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R.Brandt[1], V.S.Butsev[2], H.H.Cui[3], G.Dersch[1],
E.M.Friedlander[1,6], E.Ganssauge[4], G.Haase[1],
M.Heck[1], M.I.Krivopustov[2], B.A.Kulakov[2],
E.-J. Langrock[5], F.Pille[5], W.Schulz[4]

ENHANCED PRODUCTION OF ^{24}Na BY WIDE-ANGLE SECONDARIES PRODUCED IN THE INTERACTION OF RELATIVISTIC CARBON IONS WITH COPPER

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[1] Kernchemie, Philipps-University, Marburg, FRG
[2] Joint Institute for Nuclear Research, Dubna
[3] Institute for High Energy Physics, Beijing, P.R.China
[4] Fachbereich Physik, Philipps-University, Marburg, FRG
[5] Sektion Naturwissenschaften, Technische Hochschule, Leipzig, DDR
[6] Permanent address: Lawrence Berkeley Laboratory, University of California, Berkeley, CA, USA

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1. INTRODUCTION

The experiments described in this paper are meant to extend to a much wider range of energies per nucleon a previous experiment (ref. [1]- [9]) introducing a *sui generis* technique of "calorimetry" in the investigation of interaction properties of projectile fragments (PF's) from relativistic heavy ion collisions.The idea of the experiment as well as the peculiar target/detector setups (in several increasingly sophisticated geometries)) were initially motivated by the ongoing debate over a possible anomalously shortened mean free path (abbreviated hereafter as SMFP) for nuclear interaction of such projectile fragments. Although, at the present stage of our investigation, our experimental results have provided no clear-cut evidence either for or against such an effect, they *have* provided evidence for a very high partial cross-section of ^{24}Na -production by such PF's emitted at relatively wide angles to the incident heavy ion beam.Whether this effect can be explained, or not, in terms of "conventional" relativistic heavy ion physics was explored in ref.[2] and will be discussed in greater detail in connection with the new experimental evidence presented in the present paper.

However, in order to better explain the rationale underlying our technique, it appears useful to briefly review the experimental evidence which prompted this investigation.

Evidence for a SMFP was first observed in nuclear emulsions. Ref. [10] gives the basic experimental facts together with their early history. Essentially, this effect concerns a considerably reduced interaction mean free path of heavy secondary projectile fragments $Z \geq 3$ within the first few centimeters after the interaction point where they were produced in the interaction of relativistic heavy ions with emulsion nuclei. This work stimulated a wide variety of investigations with often conflicting results [11] - [21]. Of particular interest is the more recent supporting experimental evidence concerning this effect, obtained at the Joint Institute for Nuclear Research (JINR) in Dubna [22, 23, 24]. This field has been reviewed recently [25] - [30]. Some older references have been mentioned frequently [31] - [36]. However, one should remember some possible "prehistoric" evidence for SMFP such as peculiar transition effects observed with very thick targets in cosmic rays by Roessle and Schopper [37] as early as 1954 and confirmed later by Varsimashvili [38] and possible evidence for SMFP of pions shortly after their emission from kaon decays reported by G. Alexander *et al.* [39] in 1957. This latter SMFP effect has never been challenged experimentally, nor has it been understood from a theoretical point of view.

The interest in the SMFP effect was stressed by its hypothetical connection with the possible appearance of "open colour states" for quark-gluon-matter, as formulated within certain quantum chromodynamic models [27]. Due to such possible fundamental implication and especially to the wide-ranging controversy aroused by this subject, it appeared important to bring as many different techniques as possible to bear on this problem. Therefore, some time ago, several of us started an experimental program to investigate the interactions of relativistic heavy ions with relatively massive copper targets [1]. The radiochemical activation technique has been used to search for the possible formation, interaction and decay of anomalous projectile fragments. So far, the most detailed investigation has been carried out in the interaction of 72 GeV ^{40}Ar and 36 GeV ^{40}Ar with copper. At the lower Ar-energy we encountered no difficulties in trying to understand the experimental results in terms of conventional models and of the ensemble of available experimental facts.

However, at the higher Ar-energy (72 GeV) it was impossible to understand the large cross-section of secondary fragments for producing ^{24}Na in copper within the framework of widely accepted theoretical models: in particular, one had severe difficulties to understand the wide -angle emission $10° \leq \theta_{lab}$ of energetic secondary fragments. Ref. [2] gives a detailed account of the "conventional" arguments which failed to explain the effect.

Consequently, it was of interest to extend the investigation beyond the range of energies per nucleon covered by the Berkeley BEVALAC in the hope of observing some general new features of relativistic heavy ion physics irrespective of whether SMFP's were involved or not.

We start this paper with a general survey of the corresponding experiments. Then a detailed experimental and theoretical account is given of our studies using the 44 GeV ^{12}C beam of the JINR SYNCHROPHASOTRON, Dubna. "Calibration" experiments with 4 GeV ^{4}He and 2.6 GeV p beams from SATURNE, Saclay, are also reported. In view of the negative result of a search of unexpected features in the reactions induced by the lower-energy beam at the BEVALAC (36 GeV ^{40}Ar) one would *a fortiori* not expect any "anomalous" behavior of particles produced at the energies of the SATURNE accelerator.None was found.

2. THE COPPER-DISK TECHNIQUE: ITS DESCRIPTION AND RESULTS

Our first experiment of this kind may serve as an intuitive illustration to our technical approach; it was carried out as a parasitic exposure to a 25 GeV ^{12}C beam at the Lawrence Berkeley Laboratory BEVALAC, behind a thin target ($< 500 mg/cm^2$) [40]. It can be considered as an example of a "low energy" experiment with relativistic carbon.

The principle of the experiment is illustrated in Fig. 1a. Two 1 cm-thick circular copper disks (r=4 cm) were irradiated with 25 GeV C-ions. Typi-

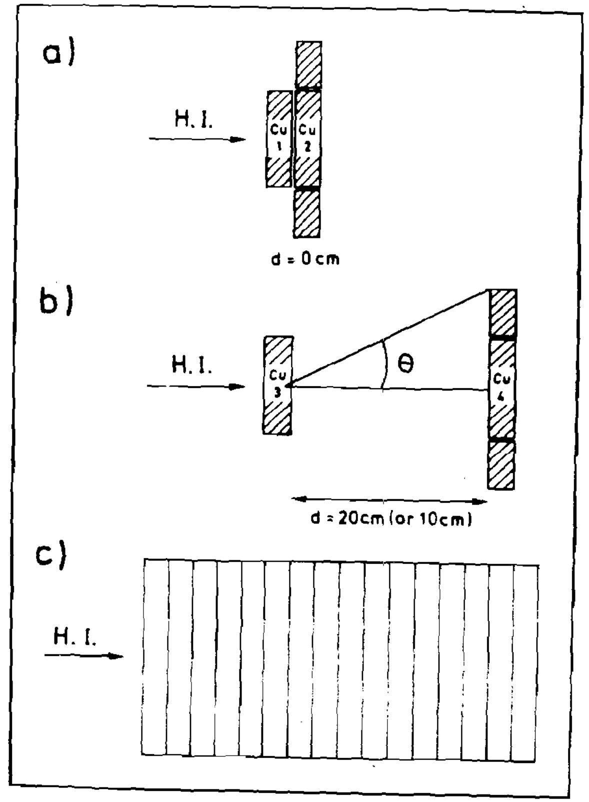

Fig. 1. Some typical experimental arrangements of Cu disks and rings. All Cu disks are 1 cm thick. a,b) arrangement to study decay-versus "wide angle" effects as described in details in [1, 2] c) a very compact stack of 16 Cu disks ($\phi = 8$ *cm*)as some kind of calorimeter.

cally, $\approx 10^{12}$ ^{12}C ions passed through the Cu-disks in a period of 2-4 hours. The beam was well focussed (nominal diameter $< 1cm$). Pairs of Cu -disks were irradiated together in a "contact" configuration (d=0 cm) and with a separation of 10 cm (Fig. 1b). Both Cu-disks in a particular configuration serve as targets for the primary beam, as well as for secondaries interacting within the same disk in which they were produced.Our measure for the number of interactions induced by all these projectiles is the amount of radioactive residues of the target nuclei, detectable via their gamma activity. However, secondaries produced in the first disk (the "target" disk) and interacting in the second disk (the "detector" disk) will enhance radioactive nuclide production in the "detector" disk as compared to the "target disk" (obviously, at the same projectile fluence). This enhancement could be especially strong if, among other reasons, such a projectile fragment had an unexpectedly high interaction cross section, i.e., a "too short" mean free path. After the completion of the irradiation, short-lived activities were allowed to decay for approximately 12-24 hours. Afterwards, the radionuclides present in the irradiated Cu-disks were assayed by off-line gamma-ray-spectroscopy. Measurements were made with Ge(Li) detectors (resolution $\approx$ 1.8 keV). The analysis of the gamma-ray spectra was based on standard radiochemical procedures [41]. Counting was carried out for approximately one week at LBL and then continued for several months at Marburg. For specific nuclides we determined the ratio R_d of the activity in the downstream disk (Cu 2, or Cu 4) to that in the upstream disk (Cu 1, or Cu 3) as a function of disk separation d between the pair of Cu-disks. Because each such pair was irradiated with the same particle beam simultaneously and assayed later for its gamma activity in a fixed position with the same Ge(Li) gamma-ray detector, the activity ratio R_d for a specific nuclide can be determined to a high degree of precision. All uncertainties due to particle fluxes, counting efficiencies, branching ratios in the decay scheme for a specific radioactive nuclide, etc., cancel out in R_d. Essentially, the only experimental uncertainty in this ratio comes from counting statistics. As the number of counts is typically $\geq 10^4$, our activity ratio R_d can be determined within $\approx$ 1%. Such a precision is comparable only to that of large counter experiments or of high-statistics bubble chamber experiments.

We show in Fig. 2 the dependence of R_d on the product mass number for two different separations (d=0 cm, d=10 cm) of the disks for reactions induced by 25 GeV ^{12}C ions. The dependence of R_d on A is a reflection of the energy spectrum and angular distribution of the secondaries inducing reactions in the disks. The results show that when the two disks are in contact (R_0), the projectile fragments (PF) most likely to strike the detector disk lead to the formation (by target fragmentation) of products with A$\approx$ 55 and substantial yields are seen for all products with $A > 40$. The products with $A < 30$ (^{7}Be, ^{22}Na, ^{24}Na, ^{28}Mg) are formed only in high-deposition energy target fragmentation events [42]. Such nuclides cannot be PFs because those are much too energetic to stop in the copper disks. When the disks are moved 10 cm apart, the "detector" disk samples a different subset of the PFs created in the "target" disk, i.e., the more strongly forward-focused and thus higher energy fragments. As a result, the PFs most likely to reach the second disk now lead to the formation of products with A $\approx$ 45 and the formation of heavier fragments is less likely. Not surprisingly, R_0 for these products is larger than R_{10} reflecting production by low-energy, wide-angle secondaries. The fragments with $A < 30$ are produced with about the same yields regardless of disk separation because they are only produced by highly forward-focused, energetic projectile fragments. As we are interested mainly in reaction channels due pratically only to relativistic high-energy particles ($> 1 GeV$), we concentrate on deep-spallation products, i.e. ^{7}Be ^{22}Na ^{24}Na and ^{28}Mg since these nuclides are produced in copper only by high-energy particles. But, as Fig. 2 shows, only ^{24}Na can be measured with the necessary accuracy of $\approx (1-2)$%. Therefore, we are from here on concentrating our attention in this paper on the production of ^{24}Na from copper targets. Furthermore, the excitation function for the production of deep-spallation products is well

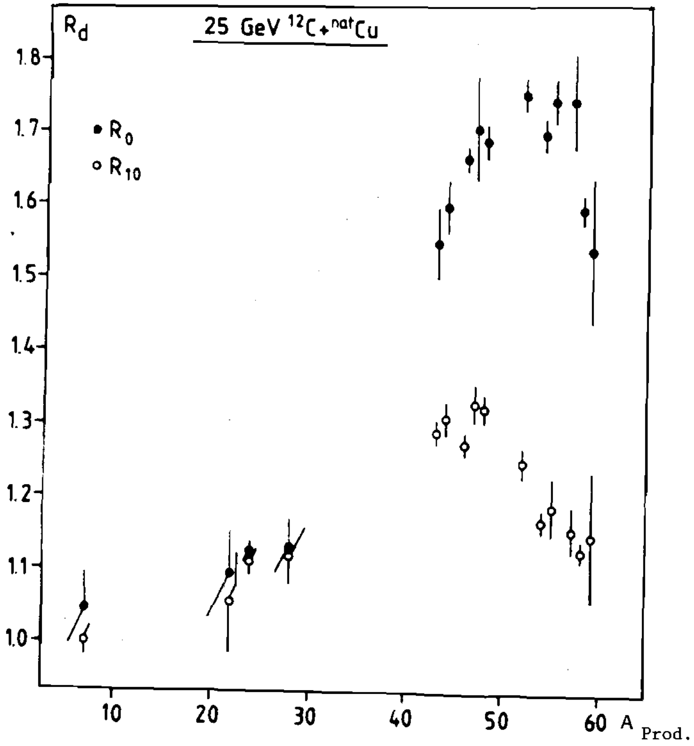

Fig. 2. R_0 and R_{10} as a function of the product mass A_{prod}. R_d is the ratio of the activity for one specific nuclide of the downstream Cu-disk to the upstream Cu-disks, d beeing the distance between the two Cu-disks, as shown in Fig. 1 a,b. (This experiment was carried out at the BEVALAC, University of California, Berkeley)

known only for the production of ^{24}Na from Cu and this nuclide has a half-life of $\sim 15h$ and a prominent and well determined gamma line at E_γ = 1.3685 MeV, both very convenient for radiochemical experiments. In this 25 GeV ^{12}C experiment we observe a ratio

$$\frac{R_0(^{24}\mathrm{Na})}{R_{10}(^{24}\mathrm{Na})} = \frac{1.127 \pm 0.015}{1.108 \pm 0.017} = 1.017 \pm 0.021 \tag{1}$$

$$R_0 - R_{10} = 0.019 \pm 0.023 \tag{2}$$

All ^{24}Na-producing fragments are emitted within a lab angle $\theta < 20°$ in this experiment, as from the $R_{10}(^{24}$Na) samples only fragments emitted into this angular foreward cone. To visualize the meaning of these numbers one should consider (Ref. [2]) the separate effects of three kinds of particles producing ^{24}Na:

- a) beam projectiles ("primaries") producing Q_P ^{24}Na atoms,
- b) their secondaries (and the cascade products thereof) interacting in the same disk in which primaries interacted, producing Q_S ^{24}Na atoms,
- c) secondaries from interacting "target" disk interacting in the "detector" (or downstream) disk and producing there $Q_{S'} \approx 2Q_S$ atoms.

It is easy to see from Ref. [2] that to a reasonable approximation the ratio R_d is given by

$$R_d \approx \exp(-\frac{x}{\lambda_P}) + \frac{2(1-f_d)}{1+\frac{Q_P}{Q_S}} \tag{3}$$

where x is the disk thickness (1 cm) and λ_P is the mean free path for inelastic collision of the primaries (hence the attenuation factor). The factor f_d is the fraction of secondaries of type (c), above, which "fail" to reach the downstream detector at distance d for one of the two reasons (a) conversion of a particle with a SMFP effect to a state with normal mean free path and / or (b) emission of energetic fragments into wide lab angles with $\theta > 20°$. Between ^{12}C and ^{40}Ar projectiles the attenuation factor varies from ≈ 0.86 to ≈ 0.80, i.e. it lies relatively close to unity. It is now understandable why such an experiment might be sensitive to secondaries exhibiting a SMFP effect.

Now, if $d \neq 0$, and the angular loss of secondaries of type (c) is small because of well focussed high-energy secondaries and their cross-section for ^{24}Na production "drops" along the way ("decay to ground state" of any weird excited state created in the upstream disk) over a flight path of 10 cm, then we would observe experimentally $R_d < R_0$. Our results reveal no unusual or "anomalous" properties of secondaries; all relativistic particles, primaries and secondaries, producing ^{24}Na in the R_0 configuration seem to do nearly exactly the same in the R_{10} configuration. The R_{10} configuration covers all secondary particles moving in a forward cone with an angle $\theta_{lab} \leq 20°$. Nothing seems to point in this experiment to "decaying" anomalous fragments over a flight path of 10 cm.

After this detailed description of one experiment, we report on a series of exposures carried out with a wide variety of projectiles of two Cu-disks in contact, a target configuration shown in Fig. 1a. The results for $R_0(^{24}$Na) are given in Fig. 3. As can be seen, R_0 seems to increase linearly with the total kinetic energy E_T of the incoming heavy ion, up to about E_T = 80 GeV. Additionally, we also show in Fig. 3b some recent results obtained from the SPS at CERN, Geneva, which extend our investigation to the highest energies of about 6.4 TeV obtained in any laboratory. However, here a word of caution is required. The experiments at the SPS were carried out in a parasitic manner close to the beam-dump and some 50 cm downstream of a 1 cm thick U-target. Therefore, the Cu-disks were irradiated with the primary heavy ions plus considerable amounts of secondary particles. Nevertheless, we might come to a "saturation" value of R_0 for $E_T > 1$ TeV.

In Fig 3a we observe a strong increase of R_0 in the range 2 GeV $< E_T <$ 80 GeV. When one moves the two Cu disks apart, the downstream Cu disk

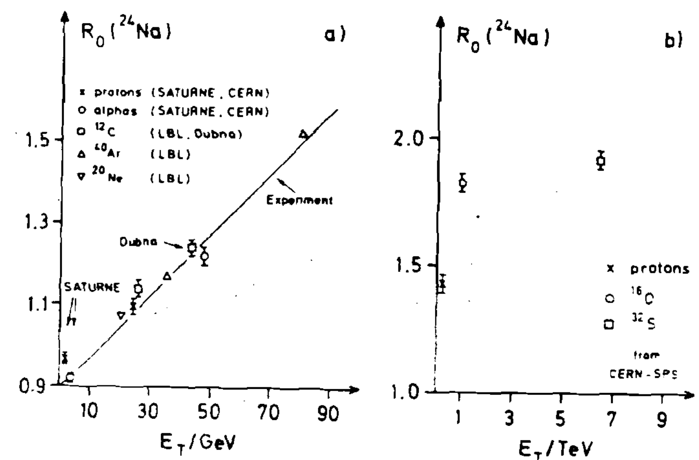

Fig. 3. The ratio $R_0(^{24}$Na) of the downstream Cu-block to the first Cu-block with the disks in contact (d=0) as a function of the total energy E_T of the incoming heavy ion. a) For $1GeV < E_T < 100GeV$. b) For $E_T > 300GeV$. A preliminary account has been published [4, 8].

no longer samples all fast secondary particles generated in the upstream Cu disk. However, we know experimentally that nearly all relativistic projectile fragments (nucleons as well as heavier ones) are emitted into a narrow forward cone and the higher the energy and the energy per nucleon of the incoming ions is, the more we expect a forward focused distribution [2]. So we expect in downstream Cu -configurations. as shown in Fig. 1(a and b) nearly all the activity for ^{24}Na which we observe at d=0 cm (i.e. R_0). As Fig. 4 shows, this expectation is fullfilled up to about a total energy $E_T \approx$ 30 GeV. However, for higher energies, we are loosing more and more ^{24}Na at distances of (10-20)cm. This is particularly true for 72 GeV ^{40}Ar and for 44 GeV ^{12}C, where the loss amounts to (16 ± 2)%, and (5 ± 1)% resp., for the downstream Cu-configuration covering the angles $\theta \leq 20°$ as shown in Ref. [2] and later in this paper. The exact distances between the front and end plates are given in the caption of Fig. 4. At present one only can state two different explanations for this puzzle: it could be caused either by the decay of anomalously excited fragments to their ground state over a flight path of (10-38)cm and/or by the wide-angle emission of "energetic" particles, having the ability to produce appreciable amounts of ^{24}Na in copper, even if they are emitted into large lab angles $\theta \geq 20°$. Following conventional wisdom, ref. [2] argues that practically only Z=1 particles, neutrons, and pions are emitted into wide lab angles, say $\theta \geq 10°$. It is well known that in high energy reactions the mean momenta drop drastically with the emission angles because the mean transverse momentum is low. Thus, the abundant production of ^{24}Na at large lab angles would lead us again to difficulties, one possibility could be an unexpectedly "hard" transverse momentum spectrum.

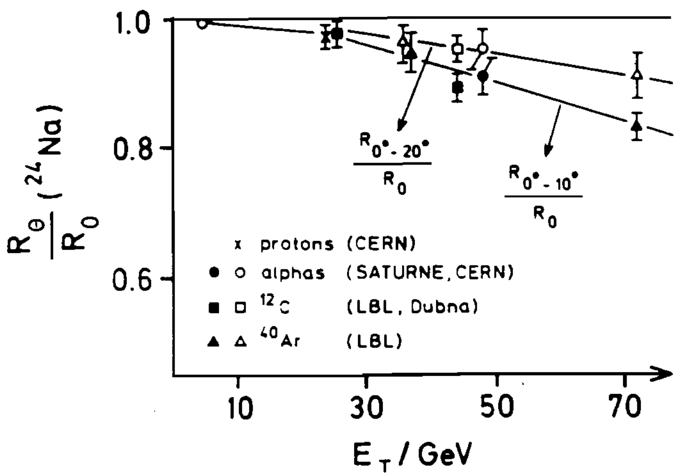

Fig. 4. The ratio R_θ (^{24}Na) of downstream Cu-disks within a certain angle θ, as compared to R_0(^{24}Na), as a function of the energy of the incoming heavy ion. R_θ gives the activity mostly at 20 cm distance within a certain angular range, say $0° < \theta < 10°$ or $0° < \theta < 20°$ [4].R_θ for 25 GeV ^{12}C and 24 GeV p is given for 10 cm, R_θ for 44 GeV ^{12}C is given for 38 cm. Full symbols indicate $R_{0°-10°}$, open symbols $R_{0°-20°}$.

3. EXPERIMENTS WITH 44 GeV ^{12}C, 4 GeV ^{4}He AND 2.6 GeV p

The results of detailed experiments with copper targets irradiated with 72 GeV ^{40}Ar have been published [1]-[9]. This reaction channel is going to be studied further [43]. Consequently, it seemed interesting to supplement such work with similar investigations using the 44 GeV ^{12}C beam from the SYNCHROPHASOTRON at the JINR, Dubna i.e. at lower total energy but at higher energy per nucleon. This should tell us, whether "unconventional" effects are a general feature in high-energy heavy ion interactions at $E_T > 40$ GeV or whether they are specific to ^{40}Ar ions. Crucial is the question of the production of ^{24}Na from energetic secondary fragments in copper at wide angles, say $\theta > 10°$. For this reason we irradiated with relativistic heavy ions a ring target arrangement covering to a first approximation a solid angle 2π, it will be referred to here after as the "2π ring target" (Fig. 5) . It covers ideally a 2π solid angle for a point-like beam and consists of two 1 cm thick Cu-disks (k=1, front disk; k=9, back disk, covering ($0° < \theta < 6°$) separated by a distance d=38 cm) and of seven Cu-rings of different shapes in between, cut out of 1 cm thick Cu -cylinders with an outer diameter of 8 cm and an inner opening of 4 cm. For an idealized point-like beam the seven Cu-rings cover an angle θ as follows: (k=2): 90°-70°; (k=3): 70°-52°; (k=4): 52°-43°; (k=5): 43°-31°; (k=6): 31°-19°; (k=7): 19°-10°; and (k=8): 10°-6°. This target was irradiated with 44 GeV ^{12}C during 19 hours with a total of $2.5 \cdot 10^{12}$ ions. The beam was well-focused, its beam spot density is gaussian with a variance $\sigma = (3-4)mm$, which was determined via the ^{22}Na-activity induced by the beam in the front disk (k=1). The gamma-activity in Cu was measured in a standard way, it should be pointed out, however, that the total activity in the Cu-rings was not too large; this, in turn, leads to relatively larger statistical errors than in the R_0 measurements. Fig. 6 gives a typical gamma -spectrum in one of those rings. A similar experiment

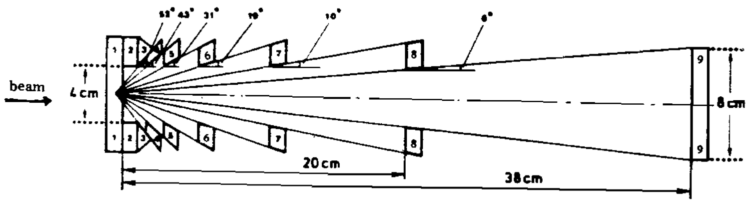

Fig. 5. The 2π ring-target exposed to 44 GeV ^{12}C. The Cu-disks (1 and 9) have a diameter of 8 cm, they are 1 cm thick. The Cu-rings (2 to 8) have a shape as indicated, their thickness is 1 cm. Details are described in the text and given in [44, 45].

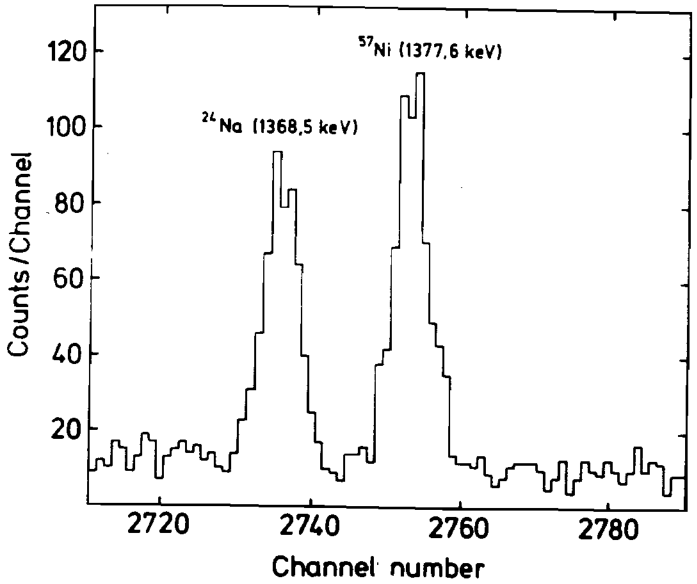

Fig. 6. A typical γ-spectrum in one copper ring, as measured with a Ge(Li) detector and using conventional techniques.

has been carried out with 4 GeV ^{4}He at SATURNE, Saclay, France. It was mentioned already, that there is no reason to expect any SMFP effects here. The target was slightly modified: the distance between the first and last Cu-disk was only 20 cm and six rings were placed in between them. In Table 1a we give the directly measured ratios R_θ (^{24}Na) for the two irradiations. R_θ-ratios for different other isotopes have also been measured [44], but are not dealt with in this publication. In Table 1b we give the results for a control experiment with 44 GeV ^{12}C. We used a slightly modified target system

Table 1a.

R_θ (^{24}Na), as observed in the 2π ring target for 44 GeV ^{12}C and 4 GeV ^{4}He. R_θ (^{24}Na) is the ratio of the ^{24}Na-activity within a certain angular interval θ as compared to the 1. copper disk in percent (see Fig. 5).

angular interval θ	R_θ (^{24}Na) for 44 GeV ^{12}C experimental observation	R_θ (^{24}Na) for 44 GeV ^{12}C *corrected** for beam halo	R_θ (^{24}Na) for 4 GeV ^{4}He experimental observation	R_θ (^{24}Na) for 4 GeV ^{4}He *corrected** for beam halo
90°-70°	1.5 ± 0.3	0.2 ± 0.6	0.2 ± 0.1	0.0 ± 0.2
70°-52°	1.2 ± 0.3	0.0 ± 0.5	0.1 ± 0.1	0.0 ± 0.2
52°-43°	1.0 ± 0.3	0.0 ± 0.5	0.2 ± 0.1	0.0 ± 0.2
43°-31°	2.7 ± 0.3	1.4 ± 0.6	0.3 ± 0.1	0.1 ± 0.2
31°-19°	5.3 ± 0.6	$3.6 \pm 0.4^{(+)}$	0.5 ± 0.1	0.3 ± 0.2
19°-10°	7.4 ± 0.6	5.6 ± 0.9	0.8 ± 0.1	0.6 ± 0.2
10°- 6°	7.7 ± 0.6	5.7 ± 0.9		
10°-0°			90 ± 1	90 ± 1
6°- 0°	107.0 ± 2	105 ± 3		

- (*) this correction is described in the text.
- (+) this value has been measured twice, with this target and the SEGMENT-2 target (see Fig. 12 and Table 5). Here we give the mean value between the two independent experimental determinations.

Table 1b.

R_θ (^{24}Na), as observed in a controll-experiment with 44 GeV ^{12}C. A modified 2π ring target consisted out of the front disk, only two rings covering the angles 43°-31°and 19°-10°, and the end disk in a distance of 20 cm, covering the angle 0°-10°. The results have not been corrected for a finite beam size

angular interval θ	R_θ (^{24}Na) for 44 GeV ^{12}C experimental observation
43°-31°	3.2±0.3
19°-10°	7.6±0.6
10°- 0°	115±2

described in the caption to Table 1b. It was exposed during an independent irradiation to about the same total ion flux as the main experiment (Table 1a). We found in three angular rings the same amounts of ^{24}Na as in the main experiments (Table 1b). The agreement of the R_θ (^{24}Na) values within Tables 1(a,b) shows, that the production of ^{24}Na within one specific ring is not influenced by the rings close-by. As one can see from Fig. 5, primary particles from the beam halo entering the outer area of the 2π ring target ($2cm < r < 4cm$) propagate through a "very thick" Cu-target, such as shown in Fig. 1c. In order to know the "true" wide-angle emission of energetic particles emitted from the center of the first Cu-disk in Fig. 5 ($r < 2cm$), one has to correct for this "very thick" target effect. Consequently, a stack of 16 Cu-disks, 8 cm ϕ, 1 cm thick as shown in Fig. 1c, has been irradiated twice with 44 GeV ^{12}C at the SYNCHROPHASOTRON, Dubna. The results for ^{24}Na-production in this "very thick" Cu-stack are shown in Fig. 7 together with the results of similar irradiations with 4 GeV ^{4}He and 2.6 GeV p at SATURNE. (These results are taken from [5, 44]). Now we can correct the "experimental R_θ (^{24}Na)" in Table 1a for beam halo effects as follows: 1) We assume, that we observe in the ring (k=2: 90°-70°) only the beam halo. 2) The "upper limit" for the beam halo correction in every ring is proportional to its weight (in g Cu) and proportional to the R_i value of Fig. 7. As we don't have a perfect "very compact stack" of copper, such as shown in Fig. 1c, some energetic secondary fragments are leaving the copper material if they are emitted into large lab angles. They don't contribute to the beam halo activity. Thus, a 20% reduction of the "upper limit" beam halo correction is considered as the "lower limit" beam halo correction, as appr. 20% of all energetic secondaries are emitted with $\theta > 6°$ (Table 1) for 44 GeV ^{12}C. For the 4 GeV ^{4}He -irradiation, only an "upper limit" beam halo correction has been considered. 3) The "correction for beam halo" in Table 1 is taken as the mean value between the "upper limit" and "lower limit" beam -correction, with an uncertainty spanning the entire uncertainty range. Such an uncertainty is a rather conservative estimate, but due to the limited statistical accuracy in our experiment this is considered as being proper. The final results for the angular distribution R_θ (^{24}Na), as corrected for beam halo effects, are given in Table 1a. From this we can conclude the following experimental facts: 1) The 2π ring target shows an appreciable amount of ^{24}Na produced by secondary fragments emitted into large lab angles ($6° < \theta_{lab} < 43°$) from a 1 cm thick Cu disk irradiated with 44 GeV ^{12}C. A similar wide-angle emission is not observed for the 4 GeV ^{4}He beam. 2) The data available from our experiments cannot give a statistically significant answer to the question whether any secondaries exhibiting the (still highly controversal) SMFP "decay" can be observed within our arrangement. Such a "decay" would show up as a significant decrease of the ^{24}Na-activity in the downstream Cu-configuration, when they are removed from the upstream Cu-disk. To answer the question quantitatively we note that if there is no "loss of anomalously large cross-section"of secondary fragments along the flight pathes shown in Fig. 5, then all the activity in the downstream Cu-disk of the contact configuration (Fig. 1a) should be found again in the rings and in the end-disk of the 2π ring target. Any loss-of-activity, ΔR_θ (^{24}Na), would be observed as follows:

$$\Delta R_\theta(^{24}\mathrm{Na}) = R_0(^{24}\mathrm{Na}) - \sum_{\theta=0^\circ}^{90^\circ} R_\theta(^{24}\mathrm{Na}) \qquad (4)$$

The results are given in Table 2. Any statistically significant deviation of ΔR_θ (^{24}Na) from zero could indicate the "decay to ground state" of "anomalous" secondary fragments. No such deviation can be observed in either of the beams, as shown in Table 2. However, due to the rather large experimental uncertainties in ΔR_θ (^{24}Na), we cannot exclude a contribution of decaying "anomalous" secondary fragments within the experimental uncertainties of 5% in ΔR_θ (^{24}Na) for 44 GeV ^{12}C and 1.5% for 4 GeV ^{4}He. It should be

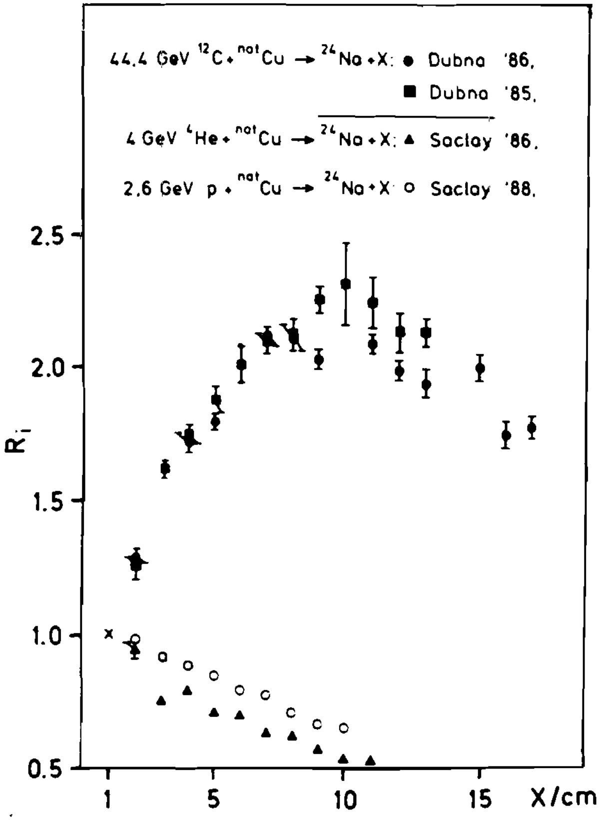

Fig. 7. The ratio R_i for ^{24}Na observed in downstream Cu disks to that in the 1st disk in a very compact stack of Cu disks as shown in Fig. 1c for four irradiations. The index (i) in R_i is given as (x/cm) on the abscissa. The cross (x) at (R_i=1; x/cm=1) is the normalisation point for all distributions.

Table 2.

On the possible decay of "anomalously" large secondary fragments. The values $R_0(^{24}\mathrm{Na})$ and $\sum R_\theta$ (^{24}Na) are the results from measurements in the compact form (Fig. 1a) and in the 2π ring target (Fig. 5), resp. $\Delta R_0(^{24}\mathrm{Na})$ is the difference between them. R_θ (^{24}Na) has been corrected for beam-halo effects (Table 1a)

	44 GeV ^{12}C	4 GeV ^{4}He[43]
$R_0(^{24}\mathrm{Na})$	1.24 ± 0.02	0.922 ± 0.010
$\sum_{\theta=0^\circ}^{90^\circ} R_\theta(^{24}\mathrm{Na})$	1.22 ± 0.04	0.920 ± 0.009
ΔR (^{24}Na)	0.02 ± 0.05	0.002 ± 0.014
flight-path between front-plate and end-plate of 2π ring target	38 cm	20 cm

recalled that the results from this experiment, where partial cross-sections are measured are not directly comparable to those in visual (i.e. emulsion and bubble chamber) experiments where total cross-sections determine the observed mean free paths. In the next section we want to address the problem: Can the abundant production of ^{24}Na at large lab angles $\theta > 10^\circ$ be understood within the framework of widely accepted theoretical models?

4. CALCULATIONS USING THEORETICAL MODELS

Obviously all there would be needed in order to allow us to state whether our experiments observe anything beyond conventional physics would be a complete set of multiplicities, fragmentation parameters, angular and energy distributions of all the secondaries. The choice of the proper theoretical models used for the interpretation of experimental results is always a problem since no theoretical model known to the authors is suitable for the description of all the aspects of relativistic heavy ion interactions. However, it is well-known that the Dubna-Cascade Model is a very advanced theoretical concept [46, 47] with quite a number of successful applications, an example is given in Ref. [48]. This model is based on the historic two-step Serber model of complex high-energy interaction: At first we calculate a fast intranuclear cascade as a succession of nucleonic interactions. This is followed by the slow evaporation of light particles from an excited nuclear state, which is left as a residue after the fast cascading interactions. This rather simple model has been refined considerably by Toneev and Gudima [46] and brought into line with many aspects of present-day high-energy phenomena (loc. cit.), including contributions due to coalescence and precompound phenomena. Additionally, a more phenomenological model for intranuclear interactions in high-energy reactions has also been used in our calculations [49]. This model describes the interaction of a high energy heavy ion A_1 (0.5 GeV/n< E_{lab} < 5 GeV/n) with a target nucleus A_2. The model can be applied to target- and projectile -ions within the mass range $4 < A < 240$ and is concerned with the production of relativistic secondary fragments h_i, such as pions, kaons, nucleons, and hyperons. This interaction

$$A_1 + A_2 \rightarrow \sum h_i + X \qquad (X = \text{target fragment}) \tag{5}$$

uses conventional nuclear geometry concepts in a conventional manner. The radii of both nuclei are calculated and the impact parameter b is determined for each interaction randomly by a Monte-Carlo procedure. This yields the natural mixture of central and peripheral interactions. The limits between these two types of interactions are determined through an average scattering angle, which is depending on A and E_{Lab}. For central collisions we subdivide the nuclei "row-on-row" into cylinders, where two-body nucleon-nucleon interactions occur. For peripheral interactions only simple nucleon-nucleon interactions are taken into account. No hydrodynamic aspects of the interactions are considered. Assuming a uniform density distribution within the interacting nuclei one can calculate the number of nucleons in both regions considered. The Fermi-momentum of the constituents can be calculated using the following phase -space distribution:

$$\frac{dn}{dp} = \frac{3p^2}{P_{FN}^3} \tag{6}$$

n being nucleons within the nucleus and the momentum p is chosen randomly ($0 < |p| < P_{FN} = 0.4(n/A)^{1/3} GeV/c$). P_{FN} is the Fermi momentum. The calculation stops, when the number of target- or projectile-nucleons is exhausted and a further emission of nucleons is prohibited due to energy or momentum conservation. Further details are described in the original literature [49]. In our calculations we were only concerned with the emission of relativistic secondary particles (p, n, π^+, π^-, d, t, ^{3}He, ^{4}He, and ^{5}Li) during the fast cascade step. The energies and the emission angles of these particles were recorded and used for further analysis. Consequently, we did neither study the effects of an extended target system, nor the role of 3rd generation particles. These fast cascade calculations gave currents N_{ijk} per unit time for the light relativistic particle (i) of energy E_j within a certain lab angular interval (k); i.e. within the acceptance of the k^{th}-ring of the 2π ring target. Then one calculated the activity A_{ijk} of ^{24}Na accounting to the standard equation:

$$A_{ijk} = \sigma_{ij} N_{ijk} N_{Cu,k} \tag{7}$$

where

- A_{ijk} - is the activity of ^{24}Na in ring (k) due to particle (i) of energy E_j
- σ_{ij} - cross-section Cu $\longrightarrow$ ^{24}Na for particle (i) with an energy E_j
- N_{ijk} - current for particle (i) of an energy E_j within the angular interval of the ring (k)
- $N_{Cu,k}$ - number of Cu-atoms [cm^{-2}] in the ring (k).

We neglect terms associated with the irradiation, as they cancel in our ratio-calculations. The crucial value in eq. (7) is the cross-section σ_{ij}. The most detailed decription on how this cross-section influences the interpretation of this type of Cu-block experiments has been given in [2]. The energy dependence of σ_{ij}, (the excitation function), is only known for protons in some detail. Furthermore, the knowledge of other cross-section σ_{ij} for the yield of ^{24}Na in copper induced by other light particles, including ^{12}C is very limited. Consequently, we acted two fold:

- 1) We determined three additional experimental cross-sections for the reactions Cu(p/d/^{12}C;X)^{24}Na with the following projectile energies: 8.14 GeV p; 7.3 GeV d; and 44 GeV ^{12}C, respectively. We used conventional techniques. The monitor cross-section was ^{27}Al (p/d/^{12}C;X)^{24}Na, the integral particle flux could be determined up to 10% accuracy. The results are given in Table 3.
- 2) In agreement with the concepts of "limiting fragmention" and "factorisation" in high-energy nuclear interactions, we always used in our calculations: $\sigma_{ij} = \sigma_{proton}(E_j)A^{2/3}$ and σ_{ij} = (const) for $E_T > 3GeV$. The resulting excitation functions are shown in Fig. 8.

Table 3.

Some cross-sections for the reaction ^{64}Cu (p/d/^{12}C;X) ^{24}Na, as determined in this work and recently by S.Y. Cho, et al.*

Projectile	Energy/GeV	(^{24}Na)/mb
p	8.15	3.4±0.5
d	7.3	5.4±0.9
^{12}C	44.0	12.3±1.8
^{12}C	0.5	1.43±0.17*

* S.Y. Cho, et al., Phys.Rev.C 36, 2349 (1987)

After the results of the phenomenological model were obtained in form of tabulated N_{ijk}-values, the calculation proceeded from eq (7) as follows:

$$A_{ik} = N_{Cu,k} \sum_j N_{ijk}\sigma_{ij} \tag{8}$$

and

$$A_k = \sum_i A_{ik}\,. \tag{9}$$

The activity A_k in the k^{th}-ring, disk resp., is the final calculation value needed. In order to simplify the further calculation, we compare the activity for ^{24}Na in the k^{th}-ring to the activity in the last two Cu-pieces, i.e. Cu-ring (k=8) plus the Cu end-disk (k=9, Fig. 5). This activity covers the angular interval $0° < \theta < 10°$ and is normalized to unity. It is calculated as follows:

- 1) $(A_8 + A_9)$ are taken from equation 9, this part is due to projectile fragments with $1 \leq A \leq 6$. To this we add the
- 2) activity induced by primary ^{12}C-ions hitting the Cu end-plate.

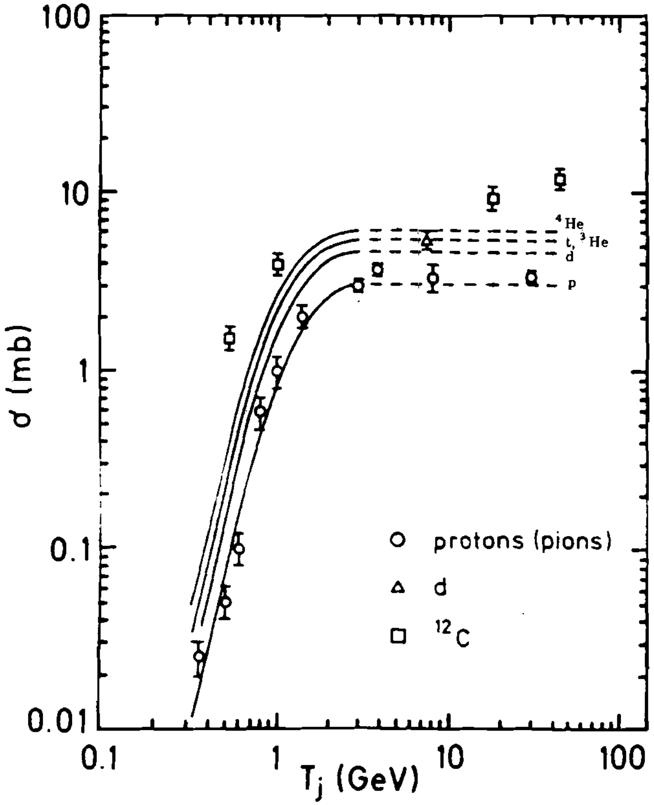

Fig. 8. Excitation function for the reaction ^{64}Cu (X;Y) ^{24}Na. The experimental points are given with error bars; the four curves (for p, d, ^{3}He, ^{4}He) are used in the calculations as described in the text.

The ^{12}C-beam intensity is reduced by 14% within the first Cu-disk (k=1), as estimated using conventional total absorption cross-sections [50] and standard formulas such as eq(3). We neglect in this approach the activity induced by heavy projectile fragments with $6 \leq A < 12$. But this contribution is small

and certainly smaller than 14%, as, at the maximum, one interacting C-ion yields only one such heavy projectile fragment. Such an uncertainty is small as compared to the other uncertainties in the calculations.

The results of the calculations are shown in Fig. 9a and compared with the experimental results, as given in Table 1a. The calculations are based on the assumption of a point-like beam for primary ions. Indeed, we were able to observe a rather narrow beam distribution with a variance of $\sigma = (3-4)$ mm for a gaussian type of beam-width. Such a narrow beam does not influence the experimental distribution $R_\theta(^{24}\mathrm{Na})$ in any appreciable manner, as it is shown in the Appendix. The comparison between experiment and theory in Fig. 9a shows a steeper decrease of R_θ with the angle θ for the two models used, as compared with the experiment. For the phenomenological model (PM) this discrepancy amounts to one-order-of-magnitude, for the Dubna Cascade Model (DCM) to about a factor of (2-3). However, as all

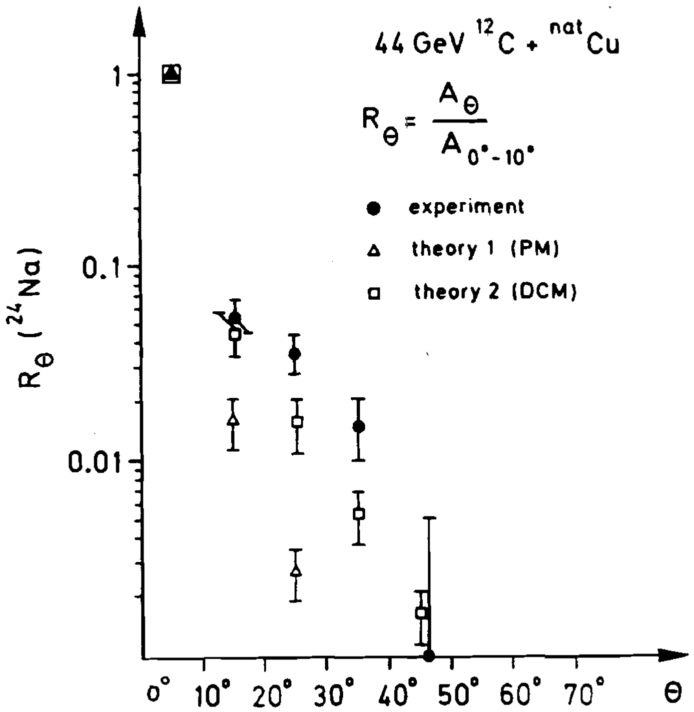

Fig 9a). Comparison between calculated and experimental distributions R_θ (^{24}Na) in the reaction (44 GeV ^{12}C + ^{nat}Cu). All distributions are normalized to the ^{24}Na-activity within the angular intervall $0° < \theta < 10°$. PM-phenomenological model , DCM - Dubna cascade model, details see text.

values are associated with rather large uncertainties, we refrain from the determination of a statistical significance between those distributions. The uncertainties in the calculated distribution are of a systematic nature, as it is very difficult to estimate in an accurate manner the ^{24}Na-activity induced by primary ^{12}C in copper (in comparison to the ^{24}Na-activity induced by secondary particles). The uncertainty in the experimental distribution is due to limited counting statistics. The PM leads to a stronger decrease with θ as compared to the DCM as it ignores all collective effects. But we take note of the fact, that the DCM in Table 4 gives only a small number of α-particles, having always a rather low kinetic energy. Experimentally, it is a well-known fact, that relativistic ^{12}C-particles quite often break up into ^{4}He-particles, emitted with relativistic energies into a tiny angular forward cone. This deficiancy in the DCM makes our calculations rather conservative.

Table 4a.

Mean energy [GeV] of secondary particles as a function of their emission angle θ. The results are obtained with the Dubna-Cascade Model [46, 47]. The model was used in a form including coalescence and precompound phenomena

^{12}C+ ^{64}Cu 44 GeV 2400 events	0°-10°	10°-20°	20°-30°	30°-40°	40°-50°	50°-60°
$\pi^{(+-)}$	0.90	0.71	0.50	0.38	0.30	0.24
n	2.38	0.96	0.49	0.28	0.17	0.11
p	2.40	0.99	0.53	0.31	0.18	0.12
d	2.17	0.57	0.33	0.20	0.15	0.11
t	0.45	0.25	0.19	0.16	0.13	0.10
^{3}He	1.03	0.30	0.20	0.18	0.15	0.12
^{4}He	0.08	0.08	0.10	0.10	0.07	0.05

Table 4b.

Relativ number of secondary particles as a function of their emission angle θ. The results are obtained with the Dubna-Cascade Model [46, 47], as shown above

^{12}C+ ^{64}Cu 44 GeV 2400 events	0°-10°	10°-20°	20°-30°	30°-40°	40°-50°	50°-60°
π^+	861	1150	1040	894	736	641
π^-	916	1220	1130	1020	884	728
n	5960	4110	3840	3560	3220	3100
p	5760	3960	3430	3110	2730	2470
d	381	514	596	664	639	571
t	25	58	75	102	108	128
^{3}He	21	51	69	79	71	78
^{4}He	16	25	68	72	89	93

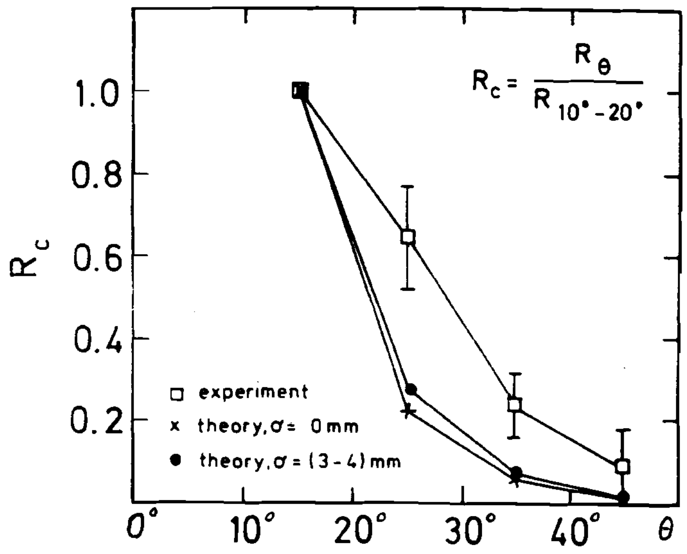

Fig 9b). Comparison between the DCM (Dubna cascade model) and the experimental angular distribution R_c. All distributions are normalized to the ^{24}Na-activity within the angular intervall $10° < \theta < 20°$. Furthermore, the small influence of the extended beam (σ = 3-4 mm) on the calculated distribution is shown. Details are given in the appendix.

A more realistic calculation would bring even less high-energy particles into large lab-angles. Such a more realistic calculation, also including results from emulsion experiments, will be presented in a future publication together with further experimental observations [51].

When we restrict our calculation to angles $\theta > 10°$, we calculate the R_θ much more accurately with the DCM, as only light secondary particles are emitted into large angles with $\theta > 10°$. All input parameters are well known, as shown in Table 4. When we now calculate

$$R_c = \frac{R_\theta}{R_{10°-20°}} \qquad (10)$$

the results are shown in Fig. 9b. Here again we observe a significant difference between the experimental and theoretical angular distribution of R_θ(^{24}Na) in the angular interval $20° < \theta < 30°$. We observe a factor of 2.3 between experiment and theory with a significance of 3 standard deviations. Here, the small influence of our extended beam ($\sigma = 3 - 4mm$) on R_c is shown. The calculated values (DCM) in Fig. 9b are given without uncertainties, and without accounting for the size of the target [7].

It is interesting to note, that even when we assume, that we can understand the production of ^{24}Na within the angular interval $10° < \theta < 20°$ (i.e. no "anomalons"), we observe at the larger angles $\theta > 20°$ considerable more ^{24}Na than can be calculated with the DCM.

In summary, one observes too much ^{24}Na-activity at large lab angles, indicating a too large flux of particles, which can induce high-energy interactions ($E_{threshold} \approx 0.8\ GeV$) in copper. In this paper we are unable to account for this discrepancy. The reasons for this discrepancy could be - among others:

- 1) We assumed a predominant emission of relativistic Z=1 particles (and neutrons) into wide angles. This is given by the "cascading" models used and it is found experimentally in nuclear emulsions [8]
- 2) The emission of energetic large fragments ($A > 6$) into large lab -angles is completely neglected. Possible experimental evidence for such unexpected emission of relativistic heavy fragments into large lab-angles might have been observed in a preliminary manner with visual detectors (see Refs. [8, 52]). If such an emission would occur, it could be in the range of a 10^{-3} probability, compared to the flux of primary ^{12}C-ions. There are theoretical conjectures, that such heavy projectile fragments might have "anomalous" properties [27], a conjecture worth further experimental investigations.
- 3) We did not consider the "anomalon-hypothesis", which states that light relativistic secondary fragments (Z≤1) can have considerable enhanced cross-section, both for the total, as well as for partial cross-sections.

Obviously, further experimental and theoretical work is needed in order to understand this puzzle better.

5. FURTHER CONTROL EXPERIMENTS

The enhanced production of ^{24}Na by wide angle secondaries produced in copper by 44 GeV ^{12}C has been the essential observation reported in this paper. It is desirable to have further experimental confirmations for this experimental fact. Consequently, we carried out the following control experiments:

1) We exposed the target system SEGMENT-1 (shown schematically in Fig. 10 (a,b)) for 23 hours to $2.5 \cdot 10^{12}$ ions (44 GeV ^{12}C) at the SYNCHROPHASOTRON. This new setup consisted of a small Cu-target T (2 cm diameter, 1 cm thick) and Cu-segments, exposed to secondary fragments emitted from the center of the Cu-target into polar angles $20° < \theta < 30°$. These three Cu-segments (A, B, C) covered always an azimuthal angle, $\varphi = 38°$ so as not to interfere with each other. They are placed at increasing distances from the target T. Each segment consisted out of three 1 cm thick sub-segments ($A_{1-3}, B_{1-3}, C_{1-3}$). We determined in the usual way the ^{24}Na-activity in all the copper-pieces and carried out the proper geometrical corrections as described in detail in Refs. [44, 51]. Then we renormalized the activity from $\varphi = 38°$ to the full azimuth of 360°; the results are given in Fig. 10c. We observe ^{24}Na-activity in all segments and sub-segments to

an extent of $\approx 4\%$. This is in agreement with the R_θ (^{24}Na) measurement of $(3.6 \pm 0.9)\%$ as found in the 2π ring-target for the angle $19° < \theta < 31°$ (ring k=6, as shown in Fig. 5). From Fig. 10c one can conclude that:

- i) the amount of ^{24}Na found within the polar angle $20° < \theta < 30°$ does not depend on the details of the two quite different constructions of Cu-target systems, shown in Fig. 10 (a,b) and Fig. 5.
- ii) comparing the ^{24}Na-activity in sub-segments A_1, B_1, and C_1, we observe always the same activity, showing no decrease of any "effect" for distances d between 7 cm up to 20 cm from the Cu -target T,
- iii) within the limits of experimental uncertainties, the ^{24}Na-activities agree within all sub-segments A_{1-3}, B_{1-3}, and C_{1-3}, although a slight tendency for decreasing activity from 1-3 is visible.

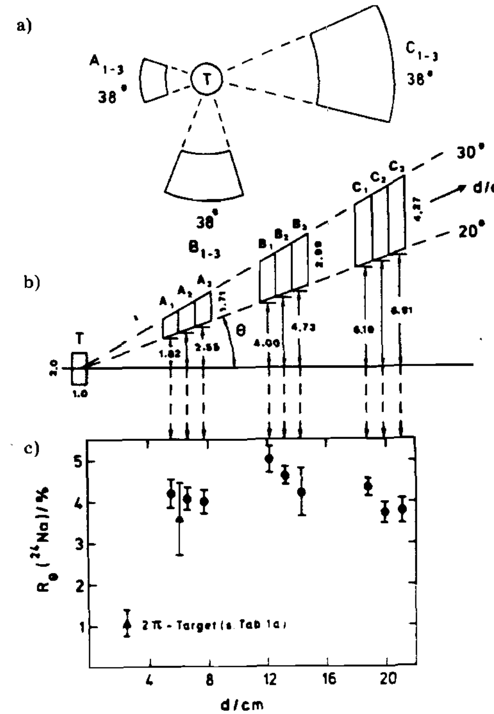

Fig. 10. The target setup SEGMENT-1 consists of a Cu-target T and Cu-segments, A_1 up to C_3 : a) shown from head-on view and b) shown in a simplified cut-view c) the results for ^{24}Na in Cu after an irradiation with 44 GeV ^{12}C: R_θ (^{24}Na) is the ratio of activity in a certain segment, say A_1 up to C_3, normalized to 2π in azimuth to that in the target T. Further details are given in the text.

We can compare this to the slight and even more pronounced decrease of R_i in a very thick Cu-target exposed to 2.6 GeV protons and 4 GeV alphas (SATURNE) as shown in Fig. 7. It appears (Fig. 7) that the slope in the dR/dx curves is a strong function of the incoming ion energy. Whether or not, it is allowed to conclude from the almost constant activity in the sub-segments that quite energetic secondary particles have penetrated these segments must be studied further [51]. The "puzzle" of this experimental finding has already been formulated in Ref. [2, 8] and shall be repeated here: From "known physics" we conclude, that secondary particles emitted into polar angles $20° < \theta < 30°$ have a low transverse momentum, consequently a low total momentum. This leads to a rather low kinetic energy, too low to produce in Cu-segments ^{24}Na in the experimentally observed large abundances. According to Table 4a, the calculated mean kinetic energy for the hadrons is approx. 0.5 GeV in this angular intervall.

2) We can exclude the production of ^{24}Na in segments A_1, A_2, and A_3 as being due only to an extended beam halo as follows: As shown in Fig. 11, we exposed a CR-39 SSNTD (solid state nuclear track detector) in front of the Cu-disk to $7 \cdot 10^7$ ions (44 GeV ^{12}C) and etched the foil as required (Ref. [8] gives the details). The decrease of the track intensity perpendicular to

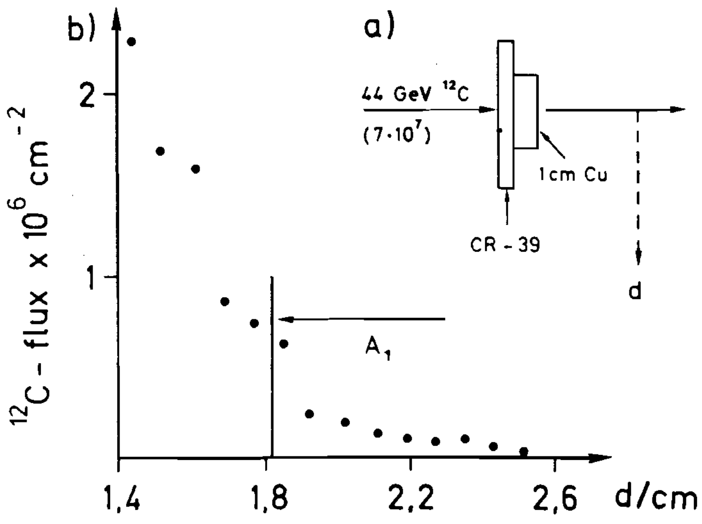

Fig. 11. a) The experimental set-up to measure the beam profile with one CR-39 plastic solid-state-track detector, irradiated with one burst of a 44 GeV ^{12}C-beam. b) The decrease of the track intensity in CR-39 (identical with the decrease of the beam intensity) outside the "beam halo", as measured from the center of the target along the vector given by the segments A_1,A_2 and A_3, shown in Fig.10.

the beam direction and in front of sub-segment A_1, is shown in Fig. 11. We estimate that < 2% of the primary ^{12}C beam has hit this sub -segment A_1 as compared to 4% of the observed ^{24}Na-activity. This shows additionally, that the ^{24}Na-activity in this segment is produced by energetic secondary fragments emitted from target T into large polar angles $20° < \theta < 30°$. But this experiment is not completely conclusive. We compare here only the beam profile for 1 burst of $7 \cdot 10^7$ ions to the beam profile of an extended 23 hour irradiation with $2.5 \cdot 10^{12}$ ions 44 GeV ^{12}C. Consequently, we must carry out one further control experiment.

3) We irradiate a further target system twice. This system is called SEGMENT-2 and is shown in Fig.12.It is similar to the one shown in Fig.10.

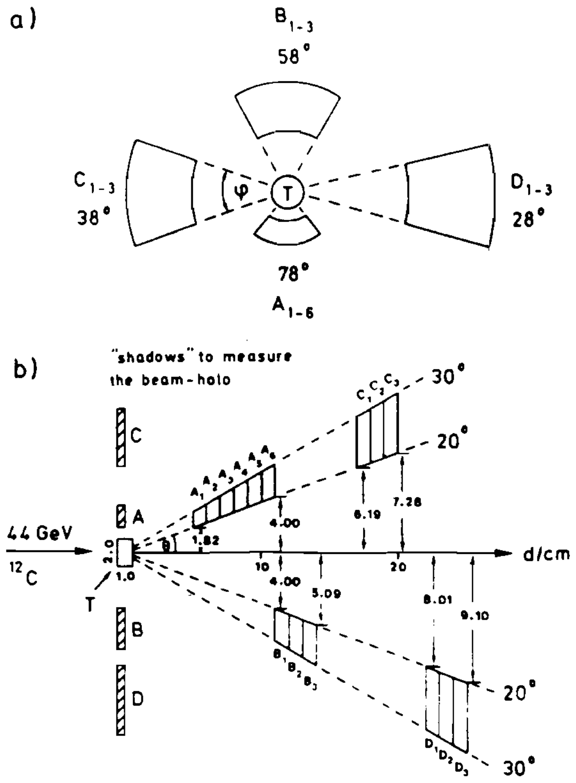

Fig. 12. The target setup SEGMENT-2 consists of a target T and Cu-segments A_1 through D_3: a) head-on view and b) shown in a simplified cut-view. Some results from this experiment are shown in Table 5. They concern the effect of the "beam halo", as measured with the "shadow" on the activity of ^{24}Na in the segments A_1, B_1, C_1, und D_1.

Again one has a target T (2 cm ∅, 1 cm thick) and a series of segments A, B, C, D; the segments cover here an azimuthal angle between 28° and 78° and again a polar angle $20° < \theta < 30°$. However, we have installed also "shadow" copper targets; their thickness is only 0.5 cm, but their area is just the projection of the first sub-segment A_1, B_1, C_1, and D_1 into the plane normal to the beam. These "shadow" targets determine completely the beam halo as seen by their first sub -segments A_1, B_1, C_1, and D_1, respectively. Two experiments were carried out:

- (1) with $3.5 \cdot 10^{12}$ ions ^{12}C(44 GeV) onto a carbon target T;
- (2) with $2.1 \cdot 10^{12}$ ions ^{12}C(44 GeV) onto a copper target T.

The results are given in Table 5. The activity ratio P, defined as ^{24}Na in the "shadow" Cu part (0.5 cm thick) compared to the ^{24}Na in the respective first Cu sub-segment (1.0 cm thick), must be multiplied by a factor of two in order to normalize to the same Cu thickness. Nevertheless, the value 2·P is always significantly smaller than unity. This shows conclusively, that the activity

Table 5.

Results for the determination of the beam halo with a "Cu-shadow" in the target system SEGMENT-2, as shown in Fig. 12. The activity ratios are given for the isotope ^{24}Na, produced in copper. The sub-segments A_1, B_1, C_1 und D_1 are placed at the polar angle $20° < \theta < 30°$ with respect to the target T

activity ratio P*	2 cm ∅ target T 1 cm thick carbon	2 cm ∅ target T 1 cm thick copper
"shadow" A / A_1	0.27±0.06	(**)
"shadow" B / B_1	(**)	0.09±0.02(+)
"shadow" C / C_1	0.26±0.06	(**)
"shadow" D / D_1	0.13±0.06	(**)
intensity of 44 GeV ^{12}C	$3.5 \cdot 10^{12}$	$2.1 \cdot 10^{12}$

- (*) The "shadow" is 0.5 cm thick and the sub-segments A_1, B_1, C_1, and D_1 are 1 cm thick. The shapes of the "shadow" are exactly those of their resp. sub-segments, as shown in Fig. 12. The factor of 2P gives the amount of "beam-halo" activity within the sub segments.
- (+) In this case, the ratio $B_1/T = (4.4 \pm 0.4)\%$ was measured. This reproduces the result shown in Table 1a.
- (**) In these cases, the measured activity of ^{24}Na within the "shadow" was too low for a statistically significant evaluation.

of ^{24}Na found in the sub-segments of copper, as shown in Figs. 10 and 12, cannot be caused only by the beam halo (measured *via* the "shadow" Cu), but a substantial fraction *must* be produced by energetic secondary fragments emitted under a polar angle $20° < \theta < 30°$ from targets T, the target T can be copper or carbon itself. The result for the measurement in the segment B_1 has already been included in Table (1a). A more detailed account of this experiment will be published later [51].

6. RESPONSE TO THE CRITICISM OF TOLSTOV ABOUT OUR CU-DISK EXPERIMENT

Finally, we want to conclude this article with a response to a Tolstov's criticism [53, 54] about our Cu-target experiments, as this is intimately connected with the problem of wide-angle emission of energetic particles. In this context it is unimportant, that Tolstov [54] describes in his article the experiment of Dersch *et al.* [1] quite accurately and quotes the essential results in Fig. 13 correctly: Dersch *et al.* irradiated targets, such as shown in Fig. 1a and 1b with 36 GeV ^{40}Ar and 72 GeV ^{40}Ar respectively. The determination of yield ratios R was carried out in the same manner, as described in our Section 2. The yield ratio R_d for deep-spallation products, say ^{24}Na and ^{28}Mg, is given in Fig. 13. R_d is the activity ratio for one nuclide in the downstream disk as compared to the upstream disk. It was stated, that we are unable to understand the results of Fig. 13 on the basis of widely accepted models in physics [1]-[9]. Tolstov attemped to show the contrary. Essentially, he assumed that relativistic protons and pions emitted during the interaction of 72 GeV ^{40}Ar with Cu have a sufficiently large kinetic energy for the production of ^{24}Na from Cu, *independent of their emission angle* in the laboratory system. He assumed that R_0 is due to the emission of energetic fragments into all kinds of large forward angeles. By increasing the distance d between the two Cu disks more and more wide angle emitted secondaries, protons as well as pions, fail to hit the downstream Cu disk, thus decreasing R_d with increasing d for 72 GeV ^{40}Ar. In this way, he indeed was able to fit the experimental points at 72 GeV ^{40}Ar quite well with his calculation as shown in Fig. 13. However, all the equations in Refs. [53, 54] ignore the energy dependence for pions and protons on their emission angle. It is well-known that in high-energy interactions the mean transverse momentum is rather low and has weak dependence on the angle. Consequently, the kinetic energy is angular dependent: practically speaking, the larger the lab-angle the lower the kinetic energy of pions and protons. This was calculated quite extensively in Ref. [2] and confirmed in this work, as shown in Table 4a. In particular, for large lab angles ($\theta > 20°$) a large kinetic energy would require quite large mean transverse momenta and correspondingly high temperatures for the source emitting such protons and pions. In addition, Tolstov used as input data for his calculation the angular distribution for secondary highly energetic protons and pions, as found experimentally for minimum ionising particles in nuclear emulsion irradiated with 80 GeV ^{22}Ne. Now it is well known, that the angular distribution for minimum ionising particles (i.e. fast protons and pions) produced by 80 GeV ^{22}Ne is more forward focused than those produced by 72 GeV ^{40}Ar because of the higher beam velocity (energy per nucleon) in the formed case. In case Tolstov would have used the proper experimental input data, his "fit" would not be as beautiful, as shown in Fig. 13. Furthermore, Tolstov only fits the radiochemical data for 72 GeV ^{40}Ar and not for 36 GeV ^{40}Ar. It is known, that the angular distributions for minimum ionising particles produced by 36 and 72 GeV ^{40}Ar are rather similar (details can be found in Ref. [2]). Nevertheless,

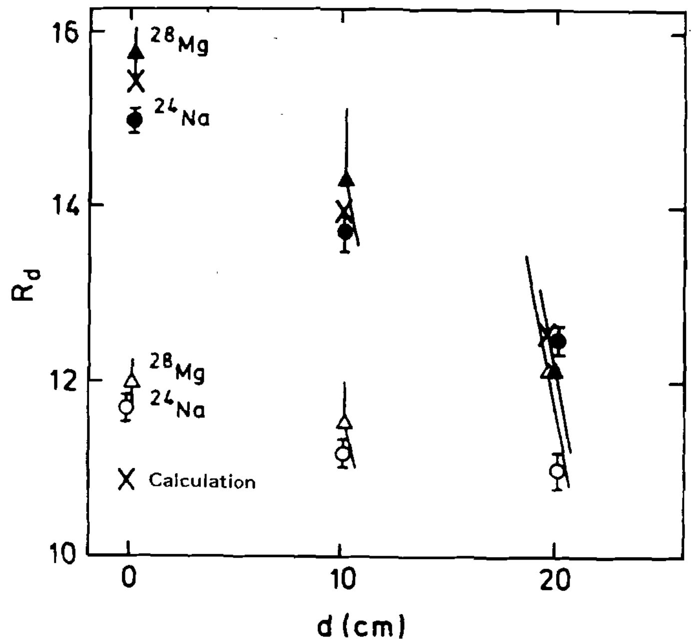

Fig. 13. Attempt of Tolstov [53, 54] to criticise our interpretation of the Cu-block experiments. The experimental results for ^{24}Na and ^{28}Mg in the interaction of 36 GeV ^{40}Ar (open points) and 72 GeV ^{40}Ar (closed point) are taken from [1]. (X) "Pacyem" stands for Tolstov's calculations. The agreement between experiment and Tolstov's model is remarkable for 72 GeV ^{40}Ar on Cu-targets. The text describes the inconsistency in Tolstov's interpretation, but also points out further work of Tolstov, which is supporting our observation of energetic fragments emitted at wide angles. Please note: This figure is taken from [54]. Actually, Ref.[53] gives only the results for 72 GeV ^{40}Ar, but not for 36 GeV ^{40}Ar.

the agreement between the experiment and Tolstovs' calculation in Fig. 13 is quite remarkable, even when HIS calculations are based on a model not compatible with other evidence. This might be the clue to the entire problem, and indeed "very energetic" protons and pions are observed at large angles. "very energetic" is defined here, as having a cross-section large enough to enhance the production of ^{24}Na, ^{28}Mg from Cu. It is interesting to note, that such surprisingly energetic pions and protons may have indeed been observed recently at large lab angles by the Tolstov-group in Dubna [55]. They studied nuclear emulsions irradiated with p, ^{12}C, and ^{22}Ne at 4.5 AGeV/c. But then the question comes up: Why did all the world observe and calculate such a low kinetic energy for pions and protons at wide angles, so far?

7. CONCLUSION

A variety of experimental results using several Cu-target arrangements were shown and described. We find an unexpectedly large production of ^{24}Na in "secondary" copper-detectors. These "secondary" copper detectors are typically 1 cm thick and are exposed to secondary particles emitted from the interaction of 44 GeV ^{12}C within the 1 cm thick upstream copper target. "Secondary" copper is exposed to larger lab angles ($6° < \theta_{LAB} < 43°$). We reported for two theoretical models a discrepancy of a factor between (2-10) between experiment and theory for the production of ^{24}Na in Cu at these large lab angles. The present situation is unclear, since some aspects of our work defy constantly any attempt to be interpreted on the basis of widely accepted theoretical models for more than 5 years. These discrepancies may reflect unperfections of the models observed to describe the overall reaction mechanism in copper for primaries and secondaries alike, or they may prove that the experimental informations needed to provide reliable calculations of our complex effects are simply incomplete. Two of us (E.G. und W.S.) are preparing a contribution which may come to other results using another ansatz.

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8. APPENDIX

Estimation of a Correction for Calculated Angular Distributions Taking into Account the Extended Beam Size of the 44 GeV ^{12}C-beam.

The calculations presented in this paper are based on the assumption of a point like beam hitting the front disk of the 2π ring-target system right in the center, as shown in Fig. 5. Now it is well-known that the 44 GeV ^{12}C-beam of the SYNCHROPHASOTRON, JINR, Dubna, is very well focused and unusually stable, even for extended irradiation periods of several days.

Nevertheless we had to consider the small effects of an extended beam size. We studied for this the activity distribution of a long lived deep-spallation product (^{22}Na, $T_{1/2}$ = 2,6 a) in Cu. We determined the ^{22}Na-activity in the Cu-front disk ("1" in Fig. 5) with the help of a Ge(Li)-gamma detector. At first we measured the full disk (8 cm ϕ), then we reduced mechanically the diameter of the disk to smaller values and measured again, until a central disk with 1 cm ϕ remained. As one can see in Table A-1, practically all the ^{22}Na-activity is concentrated in the central 2 cm ϕ disk. Such a distribution can be approximated with a gaussian shape, having σ = (3-4) mm. For this very well focused beam we consider the correction factors.

Table A-1.

Measurement of ^{22}Na ($T_{1/2} = 2,6a$) in the Cu-front disk .
The diameter of the disk is reduced mechanically step-by step. Typically we measured at least 240 hours. During this time we collected for 8 cm ϕ about 5000 counts in the γ−peak (1274.5 keV). Nearly all values got measured in duplicate.

diameter of Cu-disk (cm)	normalized activity (t=0)
8.0	6844 ± 113
4.0	6513 ± 124
3.5	6920 ± 117
3.0	6971 ± 109
2.0	6534 ± 150
1.0	4283 ± 104

We calculate the correction for the geometrical acceptance of the 2π target for an extended beam size. The angular acceptance for an ideal beam (σ = 0 mm) has already been given in Fig. 5. The model for this calculation together with the parameters used are shown in Figures A-1 and A-2.

$\vec{R}_1$ - inner radius of the copper-ring ($\geq$ 2 cm)
$\vec{R}_2$ - outer radius of the copper-ring ($\leq$ 4 cm)
$\vec{R}$ - vector from the center of the front-disk C to the point-of-interaction L within the front- disk ($\vec{R} < 4cm$). The points C and L are assumed to be in the median plane of the front-disk.
$\vec{R}_o$ - vector in the Cu-ring, starting at L' and directed to the point of secondary interaction I.
$\vec{R}_p$ - vector in the Cu-ring, starting from C' and ending at I . $\vec{R}_p$ and $\vec{R}_o$ are coplanar.
$\vec{R}_i$ - vector connecting the points L and I .
$\vec{Z}$ - vector between L and L' . This vector is parallel to the center axis.
φ - angle between the two vectors $\vec{R}$ and $\vec{R}_o$. For this operation, the vector $\vec{R}_o$ has been moved parallel from L' to L , i.e. from the "Cu-ring" plane to the median plane in the front-disk.
θ - angle between the vector $\vec{Z}$ and $\vec{R}_i$.

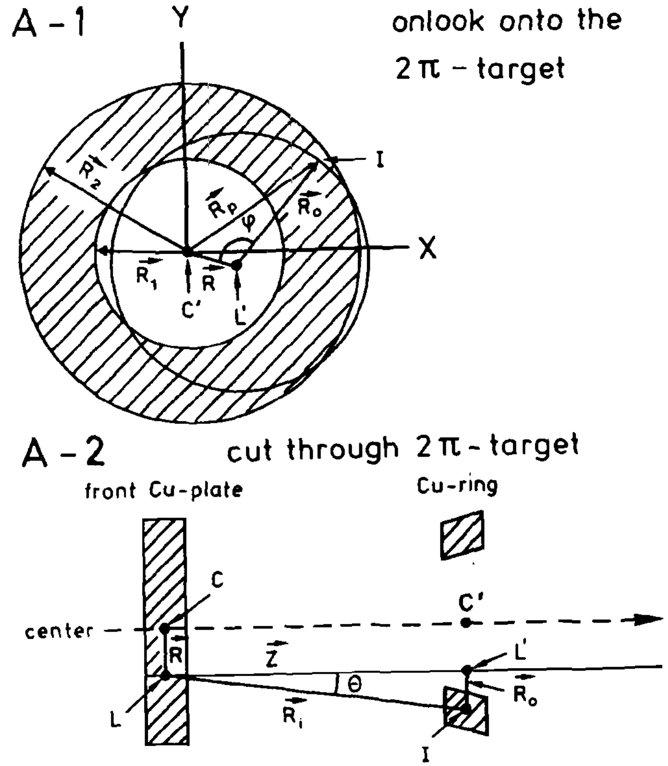

Fig. A-1,2. Schematic drawing in order to define the parameters needed for the calculations of the effects of an extended beam size.

The vector $\vec{R}$ is gaussian distributed around the center axis with a given variance σ. The point L with its cartesian coordiantes (X_L, Y_L) is determined randomly by two independently chosen values for the gaussian distribution along the x- and y-axis, respectively. From this we choose at random an angle φ, as defined in Fig. A-1, with $0 < \varphi < 2\pi$. Then we select an angle θ, defined in Fig. A-2, starting with $\theta = 0°$ and increasing θ in steps of 1°untill θ=75°. After having chosen the angles φ and θ_j starting from the point L, we have defined in a unique manner the vector $\vec{R}_i$. Now we look, whether any copper ring (i) has been hit by the vector $\vec{R}_i$. In the actual calculations, each Cu-ring has been divided into 10 slices, each being 1 mm thick.

The calculation shows, that for an experimentally determined variance $\sigma = 4\ mm$, one must correct the calculated angular distributions (based on $\sigma = 0mm$) only by about 15 % within the angular interval $10° < \theta < 30°$. The corrected distribution is also shown in Fig. 9b. We have not included any energy dependence of secondary particles into our calculations. But by comparing the experimental results for the two independent geometrical configurations (2π-target vs. Segment 2) for $20° < \theta < 30°$, we find the same amount of ^{24}Na in these two configurations, confirming our claim, that the statistical uncertainties of our experimental results are larger than the systematic uncertainty in the correction for an extended beam size in the 2π-target experiment.

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Брандт Р. и др. E1-89-803

Повышенный выход натрия-24, образованного вторичными частицами, рожденными под большими углами во взаимодействиях релятивистских ионов углерода с медью

С помощью активационной методики изучено поведение фрагментов снаряда, образующихся во взаимодействиях ядер углерода-12 с энергией 44 ГэВ с толстыми мишенями из меди. Приведен краткий обзор данных, полученных нами до сих пор, и описаны результаты исследований взаимодействия ядер углерода с медными мишенями различной конфигурации с образованием натрия-24 в реакциях глубокого расщепления. Высокоэнергетичные фрагменты, которые испускаются в интервале углов $10^\circ \leqslant \theta_{\text{лаб}} \leqslant 45^\circ$, приводят, по-видимому, к образованию бо́льшего количества натрия-24, чем это ожидается по феноменологической модели. Выполнены расчеты по модели внутриядерного каскада, которые показывают, что имеется расхождение на фактор два между экспериментом и теорией. Описаны калибровочные эксперименты, проведенные на пучках гелия-4 и протонов с энергией 4 ГэВ и 2,6 ГэВ соответственно.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1989

Brandt R. et al. E1-89-803

Enhanced Production of ^{24}Na by Wide-Angle Secondaries Produced in the Interaction of Relativistic Carbon Ions with Copper

Radiochemical activation techniques were used to study the behavior of projectile fragments formed in the interaction of 44 GeV ^{12}C ions within thick Cu-targets. After a short review of the results obtained hitherto with this Cu-target technique, the interaction of 44 GeV ^{12}C with several copper target configurations yielding the deep spallation product ^{24}Na is described. Energetic fragments which are emitted into lab angles $10^\circ \leqslant \theta \leqslant 45^\circ$, appear to produce more ^{24}Na (by about one order of magnitude) than calculated with a phenomenological model. An intranuclear cascade model was also used, giving a discrepancy of a factor of two between experiment and theory. Some normalisation experiments with 4 GeV ^{4}He and 2.6 GeV p are described.

The investigation has been performed at the Laboratory of High Energies, JINR.

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