otherwise the data of the Groups which have used the HETC codes don't contradict each other. The data of the INR Group (the SHIELD code) for the leakage are close to them also however INR data for the neutron yield are some above others. The reason for this discrepancy can be the same as mentioned above (not unique interpretation of the notion "neutron yield").

Unfortunately it is difficult to compare the data of the INFN Group on the leakage with the data of the other Groups as the INFN energy mesh not only differs from the one accepted in this benchmark, but has some gaps below energy 17.499 MeV as well (see NSC/DOC(95)2, p.80).

W-target. Passing on to the W-target (see Table 4) let us remark that all comments have been done above for the lead target are mainly valid in this case too. Therewith one can find some more scattering of the leakage values reported by different Groups.

Let us compare now the data for Pb- and W-targets. Due to essentially higher density of the tungsten, the number of interactions in W-target and consequently the neutron yield should be higher than for lead one. However due to higher neutron capture cross section in tungsten as well as to the absence of neutron multiplication in (n,2n) reactions at low energies, the leakage from W-target should be lower. This is observed for results of most Groups

excluding ENEA, CDF, and JAERI which give very close values for both Pb and W targets (see Tables 3 and 4).

Resume. The most consistent and free of inner contradictions seem the data for both Pb and W targets obtained with the HETC codes (the LANL, KFA, KfK-1 and PSI-2 Groups) and with the SHIELD code (INR). The JINR, ENEA, and JAERI Groups' values for leakage from Pb-target seem appropriate too. All these results don't contradict with the experimental data available for lead target of such dimensions (near 20 n/p at proton energy 0.8-1 GeV). However the ENEA and JAERI data for leakage from W-target seem some overestimated.

Unfortunately the CDF and INFN Groups, which used the GEANT, FLUKA, and GHEISHA packages, have presented insufficient information for definite conclusions.

4. Differential Distributions of the Neutron Yield and the Leakage

As one can see from the previous Section even for integral characteristics of the neutron generation process there are essential disagreements between results of several Groups and some inner contradictions which require clarifying. Therefore differential distributions presented below in graphic form should be considered rather as illustrative.

Fig. 1a, 1b, 1c show the energy spectra of the neutron yield and leakage for Pb-target (in units neutron per unit lethargy per proton). The figures illustrate a transformation of neutron yield spectrum during neutron transport before escape the target. Each subfigure is marked with corresponding Group's name.

Fig. 2 gives a spatial distribution of the neutron leakage along axis of Pb-target (in units neutron per cm² per proton). The figure displays the hadron cascade intensity in dependence on depth in the target.

Figures 3a,b,c and 4 depict the same distributions correspondingly for the W-target.

5. Spallation Product Yield Distributions

Passing to generation of the spallation products in the targets let us note that this characteristic of hadron-nucleus interaction is much more sophisticated than multiplicity and spectra of secondary particles. Different computer models can give close inclusive spectra but different cross sections for formation of some specific residual nucleus.

A- and Z-distributions of spallation product yields presented in Report NSC/DOC(95)2 illustrate this point well. Two of them (A-distributions for both targets) are reproduced in present Conclusion as Fig.5 and 6. As one can see from the figures the discrepancies between results of different Groups in some areas of A can achieve an order of magnitude and more. It is clear that yields of specific nuclides can differ still stronger. Herewith no regularity can be observed. So the KFA and LANL data for Pb-target basically agree but are essentially different from the INR data (see Fig. 5) while for W-target the KFA and INR data agree better but both differ strongly from the LANL data (see Fig. 6) and so on.

Therefore it is appropriate to compare at first the formation cross sections immediately for hadron-nucleus reactions. It is known that such a comparison is in progress now on NEA OECD's initiative (see NEA/NSC/DOC(95)8: "Specifications for an International Codes and Model Intercomparison for Intermediate Energy Activation Yields" by R.Michel and P.Nagel).

Some participants of the present Benchmark take part in this comparison and the preliminary results will be known by May 1996.

6. Conclusion and Suggestions for Further Codes Development

At first it is necessary to mention that the present intercomparison is very useful as it stimulates further works on development of computer models of particle-matter interaction drawing attention to discrepancies and inner contradictions.

On the other hand the present intercomparison shows that discrepancies amongst the most of the codes are not very large, at least for integral values. Each code has some free parameters which permit to change the results noticeably to one side or another. Therefore for further progress in the development of the hadron transport codes a lashing to reliable experimental data is necessary. However at the present time the lack of complete enough and uncontradictory measurements is perceived.

To stimulate setting up a complete, informative, and adequate to the ADT problem experiment with a macroscopic target it would be desirable to formulate a proposal and carry out computational design of such experiment involving neutronics as well as spallation product and energy deposition distribution over a target volume. This task could serve as a background for the next thick target benchmark.

It seems appropriate also to compile the experimental data on thick target measurements. This could create some basis for testing the hadron transport codes and stimulate the experimentalist drawing attention to contradictions and gaps in experimental data. Some attempts to create such a compilation were undertaken but proved far from completeness and not quite adequate to the ADT problem (see e.g. Report KEK 92-17 "Accelerator Shielding Benchmark Problems").

The other condition of a progress in the field under consideration is further improvement of hadron-nucleus interaction models included in the transport codes. Even a cursory comparison of the energy spectra of the yield and leakage reveals significant differences in shape (see Fig. 1, 3). The results on spallation product yields in the target (Fig. 5, 6) demonstrate large and irregular dispersion of the values too. All these results should be considered as an impetus for future enhancement of nuclear models since it is these models that are responsible in the first instance for denoted discrepancies.

Thus the principal task appears to be the further development of computer models of hadron-nucleus interaction, namely those which are being used practically in hadron transport codes. As a basis for this activity a systematic comparison with the whole bulk of available experimental data (not with some selected subset of them) should be taking place with the final goal of quantitative reconstruction of accumulated measurements and reliable extrapolation where experiments have not been made. In fact, such an approach opens the way to computational generation of reliable nuclear data.

In connection with the preceding, work on compilation of experimental data acquires special importance. While such an activity take place on nuclide production cross sections, in the fields of multiplicity and differential cross sections of secondary particles there were a few attempts having only a limited success. The main difficulty here is representation of heterogeneous data presented in original papers and databases in consistent form convenient for comparison with the computations (reference system, kinematics variables and so on). Thus there is a wide field for activity.

The questions of radiation damage of structural materials have close relation to the ADT problem. Therefore calculations of primary knock-out atoms (PKA) generation in materials under primary and secondary irradiation are of great interest. Here a correct reconstruction of recoil nuclei energy spectra, not only the production cross sections, is essential, so that still more high requirements are imposed on computation of hadron-nucleus interactions.

Finally, a possibility of neutron generation by high and superhigh energy proton beams should not be overlooked. Estimates show that this way has some advantages as compared to traditional one (high current proton beam at energy about 1 GeV) due to significant lowering of beam intensity and respective softening of the first wall problem and energy release tension. Hence a computation of interaction of high energy beam with extended target could have certain interest.

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Table 1. List of contributing authors and laboratories

Laboratory	Authors	Used Codes
1.ANSALDO (Genoa)	P.Neuhold P.Riscossa	Moving Source Model + MCNP
2.JINR (Dubna)	A.Daniel	SITHA = Linear transport eq.+ENDL82
3.CDF (Paris)	F.Bacha J.Maillard	GEANT + FLUKA + GHEISHA
4.INFN (Milano)	A.Ferrary P.Sala	FLUKA + PEANUT
5.INR (Moscow)	A.Dementyev N.Sobolevsky	SHIELD = INC+DEEXitation+BNAB
6.ENEА (Roma)	P.A.Landeyro A.Orazi, A.Santilli	HETC(NEA) + MCNP
7.JAERI (Japan)	H.Takada	MNTC(JAERI) + MCNP
8.LANL (Los-Alamos)	L.L.Daemen G.Russel	LAHET + MCNP
9.KFA (Julich)	P.Cloth, V.Druke D.Filges, R.D.Neef	HERMES = HETC(KFA) + MORSE
10.KfK-1 (Karlsruhe)	C.Broeders I.Broeders	HERMES = HETC(KFA) + MORSE
11.KfK-2 (Karlsruhe)	C.Broeders I.Broeders	HERMES = HETC(KFA) + MCNP
12.KfK-3 (Karlsruhe)	M.Segev	HERMES = HETC(KFA) + MCNP
13.PSI-1 (Villigen)	F.Aтчison Y.Kadi, H.U.Wenger	HETC(PSI) + TWODANT
14.PSI-2 (Villigen)	F.Aтчison Y.Kadi, H.U.Wenger	HETC(PSI) + 05R

Note: The INR and JAERI Groups have presented a revised results after SC/DOC(95)2 was issued.

Table 2. Laboratory participation in intercomparison

Laboratory	Pb-target			W-target		
	Yield n	Leak. n	Spall. prod.	Yield n	Leak. n	Spall. prod.
1.ANSALDO	X	-	X	X	-	X
2.JINR	X	X	-	-	-	-
3.CDF	X	-	-	X	-	-
4.INFN	-	-	X	-	-	X
5.INR	X	X	X	X	X	X
6.ENEА	X	X	X	X	X	-
7.JAERI	-	X	-	-	X	-
8.LANL	X	X	X	X	X	X
9.KFA	X	X	X	X	X	X
10.KfK-1	X	X	X	X	X	X
11.KfK-2	X	-	-	X	-	-
12.KfK-3	X	-	-	X	X	-
13.PSI-1	X	X	X	X	X	X
14.PSI-2	X	X	-	X	X	-

Table 3. Neutron yield and leakage foPb-target

Laboratory	Neutron Yield			Neutron Leakage		
	En>20 MeV	En<20 MeV	Total	En>20 MeV	En<20 MeV	Total
1.ANSALDO	0.21	10.32	10.53	-	-	-
2.JINR	0.72	19.47	20.19	0.66	17.33	17.99
3.CDF	1.06	8.43	9.49	-	-	-
4.INFN	-	-	-	-	-	-
5.INR	2.28	19.46	21.74	0.88	15.43	16.31
6.ENEА	0.95	18.75	19.70	1.30	19.73	21.03
7.JAERI	-	-	-	0.77	19.77	20.54
8.LANL	2.50	15.79	18.29	1.17	15.02	16.19
9.KFA	1.98	14.59	16.57	0.90	13.37	14.27
10.KfK-1	1.98	14.59	16.57	0.89	13.06	13.95
11.KfK-2	1.98	14.94	16.92	-	-	-
12.KfK-3	1.98	14.69	16.67	-	-	-
13.PSI-1	0.11	16.36	16.47	1.50	12.37	13.87
14.PSI-2	0.11	16.52	16.63	1.50	14.47	15.97

Table 4. Neutron yield and leakage for W-target

Laboratory	Neutron Yield			Neutron Leakage		
	En>20 MeV	En<20 MeV	Total	En>20 MeV	En<20 MeV	Total
1.ANSALDO	0.14	11.72	11.86	-	-	-
2.JINR	-	-	-	-	-	-
3.CDF	0.75	8.30	9.05	-	-	-
4.INFN	-	-	-	-	-	-
5.INR	2.59	21.49	24.08	0.57	12.27	12.84
6.ENEА	0.63	20.52	21.15	2.40	18.60	21.00
7.JAERI	-	-	-	0.51	22.67	23.18
8.LANL	2.92	18.92	21.84	0.80	14.38	15.18
9.KFA	2.21	18.43	20.64	0.61	13.92	14.53
10.KfK-1	2.21	18.50	20.71	0.61	13.08	13.69
11.KfK-2	2.21	17.69	19.90	-	-	-
12.KfK-3	2.22	17.34	19.56	-	-	-
13.PSI-1	0.12	18.50	18.62	1.05	9.46	10.51
14.PSI-2	0.12	19.12	19.24	1.05	12.60	13.65

Pb-Target

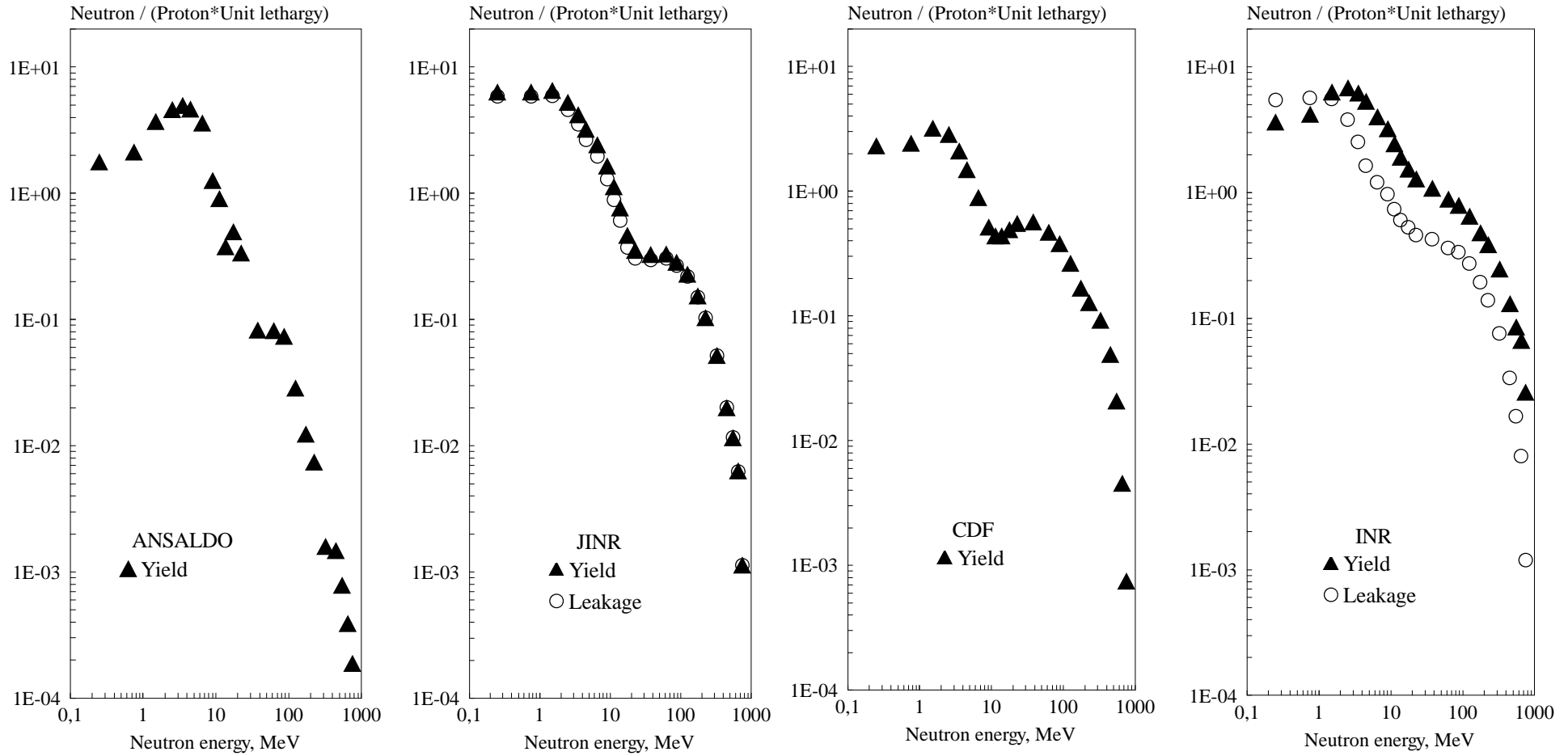


Fig.1a. Neutron yield and leakage spectra for Pb-target

Pb-Target

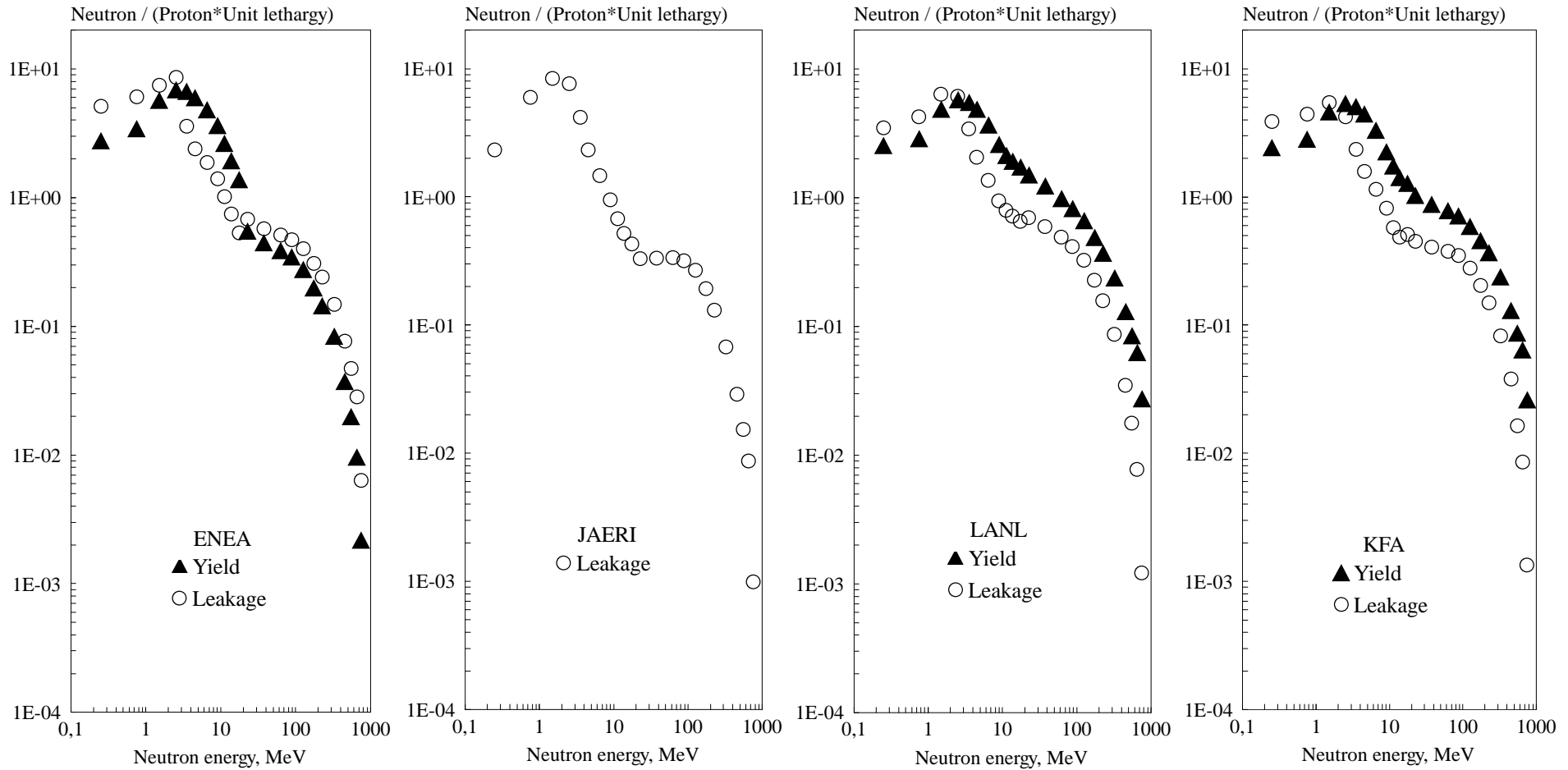


Fig. 1b. Neutron yield and leakage spectra for Pb-target

Pb-Target

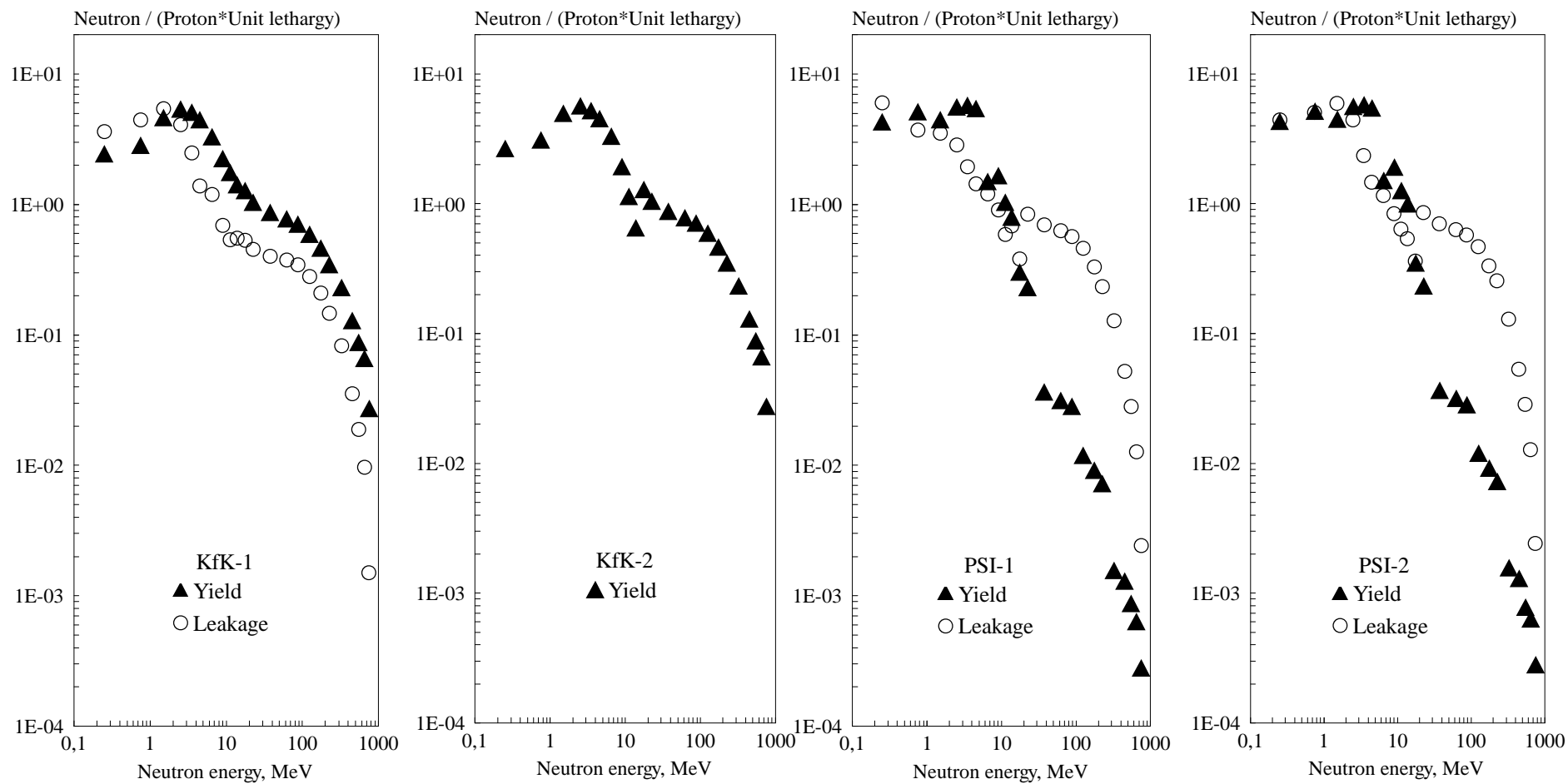


Fig.1c. Neutron yield and leakage spectra for Pb-target

Pb-Target

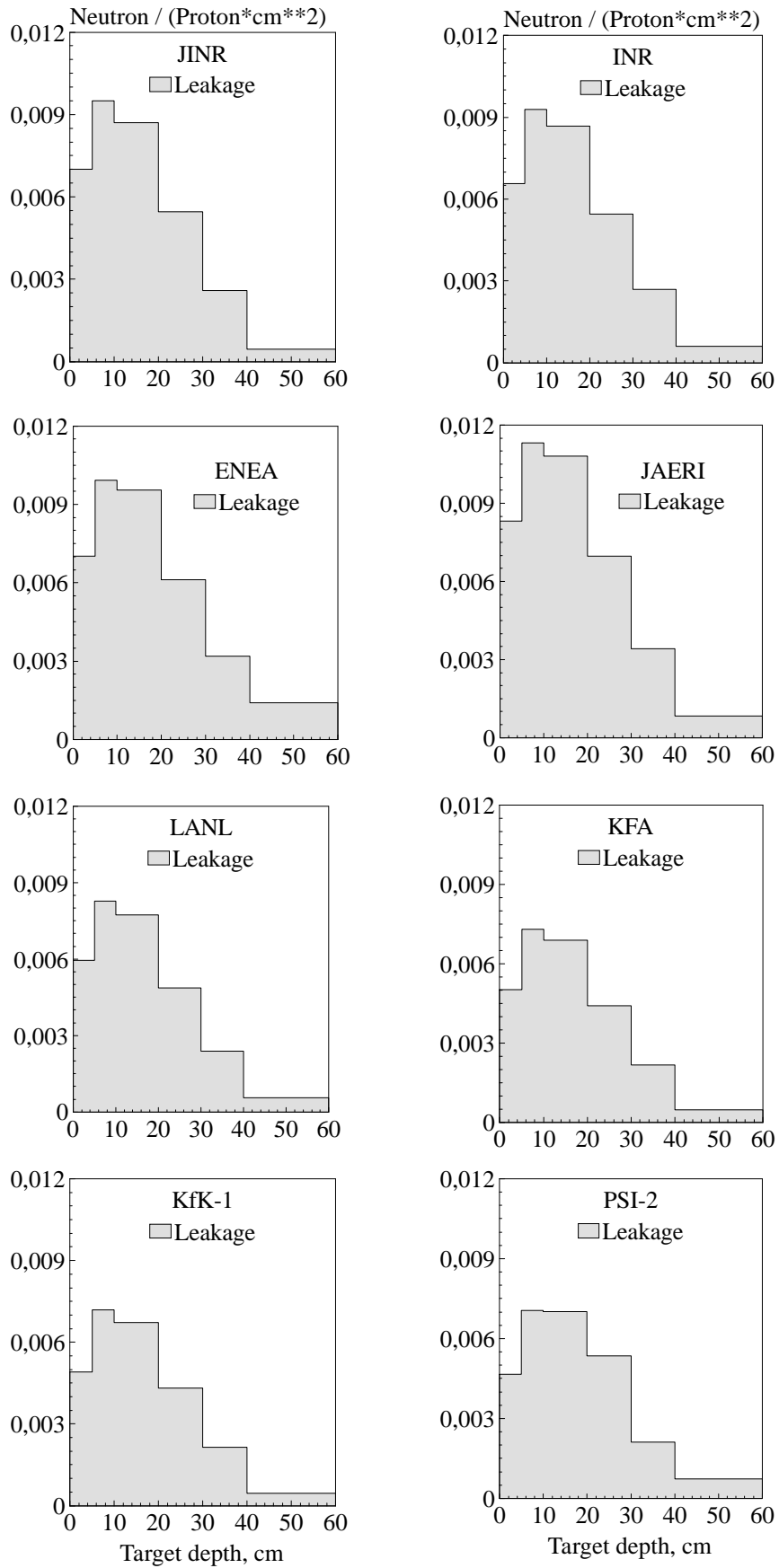


Fig.2. Leakage distribution along z-axis of Pb-target

W-Target

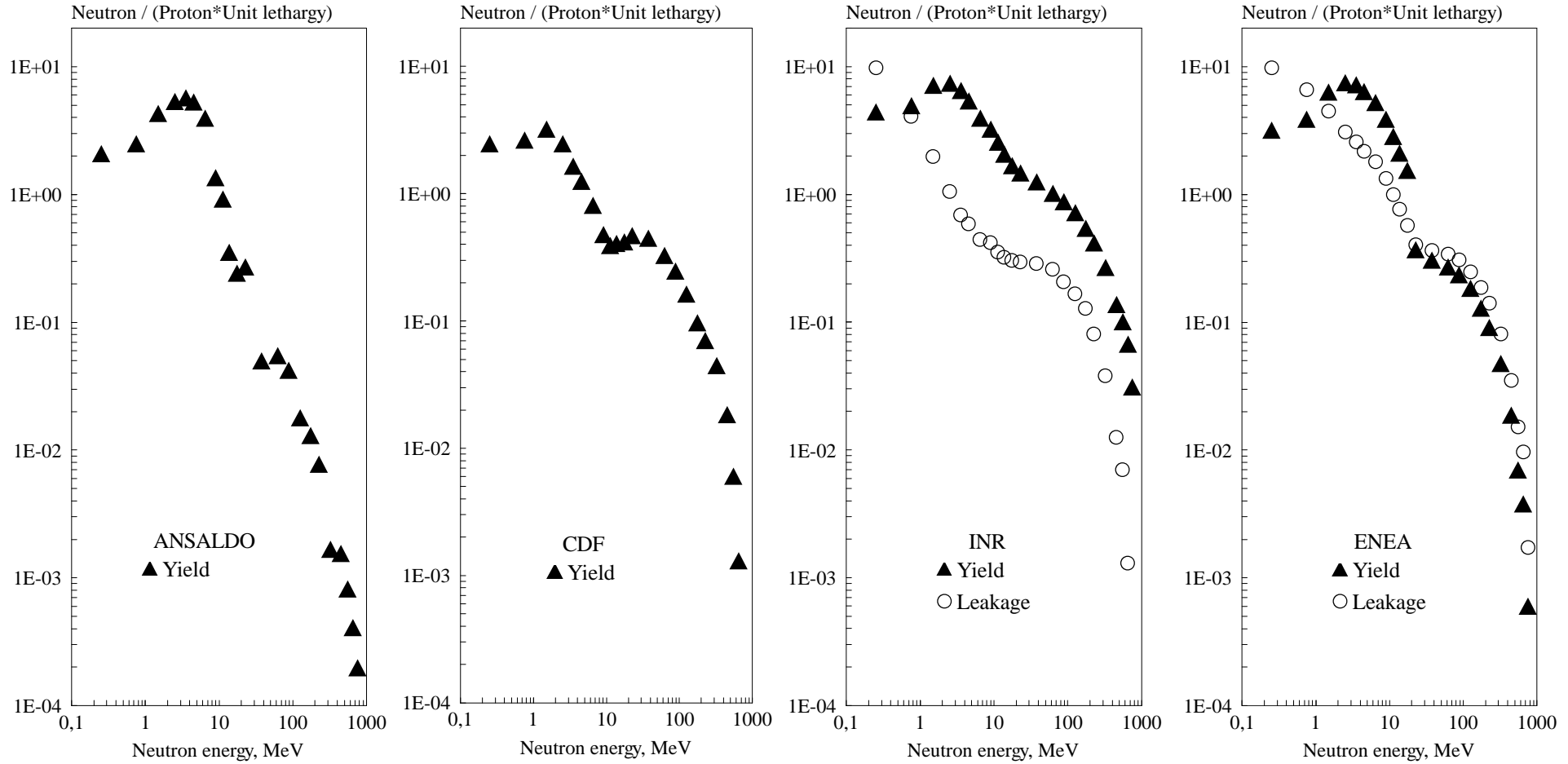


Fig.3a. Neutron yield and leakage spectra for W-target

W-Target

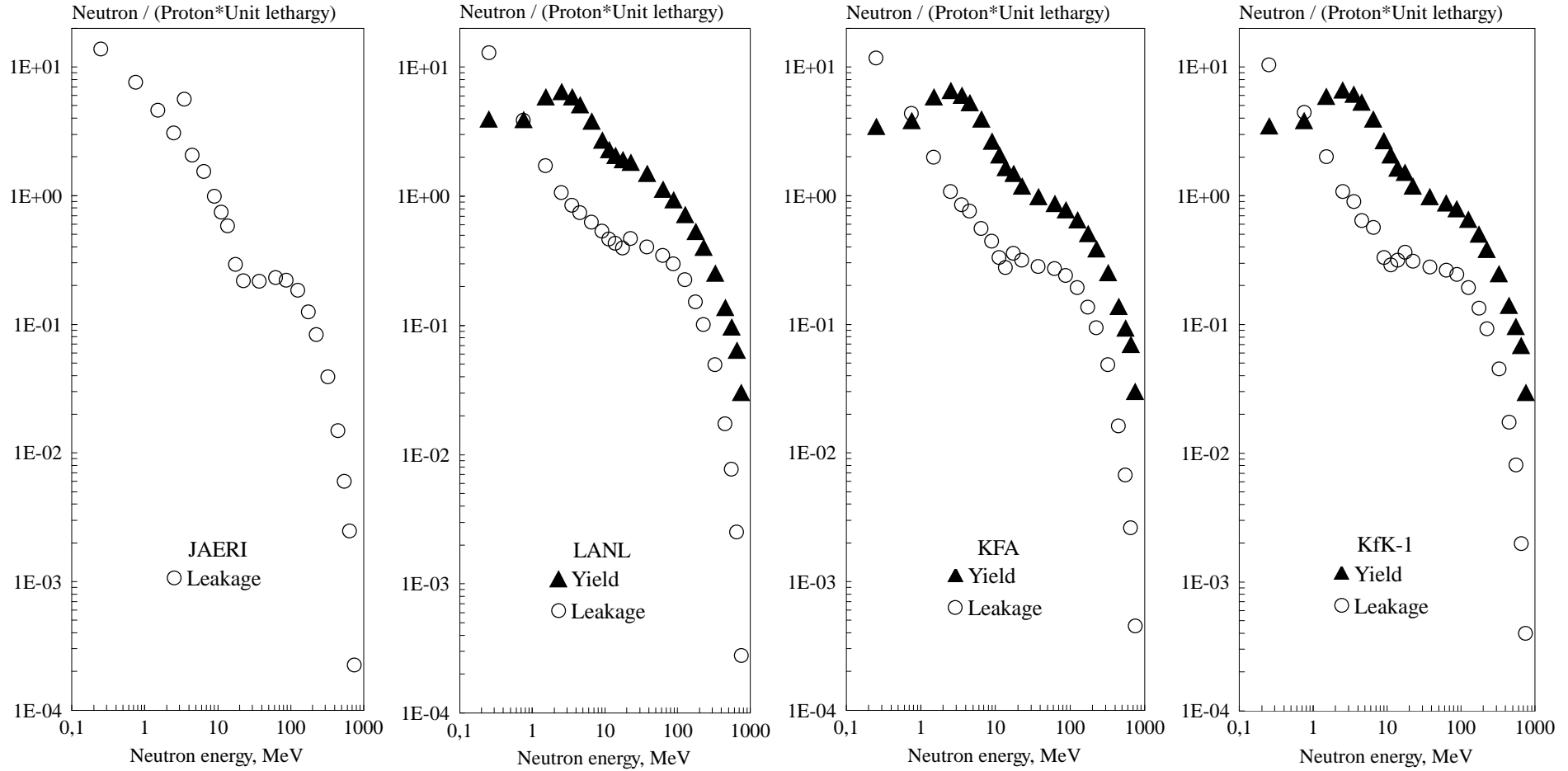


Fig.3b. Neutron yield and leakage spectra for W-target

W-Target

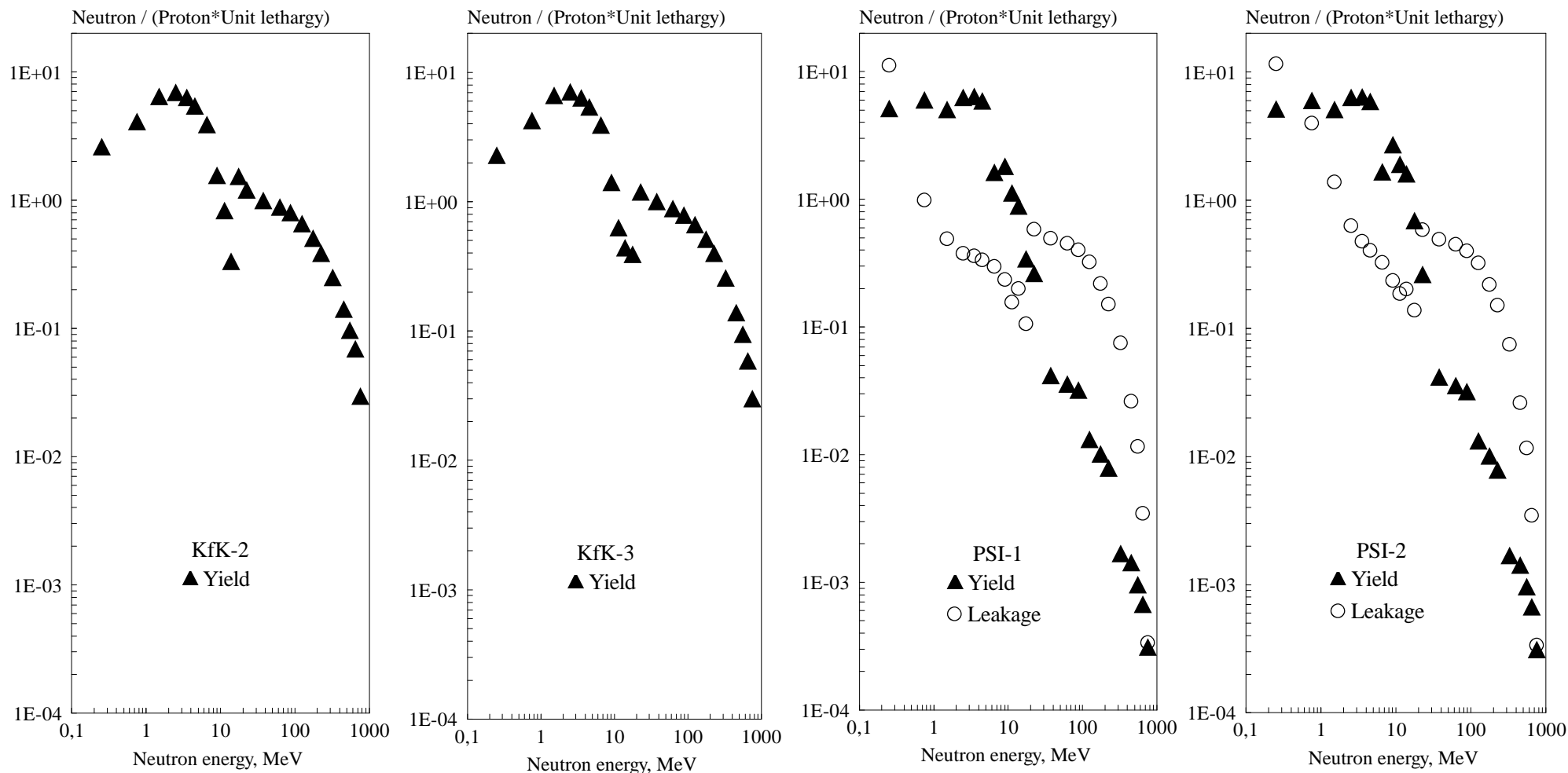


Fig.3c. Neutron yield and leakage spectra for W-target

W-Target

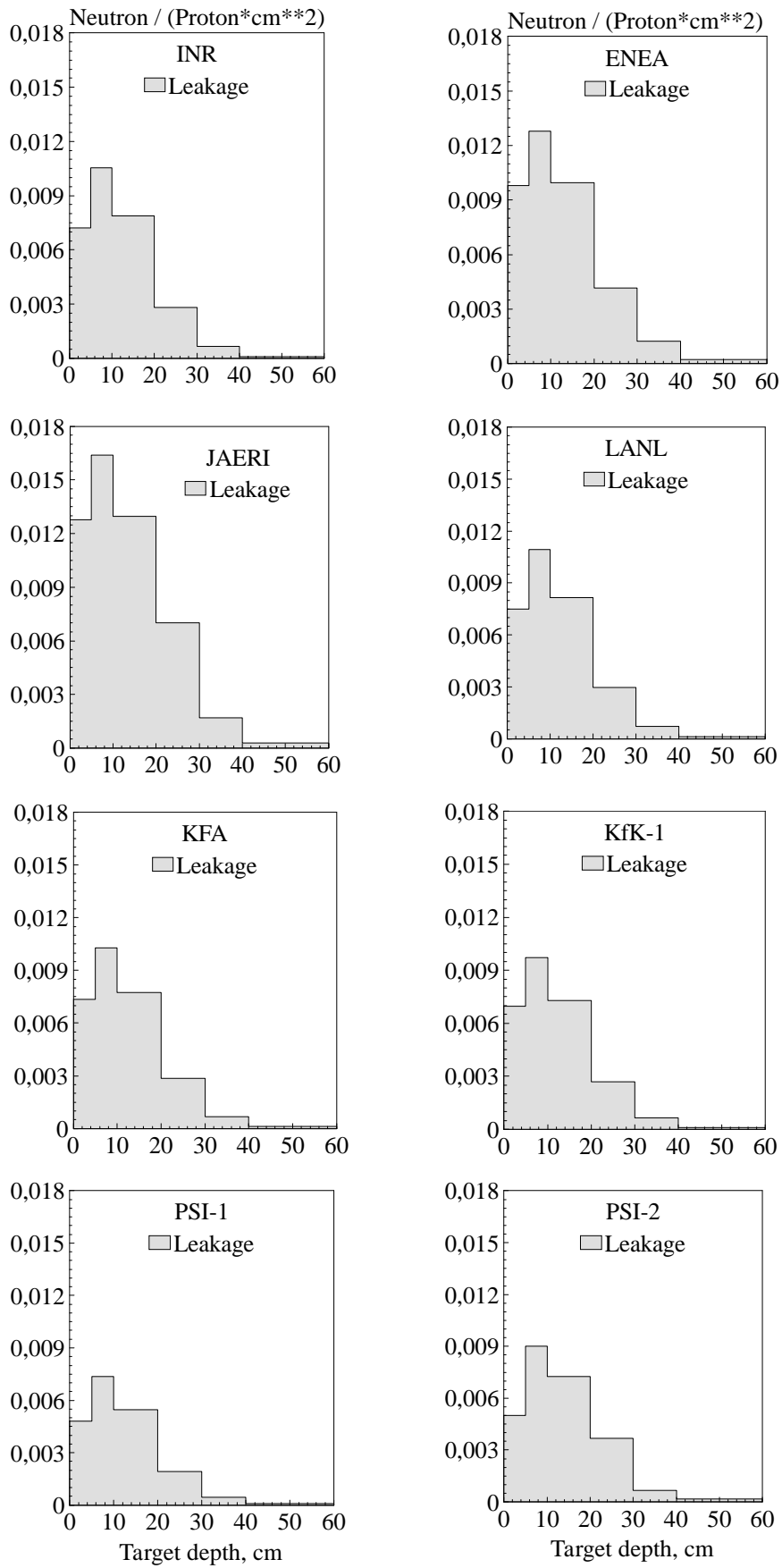


Fig.4. Lethargy distribution along z-axis of W-target

Pb-Target

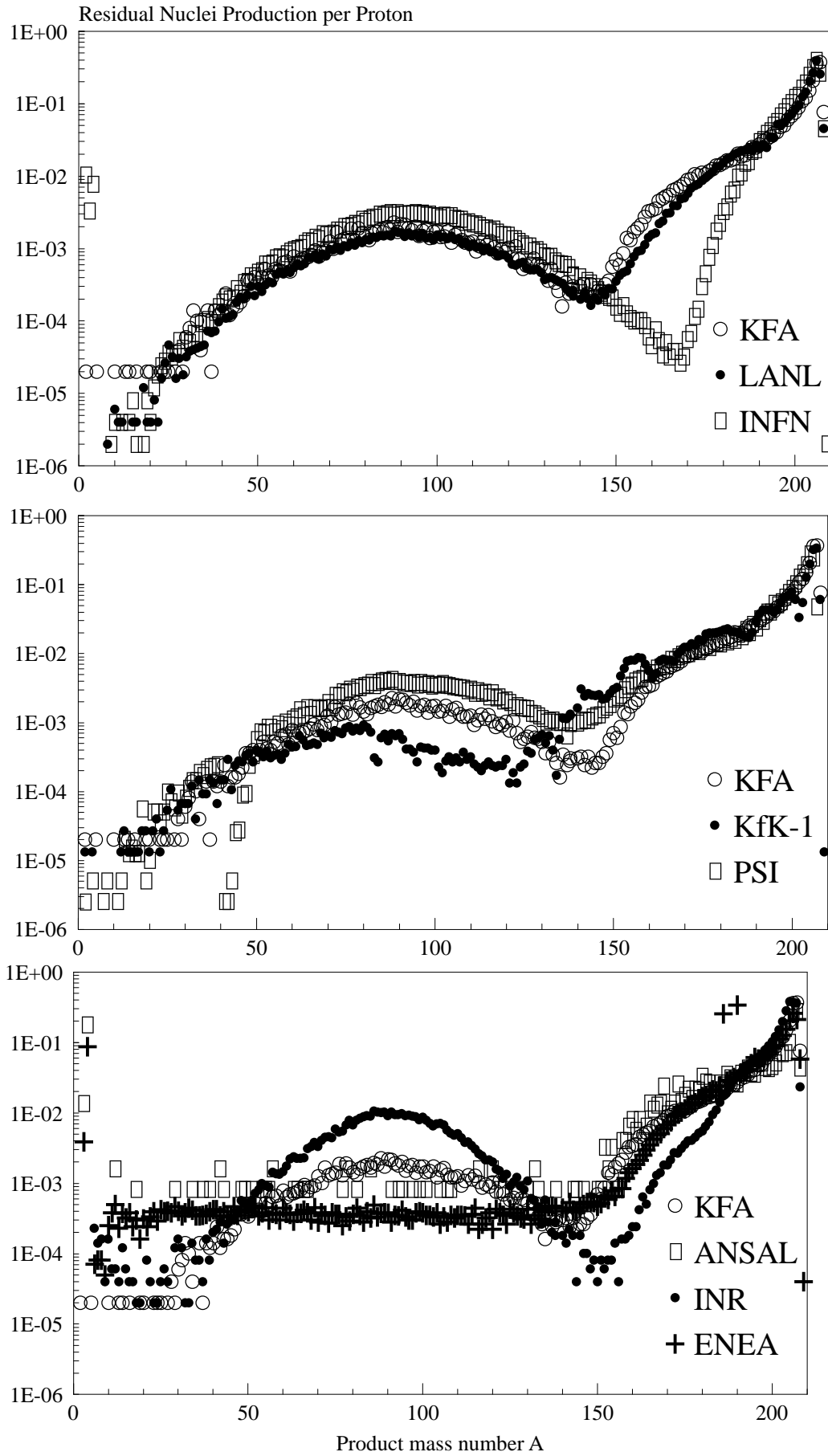


Fig.5. Spallation product distribution over whole Pb-target

W-Target

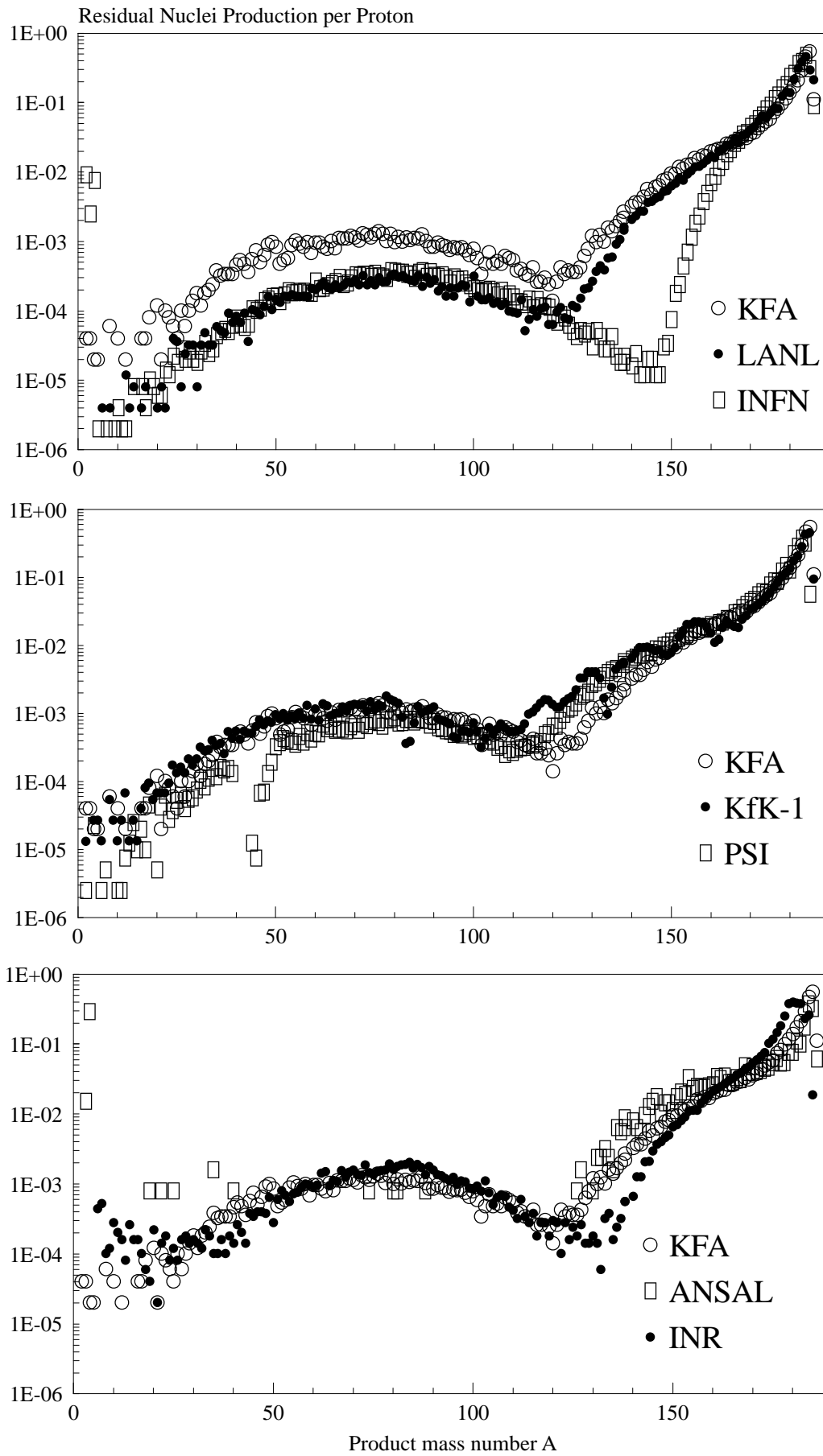


Fig.6. Spallation product distribution over whole W-target