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Neutron emission from an extended lead target under the action of light ions in the GeV region

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ABSTRACT Experimental data are presented on yields and spectra of neutrons, emitted from a lead cylinder 020×60 cm, bombarded by beams of p, d, ^{3}He, ^{4}He, ^{12}C with energies 1-7,3 GeV per unit of ion charge. Measurements have been carried out by the neutron moderation technique and with solid state nuclear track detectors (SSNTD). The results obtained will be used as a scientific base for the power accelerator-based neutron sources.

1. Capability estimations and practicality considerations, with regard to large-scale accelerator-based methods of free neutron production for the nuclear fuel cycle, have prompted us to start gathering the relevant data sistematically. Experiments are carried out on some simple targets, placed at the Dubna (JINR) synchrophasotron slow ejection channel MV-2, beam line N40. Modest efforts are also being made to develop calculational codes. On the whole these activities are supported by MuCF program.

At present there are three targets on our experimental area (fig.1):

a) "naked" thick lead cylinder (as a rule 020x60 cm), used

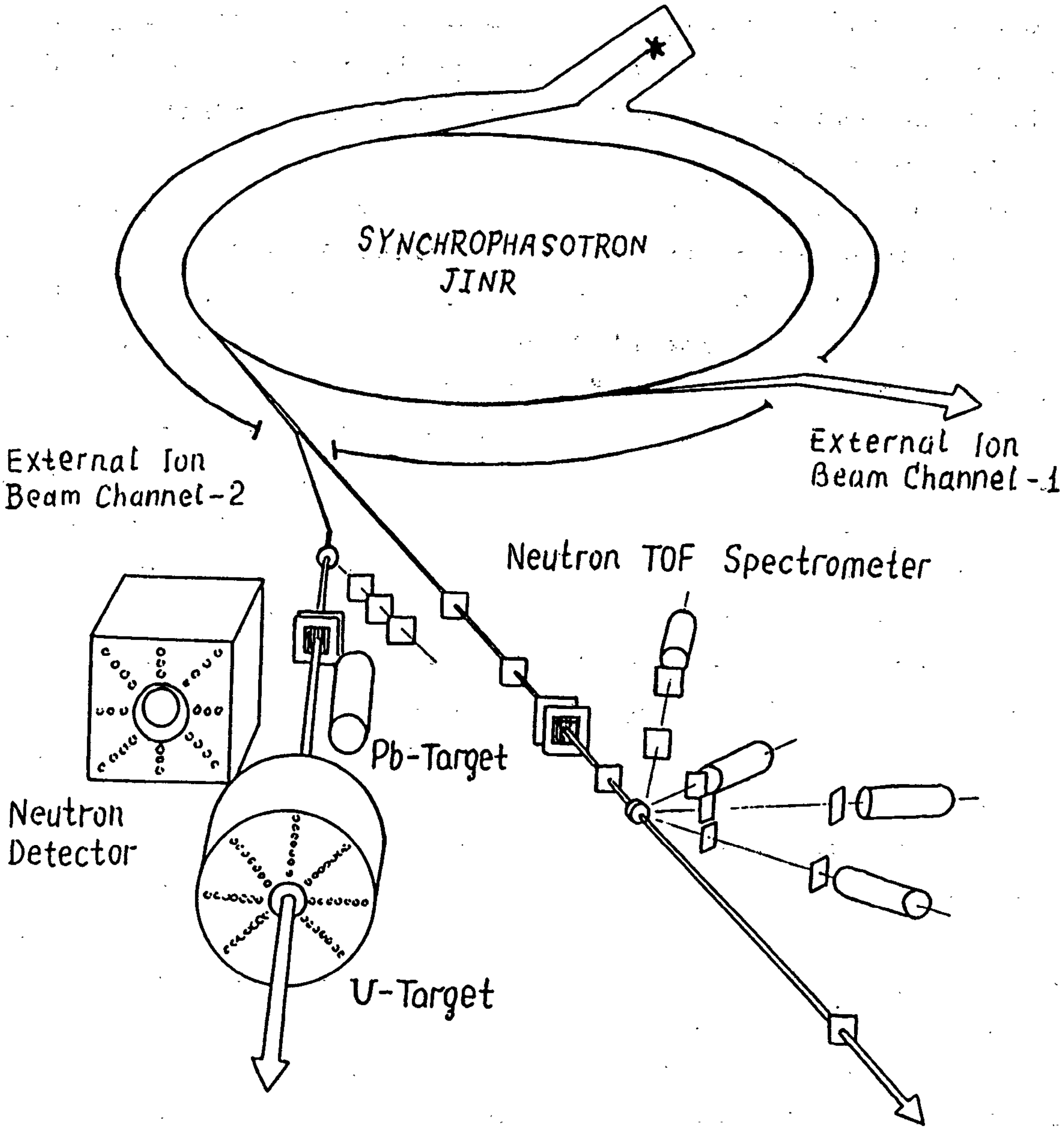

Fig. 1 A sketch of an experimental area with MRTI-IAE targets on beamline N40 of synchrophasotron JINR

for measuring neutron spectra by solid state track' nuclear detectors (SSNTD) technique; the data obtained are being combined with the results of time-of-flight spectrometer, which inhabits a neighbouring beam line and deals with thin and modest size targets of various materials.

b) The same cylinder in a hydrogenouos moderator for measuring yields of neutrons with energies ≤ 15 MeV.

c) The same lead cylinder again (later also uranium and thorium ones) will be inserted into a large uranium blanket of the depleted metal (Ø120x100 cm,full weight 21 metric ton).

The data gathered will make it possible to obtain reliable neutron characteristics for the heavy material targets bombarded by slightly relativistic hydrogen ions, i.e. in the energy region, where the energy cost of the free neutron is expected to be minimal. Moreover, the data would be useful for testing the calculational codes and improving their predictive power. Actually a calculated pattern of the total absorption of the high energy ion in, for instance, quasi infinite metal uranium block is now far from certain.

The experiments with Pb cylinders are now under way. Next january measurements will be started with a U target-blanket; work on the TOF spectrometer will also continue. However, it is feared that the synchrophasotron will be shut-down in late 1991 and subsequently dismantled.

2. The spectrum of neutrons emitted by a thick heavy target under the action of high energy ions ($\sim 10^2-10^3$ MeV) is rather complex and stretches over at least two orders more than the fission spectrum, the target size and material as well as the type of bombarding ion and its kinetic energy affect it significantly also. In order to measure a) the yield of neutrons with energies ≤15 MeV from (nonfissioning) extended target, say Pb, we have used the well developed neutron moderation technique; b) as to neutrons of higher energies the SSNTD technique was applied, with some modifications to fit our task.

The first series of the experiments was conducted on the beams of p, d, ^{3}He, ^{4}He and ^{12}C (moderation technique) with energies $E_i/Z_i=1-7.3$ GeV per unit of ion charge (for protons 8,1 GeV) or only p and d beams in the energy interval 1-3.65 GeV

(SSNTD technique).

a) In the neutron moderation experiments the lead cylindrical target was placed inside a CH_2 block 1.35x1.2x1.2 m^3 [1]. Counters of thermalized neutrons in 10 channels (parallel to the ion beam, i.e. target axes z). The neutron detector (counters + moderator) was calibrated by Ra-Be standard sourse ($5.22 \cdot 10^5$ n/s ±2.8%). There were neutron counters of three types: short boron (0 0.8x4 cm) and long (0 2x115 cm) filled with ^3He or BF_3.

The short counters measured reaction $(n,^{10}B)$ density distributions along the beam axis z; the distributions were approximated by polynoms of third power and then integrated. The long counters integrated these distributions physically. Because we did not observe any noticeable differences between the results obtained by the two methods, bulk of the data was gathered with long BF_3 neutron counters.

The primary ions bombarding the target were counted by a scintillation telescope with 1-2% errors. At beam intensities $\leq 10^5$/cycle and of slowly ejected ion pulses 350-400 ms the dead times of neutron channels did not exeed 5-6 mcs, so that missed counts amounted to ≤ 1%. An absorption of the high energy nuclear cascade in the target is rather full: the addition of 12-16 cm of lead to an initial 60 cm increases the neutron yields only by 1.5-2%.

On fig.2 E-dependences of the neutron yields Y_i/Z_i are given for various primary ions. Fig.3 shows the yields measured at a fixed energy E_i/Z_i=2.55 GeV, the yields having been set along the abscissa according to parameter $Z^2/A^{2/3}$: the grater its value is, the more is the share of ion initial kinetic energy lost before a nuclear absorption event.

A hierarchy of the bombarding ions (as to their ability to minimize the energy cost of neutron, releasing from the target) observed in fig.2, thus seems obvious, because it may qualitatively be predicted on the basis of the available data on ion-nucleus inelastic cross sections and ionization losses in extended media. A crude assumption is being done, that the yield is proportional to the mean kinetic energy of the ion left with it at the nucear absorption event. These considerations are rather primitive, because they do not take some essential issues into

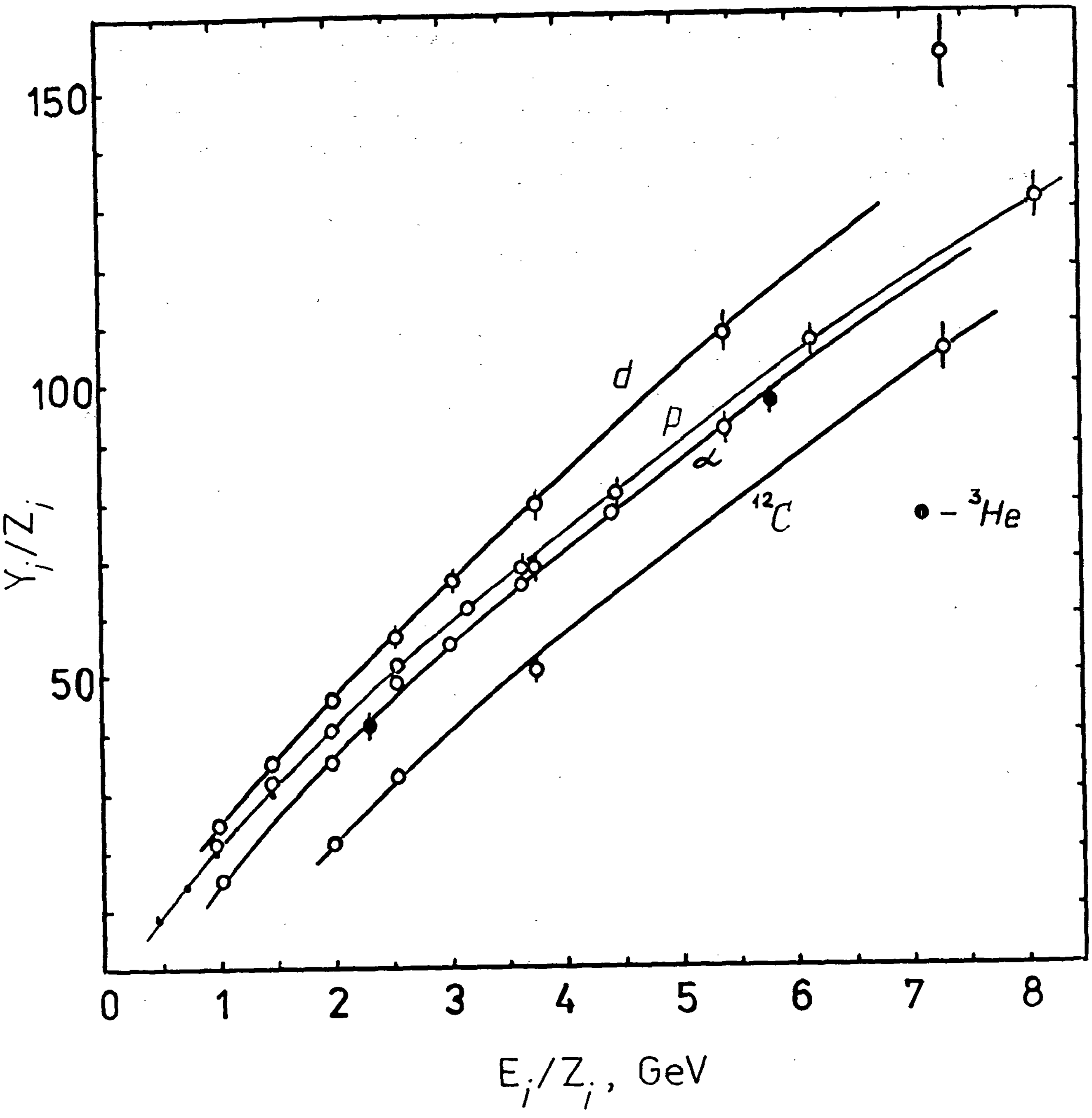

Fig. 2 Neutron yields Y_i/Z_i measured by the neutron moderation technique for lead cylinder Ø20 x 60 cm, bombarded by light ions

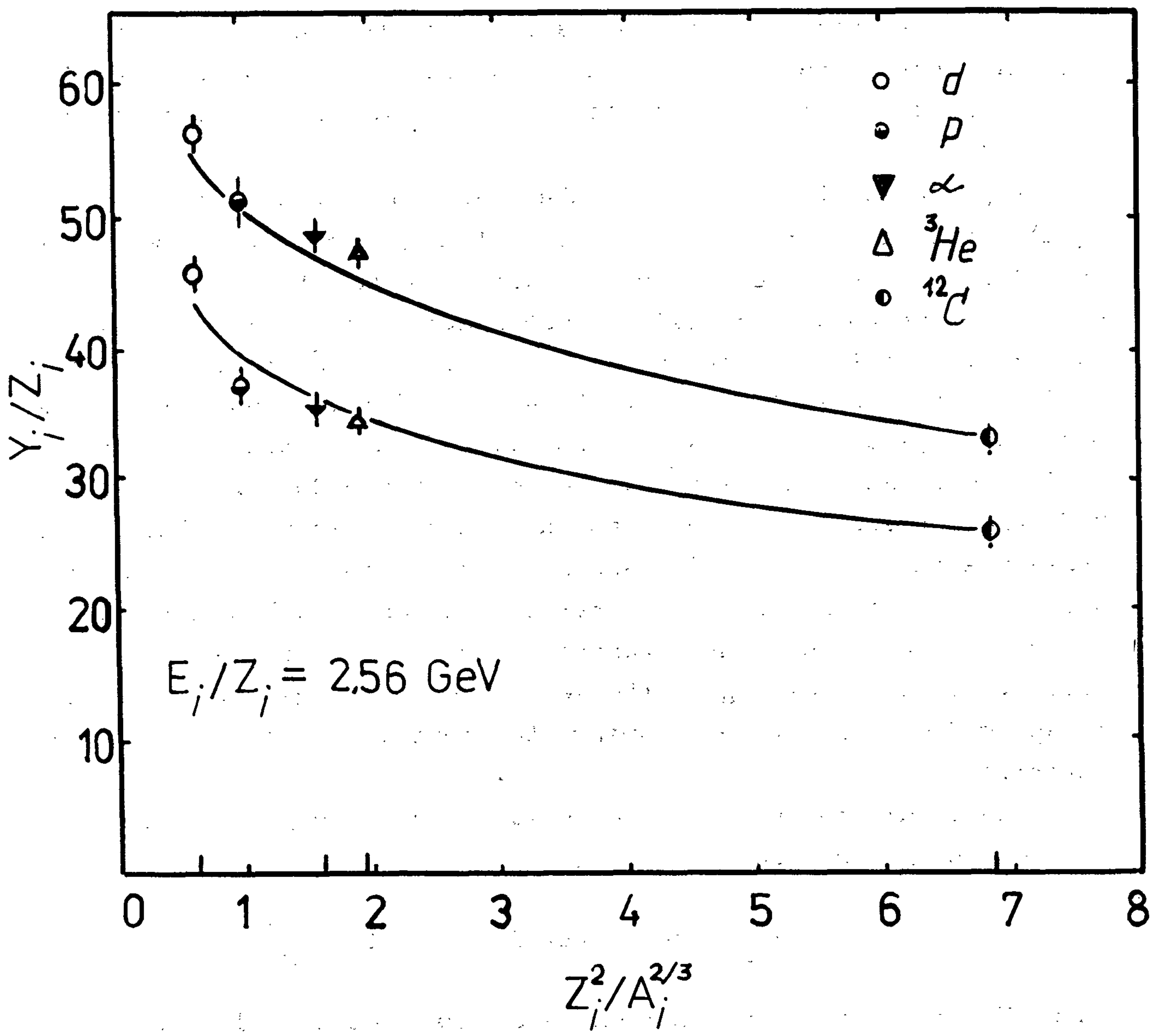

Fig. 3 Dependence of the neutron yield Y_i/Z_i on a type of bombarding ion,measured at the initial kinetic energy 2,55 GeV per unit of ion charge on the same target Ø20 x 60 cm

account, for example, the energy transfer from a hadron component of the nuclear cascade to an electron-proton one as the ion initial kinetic energy rises, but it is not very significant for the relative qualitative pattern in a rather limited energy interval.

Fig.4 presents a curve of the neutron yield for protons, $Y_p(E_p)$, separated from the entire family on fig.2, with an addition of the previously published data obtained by the moderation technique as well: in Oak Ridge - Chalk River study /2/ for E_p=0.47-1.47 GeV, in Karlsruhe group experiments /3/ for E_p=0.59 GeV, and in ICP-MIPI work /4/ for E_p=0.4-0.66 GeV. This picture helps to realize a nonlinearity of E-dependances: it is hardly noticeable in the energy region of the order of hundreds MeV, and appears to be due to an intricate combination of at least three reasons. They are a) changing specific ionization losses and nuclear absorption cross sections; b) a steadily enhancing energy transfer from h- to e-ph-component of the nuclear cascade in the matter; c) an increasing of the mean kinetic energy of neutrons, escaping from the target owing to deficiency of the target material.

The cumulative proton data is satisfactorily parametrized by the following function

$$Y^m{}_p(E_p)=-8.2(\pm1.6)+29.3(\pm1.3)E_p{}^{0.75},$$

where E_p is in GeV. For deuterons and α-particles (only our data) we got

$$Y^m{}_d(E_d)=-10.5(\pm1.9)+33.6(\pm1.2)E_d{}^{0.75},$$

$$Y^m(E_\alpha/2)/2=-16.3(\pm1.4)+31.3(E_\alpha/2)^{0.75},$$

the upper indices in all three expressions meaning "moderation".

b) On the same fig.4 the values of neutron yields $Y^t{}_p(E_p)$ are displayed, which have been obtained by integrating the neutron yield distributions over the target surface and the angle θ (with respect to proton beam): dy/dS and dy/dθ. The distributions were measured by SSNTD at E_p=1-3.65 GeV. One may get from this data

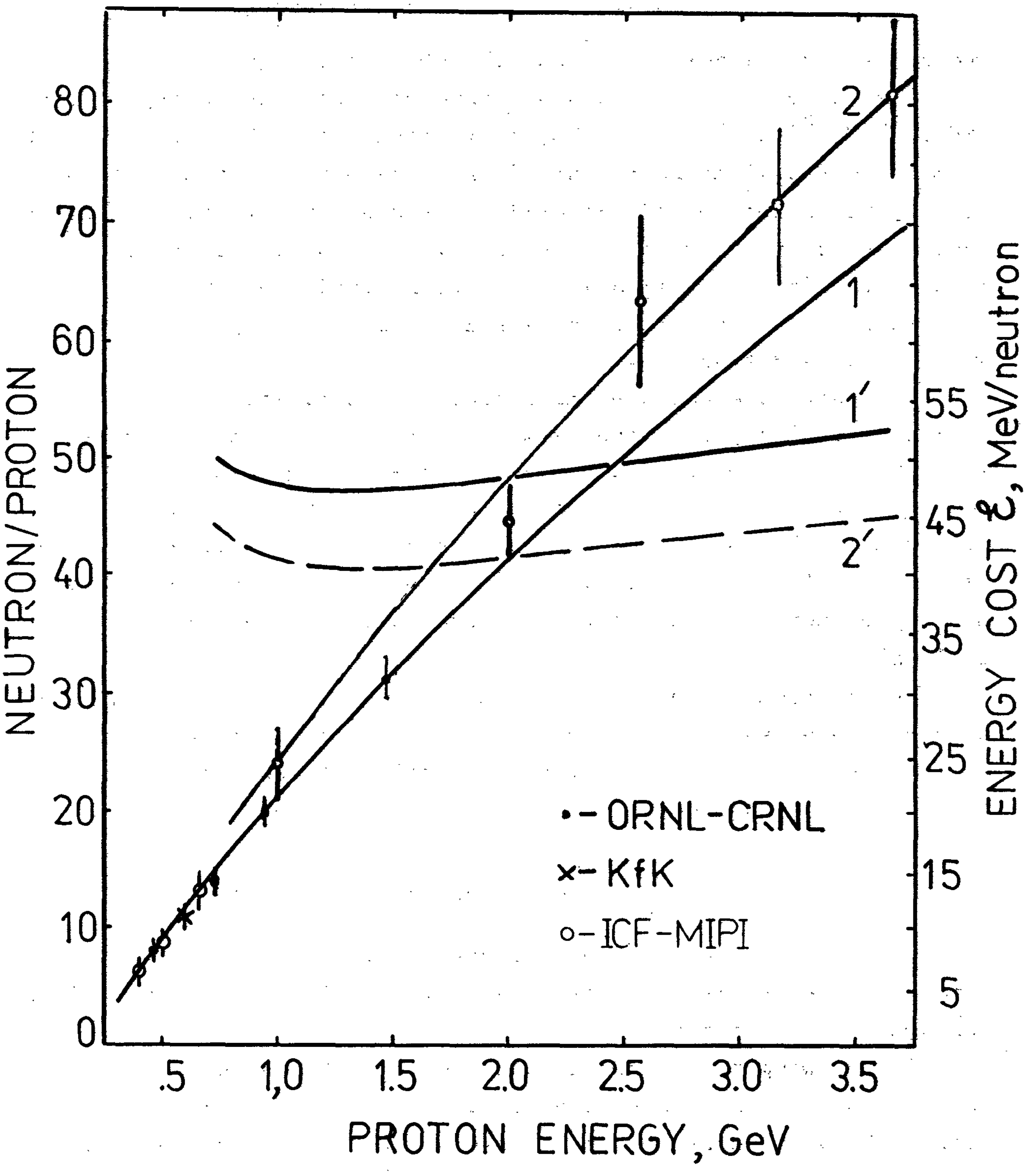

Fig. 4 The neutron yields Y_p measured by the moderation (1) and SSNTD techniques (2) on the same lead target Ø20 x 60 cm. Curves 1'and 2'refer to right ordinata.

$$Y^{m}_{p}(E_{p})=-4.8(\pm1.0)+28.6(\pm2.5)E_{p}^{0.85},$$

where the upper index "t" means "threshold technique".

The detectors included a standard set of fissioning layers (FD): ^{235}U, ^{238}U, ^{237}Np, ^{232}Th, contacting with a 6 micron thick film of polyethylenterephtalat (PETP) (SSNTD arrangement and their setting up on the "naked" Pb cylinder and around it are shown in companion report by Nikolayev et al.). To this set we have added layers of ^{209}Bi and spallation detectors (SD) Cu and Cd, that effective neutron detection thresholds amount respectivevely to ≈ 90, ≈ 400 and ≈ 600 MeV.

In order to elucidate the detecting capabilities of the SD, a series of axillary experiments was carried out with layers of Ti,Al,Cu,Cd,,Ta,Pb on proton beam in the energy interval 0.2-4 GeV. The efficiences for an entire set of layers in SSNTD, were determined, the SD with Cu and Cd layers have the steepest energy dependence of detection efficiency in the near threshold region which provides the embracing of a broad energy interval from 0 up to ~ GeV.

The neutron yield distributions dy/dS and $dy/d\theta$ (integral spectra) were measured in various energy groups over the lead cylinder surface and angle θ. By integrating these one gets the total yield of neutrons of all energies (in 4π solid angle):

$$Y^{t}=2\pi R\cdot k\int_{0}^{60cm} dy/dS\cdot dz=2\pi\int_{-1}^{1} dy/d\Omega d(\cos\theta),$$

where R is the radius of the cylinder, coefficient k takes into account the experimental fact, that (87±4)% of all neutrons leak through the side surface.

Thus, owing to the small number of thresholds we get only the integral neutron spectrum, i.e. a set of neutron yields in some rather broad energy groups. Nevertheless, there exists a mathematical procedure for restoring the full spectrum from these experimental values (code RESTOR), which is an iterative method using some a priori information as a zero approximation in the shape of the energy spectrum. Such information may be, for example, the well known representation /5/

$$F_o(T)=\sum_{i=1}^{3} c_i(T_i/T_{oi})\cdot\exp(-T_o/T_{oi}),$$

which satisfactorily describes the spectra of neutrons from thick targets at realistic values of parameters c_i and T_{oi} /6/. The additional detectors with high thresholds sharply diminish the relative error $\delta Y(E)$ of the cascade high energy neutron yield.

The code RESTOR results in energy distributions of neutrons $F(E_n)$ and yields $y_j(E_n)$ for neutron energies, exceeding some threshold values E_{nj}(0; 0.1; 1; 6; 20; 50; 100; 250; 500 and 1000 MeV). Fig.5 illustrates the capabilities of the SSNTD technique, displaying the neutron spectra, which have been measured E_p=2.55 GeV on Pb target Ø 20x20 cm at angle 90^0 by both SSNTD and TOF techniques. The SSNTD seem to be appropriate for studying neutron fields with a hard spectrum.

The spectrum of spallation neutrons generated by deutron beam is noticeably softer than in a case when primary particles are protons (fig. 6). Fig.7 compares the "hardnesses" of the neutron spectra for lead cylinder Ø 20x60 cm, bombarded by protons or deuterons with energy $E_{p,d}$=2 GeV. In fig.8 the neutron spectra are given for E_p=3.65 GeV. In the immediate future we are going "to insert" the former $E_{p,d}$=2 GeV into quasi infinite uranium blanket and to compare the result obtained with the directly measured value for real assembly "beam-Pb target-U blanket" (captures, fissions, ^{237}U ect.).

Finally in fig.9 functions $\varepsilon_i=E_i/Y_i$ are presented, implying the energy cost of the free neutron, "liberated" from the lead cylinder Ø 20x60 cm. If the fits for Y_i above menthioned are used, then from the condition $d\varepsilon_i/dE_i=0$ minima of the functions ε_i are obtained. $\varepsilon_p{}^m$ has a minimum at $E_p\approx 1.2$ GeV, functions $\varepsilon_d{}^m$ and $\varepsilon_\alpha{}^m$ are achieved respectively at $E_d\approx 1.4$ and $E_\alpha/2\approx 2.6$ GeV. The function $\varepsilon_p{}^t$ transits minimum at $E_p\approx 1.2$ GeV. This fact shows apparently on a slight sensitivity of the minimum position of ε_p to a completness of the neutron spectrum, involved in a determinating the total neutron yield, or to the target diameter.

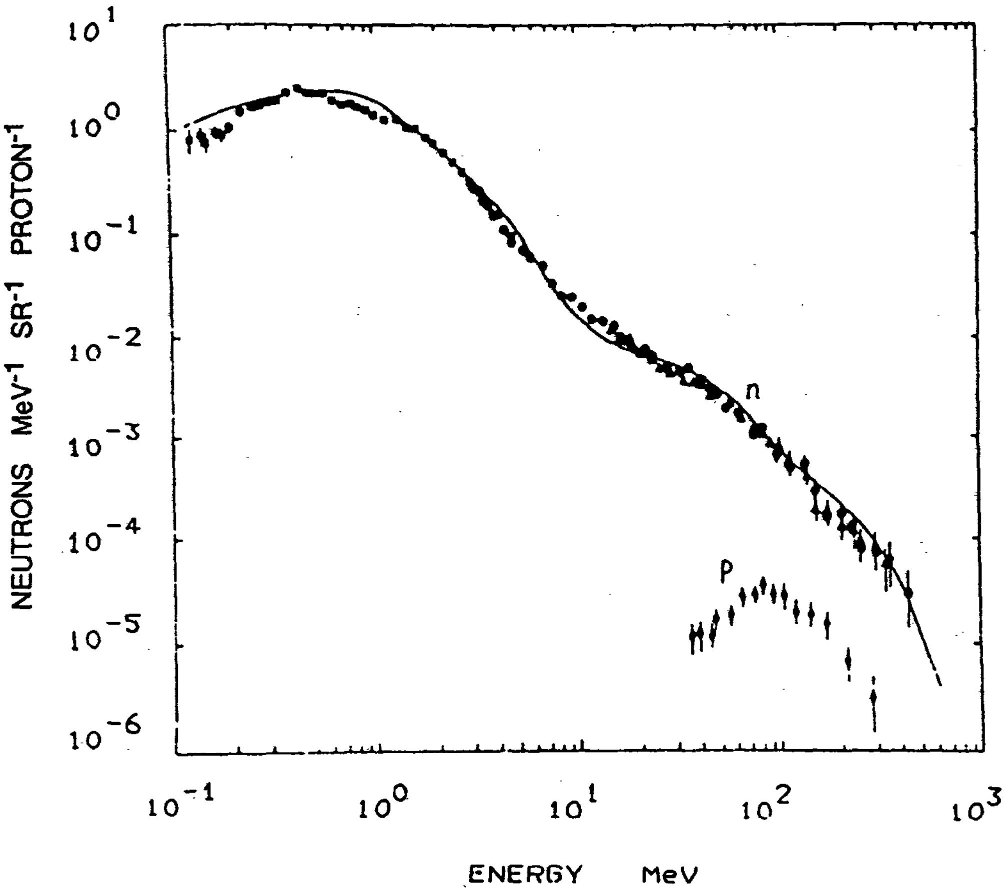

Fig. 5
Target: lead
Ø20 x 20 cm,
E_p = 2,55 GeV,
solid line -
SSNTD, points -
time-of-flight

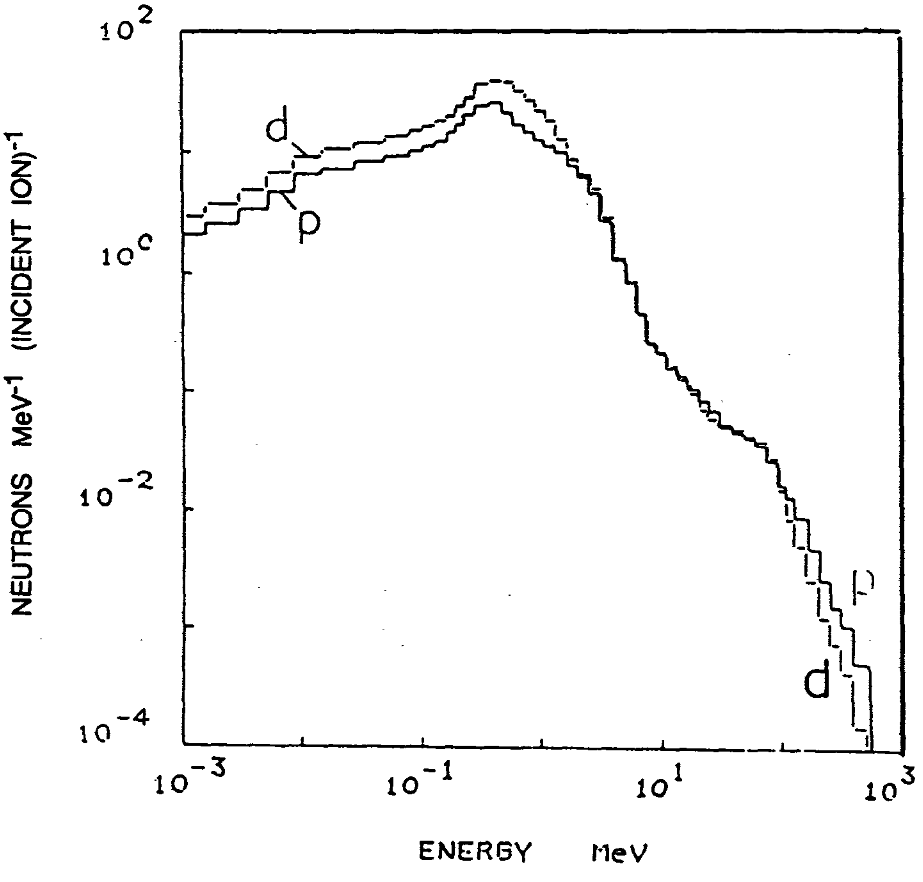

Fig. 6
Spectra of
neutrons from
lead cylinder
Ø20 x 60 cm,
measured with
SSNTD, $E_{p,d}$ =
= 2 GeV

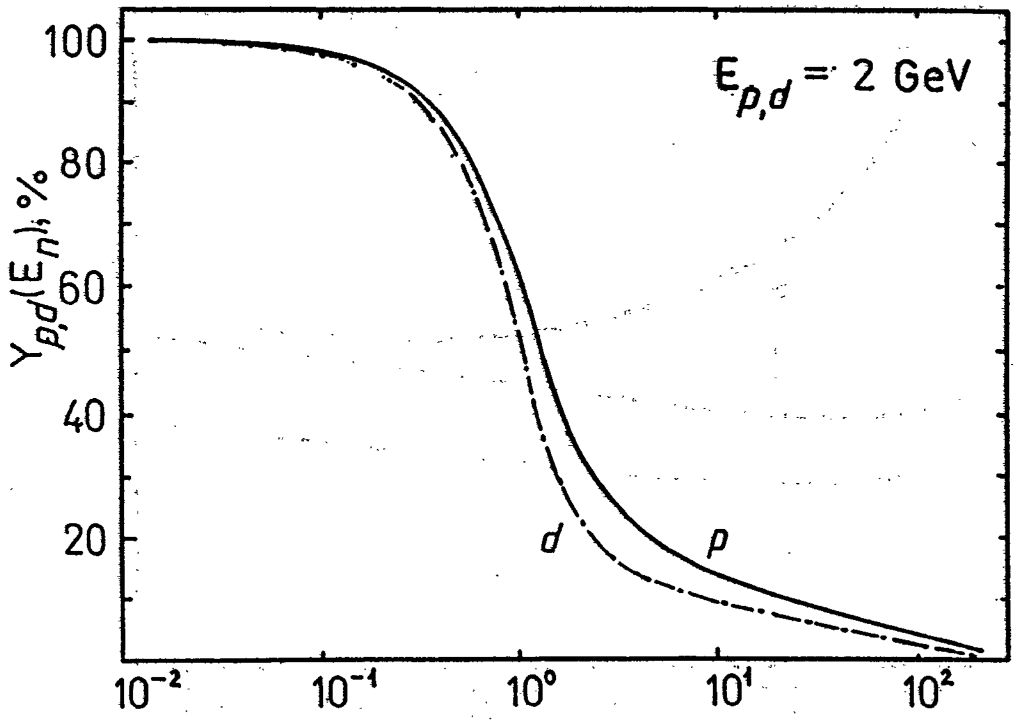

Fig. 7 "Hardness" of neutron spectra for lead target Ø20 x 60 cm, bombarded by p and d with energy 2 GeV

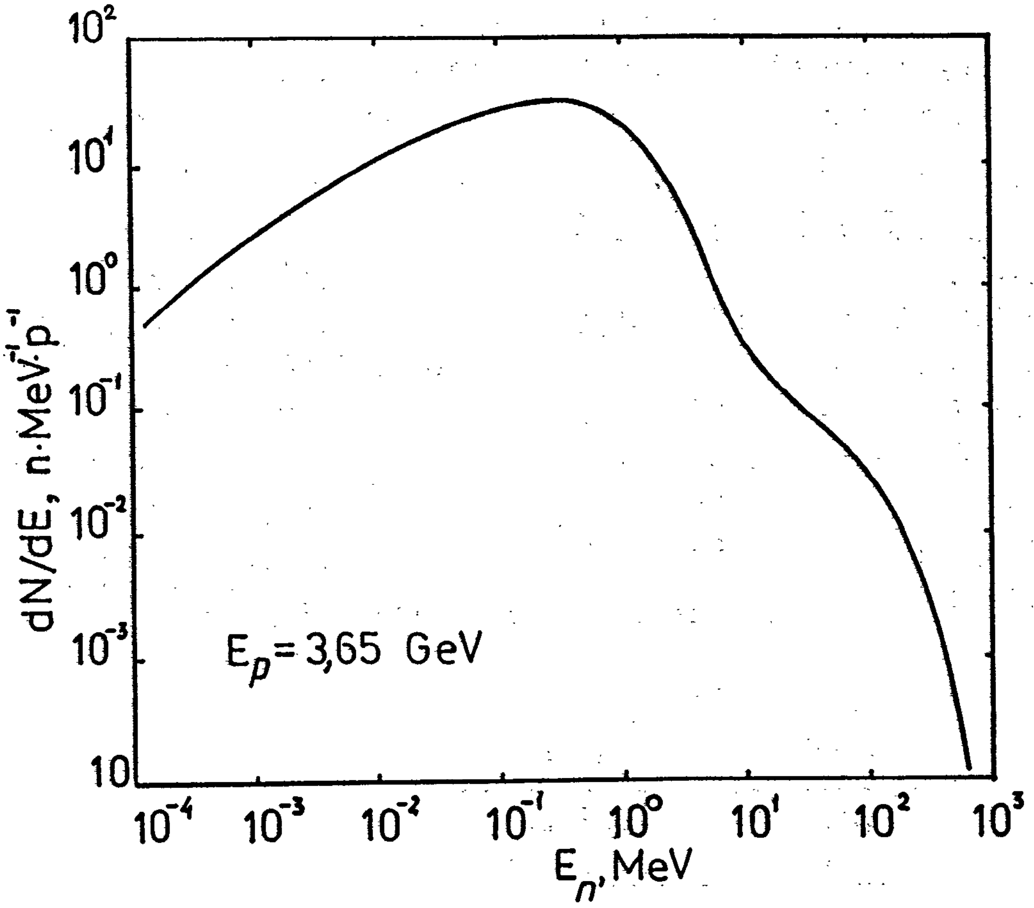

Fig. 8 Neutron spectrum for Pb cylinder ϕ20 x 60 cm, E_p = 3.65 GeV

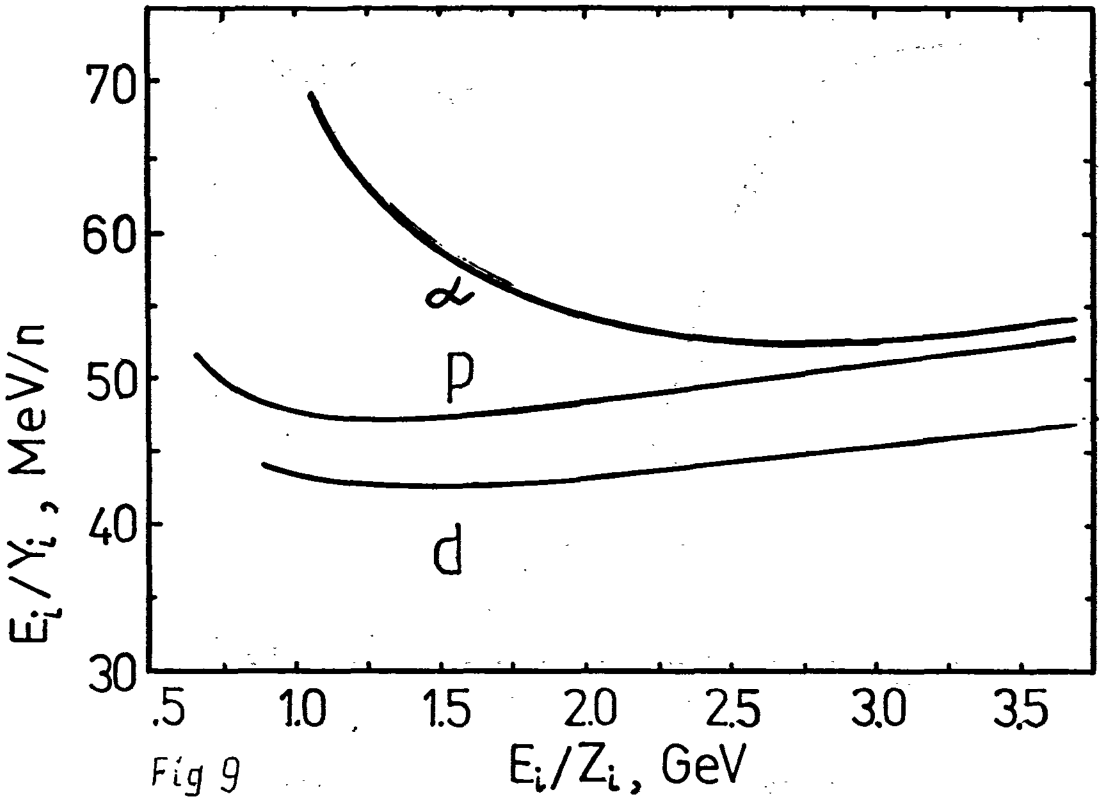

Fig 9

Neutron yields Y_i/Z_i measured
by "moderation" and "threshold" techniques,
lead target Ø 20 x 60 cm, ion energy is GeV per unit Z_i

E/Z	Y_d^m	Y_d^t	Y_α^m	Y_C^m	E_p	Y_p^m	Y_p^t
I,03	23,8±I,8	24,9±5,0	I5,4±0,8	-	0,99	2I,3±0,6	25,I±3,0
I,48	34,6±0,9	-	-	-	I,47	3I,4±0,8	-
I,98	45,8±I,2	58,5±8,2	35,2±I,4	2I,5±0,8	2,00	40,2±I,I	44,2±3,I
2,55	56,4±I,5	-	48,4±I,3	33,0±0,8	2,56	5I,3±I,5	63,5±7,6
3,03	66,6±I,7	-	55,0±I,6	-	3,I7	6I,5±I,7	7I,6±6,2
3,76	79,9±2,0	98,9±I3,8	68,8±I,9	50,3±I,3	3,65	68,I±2,5	80,7±6,9
4,42	-	-	78,7±2,0	-	4,45	8I,I±2,2	-
5,38	I08,4±2,8	-	92,6±2,3	-	6,I4	I06,8±2,8	-
7,3	I56,6±5,0	-	I36,7±4,0	I05,4±3,7	8,I	I3I,7±3,7	-

He–3

$E_{He}/2$	$Y_{He-3}/2$
2,24	42,2±I,2
5,74	98,6±2,5

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Q(I.M.Thorson): Was the last graph on energy cost per neutron normalized absolutely, i.e,, is the cost a minimum for deuterons at ~2 GeV?

A(R.G.Vassil'kov): At Ed≈1.4 GeV, normalized absolutely in a sense of kinetic energy of d spent for neutron "liberation" (releasing) from the target (Pb ø20×60 cm).