ICANS-XV

15th Meeting of the International Collaboration on
Advanced Neutron Sources
November 6-9, 2000
Tsukuba, JAPAN

23.20

Specific Neutron Yield from the Extended Lead Target under incident Protons 0.1 GeV - 10 TeV

A.V. Dementyev, D.Dementyev, N.M Sobolevsky*, Y.Y Stavisski
Institute for Nuclear Research RAS, 117 312 Moscow, Russia

The results of calculations of the specific spallation neutron yield (number of neutrons with energy < 10,5 MeV per 1 GeV proton energy) for the cylindrical lead target Ø=20, L=60 cm irradiated with the protons with the energy up to ~10 TeV are presented. The calculations made by the Monte-Carlo method, based on the universal transport code SHIELD (up to 100 GeV) and hadron codes FLUKA and CALOR (up to ~ 10 TeV). A comparison with the experimental data also given.

The specific yield have a broad maximum at ~ 1,2 GeV caused by the competition of the direct ionization losses of the primary protons and the same of electron-photon showers caused by the π^0 decays.

Computer simulation of the interaction of particles with complex extended targets is a necessary stage of broad circle of studies in fundamental and applied nuclear physics. Therefore universal computer codes that allow to perform such computational experiments are an obligatory part of modern toolbox in nuclear and particle physics and give rise to an important direction of the investigative techniques.

Presently several transport codes are in use. The modern versions of the HETC (High Energy Transport Code) [1], such as LAHET (LANL), HERMES (Jülich, KFA), NMTC (JAERI) etc. are widespread now. This codes are based on the Bertini's model of intranuclear cascades [2], which describe in details all stages of the nuclear reactions inside of a target in the exclusive approach and are used in the energy range below 10-20 GeV.

The Russian analogue of HETC is the SHIELD code. The initial version of the SHIELD code was designed at JINR (Dubna) in early 1970's.[3]. The modern version [4,19] is based on well-known Russian models of nuclear reactions. It allows to simulate nucleon, pion, kaon , antinucleon and muon transfer as well as transport of the nuclei with arbitrary (A,Z) through extended complex targets in energy range up to 0,1 TeV.

The next independent hadron transport code was FLUKA. Its first version [5] came up in 1974; it used the inclusive approach to modeling of nuclear interactions. Subsequently the code was many times improved. The modern version of the

---

*) Corresponding author: E-mail sobolevs@al20.inr.troitsk.ru

FLUKA code [6,25] uses at high energy the Dual Parton Model (DPMJET, J.Ranf), while at energy near 1 GeV it employs an original version cascade-evaporation model that allows to stimulate the hadron cascades in matter at particle energy up to 20 TeV in the exclusive approach.

There are also ingenious combinations of available codes which allow to solve a broad circle of tasks. In particular the CALOR code [7,26] includes HETC, MORSE and EGS4 as well as multichain fragmentation model of hadron-nuckleus collisions [8]. Designed interface between the codes and extrapolation procedures allow to perform the calculations in the range of energy up to 20 TeV.

In the region of accelerator energies broadly used also the inclusive hadron transport code MARS [9], the first version of which came up in 1975 (N.V.Mochov, IHEP, Protvino).

The process of neutron generation in extended heavy target (W, Pb, U and other) under proton irradiation is the base of a number any important trends in the nuclear physics and technology. This is, primarily, the neutron sources for physical research, the discussed up today concepts of the electro-nuclear breeding and the nuclear transmutations of the radioactive power plants wastes. For all this trends the questions of a total neutron yield from the targets and energy expense per neutron are very essential. For these reasons since the fifties a series of corresponding experimental and theoretical investigations has been undertaken.

Up to now the amount of measurements of the total neutron yield were made from 0,25 MeV up to 70 GeV proton energy (both this point from INR experimental groups [10,11]). Results of the early experiments in the incident energy range near 1 Gev are presented, for example, in ref. [12]. In last years data have been received in energy range 1 - 8 GeV [13] and at 12 GeV [14].

The known theoretical results, belongs, as a rule, to the narrow energy range near 1 Gev, i.e. do not cover a wide enough interval. It gives not the possibility for choice the most efficacious proton energy and to discuss other spallation neutron sources. For example , in ref.[15] were shown, that from point of view the able to work, the most useful may be the proton synchrotron on ~ 10 GeV (long life for the ion source with the relative small ion current and decreased radiation damage of the target first wall). Other possible interest - using the beam dump of the Large Hadron Collider (LHC, 7 TeV protons) for giant slow neutron pulses production [16,17]. In this TeV energy range the spallation neutron yield data is absent at all.

In our work [18] for spallation neutron yield calculations in range 0,1 - 100Gev are used the universal transport code SHIELD [4,19]. This code is dedicated to the Monte-Carlo simulation of hadron cascades in complex macroscopic targets of arbitrary geometric configurations and isotope composition. One can calculate the nucleon, pion, kaon, antinucleon and muon transfer in energy range up to 100 GeV. The ionization energy loss for charged particles and struggling are taken into account. For the transport of pions and kaons the main modes of 2- and 3-particle decays are simulated.

The capabilities and quality of the hadron transport code depends substantially on the hadron-nucleus (hA) generator used. The h-A generator of the SHIELD code includes the Russian models of nuclear reactions: Dubna version of the intranuclear cascade model detailed in monograf [20]; for more high energies - the hadron-nucleus and the nucleus - nucleus generator, based on the independent quark-gluon string model [21]; a combined nuclear deexitation model [22,23] considering multifragmentation of highly excited nuclei, equilibrium particle emission involving evaporation/fission competition for heavy nuclei and Fermi brake up for light nuclei. The ha-generator of the SHIELD code provides an exclusive desc iption of the nuclear reactions over the 100-GeV energy range and wide nuclei-targets mass area.

During hadron tree generation in the target, the source of the "evaporated" neutrons is formed as well as the sources of meson decay products - γ-rays, e^-, e^+, neutrinos. Subsequent neutron transport was simulated with original neutron code LOENT based on 26-group neutron data system BNAB [I.I.Bondarenko et al, 24]. The electromagnetic showers are simulated by means of the well-known EGS4 code which is connected to the SHIELD with special interface.

Each hadron cascade tree is stored without any loss of the physical information during the simulation, allowing complete division of modeling and registrating parts of the code as well as to the repetition of the tree processing and visualization of the tree. The SHIELD code's open architecture presumes its modification and improvements.

In this calculations the targets represent a lead cylinder of natural isotope composition of 20 cm diameter and 60 in long. Such a dimension provide a nearly complete absorption of the charged component of the hadron cascade and are the accepted standard for the topics in question. A pencil proton beam impinges on the center of target along the cylinder axis.

Here we have restricted ourselves to the neutron yield data only. A more complete information on the neutron cascade development (energy distribution among various processe, energy deposition, nuclei-product yield etc.) can be found in Ref. [4].

The estimations of the spallation neutrons yield in TeV region was performed using transport codes FLUKA [5,6,8,25] and CALOR [7,26]. For this cases the target is relative small. The neutron sources distribution along axes of the tungsten target can see on Fig.1. On Fig. 2 we can see the spallation neutron yield (below 10,5 MeV neutron energy) - proton energy dependence in the energy region 0.1 Gev - 10 Tev. On the Fig. 3 are presented the specific yield of neutrons with energies from the whole cylinder surface, namely the number escaped neutrons per incident proton divided by the incident proton energy.

As we can see, the maximum in the specific neutron yield and correspondingly the most efficient energy of protons for neutrons production are observed near 1,2 GeV. A fall at lower energies is determines by direct ionization loss of primary proton energy, while at higher energies - by energy transfer into electron-photon showers caused by the generation and decay of the neutral pions. The results of the calculations of the neutron yields show the significant discrepancy for FLUKA and CALOR codes (about 1,6 at 6 TeV). For our experimental point at 70 GeV [11] the best agreement it is with CALOR calculations. But it is to far from 7-TeV point [16]. It would be very interesting the measurements of neutron yield in this region, even at one energy. This can make, for example, at 0.9 GeV at the Fermilab Tevatron with use steady-state beam, extracted by bent crystal extraction technique [27].

References

1. Armstrong T.W.,Chandler K.G., Nucl.Sci.Eng. **49** (1972) 10.
2. Bertini H.W., Phys. Rev. **188** (1969) 1711.

3. Sobolevsky N.M. The code for simulation of the nucleon-meson cascades by the Monte Carlo method. Preprint B1-2-5458, JINR, Dubna,1970. Barashenkov V.S., Sobolevsky N.M., Toneev V.D. Atomn.Energ. **32** (1972) 123, 217. in Russian.
4. Dementiev A.V., Sobolevsky N.M. Radiation measurements, **30** (1999) 553
5. Ranf J., Routti J.T. Comp. Phys. Com. 7 (1974) 327.
6. Fasso A., Ferrari et al. Proc. of 3rd Workshop SARE 3, KEK, Tsukuba, Japan, May 7 - 9, 1997.
7. Fu C.Y., Gabriel T.A. Proc. of SARE 4, ORNL, Knoxville, USA, Sept. 14-16, 1998.
8. Ranft J., Ritter s. Z.Phys. **C 27** (1985) 569.
9. Mochov N.V. et al.Proc. of SARE 4, ORNL, Knoxville, USA, Sept. 14-16, 1998.
10. Slastnukov V.N. et al., Z. Phys. **A 311** (1983) 363.
11. Kolmichkov N.V. et al., Atomn.Energ. **75** (1993) 219. In Russian.
12. Tunniclife P.R. et al., Rep. on Intern. Conf. on Acc. in Chalk River, Ontario,1976; Barashenkov V.S., Nucl. Part. Phys. **9** (1978) 781;
    Vasiljkov R.G. et al., Usp. Fis. Nauk **139** (1983) 435. In Russian.
13. Vasiljkov R.G. and Yurevich V.I., Proc. of ICANS-XI, Tsukuba, Oct.22-26, 1990, v. 1, 340.
14. Arai M. et al., J. Neutron Research, **8** (1999) 71.
15. Stavisski Y.Y. and Senichev Y.V., Proc. of ICANS-XII, Oxford, Oct. 1993.
16. Stavisski Y.Y. The giant pulses of thermal neutrons in targets of the superhighenergy accelerators. Preprint P-0215 INR RAS, Moscow 1981, in Russian The giant slow neutron pulses in beam damp LHC, this meeting.
17. Dementiev A.V. et al. On the possibility of the direct measurements n-n scattering in beam damp LHC, this meeting.
18. Dementiev A.V. et al., NIM, **A 374** (1996) 70-72.
19. Dementiev A.V. and Sobolevsky N.M., Proc. of Intermed. Ener. Nucl. data meeting, Paris, Mai 30 - June 1, 1993. Preprint INR RAS 874/94, Moscow, 1994
20. Barashenkov V.S. and Toneev V.D. Interaction of Particles and Nuclei of High and Superhigh Energies with Nuclei. Atomizdat, Moskow, 1972. In Russian.
21. Toneev V.D. et al., The independent quark-gluon string model for heavy ion collisions at ultrarelativistic energies. Preprint 89-52 GSI, Darmstadt,1989.
22. Botvina A.S. et.al., Nucl. Phys, **A 507** (1990) 649
23. Adeev G.D.et al., The calculation of mass and energy distributions of fission residuals nuclear reactions induced by intermediate energy particles. Preprint 816/93 INR RAS, Moscow, 1993.
24. Bondarenko I.I. et al. Neutron group constants for reactors and shielding calculations. Atomizdat, Moscow, 1968. In Russian.
25. Ferrari A. et al., NIM **B 71** (1992) 412
26. Gabriel T.A. et al. Preprint TM-1160 ORNL, Oak Ridge, 1989.
27. Murphy C.T. et al. NIM **B 119** (1996) 231-238

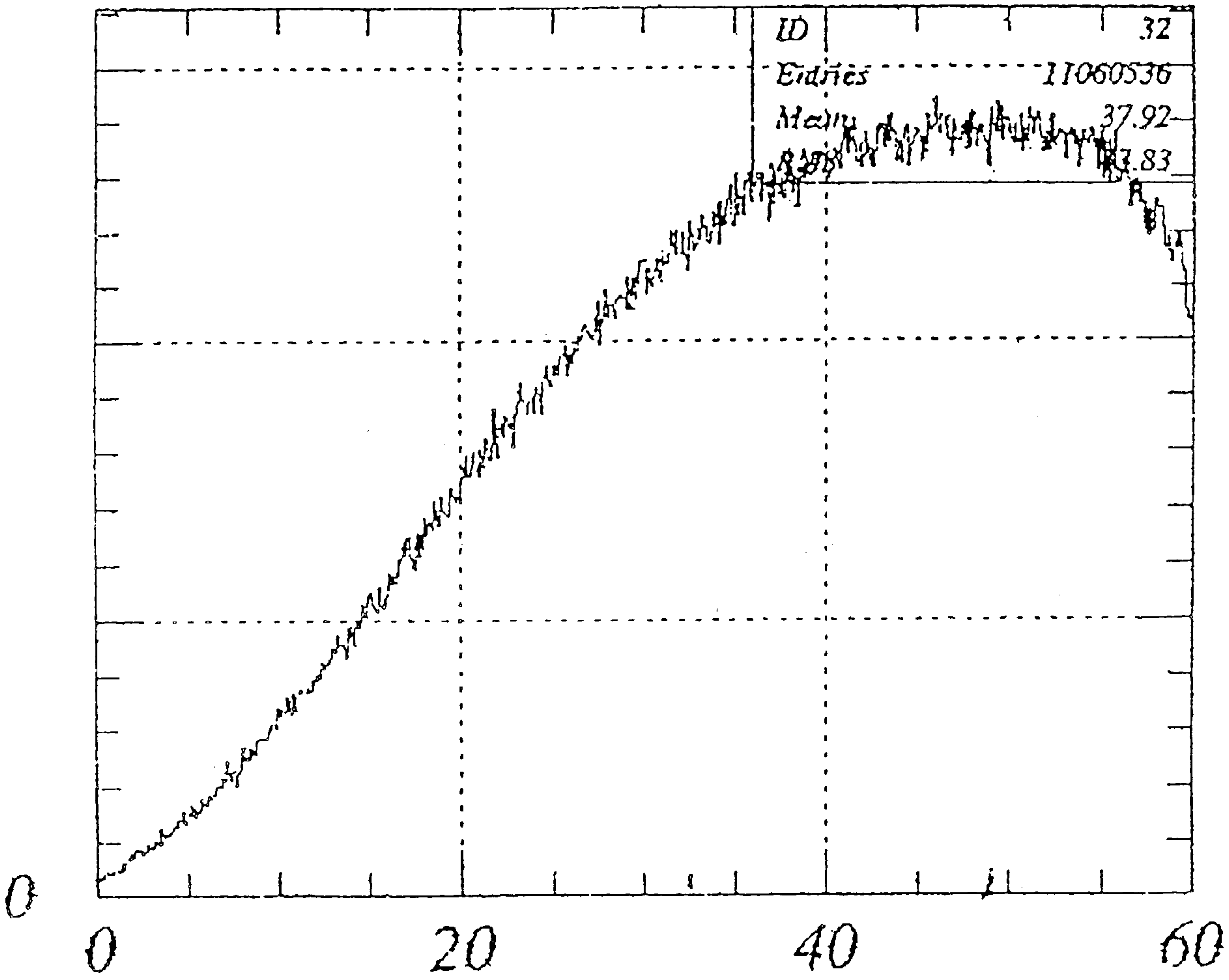

fig. 1

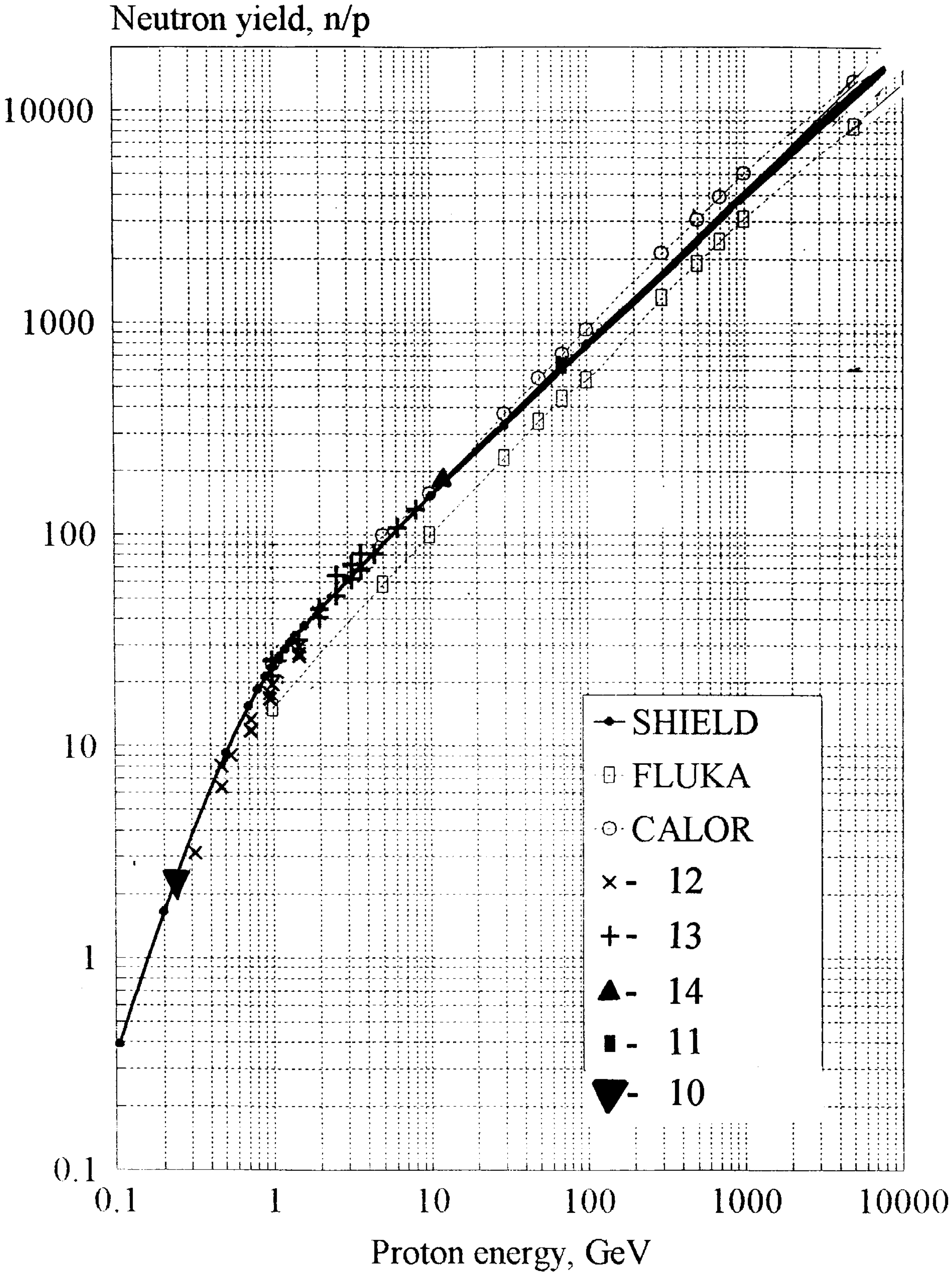
Neutron yield, n/p
10000
1000
100
10
1
0.1
0.1
1
10
100
1000
10000
Proton energy, GeV
SHIELD
FLUKA
CALOR
12
13
14
11
10

fig. 2

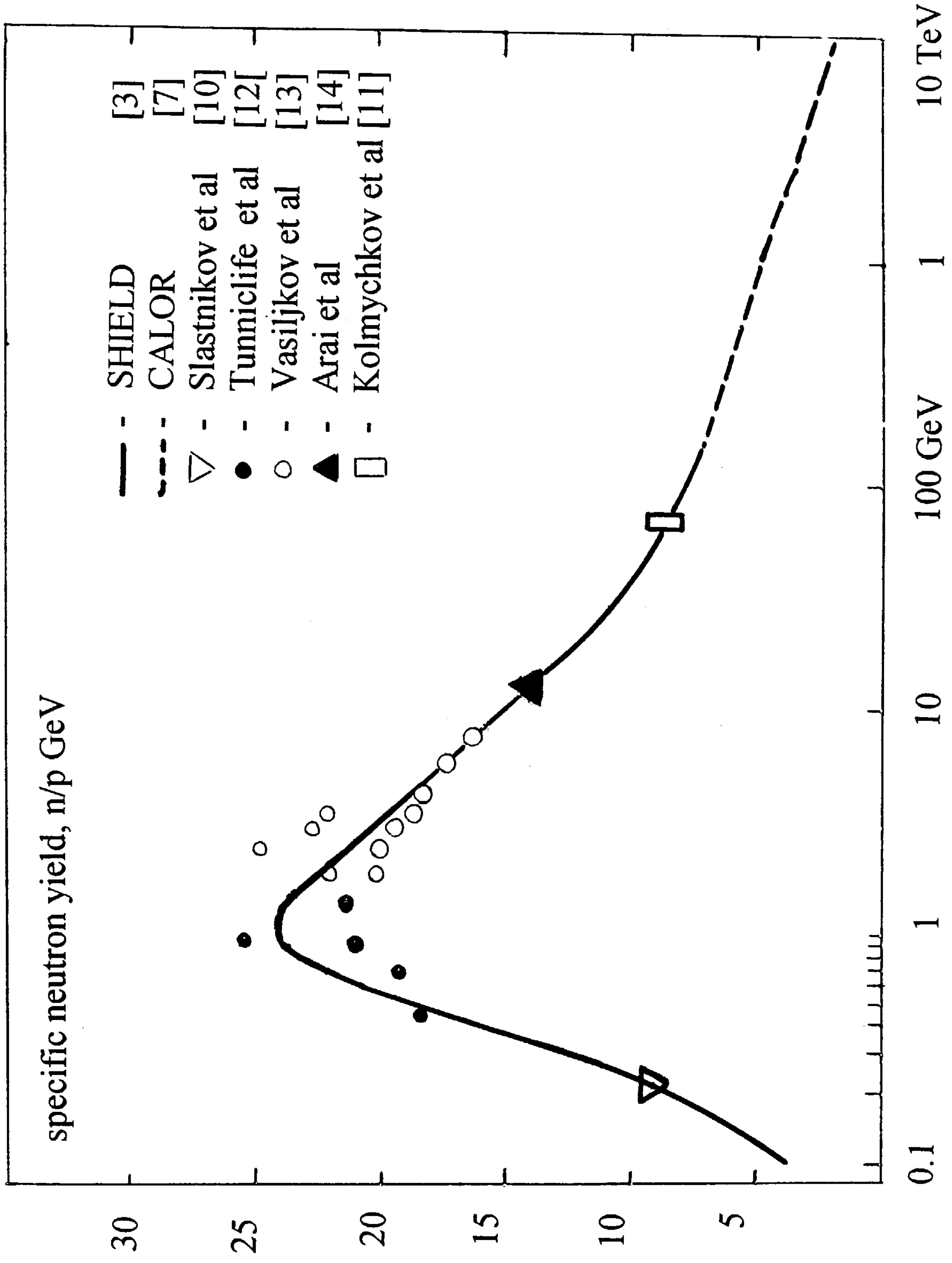
specific neutron yield, n/p GeV
30
25
20
15
10
5
0.1
1
10
100 GeV
1
10 TeV
▬ - SHIELD [3]
╍ - CALOR [7]
▽ - Slastnikov et al [10]
● - Tunniclife et al [12[
○ - Vasiljkov et al [13]
▲ - Arai et al [14]
▯ - Kolmychkov et al [11]

fig. 3