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Two Ways of High-Energy Heavy Ion Interactions: Spallation and Burst

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Abstract

A new approach to solving the observation of enhanced neutron production in high-energy heavy ion induced reactions in thick targets is presented. Two different reaction mechanisms in these interactions are considered: 1) Limited fragmentation of the projectile, called SPALLATION; 2) Complete nuclear fragmentation of the projectile fragment into individual relativistic hadrons only, referred to as "BURST". The abundance of this second path increases with the charge and energy of the projectile and may be responsible for enhanced neutron production observed with radiochemical methods in 44 GeV ^{12}C and 72 GeV ^{40}Ar irradiations. Interactions of 72 GeV ^{22}Ne in nuclear emulsions show that SPALLATION and BURST have strongly different interaction signatures, and also that the rate of BURSTS increases from $(26 \pm 3)\%$ of all interactions in the 1st generation to $(78 \pm 6)\%$ in the 2nd generation. Further experimental signatures of BURSTS will be described; however, no model based on physics concepts can be presented. This effect may have practical consequences for neutron safety considerations in the construction of advanced heavy ion accelerators.

Keywords

Thick Target, High Energy Projectile, Unresolved Problems, BURST

1. Introduction

This paper introduces two terms into the discussion of mechanisms of high-energy heavy ion induced reactions

in thick targets:

In SPALLATION reactions at least one heavy fragment with nuclear charge $Z \geq 2$ among the projectile fragments is observed.

In BURST reactions the complete fragmentation of the projectile or projectile fragments, and possibly also of part of the target nucleus, into *single relativistic hadrons* is observed in nuclear emulsion (the registered tracks are called "shower tracks").

Several *unresolved problems* have been described in high-energy heavy ion interactions in thick targets with 44 GeV ^{12}C ions at the JINR, Dubna (Russia) and 72 GeV ^{40}Ar at LBNL (Berkeley, USA) [1]-[3]. One of these problems is an enhanced neutron emission beyond MCNPX 2.7a-model calculations observed in irradiations of 20 cm extended, or thick Cu- and Pb-targets [2]. Such *unresolved problems* occur only above a center-of-mass energy $E_{CM}/u \approx 150$ MeV. Details have been discussed in [3], including a possible connection with an idea of Hagedorn dating from1965. In order to find an explanation of these phenomena, the authors follow a suggestion of the late Professor E. Schopper (Frankfurt, Germany) [4] who recalled that Tolstov [5] had already in 1991 described experimental observations in nuclear emulsions which in the present paper are defined as BURSTS. Tolstov found a probability for this process of 3.0% ± 0.3% in all nuclear interactions induced by protons in the energy range from 10 GeV up to 400 GeV. The BURST-rate increases to approx. 30% of all interactions, when the projectile mass is increased to A = 32 as measured in experiments at the Synchrophasotron in Dubna which provided ion beams with a momentum of up to 4.5 GeV/c per nucleon.

These two different reaction paths shall be discussed in detail. The experimental observations have been made with high-energy heavy ions irradiating nuclear emulsions, as well as in thick Cu- and Pb-targets using radiochemical techniques.

- SPALLATION: In this reaction channel one observes in nuclear emulsion a clear separation between relativistic projectile-like fragments (called "minimum ionizing" or "shower" tracks) and low-energy evaporation fragments (called "black" and "grey" tracks). The essential feature of a spallation reaction is that at least ONE relativistic projectile-like fragment has a nuclear charge Z greater or equal to 2. In addition, relativistic projectile-like fragments are emitted into a narrow angular cone in the forward direction. This definition is *not* strictly identical with the term spallation used in radiochemical studies. In radiochemical terminology, the word spallation is used for the observation of any target-like reaction product with a charge ($Z \geq 2$) [6].

- BURST: This term is introduced in this paper and describes nuclear interactions observed in nuclear emulsions with exactly ZERO relativistic heavy shower particles having nuclear charge ($Z \geq 2$). All relativistic fragments are singly charged (or neutrons). This reaction path is quite unusual, as one observes nearly always a few relativistic alpha particles. BURST events produce considerably more relativistic projectile fragments (shower particles) as compared to SPALLATION and these are emitted into a very wide angular cone, sometimes nearly into 4π-sr geometry. It will be shown that the enhanced emission of secondary neutrons in interactions within thick targets *may be* connected with this BURST reaction path. In this paper several phenomena of BURST reactions are described, but no attempt is made to explain this phenomenon.

Both reaction mechanisms will be discussed in detail in Sections 2 and 3. Section 4 will describe the possible correlation of the BURST mechanism with the observation of enhanced emission of secondary neutrons. Conclusions are presented in Section 5.

2. Spallation Reactions

2.1. Spallation Reactions Studied in Nuclear Emulsion

Spallation reactions have frequently been described, for example in [1]-[3] [6]. Basic concepts were presented by Cumming *et al*. [6] and they are understood to a large extent both in radiochemical experiments, as well as in emulsion studies—with the exception of some phenomena termed unresolved problems [7]. A typical microphotographic picture of a spallation reaction is shown in **Figure 1(b)**.

- Friedlander *et al*. [8] observed in nuclear emulsion irradiated with 100 GeV ^{56}Fe and 32 GeV ^{16}O a statistically significant, however small (approximately 10% to 20%), reduction of the mean-free-path for secondary fragments with charge (Z > 2) on the first 10 cm of their flight path. Due to the small size of this effect and because of complex analytical procedures, this observation started a controversial scientific debate, as reviewed by Ganssauge [9]. However, this small effect has not been considered strong enough to be responsible for the observed increase of the enhanced emission of secondary neutrons in radiochemical experiments.
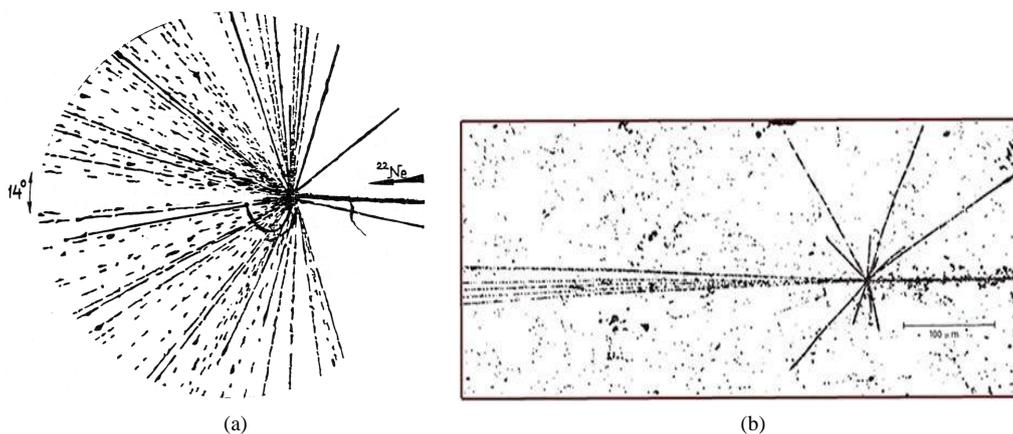
Figure 1. Micro-photographic pictures of a BURST reaction and a SPALLATION reaction. (a) BURST reaction due to 4.5 AGeV/c ^{22}Ne ion in nuclear emulsion with abundant production of relativistic projectile fragments. ONLY tracks with Z = 1 are observed by Tolstov [5]. The identical length of all tracks in the picture is due to this presentation. The real track lengths are not given. The empty gap of 14 degrees (no tracks are observed) in the forward direction is real. Such gaps are frequently observed; they will be discussed later in more detail; (b) SPALLATION reaction with a clear separation of small-angle forward emitted projectile fragments (thin tracks) and the isotropic emission of black prongs from the residual target nucleus as reported by Ganssauge [1].

- Ganssauge *et al.* [1] studied SPALLATION interactions of 100 GeV ^{56}Fe in nuclear emulsion and observed for projectile-like alpha fragments, that these either originate from a source with a temperature of ~40 MeV (20%) or of ~10 MeV (80%). Surprisingly, the temperature of the source which emits target-like protons had always a temperature around (10 - 12) MeV in both reaction channels. The authors did not present definite conclusions. Instead, they suggested adopting an image introduced by Szilard [10] in 1929, where he proposed the allegory of "intelligente Wesen" in connection with such phenomena.
- Westmeier *et al.* [3] have shown, that all unresolved problems in high-energy heavy ion interactions in thick targets were ONLY observed above a threshold in the center-of-mass energy $E_{CM}/u \approx 150$ MeV both for radiochemical and emulsion SPALLATION studies, as well as for the observation of enhanced emission of secondary neutrons.

2.2. Spallation Reactions Studied with Radiochemical Methods in Cu-Targets

The production of radioactive spallation products in 20 cm thick Cu-targets in a series of heavy ion irradiations has been studied with radiochemical methods. In such thick targets both primary and secondary fragments make reactions and produce radioactive nuclides. In the context of the present article, one special aspect will be considered: "Can the detailed analysis of the production rate of radioactive spallation products provide an understanding of the enhanced emission of secondary neutrons above the threshold of $E_{CM}/u \approx 150$ MeV?" An attempt has been made to extract from radiochemical spallation yield measurements information on the average mass <A> of all spallation products produced in these interactions. Five irradiations with heavy ions onto 20 cm thick Cu-targets (20 disks of 1 cm thickness each) were investigated in Dubna and Berkeley with the identical analytical methods. The projectiles were:
- in Dubna: 3 GeV ^{2}H, 7.4 GeV ^{2}H, 18 GeV ^{12}C, and 44 GeV ^{12}C,
- in Berkeley: 72 GeV ^{40}Ar.

Two of the above reactions, namely 3 GeV ^{2}H and 7.4 GeV ^{2}H on copper, are below the $E_{CM}/u \approx 150$ MeV threshold. Among the radioactive spallation nuclei formed in these interactions, the following 7 nuclides were selected for the estimation of the average mass <A> of all spallation products formed:

$$^{24}\text{Na}, \,^{43}\text{K}, \,^{44}\text{Sc}, \,^{46}\text{Sc}, \,^{54}\text{Mn}, \,^{57}\text{Ni}, \,^{59}\text{Fe}$$
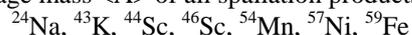
The analysis considered the 1st, 2nd, 4th, 6th, 8th, and 10th Cu-disk, as these 6 Cu-disks (1 cm thickness, 8 cm diameter) are the only ones that were measured in all five irradiations. Several gamma-ray spectra were measured from each disk in a calibrated set-up for about 1 hour each during a total period of about 10 days after-end-of-bombardment. One obtained the activity in [Bq per Cu-disk] of each isotope at the end-of-bombardment. This activity can be converted into a production cross-section for the isotope. The determination of all production

cross-sections in one irradiation allows the estimation of a product yield distribution. The calculation of an average mass <A> of such a spallation mass-yield distribution in the thick Cu-target is then a mathematical standard procedure. The details and basic experimental results are described in [7] and in the Ph.D. Theses of M. Ochs [11] and G. Haase [12].

Some results are presented in **Table 1**.

Table 1 shows that there is a drop in the average spallation product mass from <A> = (52.5 ± 1.8) for reactions below $E_{CM}/u \approx 150$ MeV to <A> = (51.3 ± 1.3) for reactions above. The average number of nucleons emitted in the spallation reaction is around

$$\Delta A = 63.3 - \langle A \rangle = (63.3 - 51.7) = 11.5$$

However, caution is advised here, as the selection of only 7 spallation products in 6 out of 20 Cu-disks is rather limited and arbitrary. Nevertheless one can see that there is a striking similarity in the observed <A> for 72 GeV ^{40}Ar and 44 GeV ^{12}C reactions. This could imply that the observed SPALLATION reactions are comparable in both cases. An enhancement and surprisingly large neutron fluence beyond theoretical expectation was measured and analyzed for the irradiation of 20 cm thick Cu- and Pb-targets with 44 GeV ^{12}C [2] [7], whereas a surprisingly large neutron fluence has only been observed but not quantified for the exposure of a 20 cm Cu target to 72 GeV ^{40}Ar [1] [7]. The results shown in **Table 1** support the conclusion that during both irradiations in Berkeley and Dubna rather similar physical processes took place.

One can deduce that on average about 11.5 nucleons (protons and neutrons) are emitted in the spallation reaction.

3. Burst Reactions Studied in Nuclear Emulsion

Tolstov [5] describes reactions leading to the complete destruction of relativistic projectiles into ONLY individual single nucleons (protons and neutrons) plus pions in high energy ion induced nuclear interactions. These interactions are called BURSTS in the present paper. A typical photographic picture of such an event in nuclear emulsion is shown in **Figure 1(a)**. One observes nearly 70 tracks due to the nuclear interaction of a 4.5 AGeV/c ^{22}Ne-ion with a target nucleus inside the emulsion plate. These tracks have been emitted within an angular cone in the laboratory system of about ±120° around the forward beam direction. These thin tracks come from minimum ionizing Z = 1 particles having an energy above 370 MeV, or from pions above 56 MeV. No relativistic alpha-particle and no Z > 2 projectile-like fragment are observed in the forward-cone, implying that this has NOT been a SPALLATION reaction. A few tracks are black prongs coming from low-energy protons with (E < 26 MeV), which have been emitted from the residual target nucleus. Such BURSTs have been observed in a number of experiments using nuclear emulsion. Tolstov reported a BURST-rate of 3.0% ± 0.3% in all proton induced reactions between 10 GeV and 400 GeV. However, using 4.5 AGeV/c high-energy heavy ion beams from the Synchrophasotron in Dubna, he observed in nuclear emulsions from beams of

^{4}He about (7 ± 1)% BURSTS,
^{12}C about (18 ± 2)% BURSTS,
^{22}Ne about (20 ± 2)% BURSTS,
^{28}Si about (26 ± 4)% BURSTS.

No additional details have been reported by Tolstov, who continued his research by studying the integral neutron emission in a THICK Pb-target ($0.5 \times 0.5 \times 0.8$ m^3) irradiated with 3.65 AGeV ^{1}H, ^{4}He, and ^{12}C ions. He

Table 1. Average mass <A> of the spallation mass-yield curve for 5 different heavy ion beams irradiating a 20 cm thick Cu-target.

Beam	E_{CM}/u (*)	<A> (amu)	
3 GeV ^{2}H	43 MeV	52.4 ± 2.6	
7.4 GeV ^{2}H	107 MeV	52.6 ± 2.6	$E_{CM}/u < 150$ MeV
18 GeV ^{12}C	194 MeV	51.8 ± 4.1	
44 GeV ^{12}C	488 MeV	51.3 ± 4.1	$E_{CM}/u > 150$ MeV
72 GeV ^{40}Ar	426 MeV	51.3 ± 1.5	

(*) E_{CM}/u in MeV is the center-of-mass energy per nucleon in the entrance channel.

measured the neutron fluence induced by secondary neutrons with radiochemical methods and found for 3.65 AGeV ^{1}H and [4]He irradiations exactly the neutron fluence which is calculated with current models, whereas for 3.65 AGeV ^{12}C irradiations, a significantly larger neutron fluence than calculated.

This finding was reviewed in [13].

Two recent studies on the observations of BURST and SPALLATION reactions induced by 72 GeV [22]Ne heavy ions in nuclear emulsions are presented.

1st Study: Ditlov *et al*. [14] [15] carried out a "Study of the number of 'black prongs', N_b, in two generations of nuclear interactions in photo-emulsions irradiated with 72 GeV [22]Ne". They separated the observed nuclear reactions into two classes: BURST and SPALLATION, using the same criteria as in the present paper.

- BURST events, N [BUR], with ZERO heavy relativistic fragments having Z > 1, and
- SPALLATION events, N [SPA], with more than ZERO heavy relativistic fragments.

The aim of this study was to measure the number, N_b, of black prongs (protons with E < 26 MeV) per interaction in the first (primary) interaction and the second (consecutive) interaction of 72 GeV [22]Ne-ions in nuclear emulsion. The black prongs, N_b, are emitted from the residual target nucleus after the fast cascade interaction. Results are shown in **Table 2**, using the data set from [15].

Table 2 shows that:

- 112/427 = (26 ± 4)% of all first reactions are BURST reactions. This is slightly larger than the ratio presented by Tolstov (20 ± 2)% [5]. However, the real surprise is the result for the 2nd generation where 100/142 = (70 ± 8)% of all reactions are BURSTS. This is more than twice as much as in the 1st generation.
- There is no theoretical model known to the authors, which can explain the relative large yield of BURSTS in the 1st generation. It is also an unresolved problem as to why the prevalence of BURSTS increases drastically in the 2nd generation.
- The average number of black prongs, <Nb>, in the 1st generation is substantially larger for BURST, as compared to the average number of black prongs in SPALLATION reactions by a factor of (11.8 ± 0.5)/(4.4 ± 0.2) = 2.7 ± 0.3 This may be the reason why in THICK target irradiations with 44 GeV ^{12}C and 72 GeV [40]Ar ions, one observes in radiochemical experiments systematically larger neutron yields than expected from model calculations in which only SPALLATION reactions are considered. This problem will be discussed in more detail in the next section.
- The N(SPA) events include both hot (T~40 MeV) and cold (T~10 MeV) interactions, as described [1]. The <Nb> is rather low both in the 1st and in the 2nd generation. This is in agreement with [1], where the same low temperature T~12 MeV is found for target-like residual nuclei in all nuclear SPALLATION interactions, both for hot and cold interactions producing relativistic projectile-like Z = 2 fragments.

The entire reaction path for 72 GeV [22]Ne is schematically presented in **Figure 2** using numerical values from [15]. It shows—taking the observed TWO generations together—that (78 ± 6)% of all original [22]Ne-tracks finally lead to BURST interactions along their reaction path in nuclear emulsion. We cannot distinguish if spallation reactions in the first and second generation proceed in the same way.

One observes 315 SPALLATION reactions in the first generation. However, due to the geometry of the 600 μm thin emulsion, only 142 SPALLATION reaction products are followed in the second generation. In the (Z = 2)—channel there is a ratio of Burst/Spallation of 66/6. This implies that approx. 90% of all secondary alphas induce BURST interactions, whereas Tolstov [5] found only (7 ± 1)% BURST reactions in the first interaction induced by alpha projectiles in the same energy range. This confirms that **secondary alphas transfer signifi-**

Table 2. Event numbers and multiplicities in 1st and 2nd generation of 72 GeV [22]Ne reactions.

	1st generation N (events)	1st generation <Nb>	2nd generation N (events)	2nd generation <Nb>
Burst + Spallation	427	6.3 ± 0.2	142	6.3 ± 0.3
Burst (BUR)	112	11.8 ± 1.2	100	7.0 ± 0.7
Spallation (SPA)	315	4.4 ± 0.2	42	4.7 ± 0.5
(BUR)/(SPA)	112/315 = 0.36	11.8/4.4 = 2.6	100/42 = 2.4	7.0/4.7 = 1.5
(BUR)/total	112/427 = 0.26	11.8/6.3 = 1.87	100/142 = 0.70	7.0/6.3 = 1.11

<Nb> is the average number of black prongs per event.
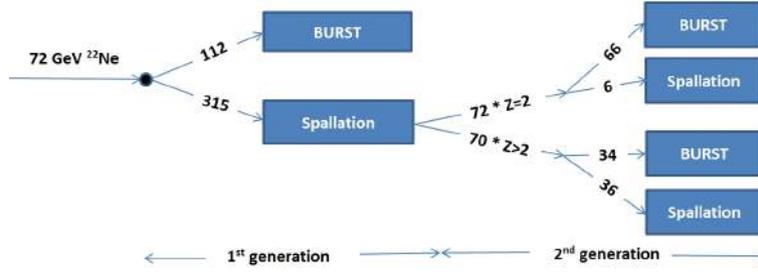
Figure 2. Schematic presentation of the two reaction paths BURST or SPALLATION in the 1st and 2nd interactions of 72 GeV ^{22}Ne and its reaction products. In the second generation Helium nuclei induce predominantly BURSTS. This figure is based on the data set of [15].

cantly more energy than primary alphas do [3].

Ditlov *et al.* [14] [15] have also published the distribution of black prongs, N_b, for both the BURST path, as well as for SPALLATION as shown in **Figure 3**. The N_b-distribution shows no surprise for SPALLATION reactions: Its maximum is at $N_b = 0$ as expected from the impact parameter favoring peripheral interactions with low energy transfer, and it decreases continuously towards lower values with increasing N_b. This is in agreement with calculations based on conventional concepts like limiting fragmentation [7].

However, the N_b-distribution for BURST reactions gives a completely different picture, which is not predicted by any model known to the authors. The distribution looks a little chaotic with its two maxima. The first one is around small N_b-values (possibly due to reactions with light CNO-nuclei within the emulsion) and the other maximum is around $N_b = 16$ which might originate from interactions with Ag- or Br-nuclei in the emulsion. Additional research is needed in order to understand the BURST reaction mechanism.

The ratio of mean values $\langle N_b \rangle$ for BURST (BUR) to SPALLATION (SPA) is:

$$\left(\text{Ratio BUR}/\text{SPA for } \langle N_b \rangle \right)_{\text{Ditlov}} = (11.8 \pm 0.4)/(4.4 \pm 0.2) = 2.68 \pm 0.15$$

2nd Study: Haiduc *et al.* [16] contributed independent results from studies in nuclear emulsion irradiated with high-energy heavy ions. Their studies of irradiations with 72 GeV ^{22}Ne are focused only on the 1st interactions of primary ions; however, they involve a very large number of interactions. They present an additional detail in that they include the measurement of the number and angular distribution of minimum ionizing particles (mostly $Z = 1$ nucleons with energy above 370 MeV and relativistic pions) for BURST and SPALLATION reactions. Haiduc *et al.* selected these two channels with the same criteria as used hitherto in this paper. The results are shown in **Figure 4**.

It is very obvious that the distributions for these two reaction channels are completely different.

Top row: The angular distribution of minimum ionizing particles, N_s, gives the distribution of the polar angle Θ with respect to the beam direction. This distribution can be completely understood with conventional models for SPALLATION reactions (**Figure 4**, Top row, right). It has its maximum in the beam direction ($\Theta = 0°$). One observes within the first two bins about (6000/25635) = 23% of all interactions. A narrow cone of $\Theta \approx 3°$ is expected because of the Fermi motion of nucleons. (Note: The number 6000 is the number of events within the angular range from 0° up to $\Theta = 3°$, the number 25,635 is the total number of events in all angles measured, data taken from tables of Haiduc *et al.* [16]. All following equivalent numbers of events have the same meaning.)

Middle row: The distribution of numbers of N_s-events for SPALLATION reactions can again be understood completely with conventional models. It has the maximum of N_s-tracks in the beam direction ($\Theta = 0°$). Within the first two bins ($N_s < 3$) there are (900/3251) = 27% of all interactions. In BURST reactions, however, one finds within the first two bins ($N_s < 3$) almost ZERO interactions. The maximum is around $N_s = 27$. The ratio of mean values $\langle N_s \rangle$ for BURST (BUR) to SPALLATION (SPA) is

$$\left(\text{Ratio BUR}/\text{SPA for } \langle N_s \rangle \right)_{\text{Haiduc}} = (26.68 \pm 0.05)/(7.62 \pm 0.24) = 3.50 \pm 0.10$$

i.e. there are over three times more relativistic protons in BURSTS than in SPALLATION.

Bottom row: A similar distribution of N_b-events has already been shown by Ditlov for the reaction of ^{22}Ne-ions. Haiduc *et al.* carried out the same investigation on a larger sample and found in both channels slightly lower values for $\langle N_b \rangle$. However, they observed nearly the same $\langle N_b \rangle$-ratio for BURST (BUR) over SPALLATION (SPA) as Ditlov:
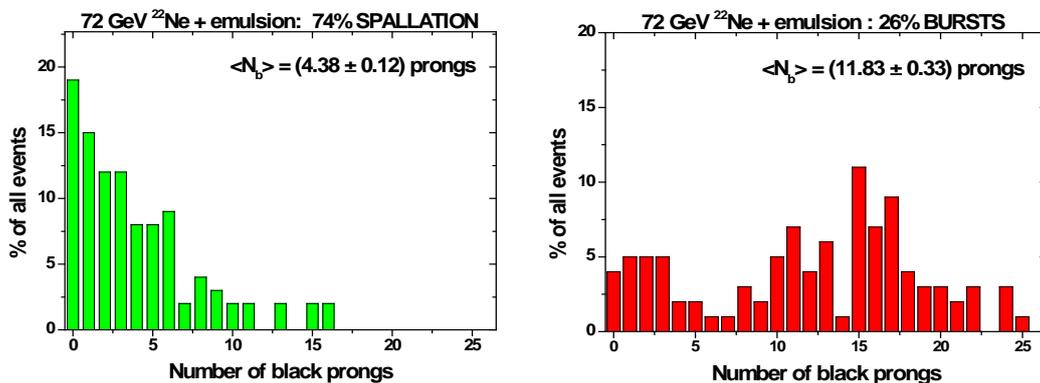
Figure 3. The N_b distribution observed in the 1st generation of a nuclear reaction as sketched in **Figure 2** for SPALLATION and BURST reactions according to [15].
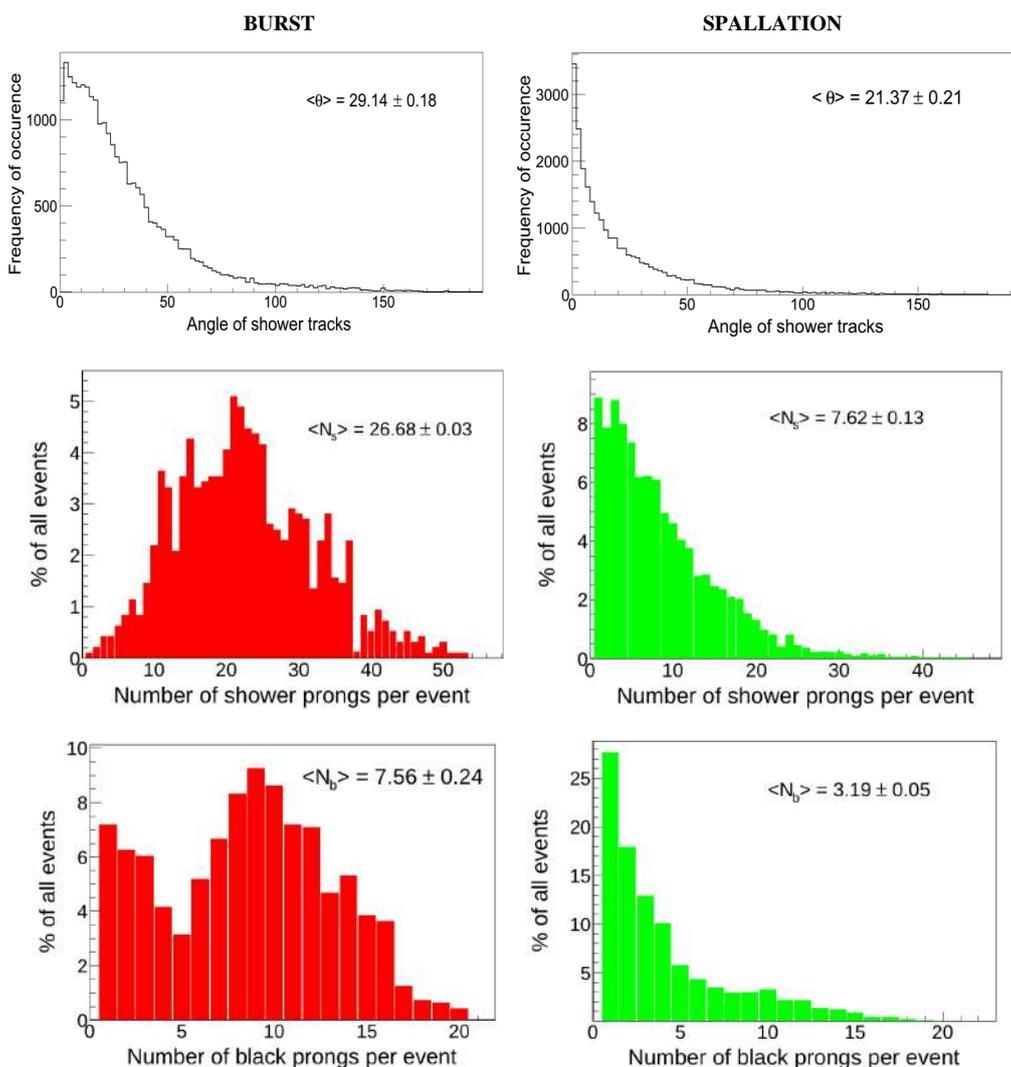
Figure 4. Comparison of track properties in the interaction of 72 GeV ^{22}Ne in emulsion [16]. **Top row:** Polar angulardistribution of*minimum ionizingparticles*, N_s, measured relative to the beam; **Middle row:** Frequency distribution of the number of *minimum ionizing particles*, N_s; **Bottom row:** Frequency distribution of the number of black prongs, N_b.

$$\left(\text{Ratio BUR/SPA for } \langle N_b \rangle\right)_{\text{Haiduc}} = \left(7.56 \pm 0.24\right)/\left(3.19 \pm 0.05\right) = 2.34 \pm 0.09$$

$$\left(\text{Ratio BUR/SPA for } \langle N_b \rangle\right)_{\text{Ditlov}} = \left(11.8 \pm 0.4\right)/\left(4.4 \pm 0.2\right) = 2.68 \pm 0.15$$

Finally, Haiduc *et al*. measured results of BURST and SPALLATION reactions for several other heavy ion reactions in Dubna at momentum 4.5 AGeV/c, as given in **Table 3**. The results of this separation into two groups are similar, however, not identical with the older result of Tolstov [5].

In addition, Haiduc *et al*. made another interesting observation in their study. They observed some events, called *very strange events* which have no particle at all in forward direction ($N_b = 0$, $N_s = 0$, and ZERO relativistic Helium or heavier ($Z > 2$) tracks) up to ($\Theta = \pm 8°$). This confirms one central aspect of Tolstov's observations [5] who also reported events with no (zero) particles emitted in forward direction. They gave also further technical details, such as their emulsion plate thickness of 500 microns, and grain size in the emulsion of 0.5 microns. The geometry of a track is determined by measuring x, y, z coordinates for each track relative to the beam direction. The polar and azimuthal angles are calculated accordingly. The picture of Tolstov's BURST in **Figure 1(a)** is a projection of the direction of the track onto the observation plane.

In **Table 3** 1015 events of ^{22}Ne-induced BURST reactions are listed. Among these are 216 events (216/1015 = 21% ± 3%) that are *very strange events* with exactly ZERO tracks within a polar angle up to ($\Theta = \pm 3°$) around the beam direction.

Figure 5 shows the N_s- and N_b-distributions for *very strange events* among BURST interactions. It is interesting to observe: neither N_s-nor N_b-distributions have a peak at low values of ($N_s < 20$) or ($N_b < 5$), as observed in the corresponding distributions shown in **Figure 4**. These *very strange events* in **Figure 5** have significantly larger multiplicities ($\langle N_b \rangle = 8.59$) and ($\langle N_s \rangle = 32.43$) as compared to the corresponding values for all ^{22}Ne-BURST interactions shown in **Figure 4**. The reasons for these observations are unclear. It is conceivable that these *very strange events* are associated with a larger energy release as compared to other BURSTS. In any case, these events are another contribution to "unresolved problems" discussed in recent publications [1]-[3].

These *very strange events* are observed up to polar angles up to ($\Theta = \pm 8°$) around the beam direction as shown in **Table 4**. The event rates decrease up to the largest angles observed. Again, there are no theoretical models known to the authors which can explain such effects.

When examining all experimentally observed properties of BURST interactions, one is not surprised that this reaction channel is not yet included in computer codes for calculating high-energy heavy ion interactions. For such an inclusion into modern codes, one must understand the basic reaction mechanism of BURST interactions.

Table 3. Numbers of first generation BURST and SPALLATION reactions in nuclear emulsion irradiated with 4.5 AGeV/c ^{16}O, ^{22}Ne, ^{28}Si, and ^{32}S ions in Dubna.

	No. of events	% of ALL events
^{16}O-BURST	907	33 ± 2
^{16}O-SPALLATION	1867	67 ± 2
^{22}Ne-BURST	1015	24 ± 2
^{22}Ne-SPALLATION	3251	76 ± 2
^{28}Si-BURST	215	16 ± 2
^{28}Si-SPALLATION	1095	84 ± 2
^{32}S-BURST	167	13 ± 2
^{32}S-SPALLATION	1125	87 ± 2

Table 4. Number of *very strange events* in BURST reactions of 72 GeV ^{22}Ne in nuclear emulsionas function of the polar angle Θ. There are ZERO tracks within this angular range.

Polar angle Θ [deg]	Number of events	$\langle N_b \rangle$	$\langle N_s \rangle$
$0 < \Theta < 8$	14	9.7 ± 2.6	30.0 ± 8.0
$0 < \Theta < 7$	20	8.7 ± 1.9	32.0 ± 7.2
$0 < \Theta < 6$	40	9.0 ± 1.4	33.0 ± 5.4
$0 < \Theta < 5$	70	9.0 ± 1.1	33.5 ± 4.0
$0 < \Theta < 4$	132	8.6 ± 0.8	33.0 ± 2.9
$0 < \Theta < 3$	216	8.7 ± 0.6	32.4 ± 2.2
$0 < \Theta < 2$	364	8.5 ± 0.2	31.3 ± 1.6
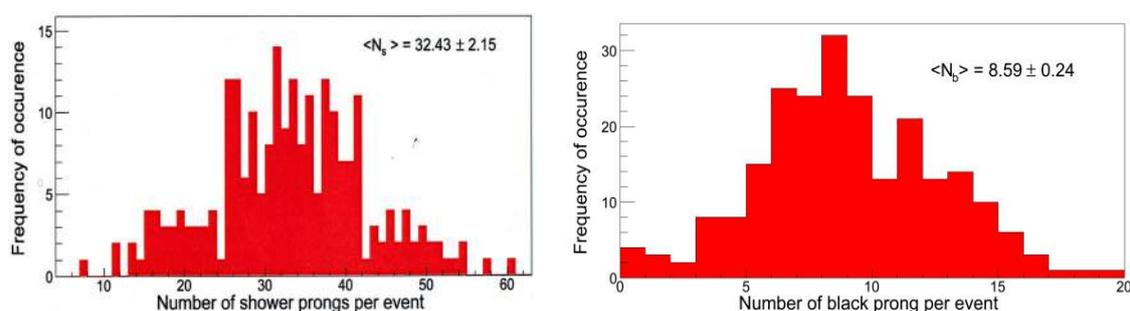
Figure 5. (Left) N_s and (right) N_b-distributions from 228 *very strange* BURST reactions in irradiations with 72 GeV ^{22}Ne. These *very strange events* have zero events with $N_s = 0$ (N_s = fast protons from the projectile) and only few events with $N_b = 0$ (N_b = slow protons/pions from the target nucleus)·

4. Heavy Ion Induced Reactions with Thick Cu and Pb Targets

4.1. Spallation Yields

For comparisons with model calculations we have used modern computer codes (DCM/CEM, LAHET, and MCNPX2a) in calculations for recent publications [1]-[3].

In this context it is interesting to look again into old radiochemical studies presented in detail in [7]. A short review may be sufficient at this place: a 1 cm thick Cu-target was irradiated with a well-focused heavy ion beam of either 4 GeV ^{4}He or 44 GeV ^{12}C. The primary target emitted a broad spectrum of secondary ions into wide angles. These secondary particles with angles ($\Theta > 0°$) are high-energy protons, pions and neutrons, which could interact in some distances (between 4 cm up to 10 cm) with five additional 1 cm thick Cu-rings exposed to angular intervals of ($0°$ - $10°$), ($10°$ - $19°$), ($19°$ - $31°$), ($31°$ - $43°$), and ($43°$ - $52°$).

Secondary particles will induce nuclear reactions in the additional Cu-rings, thus producing radioactive products, such as ^{58}Co, ^{44}Sc, and ^{24}Na, which were measured with standard radiochemical techniques. The results are shown in **Figure 6** where values in percent are the ratios of sideward activities relative to the forward activity.

In the irradiation with 4 GeV ^{4}He (a reaction below the threshold [3] of $E_{CM}/u \approx 150$ MeV) one observes within the angular interval ($43°$ to $52°$) practically only production of the nuclide ^{58}Co. This nuclide is very close in mass to the target mass of Cu (63.5 u). Only low-energy secondaries (around 100 MeV) are emitted into this large angle and one observes low excitation energy spallation reactions leading to the nuclide ^{58}Co. In the Cu-rings exposed at smaller emission angles, there is a similar reaction pattern: ^{58}Co is always the most abundant spallation product, however, there are also lower-mass products (^{44}Sc and ^{24}Na) formed in small yields due to the harder energy spectrum of secondary fragments emitted into the more forward angles. All of this is well-understood by the spallation reaction mechanism.

In the irradiation with 44 GeV ^{12}C (a reaction above the threshold of $E_{CM}/u \approx 150$ MeV) a drastically different
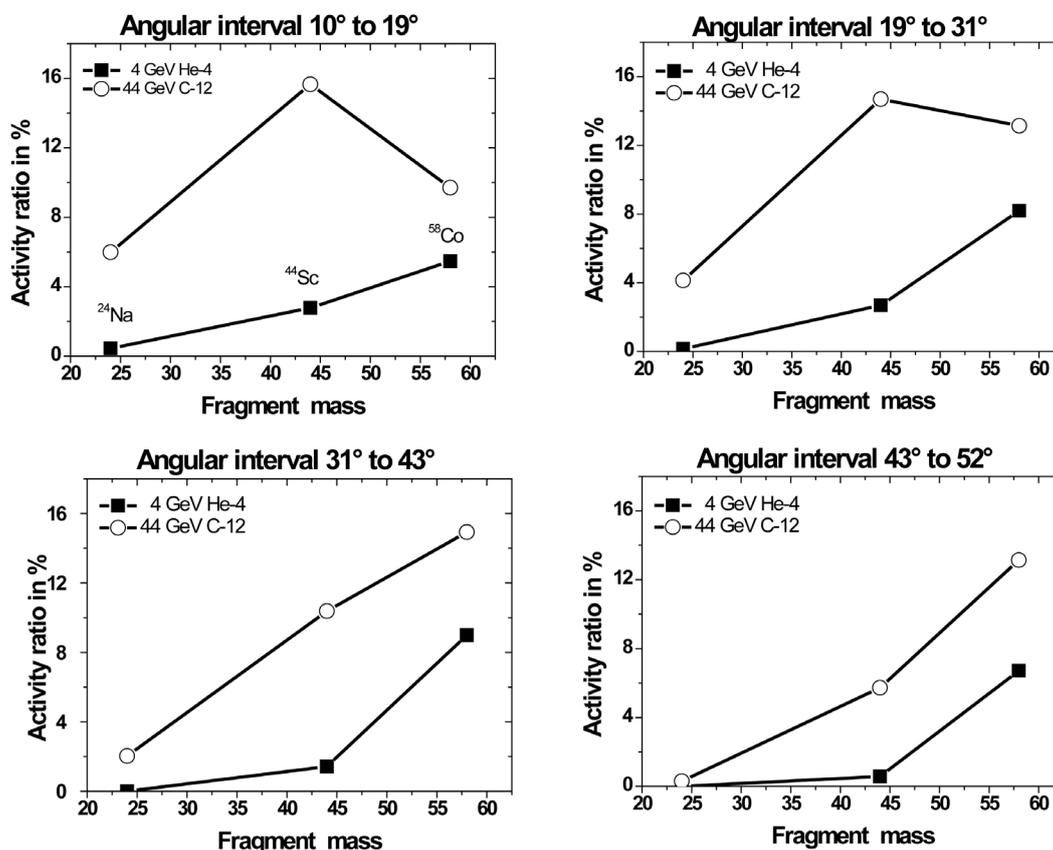
Figure 6. Three-point mass-yield curves in specific Cu rings produced by secondary fragments in the interaction of a copper target with 4 GeV ^{4}He (solid points) and 44 GeV ^{12}C (open points) ions. Yields are shown for ^{24}Na, ^{44}Sc and ^{58}Co, thus covering the mass range of spallation products.

reaction product yield pattern is encountered within the lab angular interval from 10° to 19°. The mass-yield curve now has its maximum around ^{44}Sc whereas the yields for two nuclides ^{24}Na and ^{58}Co are much lower. This yield-distribution produced by secondary fragments in a 2nd generation reaction is completely incompatible with any conventional spallation mass-yield distribution. For larger angles, the situation becomes less drastic, but still yield distributions below 31° are incompatible with well-known spallation reactions. This study was originally presented by F. Pille [17] and reviewed in [7].

Figure 6 shows that secondary fragments are emitted into large lab angles, where they interact with Cu-rings. A lot of energy is transferred into unexpectedly large angles which for example leads to significant production of ^{44}Sc in the 19° to 31° bin. The yield for a specific isotope in a given Cu ring is the ratio of its activity (in %) in the ring compared to the activity in the forward Cu-target. The experimental uncertainty is about ±8%.

4.2. Neutron Production

High-energy heavy ion irradiations of THICK Cu- or Pb-targets have been investigated with radiochemical methods [1]-[3] [7]. Radioactive product nuclides were investigated with gamma-ray spectrometry. In addition, neutron yields could be determined indirectly with radiochemical methods [18]. There are no unresolved problems observed in the study of spallation mass yields or neutron yields in heavy-ion interactions *below* a bombarding energy of about 10 GeV, or more accurately, below a center-of-mass energy per nucleon of $E_{CM}/u \approx 150$ MeV [3]. However, above this energy limit all experimental results cannot be understood with well-known models, thus constituting unresolved problems. In the context of this paper, the irradiations of 20 cm THICK Cu- and Pb-targets with 44 GeV ^{12}C in Dubna and a 20 cm THICK Cu-target with 72 GeV ^{40}Ar in Berkeley are of particular importance. Exceedingly large neutron fluences beyond theoretical estimations [1] were observed in irradiations with these high-energy heavy ions. The data will be re-examined with the more recent computer

codes, MCNPX2.6 and MCNPX2.7.

4.2.1. Dubna Experiments

In the Dubna-experiments the so-called GAMMA-2 target [18] which is a metallic target (Cu or Pb) of 20 cm length and 8 cm diameter surrounded by a 6 cm paraffin moderator was irradiated with heavy ions. The moderator contains holes, filled with a La-compound serving as a neutron sensor. The radioactivity induced in the sensor is quantified with standard gamma-ray spectrometry:

$$^{139}La\ (n,\gamma)^{140}La,\ \text{the half-life of}\ ^{140}La\ \text{is}:\ \tau_{1/2} = 40.3\ h$$

The GAMMA-2 target was irradiated with a series of heavy ions (see Section 2.2), including 44 GeV ^{12}C ions. This experiment will be re-considered here together with a recent calibration experiment using 1 GeV protons by Westmeier *et al*. [19]. The authors measured the neutron production in the GAMMA-2 target with a 20 cm long lead core irradiated with 1 GeV protons. They determined the neutron fluence through the measurement of the induced ^{140}La-activity and obtained an experimental production rate of ^{140}La, called B(^{140}La) which is defined as follows:

$$B(^{140}La) = (\text{number of}\ ^{140}La\ \text{atoms formed})/(1\ g\ La-target)/(1\ \text{primary ion})$$

B(^{140}La)-values for various samples along the target were determined experimentally and simultaneously calculated theoretically with theMCNPX2.6c code. Both, the experiment and calculation agree to better than ±10% for all samples that were distributed along the 20 cm long target. This agreement shows that calculation can well predict experimental results and that in this calibration experiment with 1 GeV protons there are NO unresolved problems. The reaction is **below** the threshold [3] of E_{CM}/u ≈ 150 MeV.

The results of the calibration experiment are shown together with two experiments with 44 GeV ^{12}C onto the GAMMA-2 target [18] in **Table 5**. The average ratio of the experimental (exp) to the calculated neutron rate (cal) in the ^{12}C experiments is:

$$\text{Neutron yield ratio in GAMMA} - 2\ \text{for 44 GeV}\ ^{12}C:(\exp)/(cal) = 3.25 \pm 0.23$$

which means that calculation can well reproduce the experiment at an energy below E_{CM}/u ≈ 150 MeV but it significantly underestimates neutron production above this threshold.

Another aspect of these GAMMA-2 target experiments was re-analyzed with an advanced theoretical model: These simulation calculations used the MCNPX2.7 Monte Carlo code implementing the INCL4 intra-nuclear cascade and the ABLA fission/evaporation model. The theoretical neutron yields were compared with the experimental yields of Ochs *et al*. [18]. The experiments involved the measurement of secondary neutrons via the radiochemical sensors ^{140}La.

In the calculation of both ^{2}H and ^{12}C irradiations one finds the same increase in *calculated* neutron yields between 1.5 AGeV and 3.7 AGeV of (1.57 ± 0.01), very similar to the yield ratios that have been obtained with the DCM/CEM [18] code.

In the experiment with ^{2}H projectiles a neutron yield increase by a factor of 5.59/4.60 = 1.22 ± 0.12 was

Table 5. Experimental (exp) and calculated (cal) neutron yields for 44 GeV ^{12}C and 1 GeV ^{1}H interactions in the 20 cm thick GAMMA-2 target.

	B (^{140}La)	Neutrons/ion	Neutrons/ion	Yield ratios
Reaction	Experiment (exp)	Experiment (exp)	Calculation (cal)	(exp)/(cal)
1 GeV ^{1}H+ Pb (*)	4.69 ± 0.32 [19]	16	16 (*)	1
44 GeV ^{12}C + Cu	108 ± 8 [18]	370 ± 30	115 ± 10 (**)	3.2 ± 0.4
44 GeV ^{12}C + Pb	266 ± 19 [18]	900 ± 70	275 ± 10 (**)	3.3 ± 0.3

(*) Experimental Neutrons/ion yields are normalized to the calculated yield in the 1 GeV experiment [19]; (**) Calculated neutron yields are based on models MCNPX2a, LAHET and DCM/CEM, which yield very similar results [1] [18].

measured when the energy rose from 1.5 AGeV to 3.7 AGeV, which is even smaller than calculated.

However, the experimental increase is significantly stronger for ^{12}C as projectile when going from 1.5 AGeV to 3.7 AGeV yielding a factor of $10.8/4.13 = 2.62 \pm 0.26$.

As the calculated increase of B for both ^{2}H and ^{12}C induced reactions is about the same factor of 1.57 whereas the experimental increase of B in the ^{12}C induced reaction is much larger it may well be assumed that in the ^{12}C reactions **something happens which is not considered in the model calculation**.

4.2.2. Berkeley Experiment

In the Berkeley experiment rather similar phenomena of exceedingly large neutron fluences were observed in the irradiation of a 20 cm thick Cu-target with 72 GeV ^{40}Ar [1]. In contrast to the Dubna experiments, only one high-energy irradiation of a thick Cu-target was performed in Berkeley. No neutron measurements have been published but spallation product yields in 2 Cu-disks in contact (each disk 1.0 cm thick) have been extensively studied [20] in irradiations with 72 GeV ^{40}Ar and 36 GeV ^{40}Ar. A large number of radioactive spallation product yields, (^{A}Z), were measured and the analysis of the results revealed several unresolved problems, such as [3]:

- The yield-ratio $R_0(^{A}Z)$ is defined as the activity of the nuclide (^{A}Z) in the second (downstream) Cu-disk divided by the corresponding activity in the first (upstream) Cu-disk. These yield-ratios $R_0(^{A}Z)$ are expected to peak at a mass closely below the target mass, however, the maximum for these ratios $R_0(^{A}Z)$ is observed around mass $A \approx 50$, *i.e.* far away from the target mass.
- The yield ratio $R_0(^{A}Z)$, for light spallation products, in particular for the isotope ^{24}Na, is unexpectedly always $R_0(^{24}Na) > 1.0$. This ratio is significantly larger than any calculation will predict [7].

Another detail observed for nuclides (^{A}Z) which is important for discussions in the context of this paper is given in **Figure 7**. It shows the yield ratio $R_0(^{A}Z)$ observed for irradiations with 72 GeV ^{40}Ar on Cu divided by yield ratios $R_0(^{A}Z)$ observed for irradiations with 36 GeV ^{40}Ar ions on Cu for all investigated radioactive spallation nuclides [20]:

$$R_0(72)/R_0(36) = \left[R_0\left(^{A}Z\right) \text{ for 72 GeV } ^{40}\text{Ar} \right] / \left[R_0\left(^{A}Z\right) \text{ for 36 GeV } ^{40}\text{Ar} \right]$$

For the higher Ar-projectile energy there is a significantly enhanced production of light spallation products (^{A}Z) in the mass range $20 < A < 30$ in the second Cu-disk. Any ratio exceeding unity is completely unexpected because one must assume that production of nuclides far away from the target or projectile mass requires plenty energy which is more abundant in the first disk than in the second one. It appears that reaction products (fragments) after the first interaction transfer energy much more effectively than the primary beam particle and this effect is even amplified with rising beam energy. No such enhanced energy transfer is experimentally seen below $E_{CM}/u \approx 150$ MeV.

It would be interesting to compare these radiochemical results with mass distributions from the investigation of 72 GeV ^{40}Ar and 36 GeV ^{40}Ar in nuclear emulsions. Unfortunately, relevant results from such a study are not
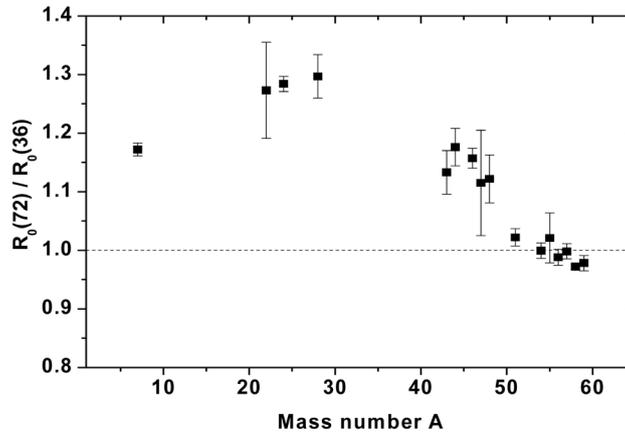
Figure 7. The yield ratio $R_0(^{A}Z)$ observed in irradiations with 72 GeV ^{40}Ar divided by the same yield ratios $R_0(^{A}Z)$ observed in irradiations with 36 GeV ^{40}Ar ions as a function of product mass <A>. The data for the figure are taken from [20].

available to the authors. Therefore the second best choice was selected, *i.e.* the results of a study with 72 GeV ^{22}Ne presented earlier in this paper.

It was shown in Section 2.2 that the average mass loss through SPALLATION yields an average mass shift $\Delta A = 11.5$ amu (see **Table 1**). In BURST (bur) interactions, however, there is an increased charged-particle emission ($<N_s> + <N_b>$) as compared to SPALLATION (spa) interactions (see **Figure 4**) as follows:

$$\left(\left\langle N_s \right\rangle + \left\langle N_b \right\rangle \right)_{\text{bur/spa}} = \left(34.3 \pm 0.2 \right) \big/ \left(10.8 \pm 0.3 \right) = \left(3.2 \pm 0.1 \right)$$

One may expect the same increase of the average mass shift for the residual nuclei in the mass-yield curve: The average mass for residual Cu-target nuclei in 72 GeV ^{40}Ar induced BURST interactions could then be expected around mass: $(63.3 - 3.2 \times 11.5)$ amu = **26.5 amu**. That mass is very close to ^{24}Na which is near the center of the peak in **Figure 7**. *This may indicate that BURST interactions produce residual nuclei from the original target + projectile combination with a nuclear charge and mass considerably lower than SPALLATION interactions do.* The authors do not claim that this argument is convincing, but we think that an interesting correlation has been found. Further studies are certainly mandatory.

5. Conclusions

High-energy heavy ion interactions above a threshold of $E_{CM}/u \approx 150$ MeV proceed in thick targets via two separate reaction channels:
- SPALLATION
- BURST

The first channel, SPALLATION, is well-understood and model calculations fit experimental data. The second channel, called BURST, releases 2 - 3 times more particles (protons, neutrons and pions) in the interaction. Its origin is unclear and there is no model known to the authors which calculates the observed phenomena. The rate of BURST reactions is enhanced when secondary reactions in thick targets are involved. The rate of BURST reactions increases significantly with increasing heavy ion energy and dominates by up to 80% in 72 GeV ^{22}Ne interactions in nuclear emulsions. This effect appears to be the reason for the observation of exceedingly large neutron fluences found in thick-target nuclear interactions.

- There are exceedingly large neutron fluences in interactions of 44 GeV ^{12}C in 20 cm thick Cu- and Pb-targets and of 72 GeV ^{40}Ar in 20 cm thick Cu-targets. The neutron fluence was measured in 44 GeV ^{12}C-induced reactions on Cu and Pb to be a factor of (2 - 3) times larger than model-based MCNPX or DCM/CEM codes have calculated. These codes consider only conventional spallation interactions as known from thin-target experiments.
- Nuclear emulsions irradiated with 72 GeV ^{22}Ne ions allow a detailed study of both SPALLATION and BURST interactions. The fraction of BURSTS among all nuclear interactions [BUR/INT] is (26 ± 4)% in the first interaction. This ratio (BUR/INT) increases up to about 80%, when the 1st and 2nd interactions are considered together. Thus, because of their high abundance BURST-interactions must be considered simultaneously with SPALLATION-interactions in realistic descriptions of high-energy heavy ion interactions above the threshold of $E_{CM}/u \approx 150$ MeV. The number of charged-particles emitted per reaction (minimum ionizing particles plus black prongs) in BURST reactions is about a factor of (2 - 3) times larger than the corresponding number for SPALLATION reactions.
- A correlation between these two essential results depicting the finding ["a factor of (2 - 3) times larger"] obtained with completely different experimental techniques is considered: The enhanced number of charged-particle emissions per interaction in BURSTS—as seen in nuclear emulsions—should be correlated with the observation of large neutron fluences measured with radiochemical methods in thick targets.
- Further studies are necessary, for conceptual as well as for practical reasons. There have been experiments with 200 GeV ^{238}U in which the total breakup of the uranium ion into 92 singly charged ions was measured [9] [21]. This implies that 146 neutrons were produced as well. Reactions of this type require careful radiation safety measures in new heavy-ion accelerators which provide multi-GeV per nucleon ions up to 400 GeV ^{238}U or above.

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