SPECTATOR DISTRIBUTION IN RELATIVISTIC NUCLEUS-NUCLEUS COLLISIONS

By T. Lesiak and J. Turnau

Institute of Nuclear Physics, Cracow*

(*Received December 22, 1987*)

The Glauber picture of the nucleus-nucleus collisions is tested in the most direct way, i.e. by comparison of the Glauber-type calculation of the wounded nucleon number distribution with the data on spectator charge distribution measured in several Dubna experiments. We get reasonable agreement with the propane bubble chamber and streamer chamber data. The emulsion data seem to disagree with our calculation.

PACS numbers: 25.70.Np

1. *Introduction*

The search for the quark-gluon plasma is the main motivation for studying of the ultrarelativistic collisions of nuclei. Such effects, if exist, will have to be carefully sorted out from the overwhelming majority of "trivial" events explainable in terms of the binary inelastic nucleon-nucleon collisions. There exist several Monte-Carlo generators of the "trivial" nucleus-nucleus collisions based on Glauber picture (i.e. straight line geometry, binary independent subcollisions), supplied with some particular model of hadron production [1, 2]. The aim of the present paper is to test their underlying structure in a most direct way without any reference to multiple production of hadrons. We compare the spectator charge distribution measured in several Dubna experiments at 4.2 GeV/c/A with the appropriate Glauber type calculation. The paper is divided into four sections. After this introduction we describe exact Monte Carlo calculation of the wounded nucleon number distribution in nucleus-nucleus collisions and test various approximations to such calculation used in the literature. Then we compare results of our calculation with the experimental data. The last section contains summary and conclusions.

* Address: Instytut Fizyki Jądrowej, Kawiory 26a, 30-055 Kraków, Poland.

2. *The Monte-Carlo program to calculate the wounded nucleon number distribution*

The structure underlying existing models of the nucleus-nucleus interactions i.e. the Wounded Nucleon Model [3], the Dual Parton Model [4] and the String Model [5] is the Glauber picture of collision. Each nucleon follows the straight path with fixed impact parameter and is subject to incoherent binary interactions. Each nucleon which interacted inelastically is called wounded. In the above mentioned Monte-Carlo generators simulating the nucleus-nucleus collision the wounded nucleon configuration is always a starting point for the event generation. The Monte-Carlo procedures for calculation of the wounded nucleon number distributions are time consuming for large nuclei, therefore various approximations are employed in the literature. Our aim is to check their validity. In the following we describe what we mean by exact Monte-Carlo calculation and then consider approximations due to the modifications of the details of the nucleon-nucleon interaction. The influence of the recoil correction is also studied. Finally we compare the exact results with the optical limit.

We consider only the inelastic, nondiffractive collisions. The probability of such interaction at the impact parameter b is

$$\sigma_{\text{in}}(b) = \int \prod_{i=1}^{A} d^2 s_i \int \prod_{j=2}^{B} d^2 \bar{s}_j D_A(\vec{s}_1 \dots \vec{s}_A) \times D_B(\vec{\bar{s}}_1 \dots \vec{\bar{s}}_B)$$
$$\times \sigma(b; \vec{s}_1 \dots \vec{s}_A; \vec{\bar{s}}_1 \dots \vec{\bar{s}}_B), \tag{1}$$

where $\sigma(b\dots)$ is the probability of interaction for a fixed transverse configuration of nucleons inside nuclei and

$$D_A(\vec{s}_1 \dots \vec{s}_A) = \int dz_1 \dots dz_A \varrho_A(\vec{r}_1 \dots \vec{r}_A), \tag{2}$$

where ϱ_A is the nuclear density and $z_1 \dots z_A$ are coordinates along the beam direction. We assume that incoherent inelastic collisions between pairs of nucleons inside nuclei are independent i.e. $\sigma(b\dots)$ is fully determined by the binary probabilities of nucleon-nucleon inelastic collision at impact parameter $b-\vec{s}_i+\vec{s}_j$ (Fig. 1)

$$\sigma_{ij} = \sigma(\vec{b}-\vec{s}_i+\vec{s}_j).$$

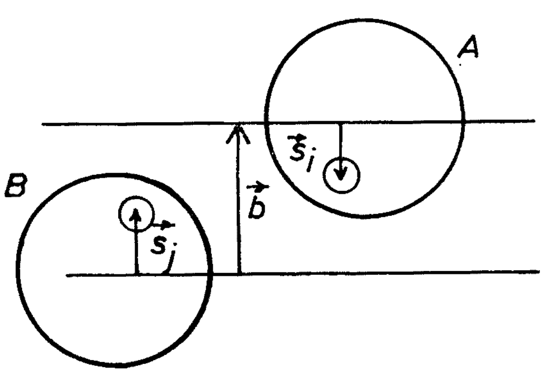

Fig. 1. Geometrical picture of nucleus-nucleus collision

Projectile and target constituents are distributed according to the formula

$$\varrho_A(\vec{r}_1 \dots \vec{r}_A) = \varrho(\vec{r}_1) \dots \varrho(\vec{r}_A)\delta(\sum_{i=1}^{A} \vec{r}_i),$$

i.e. the only correlation is introduced by delta function corresponding to the recoil correction. For $A < 20$ $\varrho(\vec{r})$ is the gaussian distribution with $\langle r^2 \rangle$ given in Table I, for $A > 20$ we take the Saxon-Woods density

$$\varrho(r) = 3/4\pi R^3(4+a^2\pi^2/R^2)\,[1+\exp{(r-R)/a}]^{-1} \tag{3}$$

TABLE I

Nuclei radii (in fm)

^AX_Z	$^4He_2$	$^6Li_3$	$^{12}C_6$	$^{14}N_7$	$^{16}O_8$
Ra	1.37	2.00	2.04	2.00	2.16

with $R = 1.14 \cdot A^{0.33}$ fm and $a = 0.545$. The recoil correction can be easily implemented into the Monte Carlo procedure in the case of the Gaussian nucleon density. The folded Gaussian density

$$\varrho(\vec{s}) = \int_{-\infty}^{\infty} dz\varrho(\vec{s}, z) \tag{4}$$

is then also Gaussian so the Van Hove method [6] can be directly applied. We generate $A-1$ two-dimensional vectors $\vec{s}_1 \dots \vec{s}_{A-1}$ with normally distributed lengths and construct A vectors according to the formula

$$\vec{\tilde{s}}_k = \sum_{i=1}^{A-1} O_{kj}\vec{s}_j \quad (k = 1, \dots, A) \tag{5}$$

O_{kj} is $A \times A$ orthogonal matrix such that

$$\begin{aligned} O_{ij} &= 1/\sqrt{i(i+1)} \qquad i \leqslant j;\, i < A, \\ O_{Aj} &= 1/\sqrt{A}, \\ O_{i+1,i} &= -i/\sqrt{i(i+1)}, \\ O_{ij} &= 0 \qquad i > j+1. \end{aligned} \tag{6}$$

It is shown that vectors $\vec{\tilde{s}}$ fulfill constraint $\sum_{i=1}^{A} \vec{\tilde{s}}_k = 0$ and their lengths are normally distributed. For a non-Gaussian distribution, in particular for the Saxon-Woods density of nucleons, the above procedure can be treated as the first approximation of the correct one as it slightly changes the shape of distribution leaving untouched the average sum of squares of distances from the origin. Further sophistication in this point seems to be rather academic because for $A \geqslant 12$ the influence of the recoil correction on cross-section

TABLE IIa

$^4H_2$–$^{12}C_6$ MC results with and without the recoil correction

Exact MC	Cross sect. (mb)	Fraction of n wounded nucleons				Fraction of n wounded charges		
		1	2	3	4	0	1	2
With recoil corr.	460.3 ±4.0	0.4470	0.2778	0.1899	0.0853	0.2773	0.4953	0.2273
Without recoil corr.	469.7 ±4.1	0.4556	0.2687	0.1886	0.0871	0.2680	0.5029	0.2291

TABLE IIb

$^{12}C_6$–$^{12}C_6$ MC results with and without the recoil correction

Exact MC	Cross sect. (mb)	Fraction of n wounded nucleons					
		1	2	3	4	5	6
With recoil corr.	837.7 ±6.5	0.3232	0.1830	0.1243	0.0975	0.0850	0.0667
Without recoil corr.	830.1 ±6.4	0.3200	0.1829	0.1298	0.0963	0.0819	0.0687

Exact MC	Cross sect. (mb)	Fraction of n wounded nucleons					
		7	8	9	10	11	12
With recoil corr.	837.7 ±6.5	0.0524	0.0369	0.0197	0.0089	0.0022	0.0003
Without recoil corr.	830.1 ±6.4	0.0528	0.0343	0.0208	0.0095	0.0025	0.0004

and wounded nucleon number distribution is only few percent and diminishes with the nucleus mass as can be seen in Table II.

Given nucleon positions in both nuclei, we loop over all pairs and generate random binary interactions according to the probability distribution called here the nucleon-nucleon profile function. The above we will call further the exact Monte-Carlo procedure.

As a starting point and test of performance of our Monte-Carlo procedure we take α–α collision for which the exact calculation has been performed analytically [7]. Using the same parameters for α-nucleus density and nucleon-nucleon interaction profile function as in Ref. [7]

$$\sigma(b) = \sigma/\pi R^2 \exp(-b^2/R^2), \tag{7}$$

TABLE III

MC results for He-He

Method of calculation	Cross sect. (mb)	Fraction of wounded nucleons				Fraction of wounded protons		
		1	2	3	4	0	1	2
Exact MC	220.5	0.602	0.272	0.105	0.021	0.337	0.542	0.121
Square cells MC	224.7	0.600	0.287	0.095	0.018	0.348	0.539	0.113
Black disk approx.	203.2	0.575	0.274	0.122	0.028	0.335	0.528	0.137

TABLE IV

MC results for C-C

Method of calculation	Cross sect. (mb)	Fraction of n wounded nucleons					
		1	2	3	4	5	6
Exact MC	837.7	0.3232	0.1830	0.1243	0.0975	0.0850	0.0667
Square cells MC	817.6	0.3205	0.1891	0.1262	0.1009	0.0839	0.0643
Black disk approx.	785.6	0.3239	0.1778	0.1224	0.0952	0.0846	0.0679

Method of calculation	Fraction of n wounded nucleons					
	7	8	9	10	11	12
Exact MC	0.0524	0.0369	0.0197	0.0089	0.0022	0.0003
Square cells MC	0.0472	0.0323	0.0201	0.0113	0.0037	0.0006
Black disk approx.	0.0518	0.0385	0.0232	0.0101	0.0037	0.0007

Method of calculation	Fraction of n wounded protons						
	0	1	2	3	4	5	6
Exact MC	0.2217	0.3486	0.1852	0.1306	0.0744	0.0321	0.0075
Square cells MC	0.2176	0.3496	0.1951	0.1251	0.0733	0.0311	0.0083
Black disk approx.	0.2133	0.3485	0.1935	0.1225	0.0784	0.0353	0.0086

we get results within 0.25% of the exact analytical result at the level of 3×10^4 MC events (Figs. 1 and 2). For all practical purposes 1% precision obtained for 10^4 MC events seems to be sufficient.

Let us now consider two approximations to the exact MC procedure. Their idea is to modify nucleon-nucleon profile function so that only pairs with high probability of interaction are taken into account. In the first one called cylinder approximation the Gaussian profile is replaced by black disc corresponding to the same inelastic cross-section

$$\sigma_{\text{in}}(b) = 1 \quad b \leqslant R,$$
$$\sigma_{\text{in}}(b) = 0 \quad b > R, \tag{8}$$

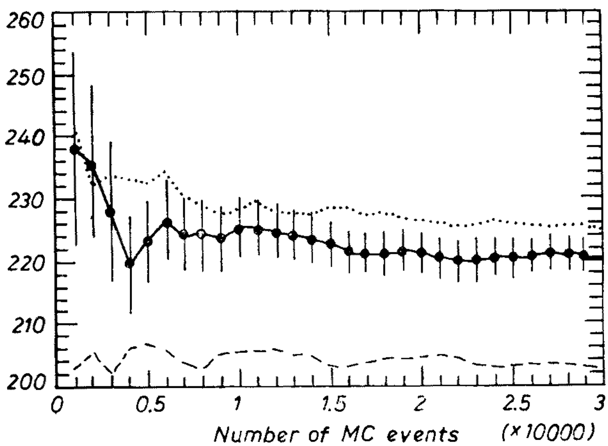

Fig. 2. ^{4}He-^{4}He inelastic cross-section vs number of MC events. Full line — exact MC calculation; dotted line — square cells calculation; dashed line — black disk calculation

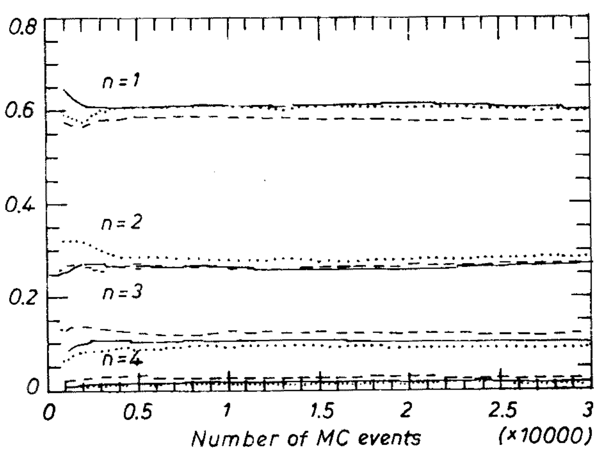

Fig. 3. Fraction of n wounded nucleons vs number of MC events in ^{4}He-^{4}He collision. Full line — exact MC calculation; dotted line — square cells calculation; dashed line — black disk calculation

TABLE V

Distributions of wounded nucleons and protons in optical approximation and in MC calculation

No of wounded nucleons n and protons z	He-Li		He-C		He-Al		He-Cu	
	Opt. appr.	Monte Carlo	Opt. appr.	Monte Carlo	Opt. appr.	Monte Carlo	Opt. appr.	Monte Carlo
$n = 1$	0.567	0.550	0.444	0.473	0.358	0.346	0.276	0.279
$n = 2$	0.272	0.286	0.259	0.262	0.232	0.247	0.185	0.212
$n = 3$	0.125	0.126	0.189	0.173	0.222	0.209	0.206	0.198
$n = 4$	0.028	0.037	0.103	0.093	0.188	0.198	0.334	0.311
$z = 0$	0.136	0.147	0.243	0.220	0.338	0.345	0.467	0.454
$z = 1$	0.530	0.531	0.492	0.502	0.445	0.452	0.364	0.367
$z = 2$	0.331	0.322	0.265	0.277	0.218	0.202	0.169	0.178
Cross-section (mb)	353	326 ± 4	486	451 ± 5	808	742 ± 7	1251	1158 ± 16

TABLE VIa

Ne-emulsion interaction. Optical approximation and MC results. Cross-sections are in mb

Spectator charge	Ne-H		Ne-C		Ne-N	
	Opt.	MC	Opt.	MC	Opt.	MC
0	0.0	0.0	0.7	0.1	1.9	0.3
1	0.0	0.0	5.0	2.0	10.4	1.9
2	0.0	0.0	17.0	6.1	28.7	9.7
3	0.0	0.0	37.5	16.3	52.2	22.8
4	0.0	0.0	61.9	36.6	73.5	44.3
5	0.2	0.4	84.5	59.0	90.0	66.1
6	1.5	2.7	105.1	92.4	105.5	93.0
7	9.4	9.6	131.0	127.5	128.6	133.8
8	43.0	39.2	180.6	185.7	176.5	199.1
9	163.4	139.6	334.2	346.2	327.7	333.2
10	142.6	140.2	248.8	231.4	244.0	238.1
σ_{inel}	358.6	351.6 ± 5.6	1206.3	1103.2 ± 13.0	1239.0	1142.3 ± 13.1

where $R = (\sigma_{in}/\pi)^{1/2}$. The results of this approximate procedure differ from those given by exact calculation by ca. 10% for inelastic cross-section. The fraction of wounded nucleon number is quite correctly reproduced except for fraction of the most central collisions (almost all nucleons wounded). The fractions of wounded protons are within few pecent of the exact result even for semicentral (all protons wounded) collisions.

In the second approximate method the interaction plane is divided into square cells

TABLE VIb

Ne-emulsion interaction. Optical approximation and MC results. Cross-sections are in mb

Spectator charge	Ne-O		Ne-Br		Ne-Ag	
	Opt.	MC	Opt.	MC	Opt.	MC
0	3.0	0.7	256.6	108.9	408.7	182.7
1	15.0	4.6	231.7	125.5	274.3	182.5
2	37.1	16.0	181.8	136.5	204.3	167.9
3	62.1	35.9	156.9	140.9	167.9	161.6
4	82.2	54.3	149.5	160.8	159.5	186.9
5	97.0	70.1	152.0	146.0	162.3	174.2
6	112.0	107.2	164.4	176.0	176.3	181.9
7	137.0	148.0	194.3	237.7	207.1	214.3
8	189.0	211.1	261.6	295.9	274.3	309.0
9	359.0	367.9	423.5	511.7	447.8	493.2
10	261.5	246.2	303.9	317.6	316.3	337.3
σ_{inel}	1354.9	1262.1 ± 14.1	2491.0	2357.3 ± 27.9	2799.0	2591.6 ± 31.0

TABLE VIc

C-emulsion interaction. Optical approximation and MC results. Cross-sections are in mb

Spectator charge	C-H		C-C		C-N	
	Opt.	MC	Opt.	MC	Opt.	MC
0	0	0.0	13	6.8	23	9.2
1	0	0.1	45	25.4	61	31.8
2	1	1.6	81	59.9	91	64.7
3	5	7.9	112	102.2	115	105.5
4	24	27.0	156	159.5	154	156.5
5	104	94.5	284	285.8	279	302.8
6	80	69.0	180	177.9	177	179.6
σ_{inel}	214	200.2 ± 3.2	871	817.6 ± 6.5	900	850.2 ± 9.4

of area equal to the nucleon-nucleon inelastic cross-section. If the nucleon from A nucleus occupies the same cell as nucleon from B nucleus, it is considered as wounded. As can be judged by inspection of Table III and Table IV, the results obtained with this method are quite similar to the previous one except for the inelastic cross-sections which come out within 3% of the exact result. This method leads also to the faster code so we have chosen it for the calculations which we compare with the experimental data.

Finally, it is of some interest to compare our Monte Carlo calculation with the numerical results obtained in the optical limit [8]. The optical limit is often used for various estimations of parameters characterising nucleus-nucleus collisions (e.g. energy density,

TABLE VId

C-emulsion interaction. Optical approximation and MC results. Cross-sections are in mb

Spectator charge	C-O		C-Br		C-Ag	
	Opt.	MC	Opt.	MC	Opt.	MC
0	29	14.4	406.0	252.3	569.3	361.0
1	71	42.2	271.3	218.7	302.2	241.6
2	102	75.6	212.1	211.9	227.3	240.7
3	126	116.1	210.1	236.1	224.9	262.0
4	167	179.2	255.0	285.2	271.8	312.1
5	302	309.3	424.3	448.1	459.2	511.2
6	192	185.4	261.1	268.1	297.6	296.8
σ_{inel}	989	922.7 ± 10.1	2040.0	1920.5 ± 22.1	2343.0	2225.2 ± 25.4

TABLE VIIa

Inclusive fragment production and semicentral cross-sections for alpha-A interaction (A = Li, C)

Cross-sections (mb)	He-Li			He-C		
	Exp.	Opt.	MC	Exp.	Opt.	MC
$\sigma_{incl}(^1H_1)$	166 ± 13	166	146	227 ± 20	208	202
$\sigma_{incl}(^2H_1)$	84 ± 15	59	55	91 ± 27	70	68
$\sigma_{incl}(^3H_1)$	47 ± 5	52	47	58 ± 9	56	53
$\sigma_{incl}(^3H_2)$	48 ± 5	50	45	49 ± 8	54	51
$\sigma_{semicentr.}$	51 ± 5	48	48	106 ± 10	117	105
$\sigma_{inelastic}$	320 ± 15	353	326	410 ± 25	486	451

fraction of cental events etc.). Using methods developed in Ref. [9] wounded nucleon and wounded proton number distributions σ_W and σ_Q can be obtained in the closed form

$$\sigma_W = \int d^2\vec{b}\binom{A}{W} X(\vec{b})^{AB-BW}(1-X(\vec{b})^B)^W, \tag{9}$$

$$\sigma_Q = \int d^2\vec{b}\binom{Z}{Q} X^{BQ}(1-X(\vec{b})^B)^{Z-Q} \quad Q < Z, \tag{10}$$

$$\sigma_{Q=Z} = \int d^2\vec{b}(X^{BZ}-X^{AB}), \tag{11}$$

TABLE VIIb

Inclusive fragment production and semicentral cross-sections for alpha-A interaction (A = Al, Cu)

Cross-sections (mb)	He-Al			He-Cu		
	Exp.	Opt.	MC	Exp.	Opt.	MC
$\sigma_{\text{incl}}(^1H_1)$	319 ±34	319	294	417 ±45	409	398
$\sigma_{\text{incl}}(^2H_1)$	113 ±38	99	92	159 ±45	120	121
$\sigma_{\text{incl}}(^3H_1)$	73 ±20	75	67	95 ±14	90	84
$\sigma_{\text{incl}}(^3H_2)$	70 ±15	72	64	95 ±20	86	81
$\sigma_{\text{semicentr.}}$	248 ±28	273	255	525 ±50	586	516
$\sigma_{\text{inelastic}}$	720 ±30	808	742	1150 ±50	1251	1158

TABLE VIII

C-Ta data, optical approximation and MC results for charged spectators distribution

Q	Exp.	Opt. approx.	MC $\varepsilon = 0$	MC $\varepsilon = 0.1$
0	0.26	0.326	0.232	0.123
1	0.10	0.120	0.120	0.153
2	0.09	0.088	0.099	0.127
3		0.087	0.101	0.115
4		0.104	0.125	0.132
5		0.170	0.201	0.207
6		0.104	0.122	0.143
3, 4, 5, 6	0.55	0.565	0.549	0.587
Error	0.01		0.007	0.007
σ_{inel}		2919.3	2778.8 ±18.5	2778.8 ±18.5

where

$$X(\vec{b}) = 1-\sigma_{\text{in}}T_{AB}(b), \tag{12}$$

$$T_{AB}(b) = \int d^2\vec{s}\,T_A(\vec{s})T_B(\vec{b}-\vec{s}). \tag{13}$$

T_A and T_B are nucleus thickness functions (folded densities). In Tables V to VIII we compare the exact and approximate MC results with the optical limit calculation. If $A\times B\times\sigma_{\text{in}}$ is not too large optical approximation is quite good. However, for heavier nuclei it can serve at best as the order of magnitude estimator, especially when fraction of central or semicentral collisions is concerned (it should be noted that the approximate MC already overestimates slightly the fraction of most central events).

3. *Spectator distribution in nucleus-nucleus collision*

The measurement of charged nuclear fragments emitted in a narrow forward cone in the nucleus-nucleus collisions provides a most direct test of the Glauber-like calculation of the wounded nucleon number distribution. Although connection between Glauber picture of collision and the above mentioned data is not completely model independent, we shall see that our conclusions are not influenced by this uncertainty.

The forward cone 3–5° for 4 GeV/A nucleus-nucleus collisions is large enough to contain all remnants of the projectile breakup after collision (stripping fragments and protons) and at the same time small enough not to contain most of protons from inelastic interaction. Therefore, up to some corrections the total charge Q_s of the relativistic particles in the narrow cone along the collision axis is

$$Q_s = Z_p - Q_w,$$

where Z_p is the projectile charge and Q_w is the number of wounded protons in the projectile nucleus. The mentioned corrections are the following:

1°. Relativistic particles from the production process (mostly pions) and relativistic recoil particles from the target nucleus can enter the forward cone. Estimated contamination from this source is about 10% [10].

2°. Protons after the inelastic interaction can also enter the forward cone with small model dependent probability ε. If we assume that ε does not depend on details of the interaction with nucleus and equals that in nucleon-nucleon collision, it can be estimated from the data. For interaction 4 GeV/A and 4° forward cone $\varepsilon \simeq 10\%$. Let us denote by $W(N)$ the probability that N out of Z_p protons of the projectile nucleus have been wounded. Then the probability $P(M)$ that M protons are outside the forward cone, so that the total charge there is $Q_s = Z_p - M$, is given by the formula

$$P(M) = \sum_{n=M}^{Z_p} W(n)\,(1-\varepsilon)^M \varepsilon^{n-M} \binom{n}{n-M}. \tag{14}$$

The emulsion technique can provide also particularly clean sort of the data by counting only the charged fragments with $Z \geqslant 2$. In this case neither pions nor fast protons from the interaction contribute to the background. Then, however, we can account for stripping protons only by use of the detailed model of nucleus fragmentation.

At first we consider α-nucleus collisions at 4.5 GeV/A [11] studied at Dubna with the streamer chamber. The inclusive cross-sections for emission of various projectile fragments into the forward 4° cone were obtained. Also the cross-section σ_{sc} (semicentral) for events with no charged particles in the forward cone was determined. Let us denote by σ_{ik} the cross-section for stripping i protons and j neutrons from the projectile nucleus. After stripping, the excited fragment F1 is formed. It can further fragmentate into the fragment F2 (inclusively) with probability α(F1, F2). We can express the cross-section for inclusive production of various fragments σ(F) in terms of σ_{ik} and $\alpha(\ldots)$ as follows

$$\sigma({}^1\mathrm{H}) = \sigma_{12} + \sigma_{11}\alpha({}^2\mathrm{H}, \mathrm{p}) + \sigma_{10}\alpha({}^3\mathrm{H}, \mathrm{p}) + \sigma_{01}\alpha({}^3\mathrm{He}, {}^2\mathrm{H}) + 2\sigma_{01}\alpha({}^3\mathrm{He}, \mathrm{pp}) + 2\sigma_{02},$$

$$\sigma(^2\mathrm{H}) = \sigma_{11}\alpha(^2\mathrm{H}, {}^2\mathrm{H})+\sigma_{10}\alpha(^3\mathrm{H}, {}^2\mathrm{H})+\sigma_{01}\alpha(^3\mathrm{He}, {}^2\mathrm{H}),$$
$$\sigma(^3\mathrm{H}) = \sigma_{10}\alpha(^3\mathrm{H}, {}^3\mathrm{H}),$$
$$\sigma(^3\mathrm{He}) = \sigma_{01}\alpha(^3\mathrm{He}, {}^3\mathrm{He}). \quad (15)$$

The α's are subject to the condition $\sum_{\mathrm{F}_2} \alpha(\mathrm{F}_1, \mathrm{F}_2) = 1$. The semicentral cross-section is given by

$$\sigma_{sc} = \sigma_{20}+\sigma_{21}+\sigma_{22}. \quad (16)$$

Assuming that the fragmentation fractions $\alpha(...)$ are independent of the target nucleus we can fit 5 free parameters to 16 data points. The semicentral cross-sections are given directly by the Glauber model. In the calculation we have used $\varepsilon = 0$. It should be noted, however, that due to small charge of the projectile the precise value of ε in the range 0.0–0.15 is of no importance. The results are given in Table VII. The fitted values of the $\alpha(...)$ coefficients are the following: $\alpha(^2\mathrm{H}, {}^2\mathrm{H}) = 0.41$, $\alpha(^3\mathrm{H}, {}^3\mathrm{H}) = 0.51$, $\alpha(^3\mathrm{H}, {}^2\mathrm{H}) = 0.21$, $\alpha(^3\mathrm{He}, {}^3\mathrm{He}) = 0.51$, $\alpha(^3\mathrm{He}, {}^2\mathrm{H}) = 0.12$.

It seems that there is no problem with the Glauber picture of the nucleus-nucleus collision in this range of energy. Even if we do not believe in comparison with the data based on fitting of 5 parameters to 16 data points, we have still 4 data points (values of the semicentral cross-sections) which we get correctly without adjustable parameters.

The impression of correctness of the Glauber picture for nucleus-nucleus collisions is further confirmed by propane bubble chamber data [13] with heavier target and projectile. In Table VIII we compare results of our MC calculation with the spectator charge distribution obtained for $^{12}\mathrm{C}$-$^{181}\mathrm{Ta}$ collisions at 4.5 GeV/A. The MC results are given for two values of ε: $\varepsilon = 0$ and $\varepsilon = 0.1$. It can be seen that the data favour $\varepsilon = 0$, meaning that in the nucleus-nucleus collision nucleons fragmentate differently than in free nucleon-nucleon collision.

Fragmentation of the projectile nucleus was also thoroughly investigated in experiments using emulsion technique which seems to be particularly well suited for this task. We will compare our calculation with the spectator charge distribution measured in collisions of $^{12}\mathrm{C}$ and $^{22}\mathrm{Ne}$ 4.2 GeV/A beams with stacks of nuclear emulsion Br-2. Here the spectator charge is defined as a charge of all relativistic particles within 3° forward cone observed in collisions classified as inelastic (visible tracks from excitation or disintegration of the incident particle and/or target nucleus). Nuclear emulsion is a mixture of nuclear targets with the known composition. Although the composition of the nuclear emulsions used in Dubna experiments has never been published, for all practical purposes the standard composition given e.g. for Ilford nuclear emulsions (Table IX) can be used. In Figs 4 and 5 the fraction of events with given spectator charge Q_s of the projectile is compared to our MC results. The first observation is that the Glauber model predicts too many peripheral events, irrespectively of ε used in the calculation. The fraction of semicentral events $Q_s = 0$ is underestimated by factor 2 even for $\varepsilon = 0$. The Glauber model predicts also much more events with $Q_s = Z$ than the data show but this can be cured, at least to some extent, by inclusion of the quasielastic scattering. Our calculation also does not include

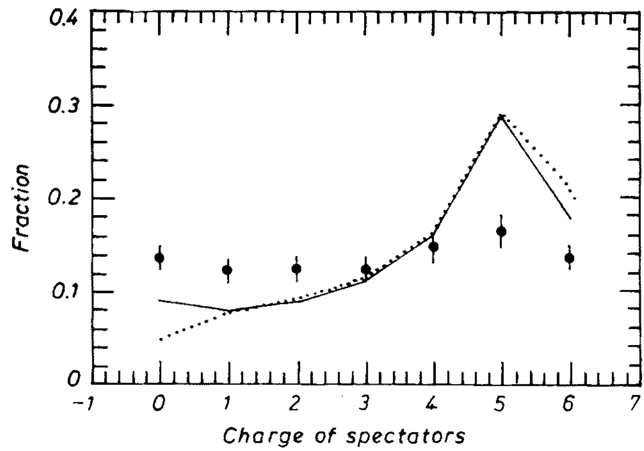

Fig. 4. C-emulsion data and MC results with $\varepsilon = 0$ (full line) and $\varepsilon = 0.1$ (dotted line)

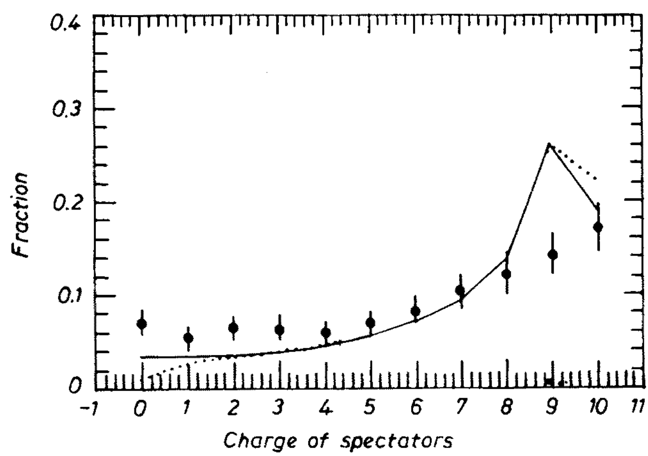

Fig. 5. Ne-emulsion data and MC results with $\varepsilon = 0$ (full line) and $\varepsilon = 0.1$ (dotted line)

TABLE IX

Contents of the nuclear emulsion Ilford-2 (N_i is the number of atoms/ml)

Nucleus	H	C	N	O	Br	Ag
$N_i \times 10^{20}$	321.56	138.30	31.68	94.97	100.41	101.01
Fraction	0.407	0.175	0.040	0.120	0.127	0.128

the process of coherent elastic scattering of the spectator nucleons (i.e. those which did not interact inelastically) but such correction is negligible due to large size of the involved scatterer resulting in a very small scattering angle. The possibility of inelastic nucleon scattering without production can be taken into account by increasing appropriately the value of the nucleon-nucleon inelastic cross-section. As we explain below, this correction has

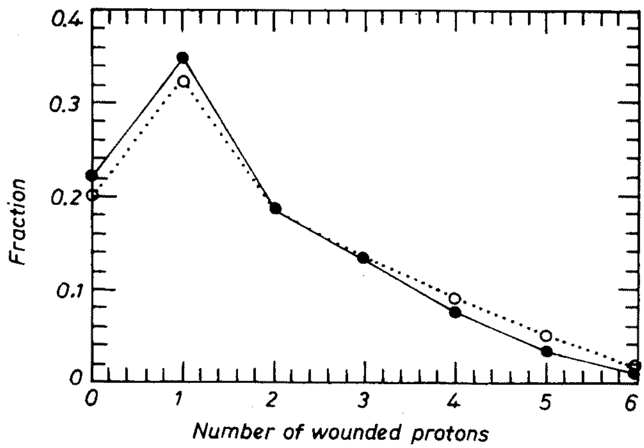

Fig. 6. Distribution of the number of wounded protons in C-C collision for different values of the inelastic nucleon-nucleon cross-section: $\sigma_{in} = 28.5$ mb (full line) and $\sigma_{in} = 40$ mb (dotted line)

TABLE X

Experimental and MC cross-sections for interactions ^{16}O and ^{32}S with ^{27}Al and ^{207}Pb. Values of σ_{exp} at 4.5 GeV/c/A are the result of fit to the low energy data

Interact.	E_{lab} (GeV/c/A)	σ_{pp} (mb)	σ_{exp} (mb)	$\Delta\sigma_{exp}$ (mb)	Ref.	σ_{MC} (mb)	$\Delta\sigma_{MC}$ (mb)
O-Al	4.5	30.0	1260			1384.5	15.4
	60–200	32.5	1610	270	[14]	1411.8	15.5
O-Pb	4.5	30.0	3364			3242.5	36.3
	60–200	32.5	4720	390	[14]	3282.1	36.6
S-Al	4.5	30.0				1811.9	21.3
	60–200	32.5				1844.0	21.5
S-Pb	4.5	30.0				3823.4	45.1
	60–200	32.5				3855.1	45.3

no significant influence on our results. Finally, we can try to enhance the centrality of the events treating nucleon-nucleon cross-section inside nuclear matter as a free parameter. The idea is that the wounded nucleon is an object physically different from the nucleon. However, Fig. 6 shows that wounded nucleon number distribution as well as inelastic cross-section depends very little on σ_{in} — the nucleus does not differ much from the black disk.

We conclude that as far as we can trust the emulsion data, the Glauber model for the spectator distribution seems to have problems, in contradiction with previously presented comparison with the streamer and bubble chamber data. Therefore it seems desirable to compare the model with wider range of the data. In Figs 7a, b, c and Table X we show the results of our MC calculation with $\varepsilon = 0$ for ^{16}O-^{27}Al, ^{16}O-^{207}Pb, ^{32}S-^{27}Al, ^{32}S-^{207}Pb collisions at 200 GeV/A (as mentioned before, the nucleon-nucleon inelastic cross-section and, therefore, energy are not the important parameters in the Glauber calculation).

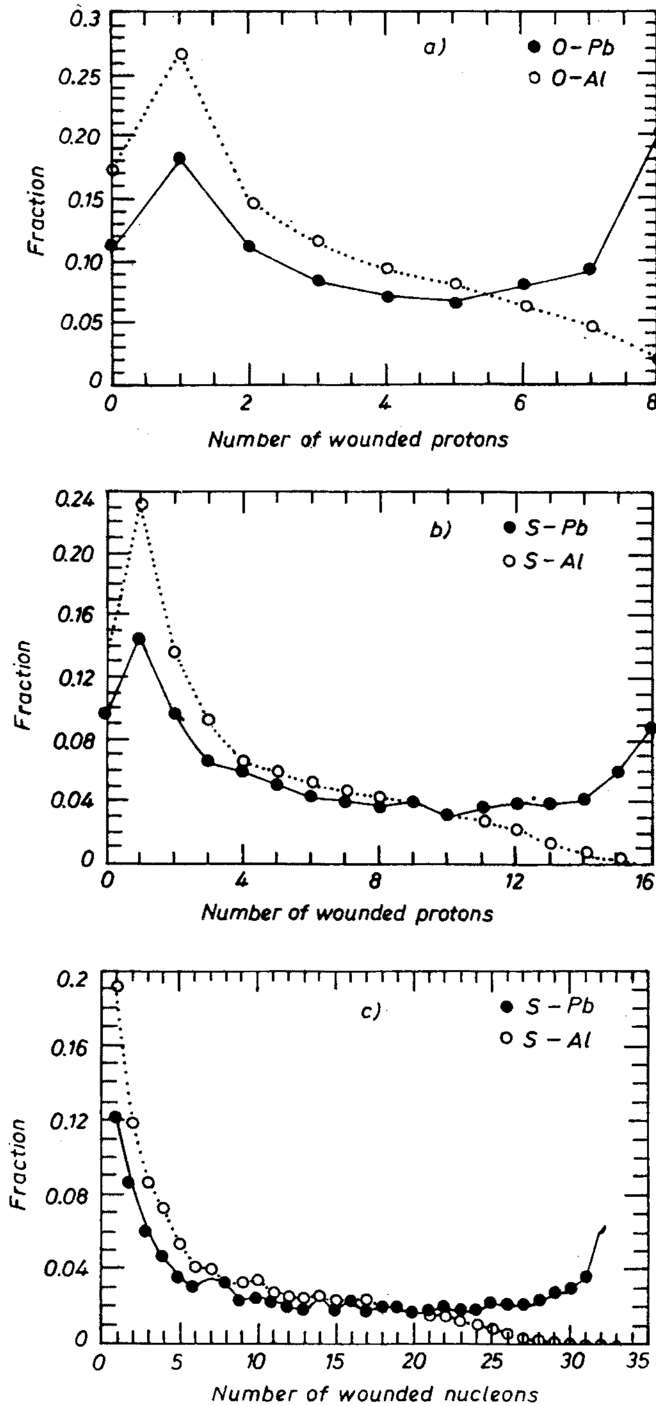

Fig. 7. Distribution of the number of wounded protons and nucleons for ^{16}O-^{207}Pb and ^{32}S-^{207}Pb collisions (a and b — protons, c — nucleons)

3. *Summary and conclusions*

After thorough checking of the approximation methods in the Glauber-type Monte Carlo calculation of the wounded nucleon number distribution we have chosen the one giving precision of several percent. Using this method we calculate the spectator charge distribution (closely related to the wounded nucleon number distribution) for several high energy nucleus-nucleus reactions for which data exist (measurements at Dubna accelerator). The agreement with the data seems to depend on the technique used for their extraction: no problems for the streamer and bubble chamber, some discrepancy for nuclear emulsion. The very scarce experimental material does not allow for any strong conclusions. Although there is no good reason to doubt the validity of the Glauber approximation for nucleus--nucleus collisions, further checks on SPS data seem to be desirable. Some relevant distributions have been calculated and the results are given in Figs 7a, b, c and Table X.

REFERENCES

[1] B. Nillsson-Almqvist, E. Stenlund, *Comp. Phys. Commun.* **43**, 387 (1987).
[2] J. P. Pansart, DPhPE 86-06, March 1986.
[3] A. Białas, M. Błeszyński, W. Czyż, *Nucl. Phys.* **B111**, 461 (1976).
[4] A. Capella, J. Tran Thanh Van, *Phys. Lett.* **93B**, 146 (1980); A. Capella et al., *Phys. Lett.* **108B**, 347 (1982).
[5] A. Anderson, G. Gustafson, B. Nillsson-Almqvist, Lund Preprint, LU-TP-86-3.
[6] L. Van Hove, *Phys. Lett.* **28B**, 429 (1969); *Nucl. Phys.* **B9**, 331 (1969).
[7] A. Białas, A. Kolawa, *Acta Phys. Pol.* **B14**, 539 (1983).
[8] W. Czyż, L. C. Maximon, *Ann. Phys.* **52**, 59 (1969).
[9] C. Pajares, A. V. Ramallo, *Phys. Rev.* **D31**, 2800 (1985).
[10] M. I. Adamovich et al., Dubna, JINR-E1-10838 (1977).
[11] A. Abdurkhimov et al., *Nucl. Phys.* **A362**, 376 (1981).
[12] H. Andrejeva et al., Dubna, JINR-P1-85-692 (1985).
[13] E. O. Abdrakhumanov et al., Dubna, JINR-E1-11517 (1978).
[14] P. D. Barnes et al., NA36 Collaboration report 188P/WG (1987).