PROPERTIES OF HOT NUCLEI ON RELATIVISTIC BEAMS OF THE NUCLOTRON/NICA COMPLEX.

(in the framework of topic 02-1-1087-2009/2020)

FASA Project

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The aim of the Project is to study the properties of hot nuclei (with an excitation energy of more than 3 MeV per nucleon). Hot nucleus, expanding due to thermal pressure, falls into the region of phase instability (spinodal region). As a result of density fluctuations, a homogeneous nuclear system disintegrates into an ensemble consisting of fragments and nucleons. The process is interpreted as a “liquid-gas” phase transition occurring at a temperature 5-7 MeV.

The study of the disintegration process of hot nuclei allows obtaining experimental information on the spinodal state of nuclear matter. The relevance of research is doubtless, because we are talking about the experimental study of nuclei with extreme excitation energy (comparable to the total binding energy of the nucleus). Experiments are carried out using relativistic beams of light ions from Nuclotron and 4π–FASA device.

The project is based on a huge methodological experience of the team gained in the research of nuclear multifragmentation in relativistic light ions beams in the last decade.

JUSTIFICATION

The aim of the Project is to study the properties of hot nuclei (with excitation energy more than 3 MeV per nucleon) produced in collisions of light relativistic ions with heavy targets. Hot nucleus, expanding due to thermal pressure, falls into the region of phase instability (spinodal region). As a result of density fluctuations, a homogeneous nuclear system disintegrates into an ansemble consisting of fragments and nucleons. The main goal is *the study of the space-time characteristics of hot nuclei and collective flows* formed in these interactions.

Experimental procedure based on the 4π-device FASA, including 30 dE-E telescopes for the detection of charged particles. Each telescope consists of a cylindrical ionization chamber (dE) and Si(Au) detectors to measure the total energy of the fragment.

Figure 1 shows all device with a set of telescopes in the foreground. Target (gold film thickness of 1.5 mg/cm^2) is located in the center of the vacuum chamber.

The main part of the total solid angle of the device detector is the fragments multiplicity detector which consists of 58 CsI(Tl) scintillators (36 mg/cm^2 thickness). Multiplicity selection allows you to “change” the average excitation energy of the fragmenting nucleus. In addition, the detector gives spatial picture of fragments in the event. Figure 2 shows a schematic view of data collection in the VME standard. There is multi-event buffer - dual port memory which can store up to 32 events. Recording takes place in the “event-by-event” using a personal computer with Intel Xeon processor. In this Project, we plan move to a VME standard our trigger system.

Figure 3 shows the typical two-dimensional spectrum (dE-E) of the telescopes where clearly visible areas corresponding fragment registration from helium to magnesium. Thirty telescopes allow spectroscopic measurement and correlation measurement in respect to relative angles (from 10° to 180°) or relative velocities.

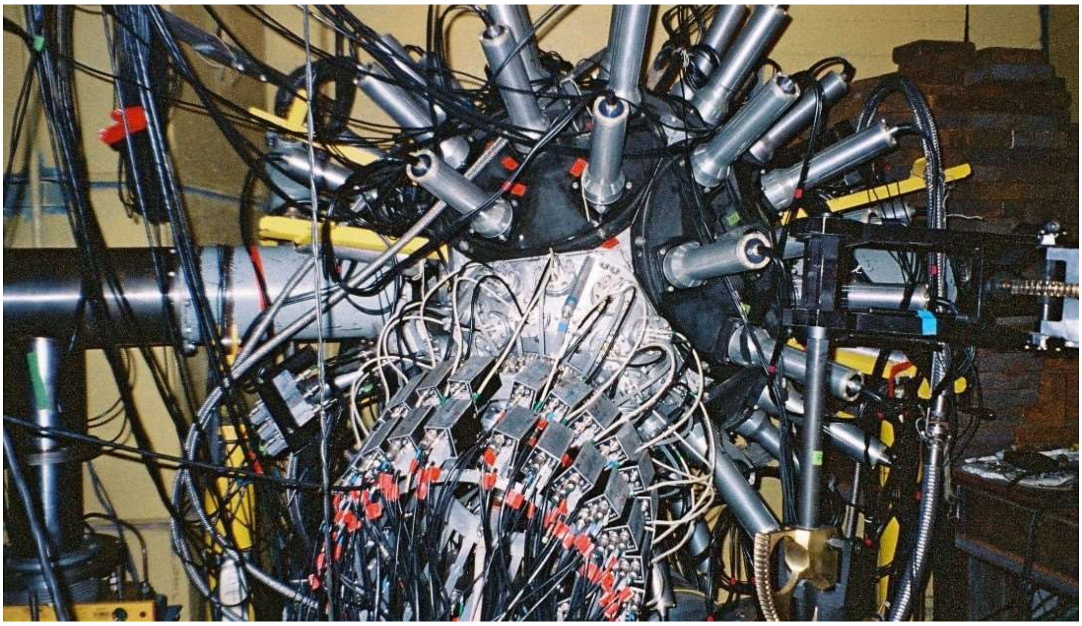

Fig.1. FASA device on the Nuclotron beam. Electronics of dE-E telescopes in the foreground. Aluminum cylinders – the multiplicity detectors of fragments.

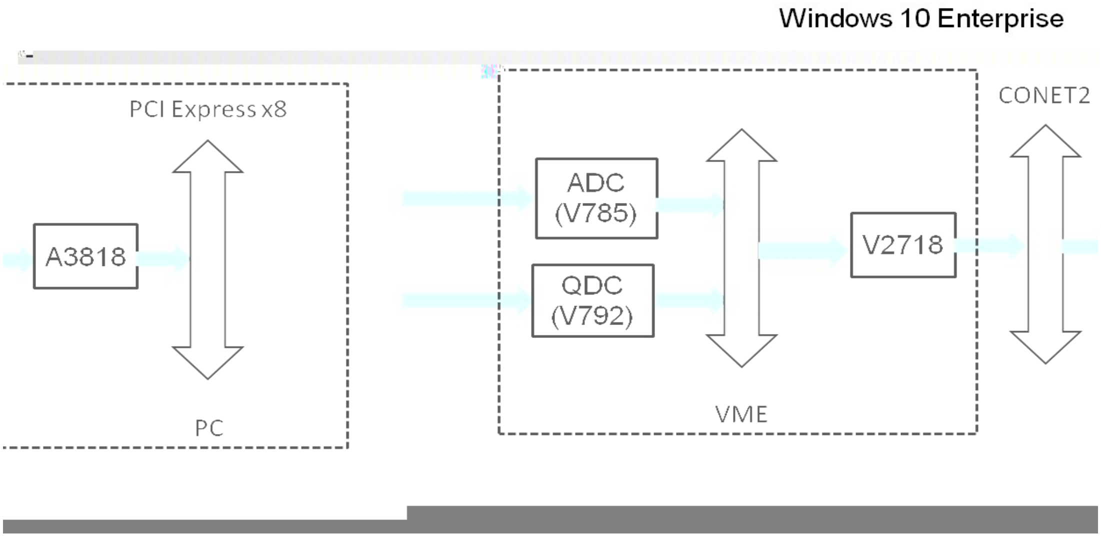

Fig.2. Schematic view of data collection:

ADC – multievent analog to digital conversion channels, *QDC* – multievent charge to digital conversion channels, *V2718* – VME-PCI optical link bridge, *A3818* – PCI express optical link.

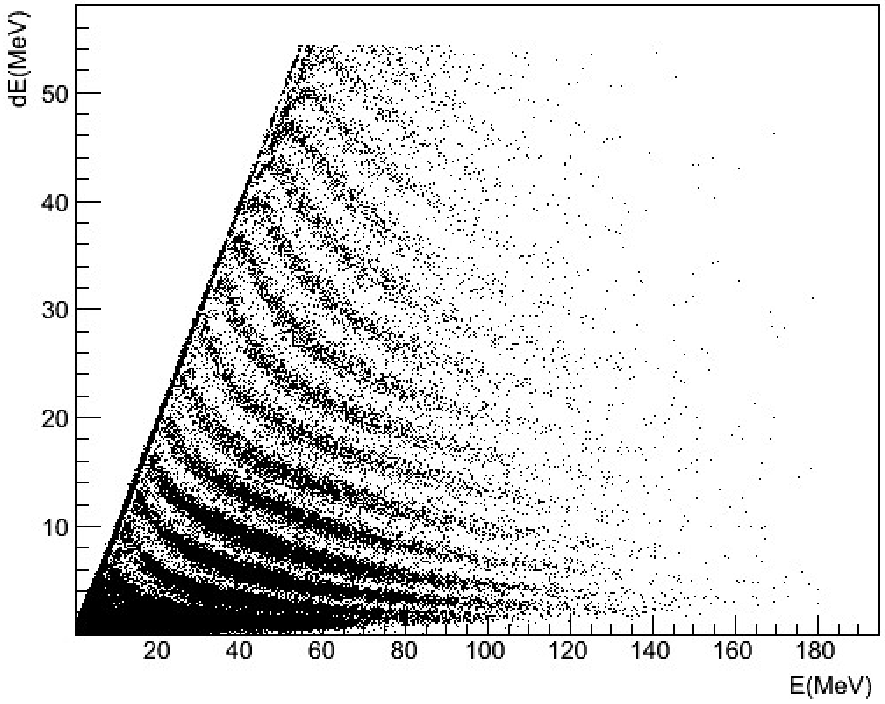

Fig.3. Two-dimensional spectrum of fragments produced in *d*(4.4 GeV) + Au reaction.

THE MAIN EXPERIMENTAL RESULTS.

1. First proved experimentally that for hot nuclei (with an excitation energy of more than 3 MeV per nucleon) produced by relativistic light ion beams (protons, deuterons, α-particles), evaporation of particles is replaced by a process of thermal nuclear multifragmentation. This – new type of decay of excited nuclei when occurs multiple emission of intermediate mass fragments. They – heavier than α-particles, but lighter fission fragments ($2 < Z < 20$).
2. This process of "explosive" type occurring during time 10^{-22}s (40 fm/c). So short time is measured for the first time in the FASA group via fragments correlation analysis in respect to relative velocity.
3. For the first time experimentally shown that multibody decay of hot nuclei occurs after their expansion due to the thermal pressure. It was found that the process of thermal multifragmentation has two characteristic volumes. The first volume $V_t \approx 3V_0$ corresponds to the time of fragments formation. This configuration is similar to "saddle" point of fission. The second characteristic configuration is similar to the breakup point in the normal fission. It corresponds to the volume $V_f \approx (5.0 \pm 0.5)V_0$ filled with separated fragments.
4. The typical process temperature (4 – 6 MeV) is considerably less than the critical temperature T_c for the phase transition "liquid-gas". The value of T_c is defined by the analyzing of charge distribution of fragments generated in p(8.1 GeV) + Au collisions: $T_c = (17 \pm 2)$ MeV. Note that for many years was a dramatic difference between this value and that obtained by L. Moretto (LBL, Berkeley, USA). Recently, this contradiction was resolved in favor of out values.
5. Our works have shown for the first time radial flow in the hot nuclei due to the thermal pressure. The analysis of the collective energy of fragments with their charge gives an unexpected and interesting information about the spatial configuration of the system at the time of the breakup. Proved that the heavier fragments are produced closer to the center of the system due to the inhomogeneous density distribution in a highly excited nucleus.
6. In case of relativistic light ions and gold target there is at least "kinetic equilibrium" of the system is achieved before fragmentation take place is found in the results of rapidity analyses.
7. This year, a paper (Proceedings of the Academy of Sciences, physical series (2018) Vol. 82, No. 6, 711) has been published which shows that the hot target spectator formed during interaction ^{4}He(4 GeV) + Au decays with a lifetime $\tau = 47 \pm 12$ fm/c, which corresponds to simultaneous multibody decay. Figure 4 shows correlation function for this interaction.

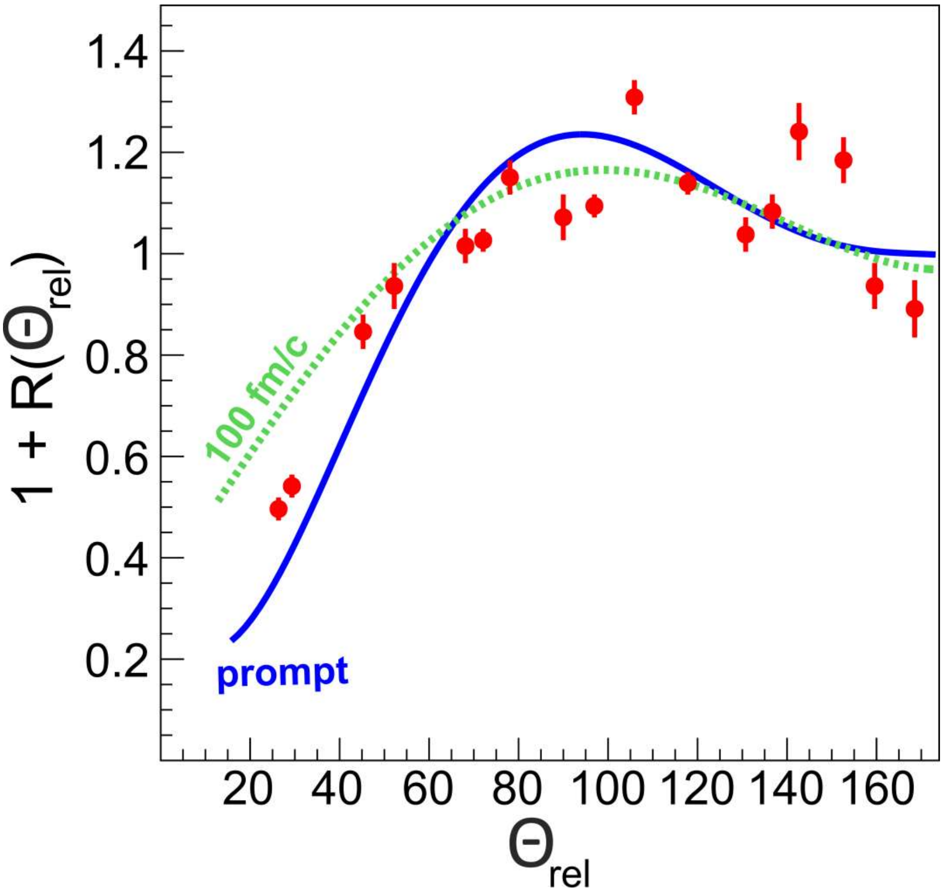

Fig.4. Relative angle correlations functions for fragments ($2 < Z < 20$) produced in ^{4}He(4 GeV) + Au reaction. Points – experimental data. Solid line – INC+SMM calculations with prompt secondary disintegration. Dotted line corresponds to INC+SMM calculations with mean time of secondary disintegration 100 fm/c.

It is known that a very effective way to get hot nuclei are reactions produced by heavy ion beams [1-4]. However, this warming is accompanied by the excitation of collective degrees of freedom: nuclei are rotated, compressed, deformed. The study of these dynamic effects is interesting in itself. However, the collective effects make it difficult to obtain information on the thermodynamic properties of hot nuclear systems.

The picture is much easier when using relativistic beams of light particles. In this case, the collective degrees of freedom are weakly excited and excitation energy of nuclei is almost thermal. This gives grounds to tell about thermal multifragmentation in case of reactions of fast relativistic particles with heavy targets. The characteristics of this process are completely determined by the excitation energy. Light relativistic beams give a unique opportunity to study the thermodynamics of hot nuclear system. Note that detailed information about the process multifragmentation has important astrophysical applications [5], as the temperature on the surface of neutron stars is close to temperature in multibody decay. Precise knowledge of the nuclei behavior with low density and temperature 5-10 MeV is essential for understanding the dynamics of supernova.

FASA collaboration successfully studied the “statistical” properties of hot nuclei, using Moscow-Copenhagen statistical model of multifragmentation in data analysis. This model has been significantly modified on base of our experimental data. A further object of the research is the *dynamics* of the process of multiple emission of fragments. In case of transition from proton beams to deuterons, α-particles, carbons, we observe a transition from a pure statistical process to processes in which dynamic effects begin to appear. We see that the fragments from target spectator have additional energy, which is provided by the collective flow. Therefore, the objectives of the Project is:

1. radial flow measurement as a function of the fragment charge;
2. measuring the velocity of the source and understanding the degree of equilibration involved in the disassembly process;
3. new measurements of the correlation function with respect to the relative angles of the intermediate-mass fragments for the collisions of relativistic light ions with a gold target.

EXPECTED RESULTS.

1) Measuring the magnitude of the radial flow as a function of the fragment charge will give information about the distribution of fragments in the freeze-out volume.
2) Analysis of the invariant cross sections as a function of the longitudinal and transverse velocity of the fragment will allow us to determine degree of equilibration in a reaction, as well as determining the average source velocity.
3) Carrying out new measurements of the correlation function for the relative velocity (relative angles) intermediate-mass fragments ($2 < Z < 20$) for collisions of relativistic light ions with heavy targets. This will provide detailed information about the average time of system disintegration and about system configuration at the break-up time

The results will be sent to refereed journals for publication.
One, two publications per year.

PUBLICATIONS OF FASA GROUP FOR THE LAST THREE YEARS.

1. «Source velocity at relativistic beams of ^{4}He», Bulletin of the Russian Academy of Sciences. Physics (2016) Vol. 80, No. 3, 330;
2. «Study of the source velocity with the light relativistic ions at CBM», CBM Progress Report 2016 (2017) 187;
3. «Source velocity at relativistic beams of ^{4}He», J. Astrophys. Aerospace Technol. (2017) Vol. 5, No. 2, 48;
4. «Time scale of the thermal multifragmentation in ^{4}He(4 GeV) + Au collisions», Proceedings of the Academy of Sciences, physical series (2018) Vol. 82, No. 6, 711;
5. «Time scale of the thermal thermal multifragmentation in ^{4}He + Au at FAIR energies», CBM Progress Report 2017 (2018) 162;
6. «Radial flow in the interaction of relativistic deuterons with a gold target», LXVIII International conference “NUCLEUS 2018”, book of abstracts, July 2-6 (2018) Voronezh, 73.

The results of the work were reported at conferences:

1. International conference **NUCLEUS-2017.**
   September 12-15, 2017, Almaty, Republic of Kazakhstan;
2. 2nd International Conference on Atomic and Nuclear Physics.
   November 08-09, 2017 at Las Vegas, USA;
3. LXVIII International conference **NUCLEUS-2018.**
   July 2-6, 2018, Voronezh, Russia.

TIME SCALE OF THE PROJECT

1. Update trigger system FASA device from CAMAC to faster VME system: 2019-2021;
2. Experiments with the FASA device on the Nuclotron beams of relativistic light ions: 2020-2021;
3. Analysis of the experimental data using both statistical and dynamic models: 2019-2021;
4. Publication of the results in the form of articles in refereed journals (one or two publications a year): 2019-2021;

There are no risks in the implementation of the Project, as there is a working device and working people.

REFERENCES.

1. - N. Buyukcizmeci et al., J. Phys. G: Nucl. Part. Phys. 39 (2012) 115102 (10pp)

2. - M. Fidelus et al., Phys. Rev. C 89, 054617 (2014)

3. - H. Imal et al., Phys. Rev. C 91, 034605 (2015)

4. - S. Barlini et al., Phys. Rev. C 87, 054607 (2013)

5. - A.S. Botvina and I.N. Mishustin, 2010, Nucl. Phys. A 843 98.

Form No. 26

Schedule proposal and resources required for the implementation of the Project

FASA
(Project title)

Expenditures, resources, financing sources			Costs (k$) Resource requirements	Proposals of the Laboratory on the distribution of finances and resources			
				1st year	2nd year	3rd year	4th year
Expenditures		VME blocks	30	10	10	10	
		Construction/repair of premises	-	-	-	-	
		s/b detectors	6	2	2	2	
Required resource	Standard hour	Nuclotron accelerator	300 hours	0	150	150	
Financing sources	Budgetary resources	Budget expenditures including foreign-currency resources.	36	12	12	12	
	External resources	RFBR grant	45	15	15	15	

PROJECT LEADER

Form No. 29

Estimated expenditures for the Project PROPERTIES OF HOT NUCLEI ON RELATIVISTIC BEAMS OF THE NUCLOTRON/NICA COMPLEX

(full title of Project)

Expenditure items	Full cost	1st year	2nd year	3rd year…
Direct expenses for the Project				
1. Accelerator Nuclotron	300 hours	0	150	150
2. VME blocks	30 k$	10	10	10
3. s/b detectors	6 k$	2	2	2
4. Travel allowance, including:	42 k$	14	14	14
a) non-rouble zone countries	36	12	12	12
b) rouble zone countries	6	2	2	2
c) protocol-based				
Total direct expenses	78 k$	26 k$	26 k$	26 k$

PROJECT LEADER

LABORATORY DIRECTOR

LABORATORY CHIEF ENGINEER-ECONOMIST