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FURTHER EVIDENCES FOR ENHANCED NUCLEAR CROSS-SECTIONS OBSERVED IN 44 GeV CARBON ION INTERACTIONS WITH COPPER

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I. INTRODUCTION

A recent article (Ref.[1]) described in great detail the enhanced production of ^{24}Na in copper induced by wide-secondary fragments generated in the interaction of relativistic (44 GeV) carbon ions with copper. The idea of this series of experiments was initially motivated by the ongoing debate on possible Shortened Mean Free Path (abbreviated hereafter as SMFP) for nuclear interactions of such secondary fragments. All effects associated with SMFP can be expressed in an equivalent manner as being due to an «enhanced nuclear cross section», observed only over short distances in the order of (0.1—10) cm and observed only in relativistic hadronic interactions. Reference [1] gives a rather complete list of the relevant literature up to 1992. Additionally some articles have appeared in support of SMFP [2—5]. R.Guoxiao et al. [6] published some positive evidence for SMFP-effects induced by 200 A GeV ^{32}S in copper and studied with CR-39 track detectors. Furthermore, Schulz and Ganssauge [7] published an article extremely sceptical about the interpretation of experiments reported in Ref. [1]. However, in a recent «Addendum» Ganssauge modifies his opinion [8]. Arisawa et al. [9] observed a SMFP of secondary hadrons (most likely pions) in very high energy cosmic ray investigations.

Nevertheless, a consistent model for the interpretation of SMFP-effects is lacking. It seems to be worthwhile to repeat again, that a series of experiments studying SMFP has never been challenged nor reproduced, as mentioned by Arbuzov et al. [10]: Alexander et al. [11], Gasparian et al. [12] and Bano et al. [13] observed clearly SMFP-effects. Ref.[10] contains some further references, describing SMFP effects with slightly reduced statistical significance.

We concentrate on effects due to «enhanced nuclear cross-sections» as observed in the interaction of 44 GeV ^{12}C with copper targets and studied with nuclear chemistry techniques. Here we give more precise arguments for the central claim of Ref.[1], in particular, that «energetic fragments which are emitted into the laboratory angles $10° < \theta < 45°$ appear to produce more ^{24}Na (up to nearly one order of magnetude) than calculated with a phenomenological model and an intranuclear cascade model. This enhanced production of ^{24}Na by wide-angle secondaries is only observed for 44 GeV ^{22}C on copper, but not for 25 GeV ^{12}C on copper». This paper describes recent experiments and calculations on the

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interaction of 44 GeV ^{12}C with various copper target configurations. Next, we will describe the absorption of protons with energies 0.6 GeV < $E(p)$ < 4.5 GeV through stacks of 8 copper blocks, each 1 cm thick. In this way the total interaction cross-section of secondary fragments emitted into wide angles is simulated. One observed experimentally that the total interaction cross-sections of primary relativistic protons and of secondary fragments emitted into large angles are rather similar. This leads to an open problem in the understanding of the properties of wide-angle emitted secondary fragments. In order to search for a possible solution, the yields of some low-energy nuclear reactions ((n, γ) and (n, f)) initiated by secondary fragments emitted from massive copper targets were measured. These massive copper targets were irradiated with relativistic carbon ions. Our irradiations with carbon ions were carried out at the Synchrophasotron, Laboratory of High Energies (LHE), JINR, Dubna in Russia. The proton irradiations were carried out at PSI, Villigen in Switzerland (0.6 GeV), SATURNE, Saclay in France (2.6 GeV) and at the Synchrophasotron in Dubna (1.3 and 4.5 GeV).

As a matter-of-record, similar experiments on extended uranium targets irradiated with relativistic protons have recently been carried out by Andriamonje et al. [14] at CERN, Geneva (Switzerland). Their experimental results will be compared with the results of similar experiments for recent years at LHE, JINR, Dubna.

II. FURTHER WORK USING COPPER TARGETS IRRADIATED WITH 44 GeV ^{12}C AND YIELDING ^{24}Na IN COPPER EXPOSED TO SECONDARY HADRONS

The 2π Ring Target, Experiment and Theory [1,15,16]

Experiments. In the preceding paper (Ref. [1]) we reported in great detail on experiments with the 2π ring target. Considering the importance of this experiment, we improved one important detail of this experiment: the handling of the beam halo correction. The following questions could then be studied: Are energetic fragments emitted into wide angles of > 10° in the interaction of 44 GeV ^{12}C with copper targets? To what extent can these energetic fragments produce deep-spallation products, like ^{24}Na, in secondary copper targets, i.e., in Cu-rings? Can this production of ^{24}Na be understood by model calculations?

For these reasons, a 2π ring target was irradiated in two different configurations with 44 GeV ^{12}C-ions.

The complete 2π ring target (Fig.1a) covers to a first approximation a 2π solid angle and consists of two 1 cm thick Cu-disks ($k = 0{+}1$, front disk; $k = 9{+}8$, back disk; separated by a distance of 20 cm) and of six Cu-rings, also 1 cm thick, of different shapes in between, with an outer diameter of 8 cm and an inner opening

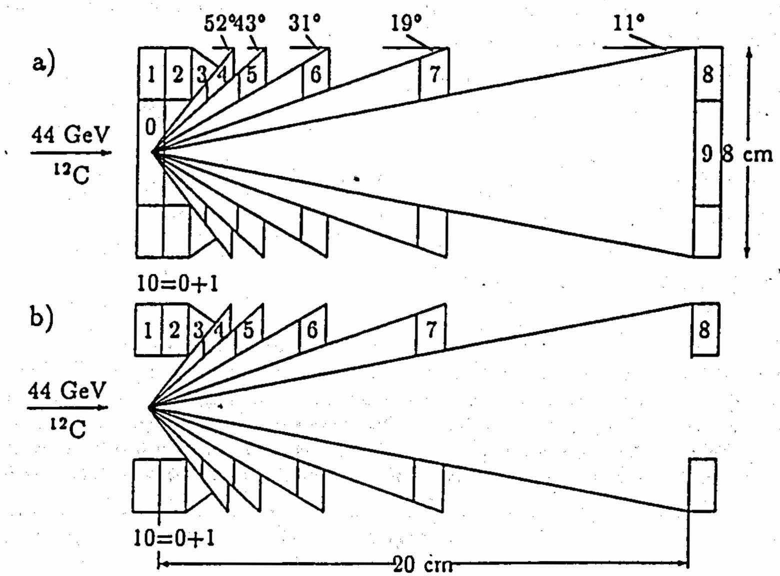

Fig.1. The ring target system, exposed to 44 GeV carbon ions: a) the complete 2π ring target; b) target-out ring target. The targets are rotationally symmetric around the beam axis and are defined with $k = 1,2,3,...,10$, as described in the text. The target material is copper

of 4 cm. For an idealized pencil beam, the six Cu-rings cover the angular ranges as indicated in Fig.1a. But the beam of relativistic heavy ions is not ideally focussed. The experimental determination of the beam profile within the disk ($k = 0$) has already been described [1].

Additionaly, primary particles from the beam halo can enter the outer area of the 2π ring target (2 cm $\le r \le$ 4 cm) within the ring ($k = 1$) and produce ^{24}Na in the next rings while propagating through such a thick Cu-target. In order to know the effect due to wide-angle emission of energetic particles emitted from the center of the front disk ($k = 0$), one has to correct for the beam halo thick-target effect. For this, a target-out ring target (Fig.1b) was irradiated under the same conditions as the 2π ring target. This target-out ring target consists of the same Cu-rings as the earlier target, however, the inner parts of the front disk for ($k = 0$) and the back disk ($k = 9$) were omitted. This new target-out ring target was irradiated for 24 hours with a total ^{12}C-flux of $9.0 \cdot 10^{11}$ ions of 44 GeV. (Further details are given in Ref.[16]): After the irradiation, the targets were immediately transported to Kernchemie, Philipps-University in Marburg (Germany) and counted there for their gamma-activity with high-resolution germanium detectors having a resolution of less than 1 keV for ^{60}Co-lines. The analysis of the gamma-spectra is concentrated on the determination of ^{24}Na-activity. The reasons for this will be summarized only briefly:

1. ^{24}Na has a very convenient half-life (15 h) and a very well-defined gamma-line (1368.5 keV). Therefore its activity can be determined quite easily and accurately. $C^{12} + Cu \to Na^{24} + \ldots$

2. ^{24}Na is formed in copper only by high-energy hadrons ($E > 0.8$ GeV). The excitation function for its production is well known in the energy range from 0.1 to 400 GeV protons. It is the one of the best known excitation functions for high-energy hadrons with copper.

Table 1. Angular distribution $R_\theta(^{24}\text{Na})$ as the ratio of the ^{24}Na activity within a certain angular interval θ (corresponding to ring k) as compared to the front disk, using the «2π ring target» for 44 GeV ^{12}C. The results are corrected for effects due to the beam halo, using the results for the «target-out» ring target (Fig.1b). These results are substituting those results, which were published in Table II, Ref.[1]. Essentially, the results of this work agree with those presented earlier. However, they are considerably more accurate due to the improved beam halo correction

Ring k	Angular interval θ	$R_\theta(^{24}\text{Na})$ %
2	70°—90°	0.0±0.1
3	52°—70°	0.0±0.1
4	43°—52°	0.2±0.1
5	31°—43°	1.0±0.1
6	19°—31°	4.4±0.2
7	11°—19°	6.4±0.1
8	6°—11°	7.0±0.2
9	0°—6°	105.0±3.0
$\sum_{\theta=0°}^{90°} R_\theta(^{24}\text{Na})$	0°—90°	124±3
$R_\theta(^{24}\text{Na})$		124±2
$\Delta R_\theta(^{24}\text{Na})$		0±4
σ_{beam}		0.73 cm

As usual, we did not calculate absolute cross-sections for the reaction ($\text{Cu} + \text{X} \to {}^{24}\text{Na} + \text{Y}$), but only cross-section ratios, normalized to the ^{24}Na-activity in the front copper disk for the complete 2π ring target ($k = 0{+}1$, Fig.1a), and normalized to the ^{24}Na-activity in the first ring for the target-out ring target ($k = 1$, Fig.1b). In this way, one could obtain rather accurate production ratios of ^{24}Na in various Cu-parts, without needing the exact knowledge of the beam intensity, the counting efficiencies for ^{24}Na in copper and other experimental details. The experimental cross-section ratios for both target-systems (Figs.1a and b) have been reported in detail by Heck [16]. Here we show the results for the 2π ring target, properly corrected for beam-halo effects, as determined experimentally for the target-out system (Tabl.1). The following conclusions were drawn from these results:

(a) The 2π ring target shows an appreciable amount of ^{24}Na produced by secondary fragments emitted into large lab angles ($10° < \theta < 43°$) from a 1 cm thick Cu disk irradiated with 44 GeV ^{12}C. The uncertainties in the actual experimental values are considerably smaller than those reported in Ref.[1]. This is due to improved beam-halo corrections.

(b) These experiments answer to some extent the question of whether any secondaries exhibiting a possible decay of the SMFP effect can be observed within our target arrangement. For this, we compared the activity ratio for ^{24}Na in two copper disks in contact (being irradiated during an independent beam exposure, such as described in Ref.[1]) with the sum of activity ratios in our 2π ring target. The first exposure yielded an activity ratio $R_0(^{24}\text{Na})$, the later yielded a sum of activity ratios:

$$\sum_{\theta=0°}^{90°} R_\theta(^{24}\text{Na}).$$

Any decay of secondary fragments due to SMFP effects would show up as a loss-of-activity as follows:

$$\Delta R_\theta(^{24}\text{Na}) = R_0(^{24}\text{Na}) - \sum_{\theta=0°}^{90°} R_\theta(^{24}\text{Na}). \qquad (1)$$

This result is also given in Table 1. No deviation $\Delta R_\theta(^{24}\text{Na})$ from zero could be observed. However, due to the experimental uncertainties in $\Delta R_\theta(^{24}\text{Na})$, a contribution of decaying SMFP secondary fragments within the experimental uncertainties of ±4% cannot be excluded. Next, the problem is, whether the abundant production of ^{24}Na at large lab angles $\theta > 10°$ can be understood within the framework of widely accepted theoretical models. In Ref.[1] we reported on a factor of (7.6±0.6) between experiment and theory for an angular interval of $19° < \theta < 31°$. We used two simulating models: at first, a Phenomenological Model (PM) and, secondly, the Dubna Cascade Model (DCM). The results based on the DCM shown in Fig.9 of Ref.[1] will have to be modified here.

We consider the Dubna Cascade Model in some detail again. Over the years of developing the cascade-evaporation model, detailed tests of the model accuracy have been carried out for describing the global characteristics of the process of

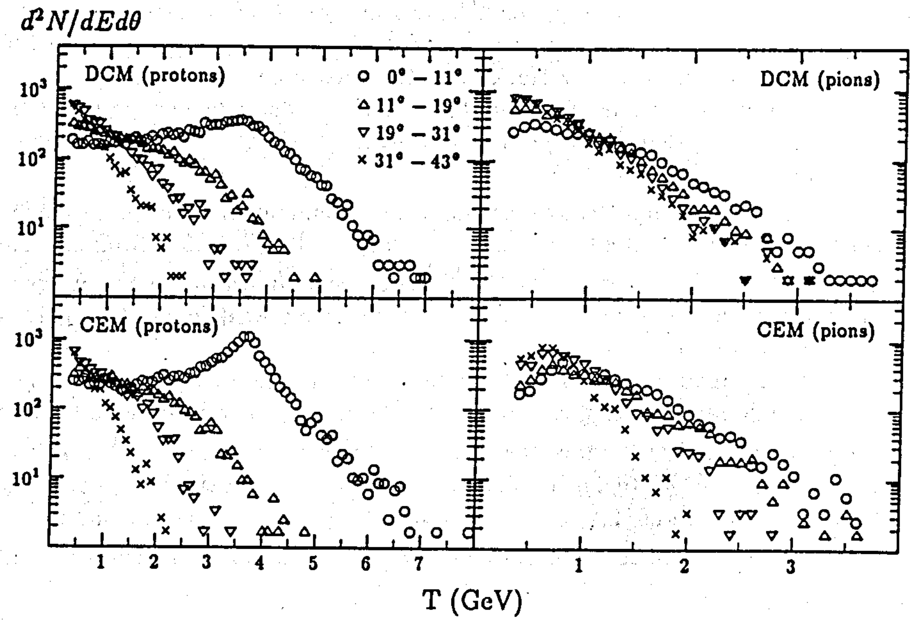

Fig.2. Calculated energy spectra in relative units for secondary protons and pions ($\pi^{\pm}$) emitted into certain angular intervals $\Delta\theta$ from the interaction 44 GeV $^{12}C + Cu$, using two versions of the Dubna Cascade Model, as described in the text

hadron-nucleus and nucleus-nucleus interaction [17—22]. In the present approach two modifications of the model were used for mutual comparison and interpretation of the avilable experimental data. The first one (DCM) deals mostly with the particle production (including isobars and heavy mesons) in rela–tivistic particle interactions with target nuclei [17]. The second approach, called the Cascade Evaporation Model (CEM) [21], includes both the modules simula–ting the particle production in any single hadron-nucleus or pion-nucleus inte–raction and those describing the particle transport in the target material. The idea to use the second model was based mostly on the attempt to study the supposed influence of the particle transport and the beam halo on the resulting activity distribution in the 2π ring target. In addition, a Phenomenological Model (PM) [23] was employed, as in Ref.[1].

Comparison between DCM and CEM. Calculated spectra of the secondary protons and pions for 44 GeV $^{12}C + {}^{nat}Cu$ reaction have been studied to compare the results obtained by the two Dubna model approaches. The comparison between the DCM and our present evaluations based on the CEM appears to be in satisfying agreement (Fig.2) except the slight bump at the angular interval of $0° < \theta < 11°$ at about 3.65 GeV.

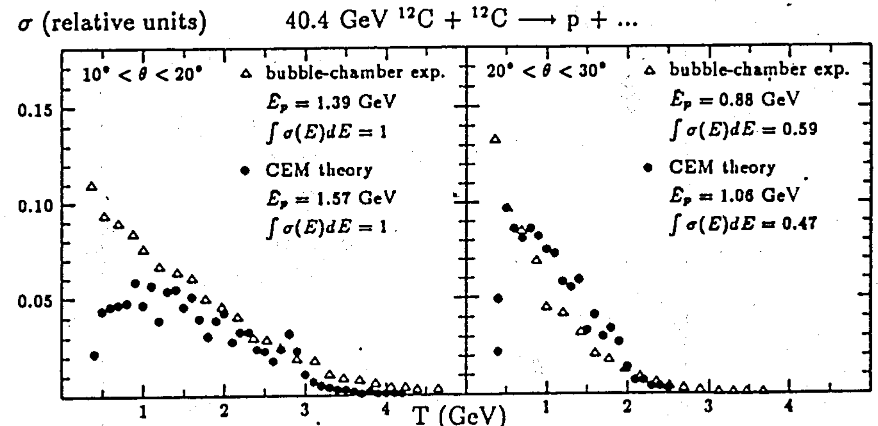

Fig.3. Experimental and calculated energy spectra for secondary protons emitted into certain angular intervals $\Delta\theta$

Comparison with other experiments. The calculated energy spectra were compared with two different sets of experimentally observed energy spectra, as obtained with the nuclear emulsion technique [24—27] and with the propane bubble chamber of the JINR (Dubna) irradiated with 40.4 GeV ^{12}C-ions [28]. The results of the later experiment are presented as double differential energy spectra for charged secondary protons emitted from carbon target nuclei in Fig.3. It shows the calculated (CEM) and experimental (propane bubble chamber) energy spectra for two important angular intervals ($10° < \theta < 20°$ and $20° < \theta < 30°$). The agreement between experiment and theory appears to be satisfying.

Table 2. Calculated (CEM) mean multiplicities (MIP) and mean energies T for «minimum ionizing particles» (MIP, $E_p > 0.3$ GeV and $E_\pi > 0.05$ GeV) produced in 44 GeV $^{12}C + {}^{nat}Cu$ and in 44 GeV ^{12}C + «emulsion» at different angular intervals in comparison to the emulsion experiments. The experimental multiplicities have been obtained with 44 GeV ^{12}C in emulsions (Ref.[24,25]), their energies with 79 GeV ^{22}Ne in emulsion (Ref.[26,27])

$\Delta\Theta$	Emulsion (MIP/event)	CEM emulsion target (MIP/event)	CEM copper target (MIP/event)	Protons T_{exp} (GeV)	Protons T_{th} (GeV)	Pions T_{exp} (GeV)	Pions T_{th} (GeV)
0°—10°	1.65	3.82	4.03	1.8	2.9	1.0	0.9
10°—19°	0.75	1.52	2.28	1.5	1.6	0.7	0.8
19°—31°	0.57	1.68	1.66	1.2	0.9	0.6	0.6
31°—43°	0.39	1.09	1.27	0.9	0.7	0.5	0.4
0°—43°	3.36	8.11	9.24	—	—	—	—

On the other hand, the comparison of nuclear emulsion experiments with CEM model calculations show some significant differences with respect to the

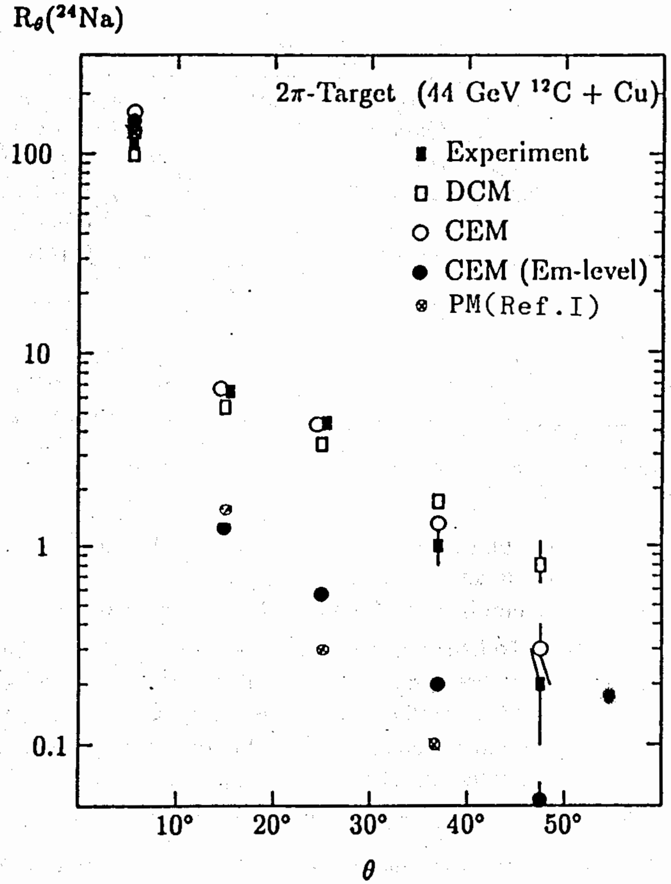

Fig.4. Comparison between calculated and experimental distributions $R_\theta(^{24}Na)$ for the interaction 44 GeV $^{12}C + ^{nat}Cu$. The results CEM (Em-level) are considered to be the most realistic model calculations. These results are similar to the results using the Phenomenological Model (PM) taken from Ref.[1]. Further details are given in the text

number of MIP (minimum ionizing particles with $\beta > 0.7$) in Table 2. The CEM-calculations give about 3 times larger multiplicities for MIP's as compared to the emulsion experiment. Simultaneously, the mean energies obtained theoretically are close to the experiment [26,27].

^{24}Na-*Production in the* 2π *ring target*. The calculation of the relative ^{24}Na-activity in the rings of the 2π ring target — based on the DCM — was carried out up to now using the hadron spectra provided by V.D.Toneev [22] according to the standard formula

$$A_i^k(E) = \sigma_i(E) \cdot N_i^k(E) \cdot N_{Cu} \quad (2)$$

considering the sodium production cross section $\sigma_i(E)$, hadron flux $N_i^k(E)$ of i-th particle at energy E and the density of the target material N_{Cu}. Details are given in Ref.[1]. New results for the 2π ring target configuration were obtained by the CEM using the technique similar to that cited in Ref.[21] considering the particle transport. This approach makes it possible to obtain some information on the influence of the target structure on the resulting activity. We consedered the ob– served beam distribution properly. The results for the calculations are presented in Fig.4 together with the experimental results. As one can see, both models, DCM and CEM, are in agreement with the observed angular distruction $R_\theta(^{24}Na)$.

The results from the PM, (taken from Fig.9 in Ref.[1]) differ considerably from the experimental distribution $R_\theta(^{24}Na)$. As has been shown by Pille [29] the important difference between the PM and the other models, DCM and CEM, is the number of secondary particles emitted in the nucleus-nucleus interaction into wide angles. The calculated numbers of secondary fragments emitted into wide angles using the PM are close to the experimental observations in nuclear emulsions. The calculated numbers of secondary fragments being MIP and calculated with CEM are about three times larger than the number of MIP, as already being stated.

Two facts are generally accepted for nuclear emulsion detection:

1) nuclear emulsions register very accurately the number of «minimum ionizing particles» (MIP);

2) nuclear emulsions consist of H, C, O, N, Br and Ag nuclei and they react collectively in relativistic interactions rather similar to a Cu-target, as has been demonstrated in Ref.[30], where related experiments have been described. Now it is interesting to look for the experimentally observed number of MIP in related emulsion experiments irradiated with hadrons over an energy range of 1 GeV/u $< E <$ 4 GeV/u, as shown in Table 3. The three experimentally observed values of the sums of MIP appear to be internally consistent.

Consequently, we have decided to use the number of MIP's observed in nuclear emulsions (Table 2) as a basis to calculate ^{24}Na-production at large angles. The calculations based on CEM have then been performed with MIP multiplicities at definite angular intervals roughly cut down to the experimental results in nuclear emulsions irradiated with 44 GeV ^{12}C (Refs.[24,25]). The results are presented in Fig.4 (CEM/Em-level). This reduction of MIP multiplicities (1:0.35) leads to a discrepancy of a factor of (7±1) between experiment and this model calculation within an angular interval of $19° < \Theta < 31°$ just as in Ref.[1].

Somewhat similar and related discussions have already been described in the literature, where the experiment (Ref.[32]) was at first challenged (Ref.[33]), but later on this challenge was retracted (Ref.[27]).

Table 3. The experimental angular distribution for «minimum ionizing particles» (MIP) in three independent nuclear emulsion experiments

Δθ	N, number of MIP in the given angular interval Δθ $dN_{exp}/d\theta$		
	3,6 GeV p [31]	44 GeV ^{12}C [24]	72 GeV ^{40}Ar [30]
0°—10°	—	1,65	4,69
10°—19°	—	0.75	2.59
19°—31°	—	0.57	1.25
31°—43°	—	0.39	0.86
43°—90°	—	0.80	0.98
0°—90°	1.63	4.16	10.38

Finally, one should compare the copper-configuration experiments of 36 GeV ^{40}Ar vs. 72 GeV ^{40}Ar, as described in Ref.[30] and [32], with those induced by 25 GeV ^{12}C vs. 44 GeV ^{12}C. At the low energies (36 GeV ^{40}Ar and 18 GeV ^{12}C) no enhanced production of ^{24}Na in copper, exposed to secondary fragments emitted into $\theta > 10°$, could be observed experimentally [1,2,16,30,32]. This enhanced production of ^{24}Na in copper, exposed to secondary fragments emitted into $\theta > 10°$ could only be observed at higher energies (72 GeV ^{40}Ar and 44 GeV ^{12}C). But the angular distribution of minimum ionizing particles observed in nuclear emulsions does not change considerably, when one increases the ^{40}Ar-ion energy from 36 to 72 GeV (Ref.[30]). This enhanced production of ^{24}Na in copper, exposed to secondary fragments emitted in the interaction of 44 GeV ^{12}C with copper, constitutes the first essential result in this publication.

Segment-Targets and the Appearance of Another Problem

One observed in the 2π ring target experiment exposed to 44 GeV ^{12}C to much ^{24}Na in copper-ring exposed to $19° < \theta < 31°$ secondary hadrons. The next question is: How does this observation change, when one does not expose a 1 cm thick copper target to these secondary fragments, but 3 cm thick copper stacks, composed out of three times 1 cm thick copper plates? Such an experiment (called Segment-1) has been described in Ref.[1] and gave the following results:

i) The observation of seeing too much ^{24}Na in copper exposed to secondary fragments with $20° < \theta < 30°$ is reproduced with another experimental set-up (Segment-1 vs. 2π-target). One observed again appr. 4% ^{24}Na in the segments, just as within the 2π ring target.

ii) This production rate of ^{24}Na does not diminish significantly within the 3*1 cm copper stack exposed to these secondaries.

iii) This observation does not show any significant variation, when the distance between the primary Cu-target and the secondary copper-target exposed to secondaries varies between 4 and 18 cm.

This experiment was slightly improved with modified technique in another experiment called Segment-2, also described in Ref.[1]. It gave essentially the same experimental results as those mentioned above and shown in Table 4. The interested reader is referred to Ref.[16] for further details.

Table 4. All results of ^{24}Na-activities in «secondary» Cu placed in the angle $20° < \theta < 30°$

Experiment/ exact angle	Distance from Cu-target to secondary Cu-target	Corrected for beam halo	R_Θ, (%)
2π ring target $19° < \theta < 31°$	6 cm	yes	4.4±0.2
Segment-1 $20° < \theta < 30°$	from 5 cm up to 18 cm	no	(4.2±0.4)–(5.0±0.3)
Segment-2 $20° < \theta < 30°$	from 5 cm up to 22 cm	no	(3.8±0.3)–(4.3±0.3)
Segment-3 $20° < \theta < 30°$	6 cm	yes	4.2±0.3

R_Θ (%) is the activity in the «secondary» Cu, as compared to the Cu-target exposed directly to 44 GeV ^{12}C.

Finally, an improved target, called Segment-3, was designed and it is shown in Fig.5. The aim of this experiment was limited to the determination of the decrease of ^{24}Na in six copper sectors exposed to $20° < \theta < 30°$ having one fixed distance between target and secondary copper. In order to improve on the counting statistics we measured the full azimuth of 360° as well for the «shadow», as for the secondary copper. Two irradiations were carried out:

i) Segment-3 was irradiated with $1.1 \cdot 10^{12}$ ions at 44 GeV with ^{12}C ions for 24.8 hours.

ii) Segment-3 without a central Cu-target T was irradiated with $0.9 \cdot 10^{12}$ ions at 44 GeV with ^{12}C ions for 24.0 hours, in order to find out the effect of the beam halo on the activation of Cu sectors.

All activities are normalized to the first sector ($k = 1$). The results are shown in Fig.6. The decrease of the activities could be fitted by an exponential law, the values are also given within Fig.6. The ^{24}Na activity decreases in this experiment from the first to the sixth sector from 1.0 down to (0.64±0.05). Finally, it is interesting to summarize the results of all 4 experiments studying the production of ^{24}Na by secondary fragments emitted into a lab. angle of $19° < \theta < 31°$, as shown in Table 4. Despite considerable different geometric constructions employed, all yields are well within a range (4.5±1.0)%. No «distance effect» has been observed.

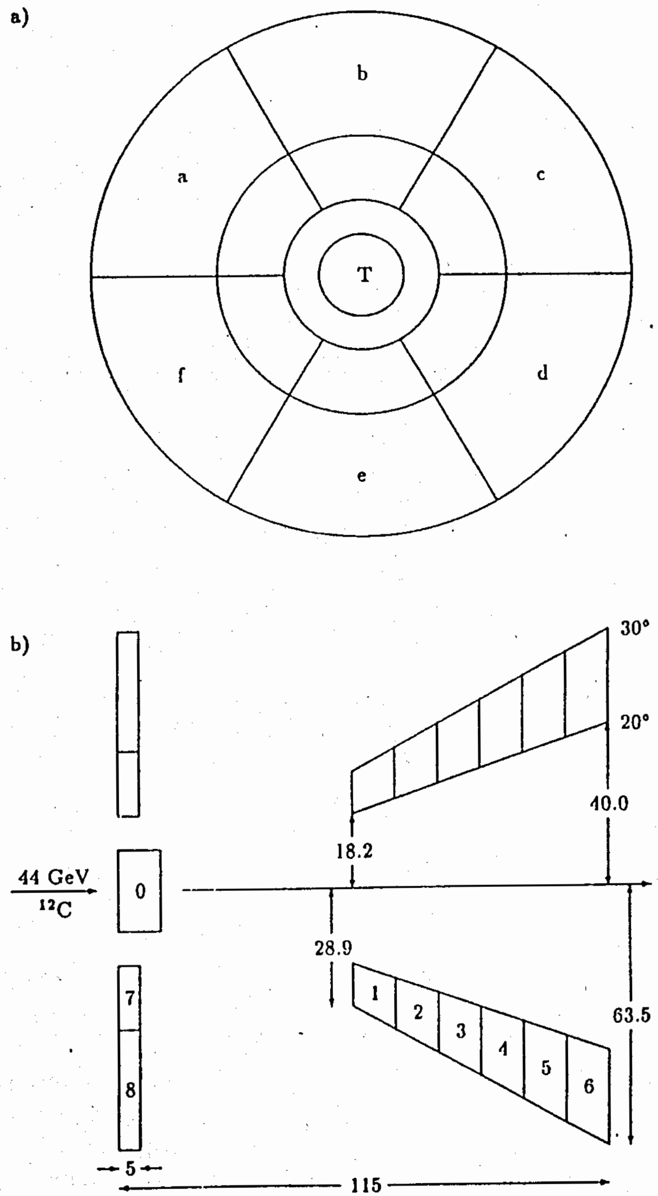

Fig.5. Schematic drawing of the target set-up Segment-3. The central target T has dimensions of a 2 cm diameter and a 1 cm thickness. All parts are machined out of copper, all distances are given in mm. a) frontal view, b) cut view

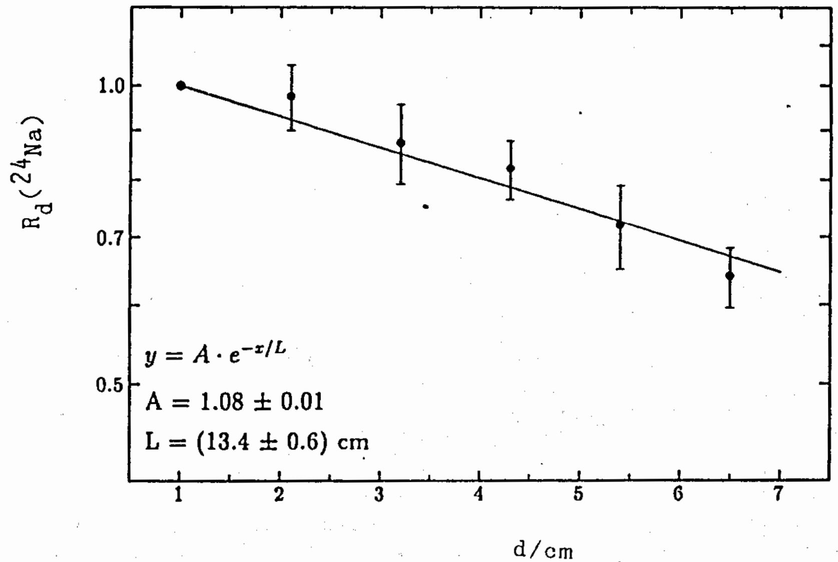

Fig.6. The decrease, $R_d(^{24}Na)$, in secondary copper as observed in the Segment-3 target. All activities are normalized to Segment-1. The target was irradiated with 44 GeV ^{12}C

In all our preceding publications concerning these copper configuration experiments it was stated that only hadrons, i.e. protons, neutrons, and — to some small extent — pions are responsible for the production of ^{24}Na in copper exposed to secondary particles emitted into $20° < \theta < 30°$ (Refs.[1—5]). Moreover, Fig.2 shows, that the proton and the pion spectra are very broad, extending from 0 up to 4 GeV in the angular interval being of interest here. Nevertheless, the decrease of ^{24}Na-activities, as shown in Fig.6, should be correlated in an approximate manner to the energy of secondary baryons (protons and neutrons). We have used, essentially, the Segment-3 target as a high-energy calorimeter. Compared to other calorimeters, used in high-energy physics, this Segment-3 target is quite simple and it can give only a very approximate answer to our problem. In this approximate manner, the Segment-3 target was calibrated with monoenergetic protons as the typical projectile for the production of ^{24}Na in copper under the prevailing conditions. Consequently, cylindrical stacks of copper, 8 cm in length, cut into sectors of a 1 cm length and having various diameters of 2.4 or 8 cm were irradiated perpendicularly with monoenergetic protons from various accelerators*.

*The following proton accelerators were used yielding as energy:
i) protons of 0.6 GeV at the PSI, Villigen, (Switzerland);
ii) protons of 1.3 GeV at the Synchrophasotron, Dubna, (Russia);
iii) protons of 2.6 GeV at the 1) Synchrophasotron, Dubna, (Russia);
2) SATURNE, Saclay, (France);
iv) protons of 4.5 GeV at the Synchrophasotron, Dubna, (Russia).

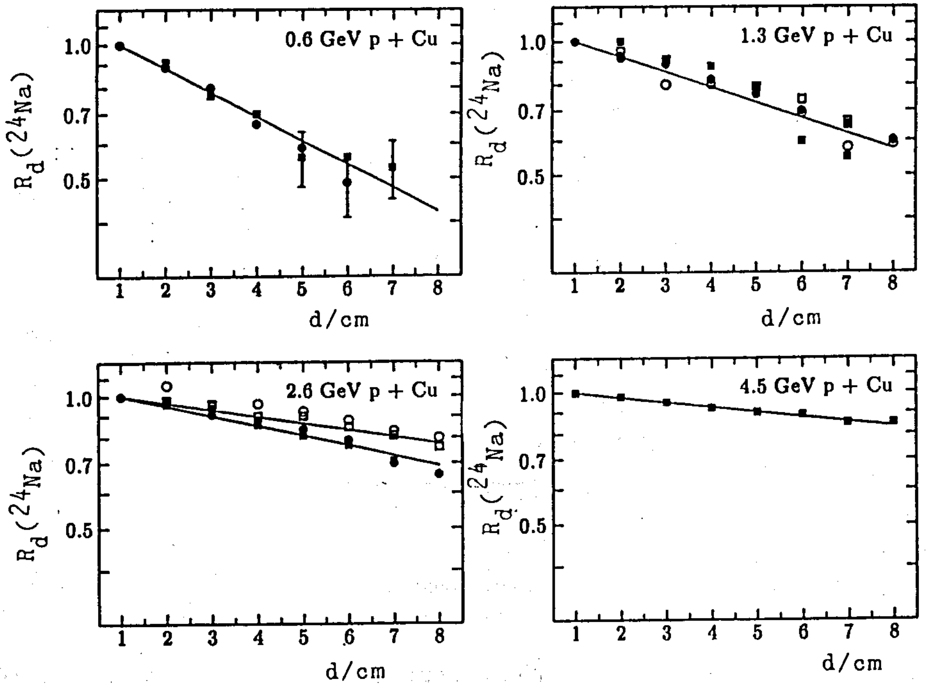

Fig.7. The decrease, R_d (^{24}Na), in a compact Cu-cylinder, composed of 1 cm thick disks with a diameter of 2 cm (full dots), 4 cm (full squares), and 8 cm (open squares) irradiated with monoenergetic protons, as indicated

The irradiations were carried out with well focussed beams of total fluence > 10^{12} protons. The results are shown in Fig.7. At a first glance, one observes, the lower the proton energy, the steeper the decrease of ^{24}Na activities with increasing sector number. However, there are some small differences between 2 cm, 4 cm, and 8 cm diameter copper rods, which were not accounted for in this work. A least square fit through all experimental points at a given energy yields a decrease, shown in Fig.8. This is the energy calibration of our system. Comparing this with the experimental results of Segment-3 one obtains the following energy for the secondary protons:

$$E(\text{secondary protons})_{20° < \theta < 30°} = (1.6 \pm 0.4)\ \text{GeV} \qquad \text{(experiment)}$$

Taking into account all the assumptions which went into our analysis and the simplicity of our experimental apparatus, we consider this value with its 25% uncertainty as satisfactory. It has been mentioned earlier, the energy spectrum of secondary protons emitted into the same angular interval can be calculated theore-

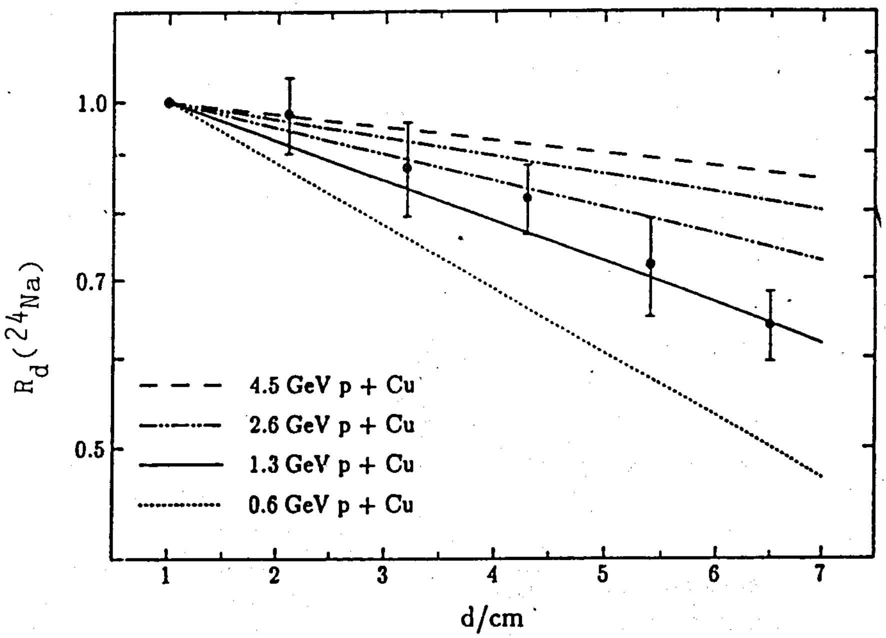

Fig.8. The Segment-3 experiment used as a high-energy proton calorimeter: The decrease, R_d (^{24}Na), in 6 consecutive «secondary» Cu-blocks, exposed to $20° < \theta < 30°$, is shown as full dots with their uncertainty (from Fig.6). Simultaneously, this figure shows 4 lines: They represent the decrease of ^{24}Na-activities in 7 consecutive Cu-blocks irradiated directly with 0.6, 1.3, 2.6, and 4.5 GeV protons (calibration), just as in Fig.7

tically, as based on the Dubna Cascade Model. In addition, the energy spectrum of secondary protons in the angular interval of interest has been determined experimentally in the magnetic field of a bubble-chamber. (Ref.[28]) Its shape agrees very well with the energy spectrum calculated [1,15,16]. Now one must fold this calculated energy spectrum with the excitation function for the reaction [1]:

$$Cu + p \rightarrow {}^{24}Na + Y \qquad (4)$$

and obtains a «product-function» in its dependence on the proton energy. The maximum of this «product-function» is exactly at the proton energy, where the ^{24}Na-production by protons in copper has in itself a maximum. This proton energy is called «most effective» proton energy and can be calculated:

$$E(\text{secondary protons})_{20° < \theta < 30°} = (1.3 \pm 0.3)\ \text{GeV} \qquad \text{(theory)}$$

This shows, that with respect to the Segment-3 target, secondary protons behave experimentally just as theoretically predicted. Now, one has a problem, this time more certain than previously reported [1,2].

I) On the one hand, secondary baryons produce in «secondary» copper ($20° < \theta < 30°$) by a factor (7 ± 1) too much ^{24}Na. Here only a partial nuclear reaction cross-section was determined.

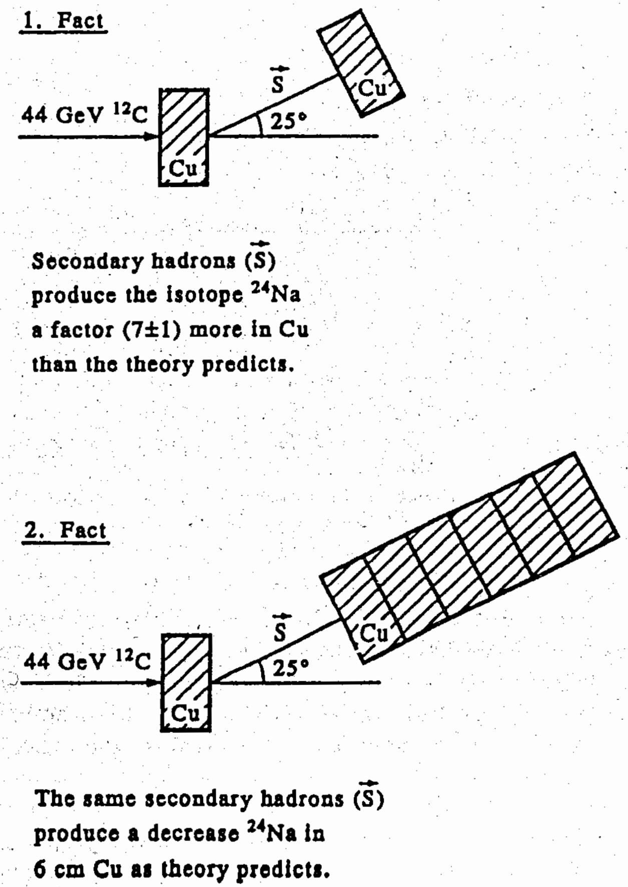

Fig.9. Schematic representation of the two important experimental facts observed in all the copper-irradiations with 44 GeV ^{12}C and yielding ^{24}Na

II) On the other hand, the same secondary baryons show just a normal behaviour, just as expected by model calculations, when their adsorption through a 7 cm thick Cu-stack is studied.

This problem has been shown in a simplified and schematic representation in Fig.9.

Suggestion to Resolve the Problem of Enhanced Production of ^{24}Na

All experiments on SMFP-effects, as described in the Introduction, show enhanced nuclear cross-section of secondary fragments. The reasons for this enhancement are unknown at present. The authors of this contribution are not commenting the speculations of Ref.[24]. However, we thick it may be worthwhile to look in a bold manner to low energy neutron induced reactions (n, γ) and (n, f) in extended Cu-targets. So far, all our radiochemistry experiments with 44 GeV ^{12}C on copper were restricted to the measurement of ^{24}Na in copper targets. It is well known that this reaction has a rather high threshold of about 0.8 GeV (Ref.[1]). As one observes too much ^{24}Na under certain conditions in copper, we want to extend our approach and see, if again such an «enhanced production» could be observed in low-energy neutron induced reaction, studied in close proximity of the irradiated extended target. It is interesting to note that a rather similar problem was studied quite recently in another area of relativistic heavy ion physics. Tolstov [34] reintroduced the idea of coupling relativistic heavy ion accelerators to subcritical nuclear reactors in order to finally produce electricity. This idea has been introduced by several authors long ago. (References are given in [35—39]). Rather similar ideas have been introduced by Bowman et al. [35] and Rubbia and coworkers [36]. However, Tolstov and coworkers carried out an experiment at the Synchrophasotron [37] in 1990. They irradiated a $2.3\cdot10^6$g lead target with 8 GeV protons and relativistic ions (d, ^{4}He and ^{12}C) at an energy of 3.65 GeV/u. They placed tiny, 1g U-detectors along the beam direction into the extended lead target and measured the production rates for ^{239}Np, produced in a low-energy nuclear reaction:

$$^{238}\mathrm{U}(n,\gamma)^{239}\mathrm{U} \xrightarrow[20\ \mathrm{min}]{\beta^-} {}^{239}\mathrm{Np} \xrightarrow[56\ h]{\beta^-} . \qquad (5)$$

Their results are shown in Fig.10. Using protons, deuterons and alphas the observed (n, γ) production rates agree with theoretical estimations of this production rate. Only in the case of 44 GeV ^{12}C irradiations, one observed (60±30)% more (n, γ) products than could be calculated. The authors (Ref.[37]) noted this discrepancy. They did not try to interpret this discrepancy. To our knowledge, Bowman et al. [29] did not carry out corresponding experiments. However,

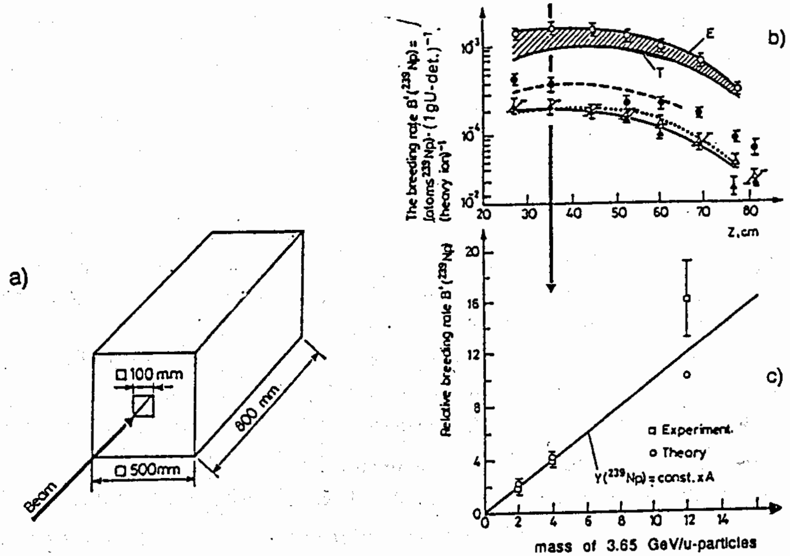

Fig.10. Summary of the experiment of Tolstov and coworkers in Dubna [37] (this figure is taken from Ref.[39]). a) The very massive Pb-target (0.5x0.5x0.8 m^3) irradiated with 3.65 GeV/u ions from the Synchrophasotron, JINR, Dubna. b) Results for the breeding of ^{239}Np in the Pb-target (Fig.a), as determined along the central beam axis. Open circles: 3.65 GeV/u ^{12}C, closed circles: 3.65 GeV ^{4}He, open triangles: 3.65 GeV/u ^{2}H, closed triangles: 8 GeV ^{1}H. For ^{4}He, ^{2}H, ^{1}H, the calculations agree with the experiment. For ^{12}C, the calculations (*T*) are below the experiments (*E*), as shown by the hatched area. c) More-than-calculated-breeding (a possibility) of ^{239}Np as seen in Fig.b. Here we show a «cut» along the line $Z = 35$ cm

Andriamonje et al. [14] — as mentioned in the Introduction — have carried out interesting experiments at CERN with protons in the energy range $0.60 \leq$ (proton) ≤ 2.75 GeV.

III. NEUTRON PRODUCTION IN EXTENDED COPPER TARGETS IRRADIATED WITH 44 GeV ^{12}C AND 18 GeV ^{12}C

The aim of these experiments was to study neutron productions. We irradiated again extended copper targets and used carbon ions at 18 GeV and 44 GeV as projectiles. The extended metallic copper target (diameter 8 cm, length 21 cm, shown in Fig.11) is surrounded by azimuthally symmetric polyethylene 10 cm in thickness. Neutrons leave the Cu-target, they enter the polyethylene moderator and there they induce various nuclear reactions in La-, U- and other probes to be studied by radiochemical or Solid State Nuclear Track Detector (SSNTD) techniques. A rather similar test experiment has been carried out; its results have already been published [38,39] (in these communications the value 18 GeV was replaced, by mistake, by 22 GeV, but the calculated data are obtained at 22 GeV).

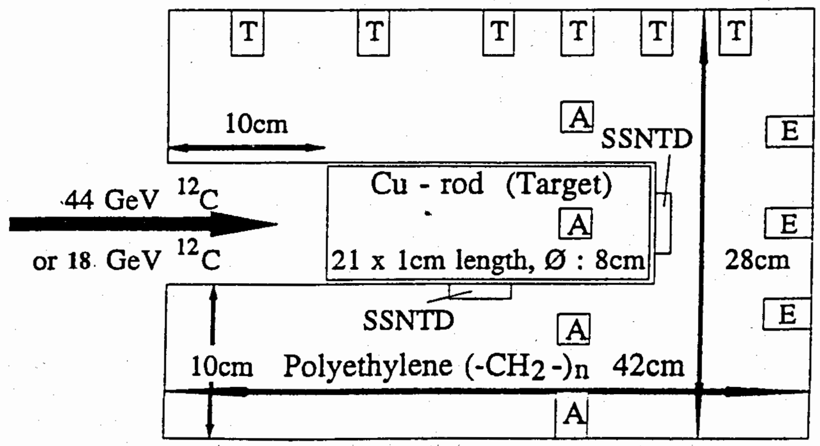

Fig.11. Cut through the experimental set-up: A 10 cm thick polyethylene moderator is axially symmetric placed around a copper rod (Ø = 8 cm, *l* = 21 cm). Small holes on the surface of the moderator are placed at various positions and filled with appr. lg samples of La- and U-compounds. Additionally, various SSNTD targets were placed around this set-up as shown and described in the text

At first, the target was irradiated for 11.9 hours with 18 GeV ^{12}C yielding in total $1.03 \cdot 10^{12}$ ions. Afterwards, all U-, La- and SSNTD-detectors, as well as 5 Cu-disks (diameter 8 cm, 1 cm thick) were exchanged and then the new target was irradiated for 7.2 hours with 44 GeV ^{12}C yielding in total $0.97 \cdot 10^{12}$ ions. The beam intensity was rather stable during most of the time, irregularities were properly taken into account. The beam diameter was smaller for 44 GeV as compared to 18 GeV; at the larger energy, the beam was also better focussed axially. The exact shape of the beam was rather similar to the test-experiment, as reported in Ref.[38]. The beam shape was determined experimentally, as described in the Appendix. The beam entered the Cu-stack about 0.5 cm off-center in the 18 GeV irradiation; however, downstream the beam was well centered, as observed with SSNTD-detector No. 4 (to be described below).

There were 2 times 6 holes (diameter 1.6 cm, depth 2.0 cm) bored into the top layer of the moderator, indicated with «T» (Fig.11). Around the center part of the moderator, there were again bored 2 times 6 holes, equally spaced azimuthally and indicated with «A». Finally, 2 times 6 holes were bored downstream at the end-side of the moderator, indicated with «E». Each set of 6 holes at «T», «A» and «E» was filled with plastic vials containing appr. 1g La (as $LaCl_3 \cdot 7H_2O$) or 1g U (as $UO_3 \cdot H_2O$). Then the vials filled with the target material were covered on top with a 1 cm paraffin stop-cock. The uranium was depleted in ^{235}U (0.4%).

Secondary neutrons induced in these samples the following (n, γ) reactions:

$$^{139}\mathrm{La}(n,\gamma)^{140}\mathrm{La}\xrightarrow[40.2\,\mathrm{h}]{\beta-},\quad ^{238}\mathrm{U}(n,\gamma)^{239}\mathrm{U}\xrightarrow[20\,\mathrm{min}]{\beta-} > {}^{239}\mathrm{Np}\xrightarrow[56\,\mathrm{h}]{\beta-}. \qquad (6)$$

Additionally, we placed several sets of SSNTD-system into our target system as follows:

1) CR-39-detectors were placed on the surface of the moderator. One could study (n, α) reactions, using boron as target and thermal neutrons as projectiles. Furthermore, one could study (n, p) reactions with neutrons in the range of (1—10) MeV.

2) «Au on mica» is sensitive to secondary hadrons with $E > 30$ MeV [40]. This target was placed in contact with the copper target, as indicated in Fig.11. The (n, f) reaction is studied.

3) «^{235}U on makrofol», is a well known target system [41]. It was placed parallel to the «Au on mica» and on the outside of the polyethylene moderator. This target is mostly sensitive to low energy neutron, however, also to high-energy hadrons, inducing (n, f) reactions.

4) At the end of the Cu-block (after 20 cm Cu), there was placed between two Cu-disks a 40 μm Pb-target foil, covered on the backward side with mylar. Heavy fission fragments emitted backwards could be studied this way.

After, the irradiations, the samples (several Cu-disks of 1 cm thickness, 17 samples of La, 17 samples of U — obtained at each energy) were transported to Marburg. There, the gamma-activity was investigated, as already described. The counting started appr. 30 hours after the end of the 44 GeV ^{12}C and appr. 27 hours after the end of the 18 GeV ^{12}C irradiation.

Experimental Results

During the test-experiment it was determined experimentally, that the flux ratio of carbon ions at 44 GeV compared to 18 GeV can be determined equally well by electronic beam monitors and by radiochemists measuring the flux via the monitor cross-section ($\mathrm{Cu} + {}^{12}\mathrm{C} \to {}^{24}\mathrm{Na} + X$) [1,38]. The uncertainty in the ratio of heavy ion fluxes at 44 GeV and 18 GeV is 4% (Ref.[38,39]).

1) **^{140}La**: In the analysis of the ^{140}La-activity in La-detectors we used the gamma lines at 487.1 keV and at 1596.5 keV. After the determination of «end-of-bombardement» decay rates and «equilibrium» decay rates for ^{140}La in all samples, one could calculate an «experimental production rate» B, which is defined as follows:

$$B = \frac{(\text{number of }^{140}\text{La–atoms formed})}{(1\text{g La–detector})\cdot(\text{single heavy ion})}. \qquad (7)$$

This value B has been intriduced by Voronko et al. [37] and it is also used in CERN by Andriamonje et al. [14]. It is specified in each experiment for:

a) a given nuclear reaction induced by secondary neutrons;

b) a well-defined experimental set-up, such as shown in Fig.11;

c) for a given particle and its energy.

The results for B are given for 44 and 18 GeV ^{12}C-ions in Fig.12. We show the results for the top-positions (T) along the beam axis of the moderator. One observes rather large yields for B within the first 10 cm of the target (or: for the first four positions in «T») but a rather steep decrease in B at the downstream end of the moderator. The B-values for the azimuthally arranged targets «A» agree within their statistical fluctuations of (2—3)% with each other. This indicates a rather homogeneous neutron flux on the outside of the moderator at this position — and this despite the slight displacement of the 18 GeV-beam at the entrance of the Cu-targets, as mentioned already.

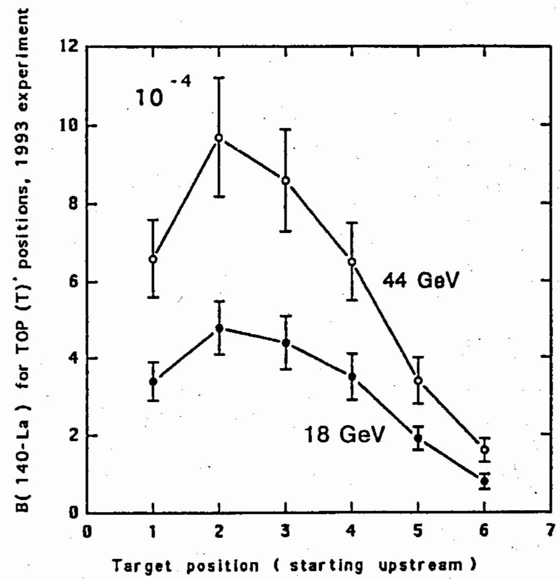

Fig.12. The experimental production rate B for ^{140}La in top-samples (T) as shown in Fig.11.

The yields of B at the backside of the moderator «E» are rather small: $1.9\cdot10^{-4} < B(«E») < 3.0\cdot10^{-4}$ at 44 GeV and $1.0\cdot10^{-4} < B(«E») < 1.5\cdot10^{-4}$ at 18 GeV, as compared to the maximum value for B at the «T»-positions, $(9.7 \pm 1.5)\cdot10^{-4}$. The uncertainties in B are approximately 15%, mostly due to the uncertainties in the counting efficients of the La-samples during gamma-ray measurements.

Another value of interest is the ratio R for B between 44 GeV and 18 GeV:

$$R = \frac{B\ (44\ \text{GeV})}{B\ (18\ \text{GeV})}. \qquad (8)$$

This ratio R is of theoretical importance and it can be measured with 5% accuracy, as here only the uncertainties in the counting rates and in the ratio of the heavy ion fluxes enter into the calculation. At first, we determine the average R-value for six «A»-positions of the La-detectors

$$R_A(^{140}La) = 1.89 \pm 0.11. \quad (9)$$

Deviations at different A-positions are again within the statistical uncertainties of (2—3)%. The $R\,(^{140}La)$-values along the «T»-positions are shown in Table 5, indicating a rather constant R-value. The values of $R\,(^{140}La)$ at the end position «E» are also given.

2) **^{239}Np**: During this experiment, the gamma-activity of the uranium samples was rather low. Consequently, the analysis gave results with rather larger uncertainties. ^{239}Np could only be measured quantitatively via its 277.6 keV gamma line (branching ratio of 14.1% in ^{239}Np-decay). Fission fragments could not be studied with sufficient accuracy. B- and R-values are given in Table 6.

Table 5. R-values for ^{140}La, as observed in the experiment shown in Fig.11

Position (starting upstream)	$R = B$ (44 GeV)/(B (18 GeV)*
Top I	1.99 ± 0.11
Top II	2.08 ± 0.11
Top III	1.98 ± 0.12
Top IV	1.89 ± 0.11
Top V	1.87 ± 0.11
Top VI	2.02 ± 0.11
Average on top-positions:	1.97 ± 0.11
Average on end-positions: (variation between 1.98 up to 2.13)	2.07 ± 0.11
Accepted average of total ensemble:	2.01 ± 0.11

*Only the uncertainties in the counting rates and the ratio of the heavy ion fluxes needed to be considered.

Table 6. B- and R-values for ^{239}Np, as observed in the experiment shown in Fig.11

Position:	B (44 GeV)$\cdot 10^{-5}$.	B (18 GeV)$\cdot 10^{-5}$	$R = B$ (44 GeV)/B (18 GeV)
Top I	9.7 ± 1.9	5.6 ± 1.2	1.7 ± 0.2
Top II	20.1 ± 4.0	9.1 ± 1.8	2.2 ± 0.3
Top III	16.6 ± 3.3	10.7 ± 2.1	1.6 ± 0.2
Top IV	18.9 ± 3.8	9.0 ± 1.8	2.1 ± 0.2
Top V	9.9 ± 2.0	5.5 ± 1.1	1.8 ± 0.2
Top VI	4.8 ± 1.0	2.8 ± 0.6	1.7 ± 0.3
Average top (T)	—	—	1.9 ± 0.2
Average «A»	15.5 ± 3.1	8.3 ± 1.6	1.9 ± 0.2
Average «E»	5.5 ± 1.1	2.7 ± 0.6	2.0 ± 0.2
Accepted average of total ensemble	—	—	1.9 ± 0.2

The B-values for uranium targets are important for practical aspects, i.e. for possible design studies of subcritical reactors used for «electrical breeding», as

already mentioned (Refs. [34—39]). Table 7 gives a summary of all relevant experimental results. All B-values appear to agree within one order of magnitude, despite quite different experimental arrangements. Our B-values are lower than the B-values reported by Voronko et al. [37] (Fig.10) by nearly one order of magnitude. This may be due to the fact that the authors measured along the central beam exis. During our experiment the U-sample was placed 12 cm off the beam axis (Fig.11).

Table 7. Summary of induced (n, γ) and (n, f) rates in uranium as observed in various «electrical breeding» experiments

Reference	Relativistic ion and its energy E	Secondary reaction studied	Production rate** B (10^{-4})	B/E (10^{-5})
Voronko et al., [37]	8 GeV p	$^{238}U\,(n, \gamma)$	~2	~2.5
JINR, Dubna (1990)	7 GeV d	$^{238}U\,(n, \gamma)$	~2	~2.8
	14 GeV ^{14}He	$^{238}U\,(n, \gamma)$	~4	~2.8
	44 GeV ^{12}C	$^{238}U\,(n, \gamma)$	~20	~4.5
Andriamonje et al. [14] CERN, Geneva (1995)	2.7 GeV p*	$^{nat}U\,(n, f)$	~8	~(30) — all(+) ~3 — due to cascade
Bisplinghoff et al. [38,39]	18 GeV ^{12}C	$^{238}U\,(n, \gamma)$	7.2	4.0
JINR, Dubna (1994)		$^{nat}U\,(n, f)$	4.8	2.7
	44 GeV ^{12}C	$^{238}U\,(n, \gamma)$	18	4.1
		$^{nat}U\,(n, f)$	11	2.4
This work,	18 GeV ^{12}C	$^{238}U\,(n, \gamma)$	1	0.55
JINR, Dubna	44 GeV ^{12}C	$^{238}U\,(n, \gamma)$	2	0.45

*)Ref.[42].

**) The B-value is defined in the text. Here, one uses those values as observed in about (11±1) cm distance from the point-of-maximum interactions (p.o.m.i.) within the prime target. In the case of the Voronko et al. experiment, the B-values were measured close the p.o.m.i. The large difference between the JINR — 1994 result and this work is due to 5 cm moderation in 1994 and 10 cm moderation in this work, as has been discussed already [43].

+) $3.6 \cdot 10^6$ g uranium were used at the CERN experiment, having a $k = 0.9$ (k — neutron multiplication factor). This means appr. 10% of all fission events are produced by the direct high-energy cascade, the rest by later generation neutrons.

3) ***SSNTD-(solid state nuclear track detectors)***: In the preceding section four SSNTD detectors and their placements were described. In all these experiments, etching procedures are well known, as follows:

— etching of CR-39: 6 hours in 6.25 n NaOH at 70°C.
— etching of mica: 30 min in conc. HF at room temperature.
— etching of makrofol: 60 min in 5 n NaOH at 60°C.
— etching of mylar: 10 min 6.25 n NaOH at 70°C.

After proper etching, one only had to determine the track density (per unit area and target thickness) for (44 GeV) — and (18 GeV)-samples. Dividing by the total heavy ion flux at each energy, one obtained directly:

$$R\,(\text{SSNTD}) = \frac{(\text{track density at 44 GeV})/(\text{total ion flux at 44 GeV})}{(\text{track density at 18 GeV})/(\text{total ion flux at 18 GeV})}. \qquad (10)$$

In this case, the data evaluation is considerably different and more straightforward than in the radiochemistry experiments. The results are given in Table 8. It is comforting to find, that all R-values reported for two different experiments and for two different experimental techniques agree within their limits of accuracy. In addition two simulations called «Theory (Dubna Cascade Model)», and «Theory (Fritjof model)» are also given in Table 8, as will be described in the next section.

Table 8. The determination of $R = B$ (44 GeV)/B (18 GeV) during all experiments: a summary

	Test-Experiment (Ref.[38,39])	This experiment
Chemistry:		
1) $^{139}La(n,\gamma)^{140}La \longrightarrow$	1.97±0.11	2.01±0.11
2) $^{238}U(n,\gamma)$ .... $^{239}Np \longrightarrow$	2.32±0.12	1.90±0.20 (low activity)
SSNTD (track-detectors)		
1) Au + hadron ⟶ fission	2.32±0.17 (side)	2.33±0.16 (side)
(mica detector)	—	1.93±0.16 (back)
2) n + H ⟶ recoil proton (CR-39 detector)	—	2.10±0.20
3) $^{235}U + n \longrightarrow$ fission	—	2.20±0.20 at Cu
(macrofol detector)		2.00±0.20 at $(CH_2)_n$
4) Pb + hadron ⟶ fission (mylar detector)	—	2.27±0.23 (in Cu)
Theory (Dubna Cascade Model)	—	1.98±0.07
Theory (Fritjof model)	—	2.03±0.09

Finally, it should be reported, that the exposure of 40 μm Pb-target foils together with mylar on the upstream side between two Cu-blocks at the end of the 20 cm Cu-target (Fig.11) allowed a direct determination of the beam profile at this position. It was confirmed that the beam was well focussed in the center.

IV. MODEL ESTIMATIONS ON THE OBSERVED R-VALUES

We used the same program (CEM) which has been described and used in section II. We calculated the entire neutron flux generated in the massive copper rod. The main purpose of our study here is to count the number of neutrons inside the moderator volume. The process of ^{239}Np generation in uranium, as well as

^{140}La production in lantanum is strongly dependent on the neutron energy. The (n,γ) cross-sections are large at energies far below 10 MeV. The calculations have been performed for incident carbon ions at 44 GeV and 18 GeV, res-pectively. In this part, one only needs the ratio of secondaries between 18 and 44 GeV. Therefore, no corrections were applied to this model here. The beam profile was considered to be the same for 18 GeV as compared to 44 GeV. The entire Cu-target was surrounded by a 10 cm thick cylindrical polyethylene moderator. The resulting neutron spectrum emitted as seen by the radiochemical targets T (Fig.11) are shown in Fig.13. The shapes of both neutron spectra are — within the limits of their statistical accuracy — identical for 18 and 44 GeV. As only low energy neutrons ($E < 1$ MeV) are of any practical importance, we consider the ratio of neutrons with 0.01 MeV $< E <$ 6.5 MeV being equivalent to the calculated ratio of (n,γ) products, as follows:

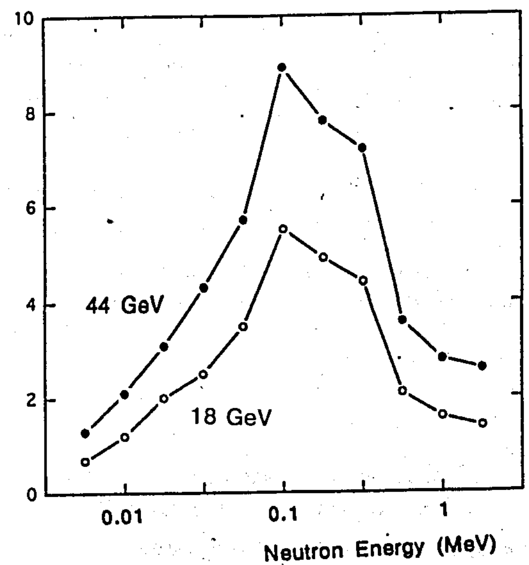

Fig.13. The calculated neutron spectra at the target position «T» (top) shown Fig.11, and using the Dubna Cascade Model in its version «CEM». Details are given in the text

$$R^{\text{Dubna}}_{\text{theoretical}} = \frac{(\text{neutrons generated at 44 GeV})}{(\text{neutrons generated at 18 GeV})} = 1.98 \pm 0.07. \qquad (12)$$

Now one can consider the result in other words: The intensity of the neutron flux, i.e., the integral number of neutrons emitted from the cylindrical surface of the copper rod and seen within the target volume T increases by $(98 \pm 7)\%$ when the ^{12}C ion energy increases from 18 GeV to 44 GeV. This should only give (1.98 ± 0.07) for the R values, as shown in Table 8. We note that some experimental R-values in this table are a little larger than the calculated ones. Ho-wever, this difference is not yet statistically significant.

Finally, another computer-code was used to estimate R with an independent theoretical model. The Fritjof-code (or Lund Monte-Carlo Model) was employed (Refs.[44—46]). This model calculates only the high-energy part of all nucleus-

nucleus interactions, but it calculates all secondary high-energy interactions within our experimental set-up (Fig.11). We calculated the number of neutrons produced per incident ^{12}C in all projectile-nucleus interactions of «primary», «secondary» and further particles and obtained:

$$R^{\text{Fritjof}}_{\text{theoretical}} = \frac{(\text{neutrons generated at 44 GeV})}{(\text{neutrons generated at 18 GeV})} = 2.03 \pm 0.09. \qquad (13)$$

This value is in agreement with the preceding one. Of course, we are aware of the fact that this model may not be quite adequate for 18 GeV ^{12}C.

V. CONCLUSIONS

Finally, one can conclude:

1. A refined experimental and improved theoretical analysis of the experiments with the 2π ring target irradiated with 44 GeV ^{12}C yielded again the following result: An enhanced production of ^{24}Na in copper exposed to wide angle secondaries produced in the interaction of 44 GeV ^{12}C with copper targets can be observed using basically the CEM (theoretical code) in order to calculate the energy spectra of wide angle emitted secondaries and the angular spectra for minimum-ionizing particles (MIP), as observed in nuclear emulsions irradiated with 44 GeV ^{12}C.

2. We carried out a series of Segment-experiments in order to study the absorbtion in copper of wide-angle secondaries produced in the interaction of 44 GeV ^{12}C with copper. No strange behaviour of «wide-angle» emitted secondary hadrons was observed: Their attenuation in the 6 cm copper target is just like the attenuation of (1.6 ± 0.4) GeV protons. This attenuation is in agreement with calculations for (1.3 ± 0.3) GeV protons.

3. In order to study this phenomenon further, rather extended copper targets (diameter = 8 cm, length = 21 cm) were irradiated. Outside the target, there was a 10 cm polyethylene moderator. It allowed the study of (n, γ)-reactions yielding the following results:

a) The breeding rates B for (n, γ) reactions in La and U are remarcably high. Other related experiments at the JINR (Dubna) and CERN (Geneva) give somewhat similar results.

b) The R-values ($R = B$ (44 GeV)/(B (18 GeV)) are found to be experimentally in the range $1.9 < R < 2.3$ with two independent experimental techniques, such as radiochemistry and SSNTD. This is substancially larger than the calculated values for R being $1.6 < R < 1.7$. Two rather independent models were used in the calculations.

There is a possible connection in the observations of the yield of neutron induced reaction products produced by secondary fragments in 44 GeV ^{12}C interactions with copper and in the production of ^{24}Na in Cu, produced by secondary fragments in 44 GeV ^{12}C interactions in copper.

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APPENDIX

The beam profile of the carbon beam during the experiment described in Fig.11 was measured properly with nuclear emulsions. The exposures were taken before the actual irradiation, once in-between, and finally at the end of the irradiation. The beam profile for the 44 GeV ^{12}C irradiation is shown in Fig.14. It was rather invariant during the entire irradiation. The shape of the beam profile could be fitted by a Gaussian distribution, having the following standard parameters:

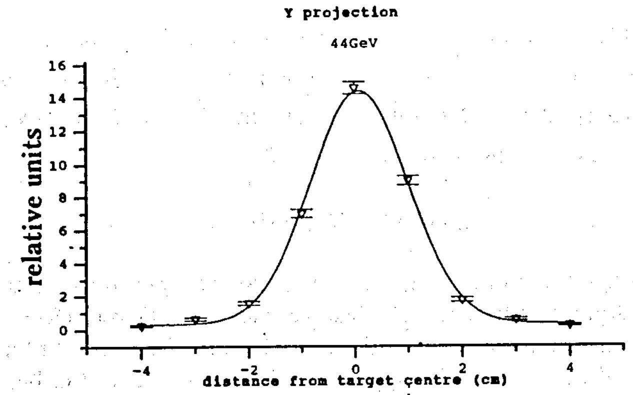
1.1) The beam was off-center by appr. (0.1—0.2) cm in the X- and Y-axis.

1.2) The 2σ width was (1.0 ± 0.1) cm in the X-axis and (1.8 ± 0.1) in the Y-axis.

The beam profile for the 18 GeV ^{12}C irradiation was similar, however, not quite as narrow. It could be fitted by a Gaussian distribution, having for following parameters:

2.1) The beam was off-center between (0.2—0.7) cm in the X-axis and (0.2—0.0) cm in the Y-axiis.

2.2) The 2σ width was (1.7 ± 0.1) cm in the X-axis and between (2.1 ± 0.1) and (3.2 ± 0.1) cm in the Y-axis.



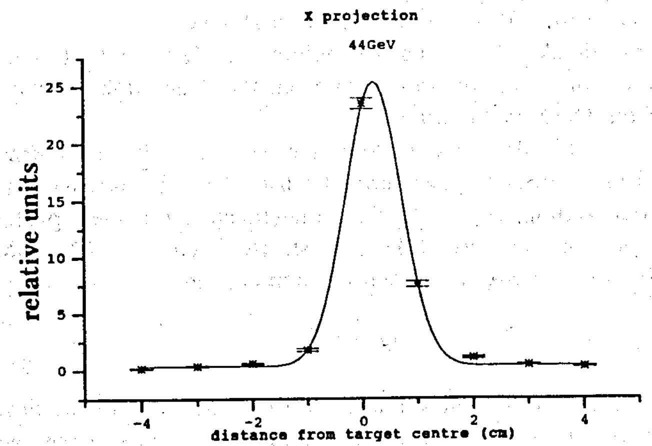


Fig.14. The distribution of the 44 GeV ^{12}C beam during the experiment as shown in Fig.11. The beam profile was measured with nuclear emulsions

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