CORRELATIONS IN NUCLEAR INTERACTIONS BETWEEN E_{CM}/u AND UNEXPLAINED EXPERIMENTAL OBSERVABLES

W. Westmeier[1]*, R. Brandt*[1]*, S. Tyutyunnikov*[2]

[1] Kernchemie, FB Chemie, Philipps-Universität, D-35037 Marburg, Germany
[2] JINR, 141980 Dubna near Moscow, Russian Federation
Corresponding author: Westmeier@Westmeier.com

A new concept is introduced for the classification of “unresolved problems” in the understanding of interactions in thick targets irradiated with relativistic ions: The centre-of-mass energy per nucleon of a hypothetical compound nucleus from a primary interaction, E_{CM}/u, is calculated and correlated with several experimental observations in thick target irradiations. One observes in various reactions of relativistic primary ions with thick targets that there appears to be a threshold for reactions leading to “unresolved problems” which lies around **E_{CM} /u ~ 150 MeV** where E is the kinetic energy of the beam. A thick target is defined so that products from the first nuclear interaction will make secondary nuclear interactions. All “unresolved problems” are exclusively observed above this threshold, whereas below this threshold no “unresolved problems” are found.

Another (the same?) threshold exists at a nuclear temperature of 158±3 MeV as a threshold for massive pion production in nuclear interactions. Hagedorn had proposed this threshold decades ago and it is known as the **Hagedorn limit**. In this paper we will only mention, but not elaborate on Hagedorn’s theoretical concept any further. Some considerations will be presented and further studies in this field will be suggested.

1. INTRODUCTION

Spallation mass-yield curves in nuclear interactions with thin targets were systematically studied in many nuclear chemistry laboratories for decades around the world. These observed spallation mass-yield curves strictly obey well-known concepts of “limiting fragmentation” and “factorisation” (see section 2.2) and are thus well understood within current theoretical models. This applies for nuclear reaction studies induced by ions from $E_{total} < 1$ GeV and is extending up to 80 GeV ^{40}Ar irradiations. Limited studies extend up to proton induced reactions with $E_{kinetic} = 300$ GeV (see Ref. [1] for details).

Several articles have recently appeared describing “unresolved problems” in the study of nuclear interactions in thick targets induced by relativistic ions and their secondary reaction products [1, 2]. Product yield distributions in thick copper targets from irradiations with 72 GeV ^{40}Ar (at the LBNL, Berkeley), 44 GeV ^{12}C (at the JINR, Dubna), and 48 GeV ^{4}He (at CERN, Geneva) [3] cannot be understood with well-established theoretical concepts, thus constituting “unresolved problems”. Moreover, exceedingly large neutron emission during the irradiation of thick copper, lead and uranium targets with high energy heavy ion beams having E_{total}>30 GeV have been observed in several laboratories; a large neutron multiplicity significantly exceeding model calculations is also considered to be an “unresolved problem”.

All attempts to characterise unresolved problems in thick-target nuclear reactions since about 1954 [4] have borne no fruit; the problem being that there are no defined ion energy, projectile mass, and target mass where these unresolved problems systematically occur.

In this paper the following approach will be introduced:

One calculates on a purely hypothetical basis the centre-of-mass energy E_{CM} per nucleon in the entrance channel of the nuclear interaction. This entrance channel is defined by the kinetic energy E_P of the primary ion (projectile) with mass A_P and the target mass A_T. The value of E_{CM} /u in units of MeV is calculated as:

$$E_{CM}/u = E_P * A_T / (A_P + A_T) / (A_P + A_T) \qquad (1)$$

Experimental phenomena are produced in thick targets by primary ions (primaries) up to the end of their range and, in addition, by secondary fragments (secondaries) making nuclear interactions in the thick target. The relative importance of nuclear reactions in thick targets due to secondaries compared to primaries increases with the thickness of the target. One correlates the value E_{CM}/u - which might be taken as the hypothetical average excitation energy of each nucleon in the entrance channel of the reaction - with experimentally observed phenomena.

Some correlations are presented in Section 2 for increasing E_{CM}/u. It is obvious that any observed correlation between E_{CM}/u of the entrance channel and interactions of secondary fragments in thick targets will not explain the reason for unresolved problems, but one does find a systematic dependence. In section 3 we will present some considerations which may be helpful as a start to understanding the observed order presented in Section 2. Section 4 contains our conclusions on the subject and new experiments are suggested which may help to shed light onto this rather old and complex set of unresolved problems.

2. CORRELATIONS BETWEEN E_{CM} /u AND UNRESOLVED PHENOMENA

Unresolved problems as discussed in detail in Refs. [1, 2] are observed only in high energy nuclear interactions with *thick* targets. Three types of experiments which reveal unresolved problems are described in more detail below.

2.1. Production of ^{24}Na in two copper discs in contact. The quantification of the isotope ^{24}Na ($T_{½}$ = 15 h) produced in a thick copper target consisting of two Cu-disks of 8 cm diameter and 1 cm thickness each in irradiations with relativistic ions requires just conventional gamma-ray spectrometry. Irradiations of two copper disks at various accelerators lasted only a few hours. After the irradiation, radioactive decay of ^{24}Na was measured in order to calculate with an accuracy of about ±1% the activity ratio:

$$R_0(^{24}\mathrm{Na}) = (^{24}\mathrm{Na\ in\ downstream\ Cu}) / (^{24}\mathrm{Na\ in\ upstream\ Cu}) \qquad (2)$$

where “upstream Cu” denotes the Cu-disk which is first hit by the beam and “downstream Cu” is the following Cu disk. There may be several downstream disks in a very thick target stack.

Correlations of E_{CM}/u with experimental $R_0(^{24}\mathrm{Na})$-values are presented in Table 1 (column 3). In Reference [1] it was shown that $R_0(^{24}\mathrm{Na}) > 1.0$ constitutes an unresolved problem. This case of an unresolved problem is systematically observed for $E_{CM}/u > 192$

MeV as seen from the data presented in the third column of Table I. The third column is divided into two sub-columns in which consistent and inconsistent (=unresolved) data are listed separately. $R_0(^{24}Na)$ was not determined in reactions of 44 GeV ^{12}C on Pb and U.

2.2. Maximum of spallation product yields in two copper discs in contact. Similarly to the activity ratio for the very distant spallation product ^{24}Na, one can determine the yield ratio for any spallation product having nuclear charge Z and mass A as:

$$R_0(A) = (^{A}Z \text{ in downstream Cu}) / (^{A}Z \text{ in upstream Cu}) \qquad (3)$$

Most product cross-sections measured some time after the end-of-bombardment are actually cumulative. One expects for standard-model nuclear reactions, based on the concept of "limiting fragmentation" and "factorisation", that $R_0(A)$ distributions have a maximum value close to the mass of the target nucleus, i.e. close to A=63 in a Cu target. The $R_0(A)$ distribution should then decrease continuously with decreasing product mass A, i.e. with increasing mass difference ΔA from the target mass. Detailed supporting arguments for the statement of continuous decrease of the mass distribution with rising mass difference ΔA between target and product masses are given in Refs. [1, 2].

For thick targets two figures shall clarify the situation of resolved vs. unresolved results: In Figure 1 the $R_0(A)$ distribution is shown for the reaction of 7.3 GeV ^2H on a thick Cu target [5]. The maximum value of spallation product ratios is found around mass A=57 from where on the distribution goes slowly down with rising ΔA, which is perfectly consistent with standard theoretical model results. On the other hand, the $R_0(A)$ distribution measured from interactions of 72 GeV ^{40}Ar on a thick Cu target [6] shown in Figure 2 has its maximum around mass A=51 which is far below the target mass and which cannot be understood by current models. In the former experiment (Figure 1) the cross-section ratio for the very distant spallation product ^{24}Na is below unity (0.90±0.05), whereas it exceeds unity (1.51±0.02) in the latter experiment (Figure 2). The system from Fig. 1 is well resolved and in agreement with calculations, whereas the system from Fig. 2 is an unresolved problem.

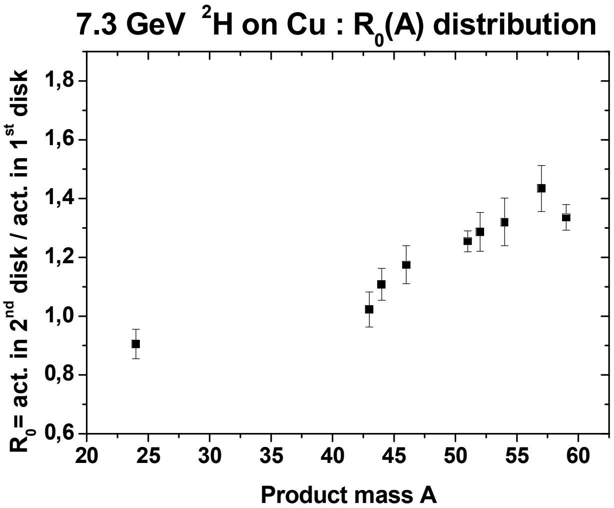

Figure 1.
$R_0(A)$ distribution for the reaction of 7.3 GeV ^2H on a thick two-disks Cu target. The maximum is around mass 57 which is consistent with model calculations and it constitutes NO unresolved problem

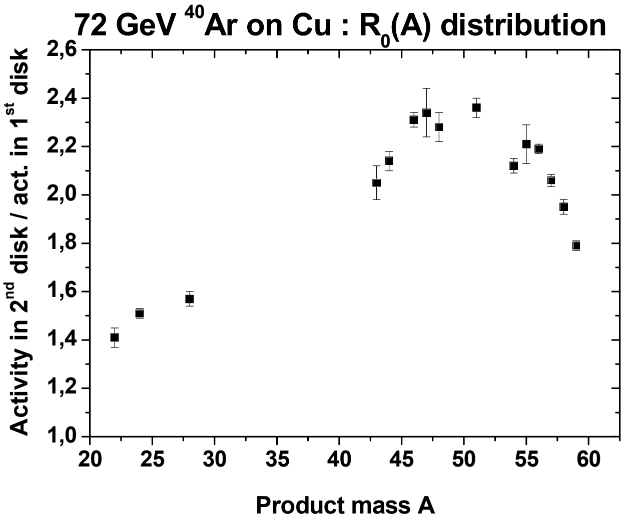

Figure 2.

$R_0(A)$ distribution for the reaction of 72 GeV ^{40}Ar on two 1-cm thick Cu target disks. The maximum is around mass 51 which is NOT consistent with model calculations and it is an unresolved problem

2.3. Neutron emission from "GAMMA-2" target. The GAMMA-2 target was described in several references [1, 3, and 7]. It is a 20 cm long copper or lead spallation target (a thick target), consisting of 20 metallic disks of 1 cm thickness and 8 cm diameter each. The metallic core is surrounded by a 6 cm thick paraffin moderator on all sides – with the exception of the front side, where the ion beam enters directly into the metallic target. The moderator surface contains small holes for plastic flasks containing low-energy neutron (n,γ) sensors, for example stable lanthanum salt. La-sensors measure directly the low-energy neutron fluence via the reaction ^{139}La(n,γ)^{140}La. The radioactive decay of ^{140}La is measured, thus allowing determination of the neutron production in the GAMMA-2 target during irradiation. This target system and the integral data measured are an IAEA benchmark for transmutation since 2007. The target allows determination of the neutron production in the system during high energy irradiations, and simultaneous measurement of the spallation product yield distribution inside the metallic core. All experimental results are compared with modern computer simulations, for example using the MCNPX2.7 code [2].

Results of comparisons between experiments on the GAMMA-2 target and model calculations are listed in Table 1, last column. The agreement between experimental and calculated neutron yields is excellent for systems such as (2 GeV ^{2}H + Pb) and (1 GeV ^{2}H + Pb) [7]. No unresolved problems are encountered. However, one observes about a factor of 3 times more neutrons experimentally than calculated in reactions of 44 GeV ^{12}C onto Cu, Pb, and U-targets [2]. This again constitutes another unresolved problem. Again, it seems to be the same threshold E_{CM}/u of primary interactions that separates resolved from unresolved thick target results.

In summary one can see from Table 1.

All nuclear reactions – without any exception – having

$$E_{CM}/u > 150 \text{ MeV}$$

are associated with "unresolved problems", when their interactions are investigated in thick targets.

Table 1. **Correlations in nuclear interactions between E_{CM} /u and several observables**

Reaction	E_{CM}/u	$R_0(^{24}$Na) in Cu		R_0(A) in Cu		Neutron emission in GAMMA-2	
	MeV	≤ 1.00	> 1.00				
48 GeV ^{4}He + Cu	664		**1.21 ± 0.02**		**Problem**		
44 GeV ^{12}C + Cu	488		**1,24 ± 0,02**		**Problem**		**Problem**
72 GeV ^{40}Ar + Cu	426		**1.50 ± 0,02**		**Problem**		**Problem**
24 GeV ^{1}H + Cu	333		**1.10 ± 0.02**		**Problem**		
25.2 GeV ^{12}C + Cu	279		**1.13 ± 0.03**		**Problem**		
36 GeV ^{40}Ar + Cu	213		**1.17 ± 0.02**		**Problem**		
18 GeV ^{12}C + Cu	194		**1.08 ± 0.10**		**Problem**		
22.4 GeV ^{22}Ne + Cu	192		**1.08 ± 0.02**				
44 GeV ^{12}C + Pb	189						**Problem**
44 GeV ^{12}C + U	168						**Problem**
7.3 GeV ^{2}H + Cu	107	0.90 ± 0.05		o.k.		o.k.	
4.5 GeV ^{1}H + Cu	69	0.98 ± 0.05					
14.7 GeV ^{4}He + Pb	68					o.k.	
4 GeV ^{4}He + Cu	55	0.92 ± 0,01					
3 GeV ^{2}H + Cu	43	0.90 ± 0,05		o.k.		o.k.	
2.6 GeV ^{1}H + Cu	39	0.96 ± 0.02					
7.4 GeV ^{2}H + Pb	35					o.k.	
6 GeV ^{4}He + Pb	27					o.k.	
1.3 GeV ^{1}H + Cu	19	0.99 ± 0.03					
3 GeV ^{2}H + Pb	14					o.k.	
2.0 GeV ^{1}H + Pb	10					o.k.	
1.0 GeV ^{1}H + Pb	5					o.k.	

Notes for Table 1: Data in bold font stand for "unresolved problems"

All nuclear reactions – without any exception – having

$$E_{CM}/u < 110\ \text{MeV}$$

exhibit NO “unresolved problems”, when their interactions are investigated in thick targets. There is no worry about this latter class of nuclear interactions; theoretical model calculations agree with experimental findings. This is an important statement from a practical (and social) point-of-view. All low-energy nuclear interactions having practical relevance, such as in nuclear reactors or most accelerator applications are understood and modelled sufficiently well. They are not associated with any unresolved problem, especially with respect to excessive neutron production.

The essential result presented so far is the clear separation of experimental phenomena associated with unresolved problems using the newly introduced parameter E_{CM}/u. This parameter separates results into two classes as coming from reactions having average centre-of-mass energy per nucleon either smaller or larger than 150 MeV. At present we have no idea why this is so, but it is interesting to note agreement with statements from Hagedorn who also considered a limiting energy (or temperature T_0) of 158±3 MeV (“Hagedorn limit”) in a paper dating back to 1965 [8]. He pointed out that above this limit one should expect to produce pions easily (their rest mass is just below 150 MeV). Therefore there should be some kind of upper limit in nuclear temperatures that are allowed to exist in nucleonic matter. We will not pursue this line-of-thinking any further at this point.

A review of physics experiments studying nuclear interactions in thin targets and the emission of secondary elementary particles and projectile fragments was presented by Friedlander and Heckmann [9]. They describe a broad range of experimental techniques used and the data measured in these investigations. They report of no experimental result that lies outside the understanding using standard models – however, with the exception of certain nuclear emulsion studies, which are in fact thick target studies. In these studies some evidence for a “short mean-free-path” of projectile fragments was observed, called “anomalons” in those days. This evidence was observed for interactions of secondary fragments and they also have recently been considered [1] as unresolved problems.

CONCLUSIONS

Various phenomena have been found in thick-target experiments induced by relativistic particles which are not in agreement with known reaction product systematics and cross-sections. These phenomena are found when projectiles of very high energies interact with a thick target or a stack of thin targets. The experimental results are divided into two groups according to their agreement or not with theoretical model calculations as well as conformity with results from thin-target experiments.

Phenomena are denoted as “resolved” when:

- the mass distribution of spallation products follows the principles of limiting fragmentation and factorisation as exemplified in Figure 1 and the cross-section of very far spallation products, such as ^{24}Na, is largest in the front of the target;
- the measured neutron multiplicity is in agreement with model calculations;
- the mean free path of secondary particles follows known systematics.

On the other hand, phenomena are “unresolved” when

– the mass distribution of spallation products in a second (or following) interaction is skewed towards large ΔA and the cross-section of very far spallation products, such as ^{24}Na, is significantly enhanced;
– the neutron multiplicity exceeds expectation values from model calculations, which seems to indicate a very high energy transfer in the interaction of a secondary fragment;
– the mean free path of secondary fragments is significantly shorter than expected from range-energy systematics.
These experimental phenomena are produced in thick targets by primary ions and, in addition, by secondary fragments making additional nuclear interactions in the thick target.

A hypothetical description of the average centre-of-mass excitation energy of each nucleon (E_{CM}/u) in the entrance channel of the reaction is correlated with experimentally observed phenomena. When one accepts this concept of E_{CM}/u of a hypothetical compound system, there seems to be a separating value of E_{CM}/u below which no unresolved phenomena are found and all reaction product cross-sections are in agreement with model calculations, whereas reactions with energies above the critical value of E_{CM}/u, without any exception, lead to unresolved phenomena. However, due to scarcity of experimental results, the separating energy is not very well defined. Results from reactions having E_{CM}/u = 107 MeV show no unexpected results whereas the outcome of each reaction having E_{CM}/u = 168 MeV is clearly “unresolved”. We adopt a limiting value of E_{CM}/u ~ 150 MeV as the critical energy separating resolved from unresolved reaction systems. This value is close to another limiting energy (or limiting temperature T_0) of 158±3 MeV which was introduced through considerations of statistical thermodynamics by Hagedorn long ago and which marks the transition energy from which on real hadrons are produced and “the number and longitudinal momentum of the secondaries produced would increase” [8].

In order to define the transition energy more precisely, we wish to propose an experiment which scans over the limiting energy and will hopefully allow us to define it well. A simple and straightforward experiment is a thick-target experiment employing various (up to 16) copper disks of 1 cm thickness each in contact, which are irradiated with a beam of ^{12}C. Beam energies of 0.6 GeV/u (7.2 GeV kinetic energy), 0.9 GeV/u, 1.1 GeV/u, 1.2 GeV/u, 1.3 GeV/u, 1.5 GeV/u and 1.8 GeV/u are recommended. The experiments scan the kinetic energy range around 1.2 GeV/u which corresponds to E_{CM}/u =158 MeV for the ^{12}C + ^{65}Cu reaction. If the hypothetical average excitation energy of 158 MeV is actually a relevant limit, then $R_0(A)$ should indicate significant enhancement for masses A far away from the target mass. Moreover, the neutron dose-rate should rise over-proportional (it is 3 times more than expected for 44GeV ^{12}C induced reactions) when the limiting energy is exceeded. As interactions between nucleons inside a nucleus can be described by statistical thermodynamics, the limiting energy (or temperature) is not expected to be a sharp boundary but one rather expects to find a smooth onset of “unresolved” data around the limiting value.

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