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ON DIFFERENT EXPERIMENTAL BEHAVIOUR OF FAST SECONDARY PARTICLES PRODUCED IN ^{12}C INTERACTIONS AT RELATIVISTIC ENERGIES AS STUDIED WITH RADIOCHEMISTRY AND IN A PROPANE CHAMBER

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1. INTRODUCTION.

During recent years, the behavior of fast secondary particles (grey particles in emulsion) produced in (15-25) GeV ^{12}C-ion interactions was studied and compared to the behavior of fast secondary fragments in (41-44) GeV ^{12}C-ion interactions. At first, this comparison was carried out in experiments using radiochemical techniques. Various Cu-target configurations were irradiated with 25 GeV and 44 GeV ^{12}C-ions.[1-4)] As one had no problem to understand the essential features at 25 GeV kinetic energy, one always had difficulties to understand the experimental results obtained with 44 GeV ^{12}C-ions on the basis of a variety of theoretical models. This was particularly true, when deep inelastic nuclear reactions, i.e. the reaction $^{nat.}$Cu $\rightarrow$ ^{24}Na, were investigated. Secondly, the behavior of 15.1 GeV ^{12}C-ions in a propane bubble chamber was studied and compared to the behavior of 41.5 GeV ^{12}C-ions. In this case, the results between the two energies studied do not show any substantial difference. This holds both for the experimental observation, as well as for the model simulations of propane data.

In this paper we want to discuss these divergent results obtained with two independent techniques in some more detail.

There is an ongoing debate since the early 80`ties on unusual large yields for certain deep-inelastic reaction products (i.e. ^{24}Na) produced in copper during the irradiation with relativistic ions at total kinetic energy of approximately $E_{(total)} \geq$ (35-40) GeV. Such effects were first observed in the interaction of 72 GeV ^{40}Ar with copper targets as shown in Fig. 1a. No unusual large yields for ^{24}Na were observed during the irradiation with 36 GeV ^{40}Ar of these copper target configurations. The experiments were carried out at the BEVALAC (LBL, Berkeley)[1,2]. Later on, this study was extended to 24 GeV protons, 4 and 48 GeV ^{4}He, and 25 and 44 GeV ^{12}C-ions using various relativistic ion accelerators[3].

2. SOME BASIC EXPERIMENTAL OBSERVATIONS IN INTERACTIONS OF RELATIVISTIC IONS IN CU-TARGETS USING RADIOCHEMICAL TECHNIQUES.

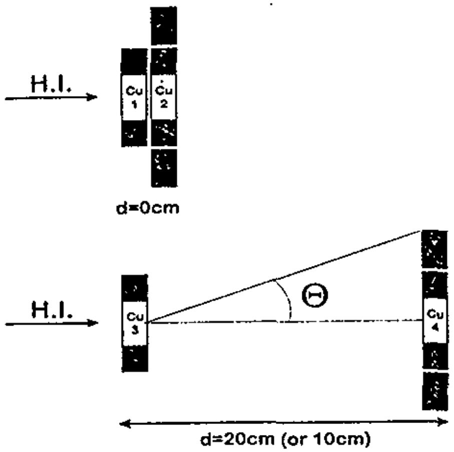

Fig. 1a

The essential experiment set-up and the corresponding results are shown in Fig. 1a (taken from Ref.3):

Two Cu-disks in contact, 1 cm thick and 8 cm diameter, were irradiated with approximately 10^{12} relativistic ions. After the irradiation one studied the gamma-activity of the Cu-disks and determined the yield of ^{24}Na ($T_{1/2}$=15 h, $E\gamma$=1368.5 KeV) with standard radiochemical techniques. This determines a ratio R_0 (^{24}Na):

$$R_0(^{24}\text{Na}) = \frac{\left[equilibrium\ decay\ rate\ of\ ^{24}Na\ in\ disk\ 4\right]}{\left[equilibrium\ decay\ rate\ of\ ^{24}Na\ in\ disk\ 1\right]} \qquad (1)$$

This ratio can be determined quite accurately within (1-2%). Detailed arguments are found in Ref. 1-3. Afterwards, two Cu-disks of the same dimensions, but placed at 10 (or 20) cm distance, were irradiated again with the same relativistic ions. Analog to equation (1) one determined the ratio R_{10} (^{24}Na) and R_{20} (^{24}Na), respectively:

$$R_{10,20}\,(^{24}\text{Na}) = \frac{\left[decay\ rate\ of\ ^{24}Na\ in\ disk\ 4\right]}{\left[decay\ rate\ of\ ^{24}Na\ in\ disk\ 3\right]} \qquad (2)$$

The results are given as:

$$Q_{10}\,(^{24}\text{Na}) = R_{10}(^{24}\text{Na}) \,/\, R_0(^{24}\text{Na}), \qquad (3a)$$
$$Q_{20}\,(^{24}\text{Na}) = R_{20}(^{24}\text{Na}) \,/\, R_0(^{24}\text{Na}). \qquad (3b)$$

and shown in Fig. 1b : Q10 (^{24}Na) and Q_{20} (^{24}Na) are close to unity for total ion kinetic energies $E_{(total)} < 40$ GeV. This is to be expected, as ^{24}Na is produced in copper mainly by relativistic hadrons ($E \geq 0.8$ GeV). Relativistic ions and relativistic secondary fragments are emitted essentially only into the forward direction. Amazingly, however, Q_{10} (^{24}Na) and Q_{20} (^{24}Na) decrease from unity for $E_{(total)} \geq$ 40 GeV.

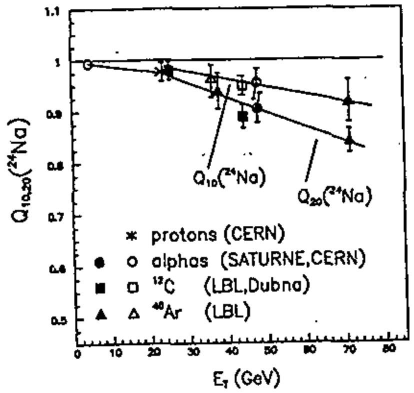

Fig. 1b

Two possible explanations could be given[1]:

Firstly, secondary relativistic fragments inducing ^{24}Na in copper are produced in disk 1 and then emitted into large lab angles missing this way disk 4. Secondly, secondary fragments moving in the beam direction change their ability to produce ^{24}Na in Cu over their flight path of 10 (resp. 20) cm. This later hypothesis was connected with the observation of "anomalons", particles having comparatively short life-times ($\sim 10^{10}$s) and originally reported by Friedlander et al (Ref. 5), who studied nuclear fragments in emulsions irradiated with relativistic heavy ions.

This puzzle was resolved in a consecutive experiment, called "2π-Cu experiment", shown in Fig. 2a. The missing activity was found at large angles ($\theta > 20^{\circ}$). The details are shown for 44 GeV ^{12}C irradiations[3,4].

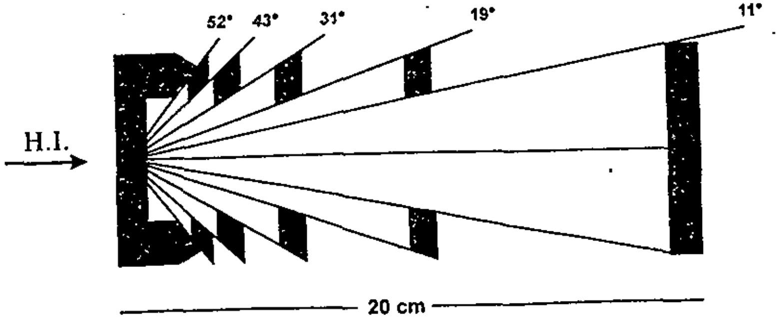

Fig. 2a

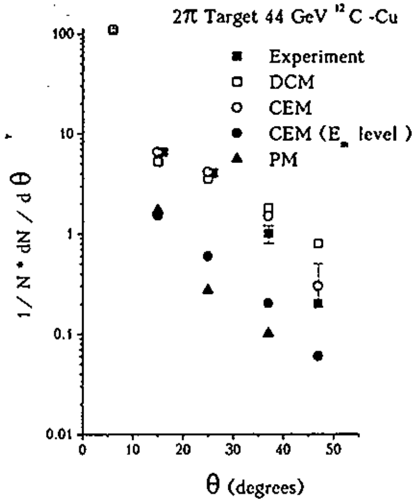

Fig. 2b

All the ^{24}Na -activity, observed in Cu-disk number "2" (Fig. 1a) could be found in Cu-disk number "4" and in the Cu-rings exposed to secondary particles emitted at $11^{\circ} < \theta < 43$ as shown in Fig. 2a. The experimental angular distribution of ^{24}Na, studied with "2π-Cu experiment", is shown in Fig. 2b.

We tried to understand this large amount of ^{24}Na in copper observed at wide angles ($\theta > 11^{\circ}$) with respect to the beam direction. Several theoretical models were employed. The phenomenological model[3,4] (PM) could not explain the large experimental yields of ^{24}Na at wide angles with $\theta > 10^{\circ}$.

The Dubna Cascade Model[3,4] (DCM) and a related model[3,4] (CEM) could explain the large yields. However, both models, DCM and CEM, predict too many relativistic secondary fragments emitted in the nuclear interaction as compared to the well-established observations of relativistic secondaries in nuclear emulsions. Taking into account the realistic number of secondary fragments as observed in nuclear emulsions (CEM, E_m-level calculations), one was again unable to understand the large amounts of ^{24}Na produced at a wide angles. This difference between experiment and calculation amounts to a factor of (7 ± 1). Detailed arguments are given in Refs. 3 and 4.

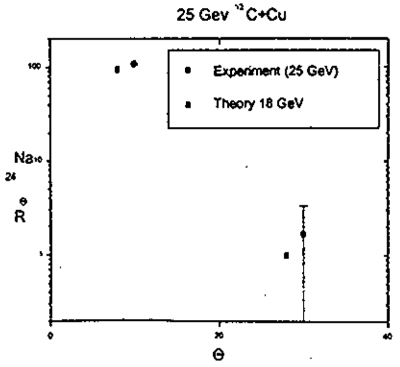

Fig. 3

In 44 GeV ^{12}C-experiments, one observed (5.6 ± 0.4)% of the ^{24}Na-activity at angles $\theta > 19^{\circ}$. However, in 25 GeV ^{12}C exposures only (1.7 ±2.1)% of the ^{24}Na-activity is observed at $\theta > 20^{\circ}$ as shown in Fig. 3. But the DCM-model predicts nearly the same decrease with angles for both energies.

It appears that the characteristic peculiarity of these unexplained phenomena is their strong dependence on the total kinetic energy $E_{(total)}$ of the relativistic ion. The emission of secondary fragments producing too much ^{24}Na in Cu as compared to standard theoretical models is restricted to heavy ions with $E_{(total)} \geq 40$ GeV. This indicates the presence of collective effects in interactions of relativistic ions with nuclei. This becomes very clear, when we compare 2.1 GeV/u ^{12}C (no effect) with 1.8 GeV /u ^{40}Ar (strong effects): both ions have about the same specific energy (GeV/u), but very different total energy (Refs. 2, 4).

3. BASIC EXPERIMENTAL EFFECTS, OBSERVED IN A PROPANE CHAMBER.

As we have difficulties to compare the radiochemical experimental observations with theoretical calculations, it is useful to study other experimental evidences in the same energy region. Emulsion experiments searching for nucleus-nuclei interactions are fairly close to our radiochemical experiments using Cu-targets, as emulsion nuclei behave very similar to copper nuclei, as was shown in Ref. 2. But we could find for our studies only results from nuclear emulsion experiments irradiated with 44 GeV (^{12}C) and no nuclear emulsions irradiated with E < 20 GeV (^{12}C). Therefore, we studied nuclear interactions induced by 15.1 GeV (^{12}C) and 41.5 GeV (^{12}C) within a propane bubble chamber. In this case, we observe mostly (C + C, H) interactions and have to compare them with (C + Cu) interactions studied radiochemically. The experimental results from the propane chamber experiments were kindly presented by the staff of the Chamber Division at the Laboratory for High Energy of the Joint Institute for Nuclear Research (JINR) in Dubna (Russia)[6].

As the propane bubble chamber is placed within a strong magnetic field, one can study directly the charge and momentum distribution of fast secondary fragments in the interactions of relativistic ^{12}C-ions with the constituents of propane (i.e. H and C).

We know[2,3] that the main input to production of ^{24}Na is due to nucleon part of secondary particles so if we study the angular distribution of secondary protons we can have an information on the questions we are interested. Additionally to the selection of protons in the positive particle assemble in propane chamber we used rapidity and kinetic energy distributions to decrease impurity of π^{+} in proton spectra.

The rapidity distribution for positive and negative particles and the rapidity of π^{-} particles with proton mass are given in Fig. 4 for 41.5 GeV ^{12}C.

The rapidity is defined as:

$$Y = \frac{1}{2}\ln\left(\frac{E + p_{\parallel}}{E - p_{\parallel}}\right) \qquad (4)$$

where E is total energy of produced secondary particles and $p_{\parallel}$ is the longitudinal momentum.

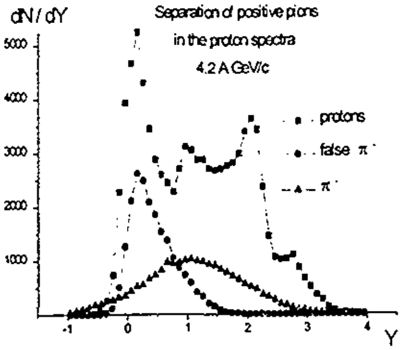

Fig. 4

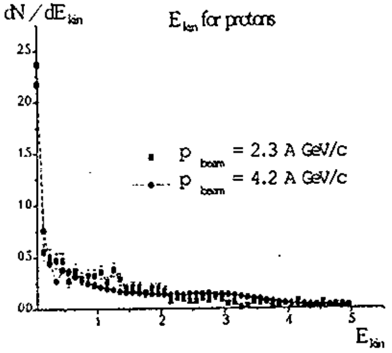

Fig. 5

One can estimate the contribution of π^+ in the spectrum of positive particles to be (10-20)%. These π^+ are concentrated on the low-energy side of the distribution. Rather similar estimations can be obtained, when one compares the kinetic energy distribution for all secondary protons as well as for 15.1 GeV and 41.5 GeV ^{12}C-interactions (Fig. 5).

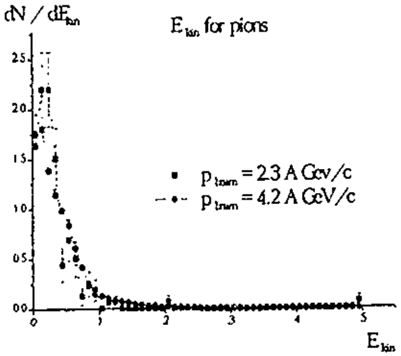

Fig. 6

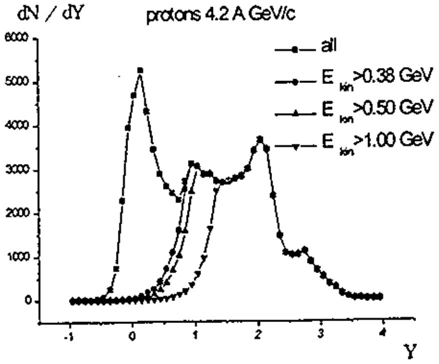

Fig. 7

The kinetic energy distribution for all pions is shown for the two energies of the incident carbon-ions in Fig. 6. Pions are observed mostly at lower kinetic energies - a result, well-known from the standard analysis of high-energy interaction. In Fig. 7 we show again the rapidity distribution for protons and pions induced by 41.5 GeV ^{12}C-ions, but this time with a certain high-energy cut-off, at 0,5 GeV or 1,0 GeV kinetic energy. Now, one has practically only protons within the $E_k > 1.0$ rapidity distribution. This high-energy cut-off is important for the comparison with the ^{24}Na-data, obtained with radiochemistry experiments and already discussed. The isotope ^{24}Na is produced in ^{nat}Cu targets practically only with high-energy hadrons having $E_{(kinetic)} \approx 0.8$ GeV. (Ref. 2). The real excitation function for the reaction Cu → ^{24}Na will be shown in Fig. 11.

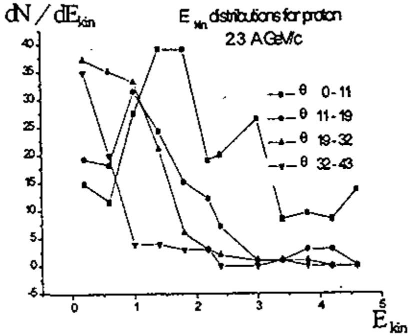

Fig. 8

So far, all 15.1 GeV and 41.5 GeV ^{12}C-experiments, as studied in a propane chamber yielded, more-or-less, the same kinetic energy distributions for secondary protons. A detailed angular distribution, comparing proton spectra within the lab-angles 0°-11°; 11°-19°; 19°-32°, and 32°- 43°, respectively, is given in Fig. 8 and 9. The peaks within the angular interval $0° < \theta < 11°$ reflect, of course, the energy of the primary carbon ion. But for $\theta > 11°$ one observes again a rather similar behavior for 15.1 GeV and 41.5 GeV ^{12}C interactions.

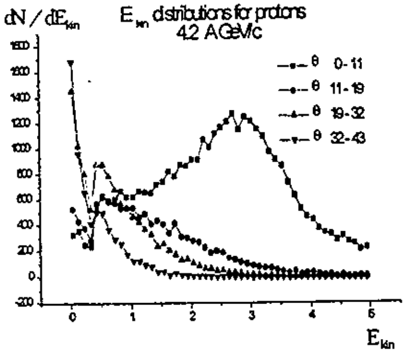

Fig. 9

4. EXPERIMENTAL AND THEORETICAL ANGULAR DISTRIBUTIONS, AS OBSERVED IN A PROPANE BUBBLE CHAMBER AND THE COMPARISON WITH RADIOCHEMICAL EXPERIMENTS.

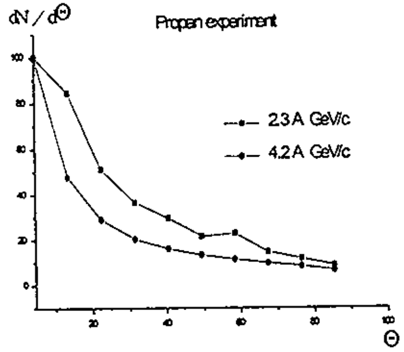

Fig. 10

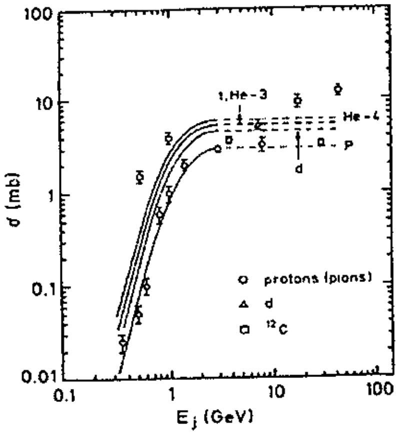

Fig. 11

In this paper we are mainly interested in the question whether one can observe any significant difference in the behavior of secondaries produced in the interaction of 15.1 GeV ^{12}C ions as compared to 41.5 GeV ^{12}C ions in propane bubble chamber experiments.

The results for the observed angular distribution of fast secondaries, as observed in a propane bubble chamber, are shown in Fig. 10: The experimental angular distribution is the same for both energies within the limits of the measured accuracy.

Finally, we want to compare the propane bubble chamber experiments more directly with the Cu-configuration experiments. Such a comparison cannot be very stringent, as in the first experiment one studies (C+C, H) interactions, whilst (C+Cu) interactions are investigated in the second case. It is important to approximate the propane bubble chamber experiment to the Cu-configuration experiment by recalling, that the excitation function for the nuclear reaction (Fig. 11) $\mathrm{Cu} + p \rightarrow {}^{24}\mathrm{Na}$ has substantial values only for protons with $E > 0.8$ GeV. Consequently, one can extract from Figs. 8 and 9 the amount of protons with $E > 0.8$ GeV for $19^{\circ} < \theta < 43^{\circ}$ as compared to all secondary protons with $E > 0.8$ GeV for all lab angles $0 < \theta < 43^{\circ}$. It can be seen in Table 1 that relatively more high-energy secondary protons are emitted into large lab angles at 15.1 GeV ^{12}C, as compared to 41.5 GeV ^{12}C interactions. Such a result is not unexpected, as one knows from the general knowledge in high-energy interactions, that the higher the incoming ^{12}C-energy, the more forward focused are the fast secondary fragments. (See Ref. 2 for more detailed argumentation's). Consequently, the results of the propane bubble chamber experiments constitute no major problems in their interpretations.

As mentioned earlier, the Cu-configuration experiments do constitute a major problem for their interpretation, as more ^{24}Na-yields are observed at 44 GeV as compared to 25 GeV (details see Table 1).

Table 1 : Observables outside $\theta > 19^{\circ}$ (% of all observables)

Propane bubble chamber		Cu-configuration experiments	
Energy (^{12}C)	second protons ($E > 0.8$ GeV)	Energy (^{12}C)	yield (^{24}Na)
15.1 GeV	~ 40	25 GeV	1.7 ± 2.1 (Ref.3)
41.5 GeV	~ 22	44 GeV	5.6 ± 0.4 (Ref.4)

5. CONCLUSIONS

The results of our analysis have lead to the following conclusions

1) One observes no large difference in the angular distribution for fast secondary fragments, both experimentally and theoretically, when one compares nuclear interactions of 15.1 GeV and 41.5 GeV ^{12}C ions in a propane bubble chamber. If there is any difference, we observe more fast secondaries at 15.1 GeV emitted into large lab angles as compared to 41.5 GeV ^{12}C ions, as shown in Table 1. Rather similar effects have been observed comparing nuclear interactions of 36 GeV and 72 GeV ^{40}Ar in nuclear emulsions (Ref. 2).

2) One observes a difference in the yield of ^{24}Na produced by secondary fragments in copper at large lab angles ($\theta > 19^{\circ}$), but this time LESS ^{24}Na produced by 25 GeV ^{12}C, as compared to 44 GeV ^{12}C, as shown in Table 1. The effect has a statistical significance of nearly two standard deviations. Again, rather similar effects have been observed comparing nuclear interactions of 36 GeV and 72 GeV ^{40}Ar in copper. But in this case the statistical evidence was much more significant: at 36 GeV only (2.2 ± 2.8)% of the total ^{24}Na-activity is found outside 19°, at 72 GeV ^{40}Ar one observes (16.1 ± 2.2)% of the total ^{24}Na-activity outside $\theta > 19^{\circ}$ (Ref. 2).

This discrepancy in the Cu-experiments can be reconciled with the hypothesis of "enhanced nuclear cross-sections of secondary fragments only at 44 GeV and not at 25 GeV" as discussed in Refs. 3, 4.

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