Краткие сообщения ОИЯИ №3[60]-93 *JINR Rapid Communications No.3[60]-93*
УДК 539.172.8

EXPERIMENTS ON RELATIVISTIC NUCLEAR PHYSICS IN BEAMS OF DUBNA SYNCHROPHASOTRON AND NUCLOTRON

A.M.Baldin, A.I.Malakhov

The programme of the experiments on relativistic nuclear physics at the Dubna Synchrophasotron and the new superconducting accelerator Nuclotron, is reviewed. The main goal of the experiments is the study of the manifestation of the quark-gluon degrees of freedom in nuclei. The beam energies of both accelerators exceed the energy at which the asymptotic regime sets ($0.3 \div 4.5$ AGeV). It makes possible to study practically all the characteristics of strongly excited nuclear matter. The project of the SPHERE 4π spectrometer, at which the first results have been obtained, is given in more detail.

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

Эксперименты по релятивистской ядерной физике в пучках дубненского Синхрофазотрона и Нуклотрона

А.М.Балдин, А.И.Малахов

Дан обзор программы экспериментов по релятивистской ядерной физике на Синхрофазотроне Дубны и новом сверхпроводящем ускорителе Нуклотрон. Главная цель экспериментов — поиск проявления кварк-глюонных степеней свободы в ядрах. Энергия пучков обоих ускорителей соответствует энергии выхода на асимптотический режим 0,3—4,5 А ГэВ. Это позволяет изучать практически все характеристики сильновозбужденной ядерной материи. Проект СФЕРА 4π-спектрометра, на котором получены первые результаты, представлен более подробно.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

1. Relativistic Nuclear Physics

Relativistic nuclear physics deals with the study of processes in which the constituents of nuclear matter move with relative velocities close to the velocity of light. The quantitative criteria of this closeness and the classification of nuclear interactions are presented below on the basis of a relativistic invariant approach [1] to the description of hadronic processes.

In this approach, the multiple particle production processes proceeding in collisions of particles (or nuclei) I and II:

$$I + II \rightarrow 1 + 2 + 3 + \ldots \tag{1}$$

are described in the velocity space $u_i = p_i/m_i$, where p_i are the four-momenta of particles involved in the reaction: $i = I, II, 1, 2, 3, \ldots$, their masses. The components

$$u_i^0 = \frac{E_i}{m_i};\quad u_i^x = \frac{p_i^x}{m_i};\quad u_i^y = \frac{p_i^y}{m_i};\quad u_i^z = \frac{p_i^z}{m_i}$$

are regarded as the coordinates of a point in a four-dimensional space (the end point of the four-vector).

The approach enables us to use all the available experimental information on the basis of the methods of self-similarity, imcomplete self-similarity, automodelity and intermediate asymptotics. Employing this method, it was found to be possible to answer the following questions:

- How to describe the states of strongly excited nuclear matter in terms of observable dimensionless quantities?
- Can anything like equilibrium of excited matter be reached in nuclear collisions?
- To what extent the quasi-stationary states of strongly excited matter are due to color degrees of freedom? Is it possible to describe them on the basis of QCD?
- How to determine the conditions for which nucleons or, in general, hadrons lose their identity so that the subnucleonic degrees of freedom play the dominant role in nuclear matter?

The approach makes it possible to:

i) classify hadron and nucleus interactions;

ii) find the laws describing multinucleon interactions of subthreshold and cumulative particle production [2,3];

iii) check the phenomenological theories formulated in terms of macroscopic variables (energy density, temperature, pressure, and so on).

Multiple particle production processes are described with the aid of relativistic invariant dimensionless quantities

$$b_{ik} = -\left(\frac{p_i}{m_i} - \frac{p_k}{m_k}\right)^2 = -(u_i - u_k)^2 = 2[(u_i u_k) - 1]. \tag{2}$$

In addition to the hitherto used reasons of dimensionality and invariance, we utilize a hypothesis that when certain $b_{\alpha\beta}$'s tend to infinity the cross sections possess a definite asymptotic behavior. From the mathematical point of view, the self-similarity principle for relativistic invariant distributions (cross sections) is formulated as follows [4]:

$$W(b_{\alpha k}, b_{\alpha\beta}, b_{\beta k},\dots) = \frac{1}{b^{n}_{\alpha\beta}} \cdot W^{1}\left(b_{\alpha k}, x_k = \frac{b_{\beta k}}{b_{\alpha\beta}},\dots\right). \qquad (3)$$

W^1 seems to be independent of $b_{\alpha\beta}$ and has self-similarity with respect to this variable. The self-similarity parameter x_k at $b_{\alpha\beta} \to \infty$ turns into the well-known light cone variable. The law (3) is valid with a definite accuracy and in definite limits of change of the variable $b_{\alpha\beta}$. Therefore the appropriate behavior is called intermediate asymptotics. It is easier to determine the quantities n from models or equations than to find general solutions.

As experiments show, the invariant distributions (cross sections) $W(\dots, b_{ik},\dots)$ possess universal properties and are very important when planning experiments. A special case $\alpha = I, \beta = II$ and $n = 0$ is equivalent to the phenomenon of limiting fragmentation [5].

$$E_1 \frac{d\sigma}{d\mathrm{p}_1} = F(b_{I\,II}, b_{I1}, b_{II1})|_{b_{I\,II} \to \infty} \to F\left(b_{II1}, x_1 = \frac{b_{I1}}{b_{I\,II}}\right) =$$
$$= \frac{2}{m_1^2} \cdot \frac{d^2\sigma}{db_{II1}dx_1} = \varphi(\mathrm{p}_1). \qquad (4)$$

Of two self-similarity parameters b_{II1} and x_1 only the latter is scale invariant. Hence, it follows that scale invariance is a particular case of self-similarity for fixed b_{II1}. In 1971 [6] it was suggested that scale invariance shows a local character of interactions, when they proceed at distances much smaller than characteristic nuclear sizes (nucleon form factors, internucleon distances). In terms of the measurable quantities, it means that for relative nuclear velocites $b_{I\,II}$ much larger than characteristic velocities of internal motions in hadrons the cross sections are no longer dependent upon $b_{I\,II}$. Experiments show that this regime is achieved for

$$b_{I\,II} \sim 5 \div 8$$

which corresponds to the kinetic energy of a nuclear beam of ~ 3.5 A GeV.

One of the most important conclusions obtained from works dealing with the analysis of multiple particle processes in the velocity space is the conclusion about the existence of two characteristic scales (correlation lengths): 1) $b_{ik} \sim b_1 \approx 10^{-2}$, nuclear scale, and 2) $b_{ik} \sim b_2 \sim 1$ quark scale [7].

We suggest to perform the classification of relativistic nuclear collisions on the b_{ik} basis in the following manner:

i) The domain $b_{ik} \sim 10^{-2}$ corresponds to the interaction of nuclei as weakly bound systems consisting of nucleons. This is the domain of classic nuclear physics.

ii) The domain $0.1 \leq b_{ik} < 1$ is an intermediate one. Here the quark degrees of freedom are important in rebuilding hadron systems.

iii) In the region $b_{ik} >> 1$ hadrons lose their meaning of the quasi-particles of nuclear matter and nuclei should be considered as quark-gluon systems. The physical meaning of the criterion $b_{ik} >> 1$ is as follows; at rather large relative velocities the interaction between the quarks entering object i and those entering object k becomes so weak that in can be treated by perturbation theory at a constituent level.

2. Accelerator Centre of the Laboratory of High Energies (LHE)

Since 1957 the major research facility of LHE has been the Synchrophasotron which provides nuclear beams shown in Table 1.

At present, feasibility studies are being performed for the possible concurrent use of heavy-ion beams (0.3 + 4.5 A GeV), polarized and aligned deuteron beams and secondary beams (neutrons, pions). Running time is 4000 h per year. Heavy-ion acceleration takes about 70 percent of the beam time. The possibilities for research will be substantially expanded after putting the world's first superconducting accelerator for relativistic nuclei, Nuclotron, into operation.

A schematic view of the LHE accelerator centre and experimental area are given in Fig.1. The main parameters of the accelerators are given in Table 2.

The classification of relativistic nuclear collisions on the b_{ik} basis and eqs.(3,4) shows that at an energy of 6 A GeV, the Nuclotron beams can be used for studying practically all the characteristics of strongly excited nuclear matter, including their asymptotic values. The commissioning effort of the Nuclotron has begun and the beam's orbit around the superconducting was successfully completed in March 1993.

Table 1

Beam	Intensity (particle per cycle)		
	Synchrophasotron (now)	Nuclotron (plan)	
		1st stage	2nd stage
p	$4\cdot10^{12}$	10^{11}	10^{13}
n	10^{10}	$5\cdot10^{9}$	10^{13}
d	$1\cdot10^{12}$	$5\cdot10^{10}$	10^{13}
d↑	$1\cdot10^{9}$	$3\cdot10^{8}$	10^{11}
^{3}He	$2\cdot10^{10}$		
^{4}He	$5\cdot10^{10}$	$5\cdot10^{9}$	$2\cdot10^{12}$
^{7}Li	$2\cdot10^{9}$	$2\cdot10^{10}$	$5\cdot10^{12}$
^{12}C	10^{9}	$7\cdot10^{9}$	$2\cdot10^{12}$
^{16}O	$5\cdot10^{7}$		
^{20}Ne	10^{4}	10^{8}	$5\cdot10^{9}$
^{24}Mg	$5\cdot10^{6}$	$3\cdot10^{8}$	$5\cdot10^{11}$
^{28}Si	$3\cdot10^{4}$		
^{40}Ar	—	$3\cdot10^{7}$	$2\cdot10^{9}$
^{56}Fe	—	—	10^{11}
^{65}Zn	—	—	$5\cdot10^{10}$
^{84}Kr	—	$2\cdot10^{7}$	$5\cdot10^{8}$
^{96}Mo	—	—	$1\cdot10^{10}$
^{119}Sn	—	—	$2\cdot10^{8}$
^{131}Xe	—	10^{7}	$2\cdot10^{8}$
^{181}Ta	—	—	$1\cdot10^{8}$
^{238}U	—	$3\cdot10^{6}$	10^{8}

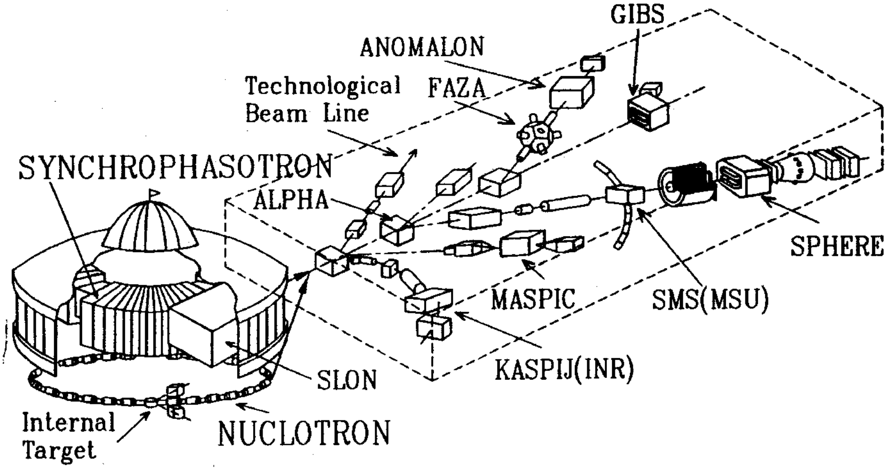

Fig.1

Table 2

Parameters		Nuclotron	Synchrophasotron
Energy (max)	A GeV	6	4
Repetition rate	p.p.s	0.5—1.0	0.1
Extraction time	s	10	0.5
Intensity	p.p.c	see Table 1	
Vacuum	Torr	10^{-10}—10^{-11}	10^{-6} (10^{-7})
Consumed power	MW	1.5	8
Mac. magnetic field in dipoles	T	2.2	1.1
Tunnel circumference	m	250	
SC dipole magnets	N	96	
SC quadrupole lenses	N	64	
Dipole aperture	mm	110	

3. Research Program of Laboratory of High Energies (LHE) of JINR

The LHE experimental programme addresses to a broad range of forefront questions in relativistic nuclear physics and includes five principal areas of investigation:

- Spin observables
- Collective states and multiple particle production reactions in the collision of nuclei
- Multinucleonic interactions, subthreshold and cumulative processes
- Exotic and multiquark systems
- Jets, cumulative jets, nuclear reactions involving charmed quarks.

The main nearby goals are:

1. Experiments on relativistic nucleus-nucleus collisions

(a) search for manifestations of quark-gluon degrees of freedom in collisions of relativistic nuclei

(b) spin effects in light nuclei.

2. Development and upgrade of the LHE accelerator complex

(a) commissioning of the Nuclotron ring for internal target experiments

(b) upgrade of the injection and external beam transport systems.

3. Applied research program

(a) image detectors for applications in biology, crystallography, medicine and industry

(b) development of microstrip silicon detectors, new scintillator materials and electronics

(c) application of the particle channeling phenomena for beam extraction and transportation

(d) neutron generation in nuclear beams.

Presently, about 500 researchers representing more than 100 institutions are involved in experiments at the Synchrophasotron. All the user groups working at the Synchrophasotron have suggested their research programmes for the Nuclotron.

First priority directions are the study of multiple production in 4π-geometry and the construction of SPHERE Spectrometer, the first line experiments on the Nuclotron and the search for non-nucleon degrees of freedom and spin effects in few nucleon systems.

Fig.2 shows a program of the investigations on 4π detectors of the LHE:

- experiments on a cumulative particle production and correlated phenomena (SPHERE spectrometer)
- search for a manifestation of quark-gluonic degrees of freedom in collisions of relativistic nuclei and phase transitions in nuclei (SPHERE, FAZA, SYaO)

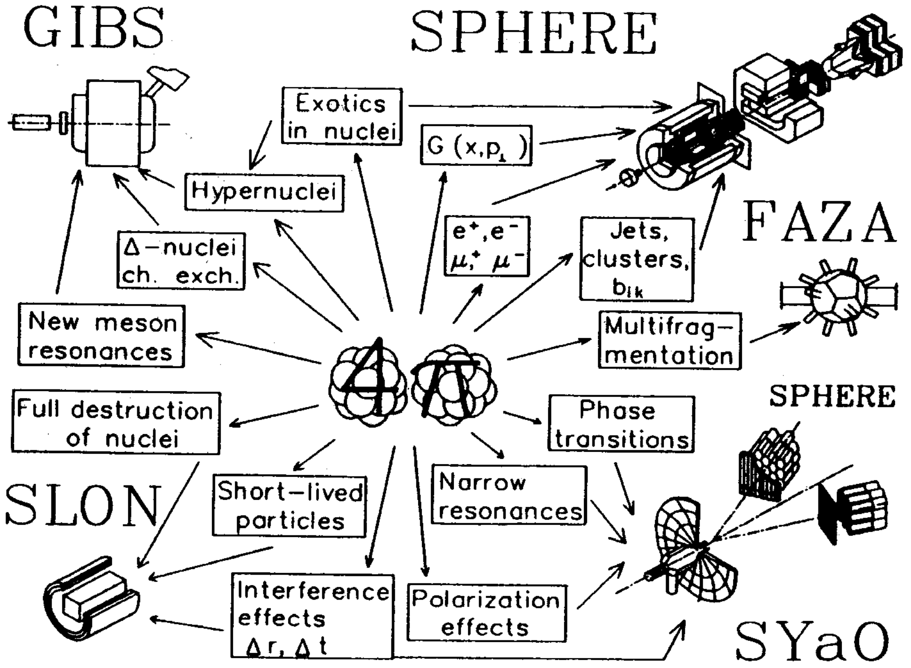

Fig.2

- a study of nuclear multifragmentation processes and a hyper- and Δ-nuclei production (SLON, FAZA, GIBS)
- Nuclotron internal target experiments: the two-arm EM calorimeter (SPHERE) and the intermediate mass fragment spectrometer (SYaO).

The basic detecting part of the GIBS is a Ne-filled 2×1×0.6 m streamer chamber in a magnetic field of 0.9 T.

The SLON setup will provide new possibilities for the experimentalists with nuclear emulsion irradiation in high pulsed magnetic fields (~ 50 T).

The FAZA setup is a fragment multiplicity detector, consisting of 55 scintillation counters made of thin CsI(Tl) films, time-of-flight telescopes and a large area position-sensitive parallel-plate avalanche chamber.

The SYaO setup consists of the telescopes of semiconductor and scintillation detectors, exposed to the internal target of the accelerator.

Fig.3 shows a schematic structure of the search for non-nucleon degrees of freedom and spin effects in few nucleon systems at the LHE.

The ALPHA-INESS, ANOMALON and MASPIK setups are magnetic spectrometers on the basis of MWPC detectors.

The DISK is a magnetic spectrometer with the ΔE, ToF scintillation counters and Cherenkov detectors.

The disposition of the experimental setups you can see on fig.1.

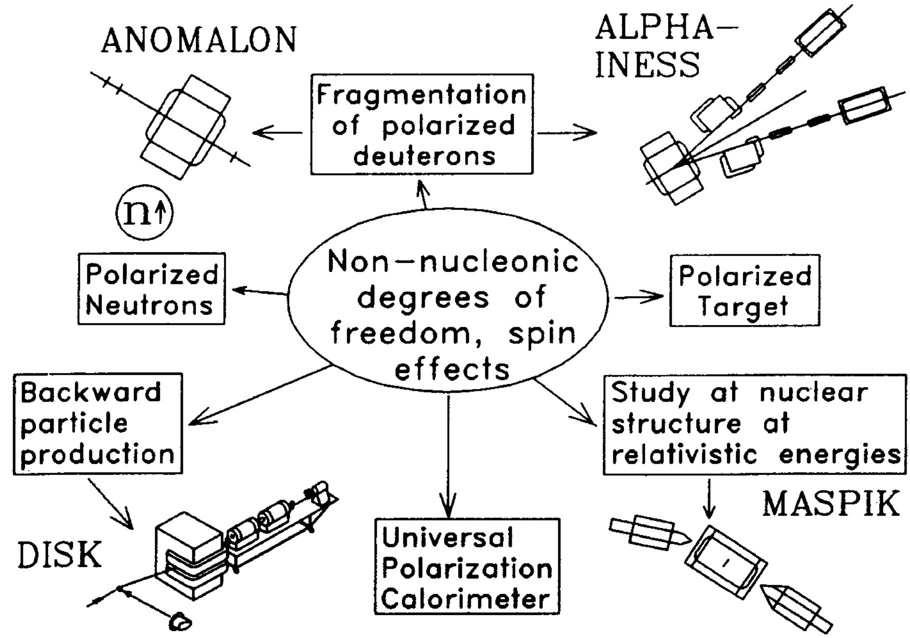

Fig.3

4. Investigation of Interactions of Relativistic Nuclei at the SPHERE 4π Detector

SPHERE (fig.4) is a 4π detector designed to obtain as much detailed information as possible on multiple cumulative particle production at the JINR Synchrophasotron and Nuclotron [8].

The spectrometer contains three major components: a central detector for the detection of particles from the target-nucleus fragmentation region, a forward detector covering the projectile-nucleus fragmentation region, and a target for the generation of muon pairs with a beam absorber. The central detector is used for the momentum and angle analysis of secondary particles produced in the target positioned in the centre of the superconducting solenoid. A uniform 1.5 Tesla field along the beam is produced in a superconducting coil 2.2 m in diameter and 2.6 m long. Particles at small angles (< 5°) are detected by the forward magnetic spectrometer. The detector system consists of electromagnetic calorimeters, dE/dx and time of flight scintillator hodoscopes and Cherenkov counters identifying γ, ε, π, K, p, d, t, α, etc. The tracks are measured with MWDC's and MWPC's. The

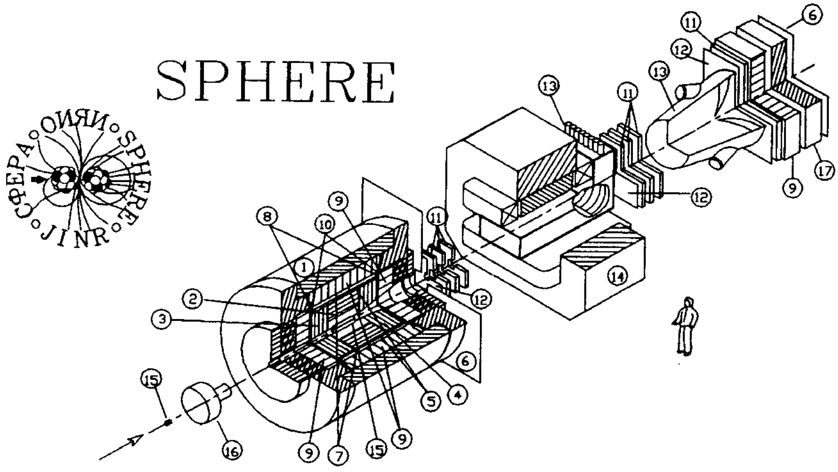

Fig.4. 1 — superconducting solenoid with iron yoke; 2 — central drift chamber; 3 — backward drift chambers; 4 — forward proportional chambers; 5 — cylindrical scintillation hodoscope; 6 — muon scintillation hodoscopes; 7 — cylindrical Cherenkov hodoscope; 8 — forward and backward Cherenkov hodoscopes; 9 — electromagnetic calorimeters; 10 — forward and backward scintillation hodoscopes; 11 — proportional chambers; 12 — scintillation hodoscopes; 13 — threshold gas Cherenkov counters; 14 — dipole magnet ; 15 — targets; 16 — beam absorber; 17 — muon filter

beam intensities for the study of multiparticle production processes are $10^7\ s^{-1}$ and up to $10^{11}\ s^{-1}$ for dimuon production. A fast data acquisition system is based on VME, FASTBUS and CAMAC.

The status of the spectrometer SPHERE is as follows: the first line of the forward detector was in operation since 1990, and it is hoped that the 4π detector will be completed by the middle of 1996. The main problems to be solved are to investigate the reactions of the production of two and more particles in the resonance region (in particular, the production of vector particles in the cumulative region), to study the production of lepton pairs in collisions of relativistic nuclei, and to investigate spin effects in large transverse momentum reactions.

To describe the cumulative processes the law of conservation of four-momentum is written in the form:

$$(X_I P_I + X_{II} P_{II} - P_1)^2 = (X_I m_0 + X_{II} m_0 + m_2)^2,$$

were $X_I P_I$ and $X_{II} P_{II}$ are the fractions of the momenta of colliding nuclei

$$0 < X_I < A_I, \quad 0 < X_{II} < A_{II}.$$

P_I and P_{II} are the four-momenta per nucleon; m_0, the nucleon mass; m_2, the mass of additional particles which should be taken into account for the laws of flavor conservation to be fulfilled (for pions $m_2 = 0$). In earlier paper on the cumulative effect it was assumed $X_{II} = 1$ and for X_I (cumulative number) use was made of the expression:

$$X_I = \frac{(P_{II} P_1) + m_0 m_2 + (m_2^2 - m_1^2)/2}{(P_I P_{II}) - m_0^2 - (P_I P_1) - m_0 m_2}.$$

In the region of limiting fragmentation of nucleus I, for $(P_I P_1) \sim (P_I P_{II}) \to \infty$, X_I turns into the light cone variable, and the particle spectra 1 are described by the exponential of this variable.

In 1990 a beam dump experiment on production of low-mass cumulative muon pairs by 9.0 GeV/c deuteron beam was performed at the JINR Synchrophasotron by means of the forward detector of the SPHERE spectrometer [9]. The physical goal of the experiment was to estimate dimuon yield at the available experimental facility. The results were obtained under an assumption of $E \cdot (d\sigma/dp) \approx C_{\mu\mu} \cdot \exp(-X/0.12)$.

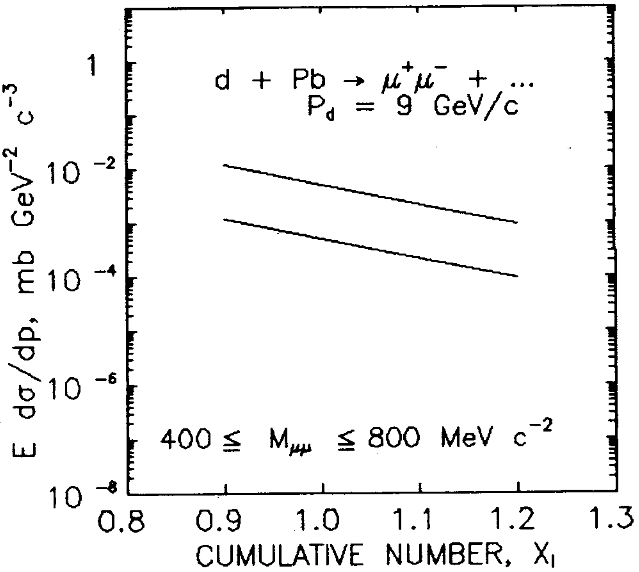

Fig.5

The upper (lower) threshold of the value of $C_{\mu\mu}$ was found to be 21 (2.1) mb·GeV^{-2}·c^3 for the region of $X_I \geq 0.9$ and $400 \leq M_{\mu\mu} \leq$ ≤ 800 MeV/c^2. Consequently, for a cumulative number $X_I = 1.2$ the value of $E \cdot (d\sigma/dp)$ is equal to 950 (95) nb·GeV^{-2}c^3 (fig.5).

In 1991 the power value of A dependence of the cross-section for 9.0 GeV/c deuteron fragmentation into cumulative pions was measured on carbon, aluminium, copper and lead targets for cumulative numbers within 0.8—1.2 [10]. In this interval the mean value of the A dependence power is equal to 0.27 ± 0.09 (fig.6). Hence the target atomic weight dependence significantly differs from the volume type.

For the ratio of the cross sections for lead and carbon (fig.7) we observe a weak X-dependence which is in correspondence with a limiting fragmentation picture of cumulative production.

Charged target fragmentation multiplicity distributions are shown in fig.8. Mean values as well as fractions of hard component ($P_T > 600$ MeV/c) show a weak dependence on the atomic weight of fragmenting nucleus [11].

In March 1992 the experimental data on cumulative pion production were acquired for a 9 GeV/c polarized deuteron beam bombarding polyethylene, carbon, tin and lead targets. A very preliminary analysis reveals the

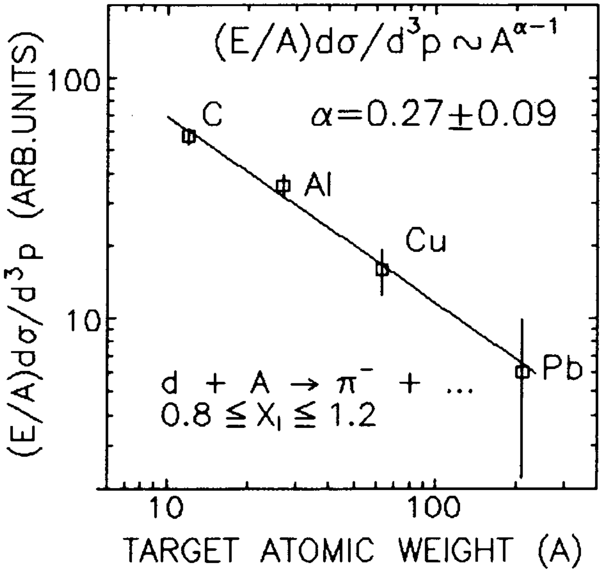

Fig.6

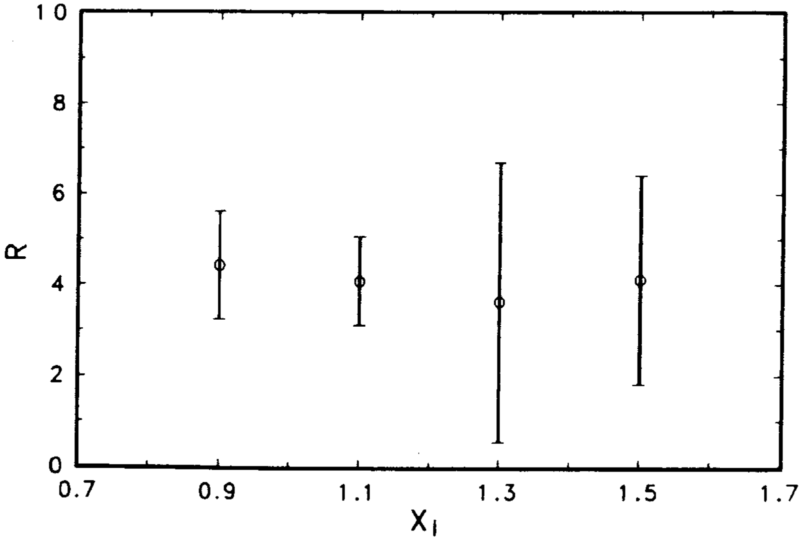

Fig.7

trand for a left-right asymmetry in the emission of particles accompaning the pion production at cumulative numbers 0.8—1.2, thus suggesting some spin effects in the cumulative productive processes under study.

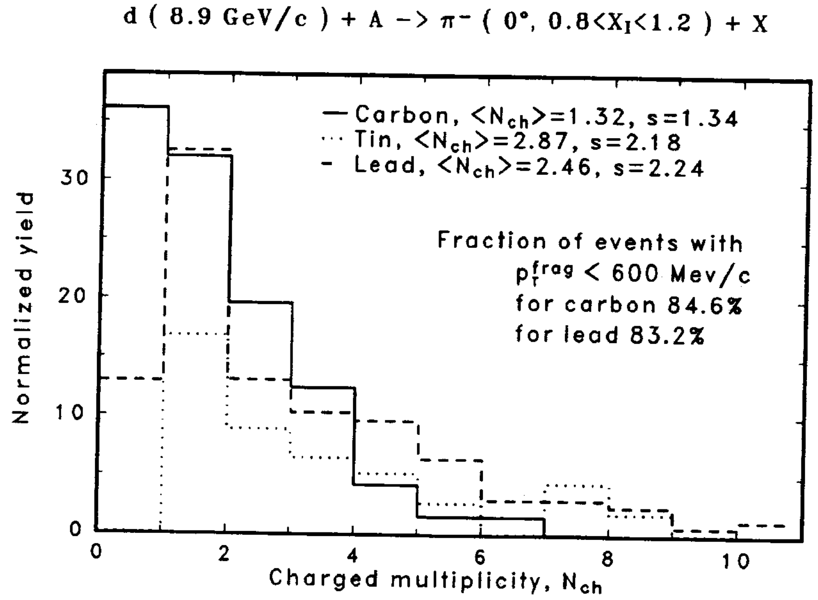
d (8.9 GeV/c) + A -> π^- (0°, $0.8<X_I<1.2$) + X

Fig.8

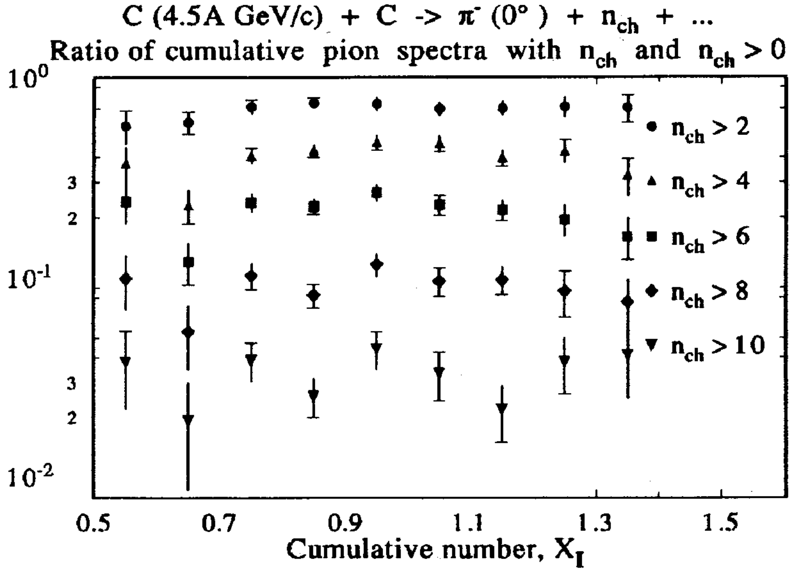
C (4.5A GeV/c) + C -> π^- (0°) + n_{ch} + ...
Ratio of cumulative pion spectra with n_{ch} and $n_{ch} > 0$

Fig.9

In October 1992 we had run in carbon beam. Figure 9 shows the raio of cumulative pion spectra for various multiplicities of the charged particles accompaning the pion cumulative production for carbon beam and carbon target. The weak X dependence indicates a weak influence of secondary interactions in nuclei.

5. The First Experiment in the Nuclotron Internal Beam

In the framework of SPHERE collaboration we have prepared two-arm electromagnetic calorimeter and nonmagnetic scintillation spectrometer for the first Nuclotron internal target experiment.

This setup includes (fig.10):

- a monitoring telescope consisting of scintillation counters
- two 1×1 m^2 scintillation hodoscopes
- 36-channels lead glass Cherenkov EM calorimeter
- $\Delta E - E$ and time-of-flight scintillation counters.

The first experimental programme includes:

- investigation of η-meson interaction on nucleons and nuclei
- study J/Ψ, ρ, ω, η, K-mesons near the threshold
- observation of lepton pairs
- study of narrow correlations of two protons

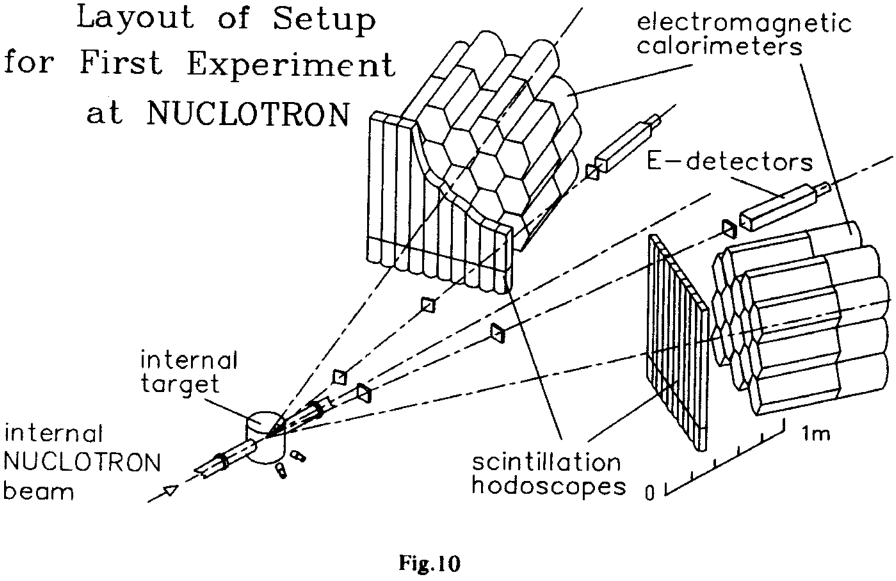

Fig.10

- investigation of the processes of nuclear collisions with $X_I > 1$ and $X_{II} > 1$ (double cumulative effect)

We plan to have the first run on the internal target of the Nuclotron in June—July'93.

6. Conclusions

From this report we conclude the following:

1. Presently some studies are being performed for the concurrent use of heavy-ion ($0.3 \div 4.5$ AGeV), polarized deuteron beams and secondary beams of the Synchrophasotron

2. The beam parameters of the novel superconducting ring Nuclotron will enable us to perform a detailed study of all global characteristics of extremely excited nuclear matter since for the Nuclotron $b_{I\,II} \approx 14$ (for the Synchrophasotron $b_{I\,II} \approx 9.7$).

3. The first results obtained in the Synchrophasotron beams with the SPHERE 4π spectrometer can be summarized as follows:
   - we have searched for the deuteron fragmentation into cumulative muon pairs and the deuteron and carbon fragmentation into cumulative pions
   - the muon pair production beyond the kinematic limit of nucleon-nucleon collisions has been observed
   - the power value of A-dependence of the cross-section for 4.5 GeV/A deuteron fragmentation into cumulative pions has been measured
   - the target atomic weight dependence significantly differs from the volume type dependence
   - the multiplicity of target nucleus fragmentation suggests a peripheral character of the process
   - the weak X-dependence of the ratio of cumulative pion spectra for various multiplicities of the charged particles accompanying the pion production favours the weak influence of secondary interactions in nuclei.

4. The first experimental facility in the Nuclotron internal beams has been prepared in the framework of SPHERE collaboration.

References

1. Baldin A.M. et al. — Zeitschrift für Physik, 1987, C33, p.363.
   Baldin A.M. — Preprint JINR, E1-92-487, Dubna, 1992.
2. Baldin A.M. — Doklady Acad. Nauk SSSR, 1975, 222, 5, p.1064; Baldin A.M. — Nucl. Phys., 1985, A447, p.203c; Baldin A.M. — Yadernaja Fizika, 1990, 52, 5(11), p.1427.

3. Baldin A.A. — JINR Rapid Communications No.3[54]-92, Dubna, 1992, p.27.
4. Baldin A.A., Baldin A.M. — JINR Rapid Communications 17-86, Dubna, 1986, p.19.
5. Benecke J. et al. — Phys. Rev., 1969, v.188, p.2159.
6. Baldin A.M. — Kratkije Soobshchenija FIAN, Moskva, 1971, p.35; Proc. Rochester Meeting APS/DPF, 1971, p.131; JINR Preprint P1-5819, Dubna, 1971.
7. Baldin A.M., Didenko L.A. — Fortschritte der Phys., 1990, v.38, p.261.
8. Malakhov A.M. — In: Proceeding of XII International Conference on Particles and Nuclei, PANIC XII, M.I.T., Cambrige, 1990. Contributed paper, p.X-26.
   Malakhov A.M. — In: Proceeding of International Conference on Nuclear and Particles Physics, Liverpool, April 8—11, 1991, p.44.
9. Afanasiev S.V. et al. — JINR Rapid Communication No.7[46]-90, Dubna, 1990, p.6.
   Afanasiev S.V. et al. — In: Proceeding of the Xth International Seminar on High Energy Physics Problems, Dubna, USSR, September 24—29, 1990, Editors A.M.Baldin, V.V.Burov and L.P.Kaptari, Singapore.
10. Afanasiev S.V. et al. — JINR Rapid Communication No.5[51]-91, Dubna, 1991, p.5.
11. Afanasiev S.V. et al. — JINR Rapid Communication No.1[58]-93, Dubna, 1993, p.21

Received on June 22, 1993.