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NUCLEAR REACTIONS OF MEDIUM AND HEAVY TARGET NUCLEI WITH HIGH-ENERGY PROJECTILES.

Fragmentation of ^{197}Au by 3.65 AGeV ^{12}C-Ions and 3.65 GeV Protons

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1. INTRODUCTION

One of the most interesting features of nuclear reactions induced by high-energy projectiles is a large number of residues ranging in mass from essentially that of the target down to a very light nuclei. In the first part of this paper[1] /from now on referred to as I/ the formation of such residues in the interaction of 3.65 AGeV ^{12}C-ions and protons with medium target nuclei has been investigated. In the present work our attention is focused on target residues produced in high-energy particle-heavy target nucleus collisions. Up to the present only experimental studies of heavy-target nuclei fragmentation in relativistic heavy ion reactions at an energy lower than 2.1 AGeV[2-7] have been performed on silver, gold, tantalum and uranium targets.

The present experiment extends the previous studies[4,5] of the gold fragmentation by relativistic ^{12}C-ions. The highest kinetic energy 3.65 AGeV available at the Dubna synchrophasotron gives such experimental possibility. Whereas our 3.65 GeV proton data can be compared with previous results[8] at higher energies, the formation cross sections of target residues from nuclear reactions of 3.65 AGeV ^{12}C-ions with ^{197}Au are presented here for the first time.

2. EXPERIMENTAL PROCEDURE

The experimental techniques used in the present study are essentially those described in I. Target stacks consisted of three 35 mg/cm^2 thick gold foils: the outers were used for recoil loss compensation, the middle was analyzed. The target foils were enclosed in Mylar catchers 17.5 mg/cm^2 thick. The induced ^{24}Na activity in the Al-foil of thickness 20 mg/cm^2 /surrounded by guard foils of the same thicknesses/ was used to calculate beam flux. The target stacks, positioned so that the beam passed through the centre, were exposed to 3.65 AGeV ^{12}C-ion and proton beams with a total intensity of about 8.4×10^{11} and 2.1×10^{13}, respectively. The monitors, catchers and target foils from a given irradiation were assayed by off-line gamma counting under identical geometry on high resolution Ge/Li/ spectrometers. Spectra were analyzed with a computer program SAMPO/9/. Radionuclides identified on the basis of gamma-ray energies, half-lives and fractional abundances are given in Table 1.

Table 1 Relevant properties of the measured nuclides

Nuclide	Half-live	Radiation measured /keV/	Fractional abundance /%/
^{198}Au	2.7 d	412	95.5
^{194}Au	39.5 h	329	63.0
^{190}Ir	12.1 d	407	27.5
		605	38.5
^{183}Re	70.0 d	162	23.5

Table 1 /continued/

Nuclide	Half-live	Radiation measured /keV/	Fractional abundance /%/
^{175}Hf	70.0 d	343	86.8
^{173}Hf	23.9 h	297	33.8
^{170}Hf	16.0 h	165	33.5
^{171}Lu	8.22d	740	47.6
^{170}Lu	2.0 d	1280	7.9
^{169}Yb	32.02d	198	36.0
^{155}Dy	10.0 h	227	68.8
^{151}Tb	17.6 h	252	26.0
		287	25.0
^{149}Gd	9.4 d	150	41.7
		299	22.6
^{146}Gd	48.3 d	634	48.0
^{145}Eu	5.94d	894	65.8
$^{138}Pr^m$	2.1 h	303	80.0
		1038	100
^{133}Ba	10.5 y	356	62.3
^{131}Ba	11.8 d	124	29.2
		496	47.1
^{127}Xe	36.41d	203	68.3
^{122}Xe	20.1 h	564	17.7
$^{121}Te^m$	154.0 d	573	80.3
		212	81.4
^{121}Te	16.8 d	573	80.3
		508	17.7
$^{118}Sb^m$	5.0 h	1230	100
^{100}Rh	20.8 h	540	78.4
^{96}Tc	4.28d	778	100
		850	97.8

Table 1 /continued/

Nuclide	Half-live	Radiation measured /keV/	Fractional abundance /%/
^{95}Tc	20.0 h	766	93.9
^{95}Nb	34.98 d	766	100
^{90}Nb	14.6 h	1129	92.0
^{87}Y	3.35d	485	92.2
		388	84.8
^{84}Rb	32.87d	882	67.8
^{83}Rb	86.2 d	520	46.0
^{75}Se	119.8 d	265	59.1
		136	59.0
^{74}As	17.78d	596	60.3
^{65}Zn	244.1 d	1115	50.7
^{59}Fe	44.5 h	1099	56.5
^{54}Mn	312.5 d	839	100
^{48}V	15.97 d	984	100
^{48}Sc	43.7 h	1038	97.5
^{46}Sc	83.83d	889	100
$^{44}Sc^m$	2.44 d	272	86.8
^{28}Mg	20.9 h	1779	100
^{24}Na	15.02h	1369	100

3. RESULTS AND DISCUSSION

The measured nuclidic formation cross sections are reported in Table 2. As discussed in I, the errors assigned to the cross section values are based on those of counting statistics, detector efficiencies and target thicknesses; a systematic error of about 15% corresponding to the beam flux monitor is not included.

Table 2 Nuclidic formation cross sections of target residues in the reactions of ^{197}Au with 3.65 AGeV ^{12}C-ions and protons. As usually, symbols I and C are used for independent and cumulative yields, respectively.

Product	Type of yield	σ_p [mb]	$\sigma_{^{12}C}$ [mb]
^{198}Au	C		190 ± 25
^{194}Au	I		66 ± 13
^{190}Ir	C		48 ± 9
^{183}Re	C	21.0 ± 2.9	55 ± 10
^{175}Hf	C	17.9 ± 2.3	37 ± 8
^{173}Hf	C		33 ± 7
^{170}Hf	C	14.8 ± 2.4	42 ± 7
^{171}Lu	C	17.0 ± 1.6	35 ± 6
^{170}Lu	C	19.0 ± 2.5	
^{169}Yb	C	13.9 ± 2.8	15.8 ± 4.2
^{155}Dy	C	4.4 ± 0.4	9.9 ± 2.1
^{151}Tb	C	7.0 ± 3.1	15.2 ± 7.2
^{149}Gd	C	14.9 ± 2.0	28.6 ± 4.5
^{146}Gd	C	11.5 ± 1.5	21.1 ± 4.0
^{145}Eu	C	13.6 ± 2.1	20.1 ± 3.8
$^{138}Pr^m$	C	5.2 ± 1.1	
^{133}Ba	C	8.4 ± 1.1	19.1 ± 2.8
^{131}Ba	C	9.0 ± 0.8	18.5 ± 3.3
^{127}Xe	C	7.9 ± 0.8	14.0 ± 2.4
^{122}Xe	C	7.3 ± 0.7	16.4 ± 2.3
$^{121}Te^m$	I		0.9 ± 0.1
^{121}Te	C	6.6 ± 0.8	8.1 ± 1.0
$^{118}Sb^m$	C	1.4 ± 0.4	
^{100}Rh	I		13.5 ± 2.9
^{96}Tc	I	2.3 ± 0.4	6.6 ± 1.1

Table 2 /continued/

Product	Type of yield	σ_p [mb]	$\sigma_{^{12}C}$ [mb]
^{95}Tc	C	3.8±0.9	10.0±1.7
^{95}Nb	C	0.8±0.1	
^{90}Nb	C	3.1±0.3	8.5±1.3
^{87}Y	C	7.1±0.9	16.8±2.4
^{84}Rb	I	1.6±0.4	
^{83}Rb	C	7.1±1.0	12.7±1.9
^{75}Se	C	3.9±0.7	7.8±1.2
^{74}As	I	2.5±0.3	6.0±1.1
^{65}Zn	C	4.0±0.6	8.5±1.8
^{59}Fe	C	2.1±0.3	
^{54}Mn	I	3.9±0.5	14.2±2.4
^{48}V	C		3.4±0.5
^{48}Sc	I	0.9±0.1	2.2±0.4
^{46}Sc	I	6.3±1.1	19.0±2.7
$^{44}Sc^m$	I	1.1±0.2	
^{28}Mg	C	2.9±0.3	13.9±3.6
^{24}Na	C	9.8±0.9	45.5±9.0

Both sets of results were examined by the fitting procedure outlined in ref./10/. The nuclidic formation cross sections $\sigma(A,Z)$, divided into six groups according to mass number, were parametrized by

$$\sigma(A,Z) = \sigma(A)\left[2\pi C_z^2\right]^{-1/2} \exp\left[-\frac{(Z_p(A)-Z)^2}{2C_z^2}\right] \qquad /1/$$

with a linear dependence of Z_p on A. The cumulative cross

sections were corrected for precursor beta decay/11/ and no isomeric states were included. The two Gaussian parameters that specify the width C_z and the center $Z_p(A)$ of the charge distributions were fitted to the measured data over limited mass region by the fitting program ROLSM/12/. The charge-dispersion parameters C_z and Z_p for a given mass region are given in Table 3. With the exception of mass range $83 \leq A \leq 96$ for proton-induced reactions, the parameters describing the charge distribution for a given group are nearly the same for every experiment. The results of this fitting procedure can be seen in Figs.1 and 2, where charge-dispersion curves /fractional isobaric yields plotted versus Z_p-Z values/ of target residues in ^{12}C- and proton-induced reactions on ^{197}Au are displayed. The fractional isobaric yields from the reactions of ^{12}C projectiles and protons with ^{197}Au are found to lie along the same charge-dispersion curves showing some differences in mass region where fission fragments are present.

Table 3 Charge-dispersion parameters

p + ^{197}Au			^{12}C + ^{197}Au		
Mass region	C_z	Z_p	Mass region	C_z	Z_p
24- 48	0.76	-0.08+0.474A	24- 48	0.80	1.11+0.434A
54- 75	0.78	0.51+0.448A	54- 75	0.75	2.05+0.423A
83- 96	0.57	5.56+0.385A	83-100	1.05	2.15+0.428A
121-133	1.20	-3.71+0.452A	121-133	0.97	-4.77+0.459A
145-155	0.86	-4.49+0.466A	145-155	1.16	-1.78+0.446A
169-183	1.14	-0.73+0.437A	169-198	1.14	-1.87+0.420A

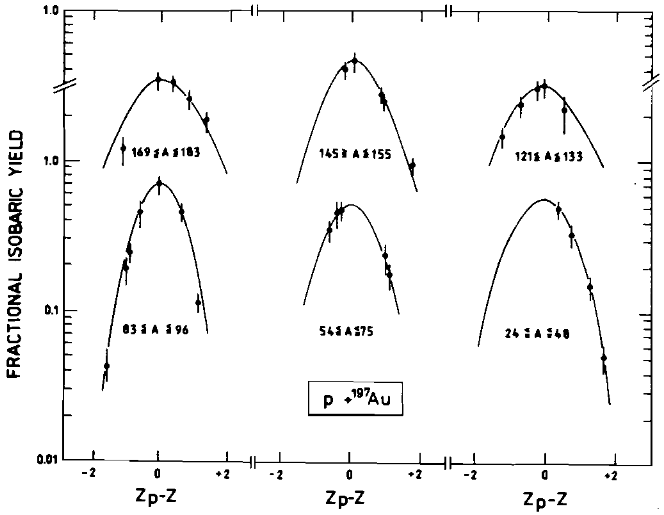

Fig.1. The charge-dispersion curves of target residues formed in the reactions of 3.65 GeV protons with ^{197}Au.

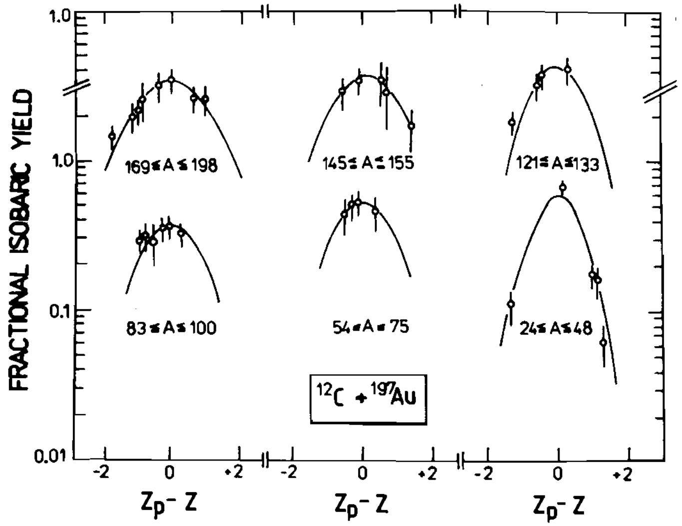

Fig.2. The charge-dispersion curves of target residues formed in the reactions of 3.65 AGeV ^{12}C-ions with ^{197}Au.

The mass yield curves, based on the set of appropriate charge-dispersion parameters /Table 3/ and the assumption of Gaussian charge dispersion are shown in Fig.3. As expected, both $^{12}C+^{197}Au$ and $p+^{197}Au$ mass-yield curves increase sharply with increasing A for the near-target products. The similarity between both mass-yield distributions is evident. The integration of the mass-yield curves over mass number gives the cross section for the production of target residues, σ^{TR}. Our integration was performed over the interval from A=40 to the mass number of the target. The results are given in Table 4, where the total reaction cross sections σ_R calculated as /13/

$$\sigma_R = \pi r_o^2 (A_P^{1/3} + A_T^{1/3} - b_{PT}) \qquad /2/$$

with the parameter r_o=1.37 fm and b=0.51 are also included. The subscripts P and T are used for projectile and target, respectively. The effective impact parameters b estimated/14/ from the total cross sections for residue production in both reactions /see Table 4/ were found to be smaller than the sum of R_P and R_T. This fact illustrates the formation of target fragments in central collisions.

To test the factorization, we compared isobaric cross sections $\sigma(A)$, normalized to the total cross sections 19.0 mb and 8.3 mb/15/ of monitoring reactions $^{27}Al/^{12}C,X/^{24}Na$ and $^{27}Al/p,X/^{24}Na$, respectively. The average value of 1.05 ± 0.14 proves the validity of the factorization hypothesis.

To test the energy independence of cross sections of target residues /limiting fragmentation/, we compared our ^{12}C projectile results with previous data at 2.1 AGeV/4/

Table 4 Comparison of the cross sections, radii and impact parameters of the nuclear reactions with ^{197}Au induced by 3.65 GeV protons and 3.65 AGeV ^{12}C-ions.

Reaction	σ^{TR} [b]	σ_R [b]	R_P [fm]	R_T [fm]	b [fm]
$p+^{197}Au$	1.6 ± 0.3	2.35	1.37	7.97	7.06
$^{12}C+^{197}Au$	2.5 ± 0.6	3.40	3.14	7.97	9.25

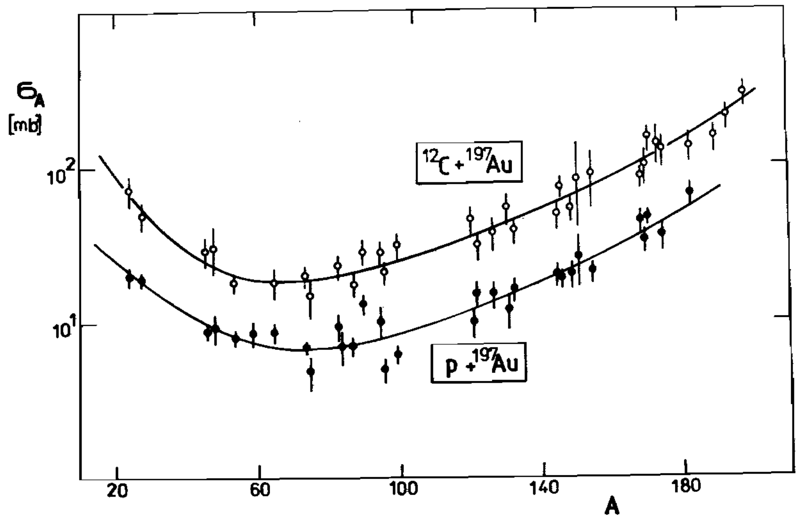

Fig.3. Mass-yield distributions of target residues in the reactions of 3.65 AGeV ^{12}C-ions and 3.65 GeV protons with ^{197}Au.

and 1.54 AGeV[5]. Even if there is a lack of experimental data in a wide range of residues at 1.54 AGeV, the obtained ratios $\sigma_{3.65}/\sigma_{1.54}$ within about 20% errors were found to fluctuate about unity. The results of the 3.65 and 2.1 AGeV comparison are displayed in Fig.4. As can be seen, the experimental ratios $\sigma_{3.65}/\sigma_{2.1}$ oscillate in a regular way with the product mass number, but does not deviate from unity by more than 30% for any of the residues. This is in agreement with the results of previous studies[1] and leads to the conclusion that the fragmentation cross sections are energy independent over the energy region between 2.1 and 3.65 AGeV. The variations of the cross section ratios

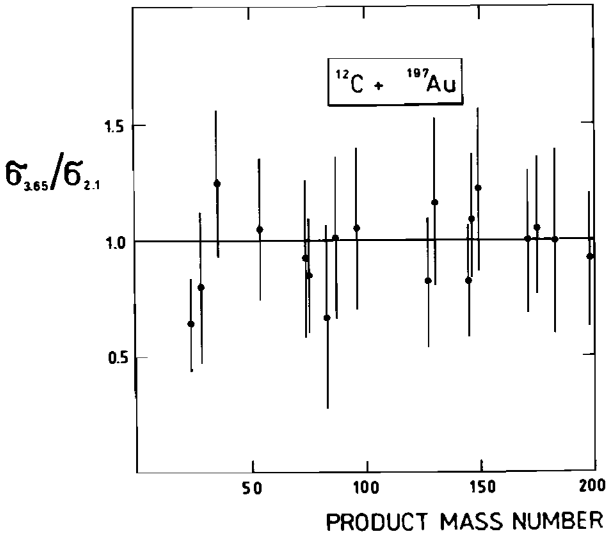

Fig.4. Ratios of cross sections measured in this work with 3.65 AGeV ^{12}C projectiles to those of ref.[4] for 2.1 AGeV.

$\sigma_{3.65}/\sigma_{11.5}$ and $\sigma_{3.65}/\sigma_{300}$ of target residues produced in $p+^{197}Au$ reactions at 3.65 GeV /present results/, 11.5 GeV[8] and 300 GeV[8] protons with product mass number are shown in Fig.5. The average values of the ratios

$$\langle \sigma_{3.65}/\sigma_{11.5} \rangle = 0.96 \pm 0.19 \quad \text{and} \quad \langle \sigma_{3.65}/\sigma_{300} \rangle = 0.97 \pm 0.18 ,$$

respectively, show that cross sections of target residues from $p+^{197}Au$ reactions are energy independent from 3.65 GeV to 300 GeV.

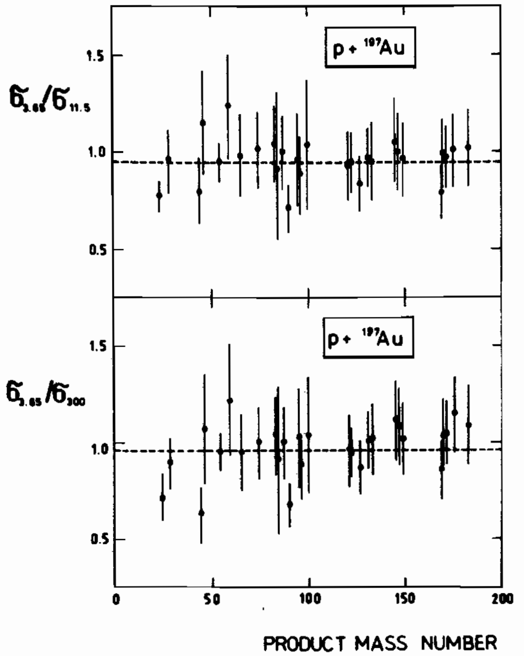

Fig.5. Ratios of cross sections measured in this work with 3.65 GeV protons to those of ref.[8] for 11.5 GeV and 300 GeV.

4. CONCLUSIONS

The cross section measurements of target fragments produced in nuclear reactions of 3.65 AGeV ^{12}C-ions and protons with ^{197}Au reported here have extended and confirmed previous results[2-8] on target fragmentation. The relative isobaric cross sections of target residues were found to be independent of projectile. This fact supported by the similarity of $^{12}C+^{197}Au$ and $p+^{197}Au$ mass-yield distributions validates the factorization hypothesis. The ratio of cross sections of target fragments from $^{12}C+^{197}Au$ reactions at the two energies 3.65 AGeV and 2.1 AGeV[4] oscillate about unity. This is in agreement with the similar comparisons of $p+^{197}Au$ results at 3.65, 11.5[8] and 300 GeV[8], and leads to the validity of limiting fragmentation at these energies.

The total cross sections 2.5±0.6 mb and 1.6±0.4 mb for residue production in $^{12}C+^{197}Au$ and $p+^{197}Au$ reactions, respectively, have been obtained by the integration of the appropriate isobaric cross sections. The impact parameters calculated from these observables indicate that target residues in both reactions are created mainly in central collisions.

References

/1/ Kozma P., Tumendemberel B., Chultem D.: Czech.J. Phys. B, 1st part of this paper.
JINR Report E1-88-244, Dubna, 1988.

/2/ Loveland W., Otto R.J., Morrissey D.J., Seaborg G.T.: Phys.Rev.Lett. 39 /1977/ 320.

/3/ Porile N.T.,Cole G.D., Rudy C.R.: Phys.Rev. C 19 /1979/ 2288.

/4/ Kaufmann S.B., Steinberg E.P., Wilkins B.D., Henderson D.J.: Phys.Rev. C 22 /1980/ 1897.

/5/ Cole G.D., Porile N.T.: Phys.Rev. C 24 /1981/ 2038.

/6/ Morrissey D.J., Loveland W., de Saint Simon M., Seaborg G.T.: Phys.Rev. C 21 /1980/ 1783.

/7/ McGaughey P.L., Loveland W., Morrissey D.J., Aleklett K.,Seaborg G.T.: Phys.Rev. C 31 /1985/ 896.

/8/ Kaufmann S.B., Weisfield M.W., Steinberg E.P., Wilkins B.D., Henderson D.: Phys.Rev. C 14 /1976/ 1121.

/9/ Koskelo M.J., Aarnio P.A., Routti J.T.: Nucl.Instrum. and Methods 190 /1981/ 89.

/10/ Kozma P., Kliman J., Leonard M.: Czech.J.Phys. B, to be published ; and JINR Report E1-87-350, Dubna, 1987.

/11/ Damdinsuren C., Kozma P., Tumendemberel B., Khorolyjav R., Chultem D.: JINR Report P1-88-135, Dubna, 1987.

/12/ Zlokazov V.B.: JINR Report P10-86-618, Dubna, 1986.

/13/ Heckmann H.H., Greiner D.E., Lindstrom P.J., Shwe H.: Phys.Rev. C 17 /1978/ 1735.

/14/ Barshay S., Dover C.B., Vary J.P.: Phys.Rev. C 11 /1975/ 360.

/15/ Damdinsuren C., Duka-Zolyómi A., Dyachenko V.M., Kliman J., Kozma P., Tumendemberel B.: JINR Report E1-87-932, Dubna, 1987.

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Взаимодействие снарядов высоких энергий со средними и тяжелыми ядрами. Фрагментация ^{197}Au ядрами ^{12}C и протонами с энергией 3,65 ГэВ/нуклон

Приводятся сечения образования остаточных ядер во взаимодействии ядер ^{12}C и протонов с энергией 3,65 ГэВ/нуклон с ядрами ^{197}Au. Определение сечений проводилось посредством прямого измерения на Ge(Li) спектрометрах выходов гамма-лучей облученных мишеней. Сравнение настоящих с другими данными служило тестом факторизации и предельной фрагментации. Полные сечения для образования остатков в обеих реакциях показывают, что остаточные ядра возникают в центральных соударениях.

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Nuclear Reaction of Medium and Heavy Target Nuclei with High-Energy Projectiles. Fragmentation of ^{197}Au by 3.65 AGeV ^{12}C-Ions and 3.65 GeV Protons

The cross sections of a number of Target fragmentation products formed in nuclear reactions of 3.65 AGeV ^{12}C-ions and 3.65 GeV protons with ^{197}Au have been measured. The measurements have been done by direct counting of irradiated targets with Ge(Li) gamma-ray spectrometers. Comparisons between these and other data been used to test the hypotheses of factorization and limiting fragmentation. The total cross section for residue production in both reactions indicates that target residues are formed mainly in central collisions.

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

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