Printed ISSN 1330–0016
Online ISSN 1333–9133
CD ISSN 1333–8390
CODEN FIZBE7

RELATIVISTIC NUCLEAR PHYSICS IN THE LABORATORY OF HIGH ENERGIES OF THE JOINT INSTITUTE FOR NUCLEAR RESEARCH (DUBNA)

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Received 5 November 2007; Accepted 7 May 2008
Online 20 June 2008

An overview of experiments with nuclear beams at the Dubna Nuclotron is given. Present status of the nuclear beams accelerated at the Nuclotron is shortly described. Some selected results obtained in the experiments performed with internal and extracted nuclear Nuclotron's beams at the Veksler and Baldin Laboratory of High Energies of the Joint Institute for Nuclear Research at Dubna during last years are presented. Future plans of the investigations are discussed.

PACS numbers: 11.55.Hx, 13.60.Hb, 25.20.Lj UDC 539.125
Keywords: proton, neutron, cross-section

1. *Introduction*

The energy interval of the Veksler and Baldin Laboratory of High Energies (VBLHE) superconducting accelerator Nuclotron (up to 4.3A Gev) is in the transition region from the effects of the nucleon structure of nuclei to the quark-gluon level of nuclear matter. A relativistically invariant description of multi-particle processes in relativistic 4-velocity space was suggested by A. M. Baldin [1]. This approach turned out to be very fruitful and made it possible to obtain a number of new properties of relativistic nuclear interactions. The process of interaction of two nuclei can be written as follows

$$I + II \to 1 + 2 + \dots , \tag{1}$$

where I and II are the interacting nuclei, and $1, 2, 3, \dots$ are the secondary particles.

Following this approach, relativistic invariant quantities $b_{ik} = -(u_i - u_k)^2$ were introduced, where $u_i = p_i/m_i$, $u_k = p_k/m_k$ are 4-velocities of the particles i and k,

$p_{i,k}$ and $m_{i,k}$ are their 4-momenta and masses. The distributions of the secondary particles as functions of b_{ik} have universal properties, which points to a common interaction mechanism on the quark-gluon level.

It was suggested that scale invariance shows a local character of interactions, when they proceed at distances much smaller than characteristic nuclear dimensions (nucleon form factor, internucleon distances) [2]. In terms of the measurable quantities, it means that for relative nuclear velocities b_{III} much larger than the characteristic velocities of internal motions in hadrons, the cross sections no longer depend on b_{III}. Experiments show that this regime is achieved for $b_{III} > 5$ which corresponds to the kinetic energy of a nuclear beam of $> 3.5A$ GeV [3].

The main branches of research at the VBLHE accelerator complex are the following

- study of spin physics at relativistic energies;
- hadron and nuclear structure at relativistic energies;
- investigation nonpertubative QCD efects in nuclei;
- applied research.

The VBLHE has international scientific cooperation with CERN, many physics centres in Russia, JINR member states, physics centres in the USA, Germany, France, Japan and in other countries.

2. *Nuclotron accelerator complex*

The accelerator complex at VBLHE is the basic facility of JINR. It produces beams of protons, polarized deuterons (as well as neutrons/protons) and multiply charged ions in the energy range up to $4.3A$ GeV. The accelerator complex of VBLHE includes:

- superconducting accelerator - Nuclotron;
- linac LU-20;
- electron beam source of highly charged ions;
- laser sources of light ions;
- polarized deuteron source;
- slow beam extraction system;
- internal target station;
- cryogenic facility;
- beam lines.

The intensities of extracted particle beams available now at the Nuclotron are shown in Table 1.

Recent progress in production of highly-charged intermediate-mass ion beams, such as Ar^{16+} and Fe^{24+}, at Nuclotron results mainly from the success of the design and application of a new EBIS-type ion source Krion-2, operationg in the string

TABLE 1. The intensities of the extracted Nuclotron beams.

Beam	Intensity (Particles per cycle)	Beam	Intensity (Particles per cycle)
p	$2 \cdot 10^{11}$	^{14}N	$5 \cdot 10^{7}$
d	$1 \cdot 10^{11}$	^{16}O	$1 \cdot 10^{9}$
Polarized d	$5 \cdot 10^{9}$	^{24}Mg	$3 \cdot 10^{8}$
^{4}He	$2 \cdot 10^{10}$	^{40}Ar	$2 \cdot 10^{8}$
^{7}Li	$2 \cdot 10^{9}$	^{56}Fe	$5 \cdot 10^{7}$
^{10}B	$5 \cdot 10^{7}$	^{84}Kr	$5 \cdot 10^{6}$
^{12}C	$1 \cdot 10^{10}$	–	–

mode [4]. This ion source, called ESIS (Electron String Ion Source), uses multiple longitudinal reflections of electrons in the drift space of the source.

Spill duration of an extracted beam of the Nuclotron has reached up to 10 seconds.

As an example, an event of interaction of ^{56}Fe ion of kinetic energy $E_{\rm kin} = 1A$ GeV with an emulsion nucleus is shown in Fig. 1.

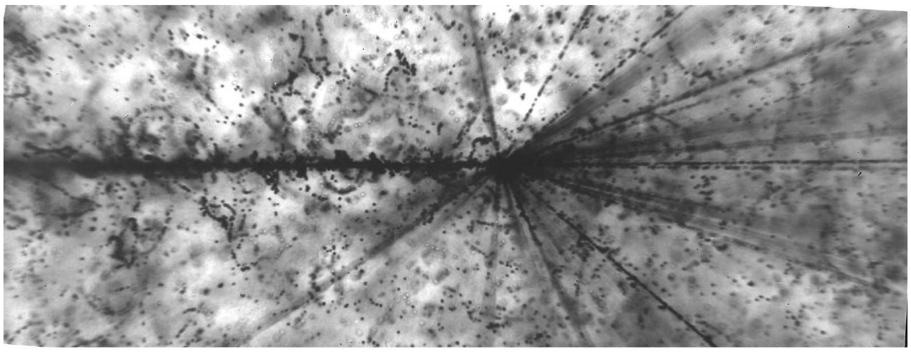

Fig. 1. Interaction of ^{56}Fe *ion with* $E_{kin} = 1A$ GeV *from Nuclotron with an emulsion nucleus.*

3. Some new physical results obtaned at the VBLHE accelerator complex

3.1. Search for η–nuclei

The study of in-medium properties of hadrons is one of the most interesting topics of contemporary nuclear physics. In particular, the in-medium meson masses depend on nuclear density and temperature. Theoretical estimations show that mesons masses are about $15 \sim 20\%$ lighter than the vacuum values already at the normal nuclear density. The structure of η-nucleus bound systems (η-mesic nuclei) is investigated as one of the tools to study in-medium properties of the N(1535) (S_{11}) resonance.

Here are presented the experimental results on the search for η-mesic nucleus with the internal deuteron beam of the Nuclotron using the reaction

$$d + \mathrm{C} \to (A_2)_\eta + \ldots \to \pi + p + \ldots\,, \tag{2}$$

where $(A_2)_\eta$-nucleus is the part of nucleus dC formed in the dC collision [5]. The hadrons emitted in the transverse direction are registered by the two-arms spectrometer. The flow of particles includes πp-pars which are product of the η-nucleus decay. A bound state of η is expected to be seen as a peak in the energy spectrum of these pairs.

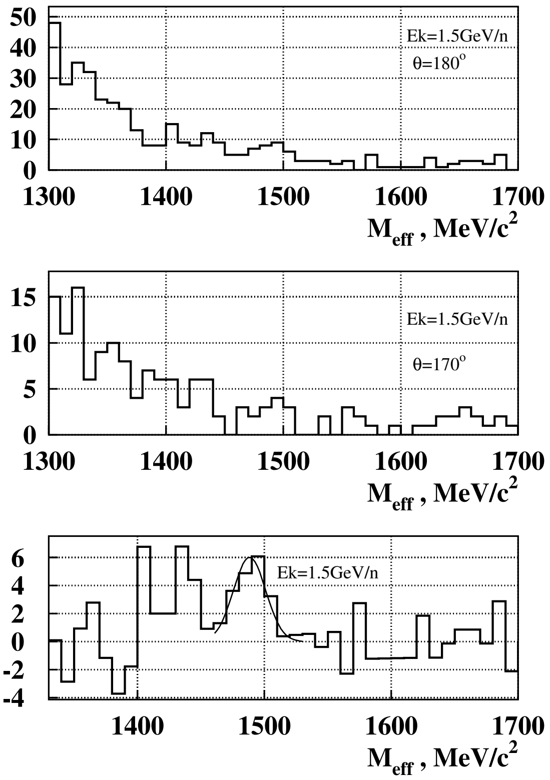

Fig. 2. Effective mass distributions of πp pairs in dA reaction at the energy 1.5A GeV.

The distribution of yields of πp pairs is shown in Fig. 2 (up and center) versus M_{eff} of these pairs in deuteron-carbon interactions at 1.5A GeV energy. The histogram in Fig. 2 (center) shows the contamination obtained at the arm angle 170°. Figure 2 (up) corresponds to a back-to-back correlation coming from the two-body decay. The histogram Fig. 2 (down) is the result of subtraction of the back-to-back (180°) data and the contamination measurements.

The ratio of the numbers of πp pairs is $N(170^o)/N(180^o) = 0.42 \pm 0.08(stat)$ in the mass region of $1450 < M_{\rm eff} < 1550$ MeV/c^2. It appears that the small peak in this region of mass could be possibly interpreted as the formation of η-nuclei.

New data were collected in 2006. They include 105 pairs coming from targets in d+Cu and d+C reactions at the energy of primary beam 1.5A GeV and 1.9A GeV. These data are being analysed.

3.2. Experiment Delta-2

In last years, several measurements on the Nuclotron internal target station at DELTA-2 setup have been carried out.

The purpose of the measurements was to study the resonant structure in reactions of formation π mesons at the beam energy of 340 − 350 MeV per nucleon [7]. The π meson yield for interactions of the internal Nuclotron deuteron beam with silver target has been measured at 73°. Preliminary data of these measurements point to the resonant structure in the excitation function of the reaction (Fig. 3).

For light targets, such as C and Al, this effect was not seen. In an earlier experiment at the Nuclotron, this effect was observed on a Cu target.

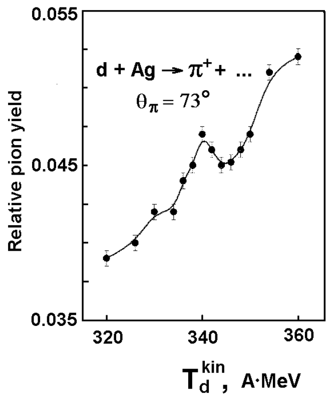

Fig. 3. Relative pion yield in $d+$Ag reaction as function of beam kinetic energy.

3.3. Experiment Delta-Sigma

Energy dependence of the ratio $R_{dp} = \left[{\rm d}\sigma/{\rm d}\Omega(nd)\right] \big/ \left[{\rm d}\sigma/{\rm d}\Omega(np)\right]$ has been measured at 0° in the laboratory system. Experimental observable R_{dp} is the ratio of a quasi-elastic nd scattering differential cross section to the free np elastic scattering cross section.

Based on a specific theoretic approach, the R_{dp} observable, measured with a nonpolarized neutron beam at the Nuclotron using cryogenic H_2 and D_2 targets, may be related to the spin-dependent np amplitudes, so that the R_{dp} data set will give an opportunity to avoid ambiguity in the reconstruction of these amplitudes. The simplest dependence of R_{dp} on np amplitudes is obtained under the impulse approximation.

For the case of the reaction at zero degrees in the laboratory system, the following expression should be valid equation

$$R_{dp} = \frac{2}{3}\,\frac{\mathrm{d}\sigma/\mathrm{d}\Omega_{SD}(np)}{\mathrm{d}\sigma/\mathrm{d}\Omega(np)}\,, \tag{3}$$

where $\mathrm{d}\sigma/\mathrm{d}\Omega_{SD}(np)$ is the "spin-dependent" part of the $np \to pn$ differential cross section.

In the measurements, the beam of neutrons was interacting with the hydrogen and deuteron targets. Results at the center-of-mass angle $\theta_{cm} = 180°$ for R_{dp} – the ratio of the quasi-elastic nd scattering differential cross section to the free np elastic scattering cross section at 0.8, 1.0, 1.2, 1.4, 1.8 and 2.0 GeV are presented in Fig. 4 [8].

These results show that the asymptotic behaviour, at least up to 2 GeV, does not exist as is usually assumed, and the impulse approximation formalism that was used to express R_{dp} in terms of the np amplitudes, which are known from the phase shift analysis (the circles), does not work in this case.

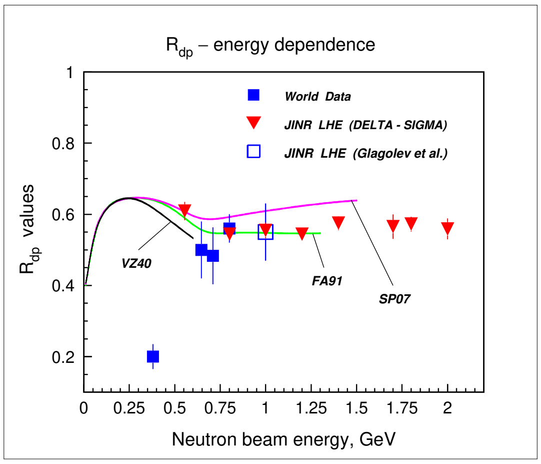

Fig. 4. Energy dependence of the ratio R_{dp} for elastic charge exchange process $np \to pn$ at 0° in the laboratory system (preliminary).

3.4. Light Nuclei Structure (LNS) project

The structure of light nuclei (helium, triton and deuteron) has been intensively investigated.

In the last several years, a new generation of nucleon-nucleon potentials are formulated. These potentials reproduce the nucleon-nucleon scattering data up to 350 MeV with a very good accuracy. But these potentials cannot reproduce the triton binding energy, and the deuteron-proton scattering and breakup data. Incorporation of the three-nucleon forces, with the interaction depending on the quantum numbers of all three nucleons, allows to reproduce the triton binding energy, and unpolarized deuteron-proton scattering and breakup data. However, the free-nucleon forces can not reproduce the polarization data which have been intensively accumulated during the last decade.

For a better understanding of the nature of the three-nucleon forces, we need new experimental data at higher energy. The possibility of measurement of *dp* elastic scattering has been investigated for the LNS project with the aid of a Monte-Carlo simulation.

The experiment was performed with the Nuclotron internal deuteron beam.

The preliminary experimental results on the differential cross section for the *dp* elastic scattering at 500 MeV measured at the internal target station of the Nuclotron are presented in Fig. 5.

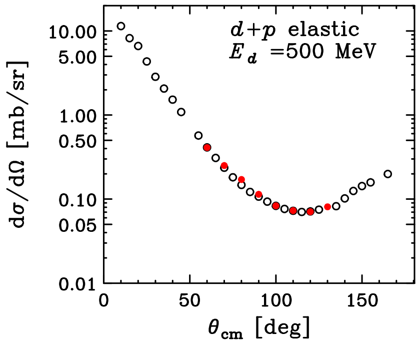

Fig. 5. Differential cross section for the dp-elastic scattering measured at Nuclotron (filled circles) and at RCNP (open circles) at 500 MeV *deuteron energy.*

These data were obtained in the framework of JINR-CNS (Japan) collaboration using the Japanese detection system [9].

The open symbols in Fig. 5 represent the data obtained at RCNP [10]. The closed symbols are the preliminary data obtained at Nuclotron. One can see that the angular behaviour of the data from Nuclotron and RCNP are in agreement.

Recently, new data at the energies of 880 and 2000 MeV at the Nuclotron have been obtained and are in the process of analysis.

3.5. The Becquerel project

Several light nuclei were produced at the Nuclotron for the study of the fragmentation processes. Obtained information is being analysed.

The angular measurements of the ^{9}Be $\rightarrow ^8$Be + n fragmentation channel, with the decay of ^{8}Be from the ground state and the first excited state into a pair of α particles, show that this channel appears to be dominant [11].

Fifty five events of the peripheral dissociation of the ^{8}B nucleus were observed in events where mesons were selected and there was no production of target-nucleus fragments. A leading contribution of the ^{8}B $\to^7$B + p mode, which has the lowest energy threshold, was revealed on the basis of these events. Information about the branching ratios of the dissociation modes characterized by a higher multiplicity was obtained. The dissociation of the ^{7}Be core in ^{8}B bears resemblance to the dissociation of a free ^{7}Be nucleus. The transverse-momentum distributions of fragments origination from the ^{8}B $\to^7$Be + p dissociation mode were obtained. For these distributions, the small mean value of $\langle P_T \rangle = 52 \pm 5$ MeV/c in the c.m. frame suggests a low binding energy of the outer proton in the ^{8}B nucleus. An indication of a strong azimutal correlation of the fragments ^{7}Be and p was found [12].

The charge-exchange reaction involving ^{7}Li nuclei at an external target provides a secondary 1.23A GeV ^{7}Be beam. This beam was used to irradiate emulsion chamber. The mean free path $\lambda_{\mathrm{inel}}(^7\mathrm{Be}) = 14.0 \pm 0.8$ cm for inelastic ^{7}Be interactions in an emulsion coincides within the errors with those for ^{6}Li and ^{7}Li nuclei. More than 10% of the ^{7}Be events are associated with the peripheral interactions in which the total charge of the relativistic fragments is equal to the charge of the ^{7}Be nucleus and in which charged mesons are not produced. An unusual ratio of the helium isotopes is revealed in the composition of the doubly charged fragments of the ^{7}Be nucleus: the number of the ^{3}He fragments is twice as large as that of the ^{4}He fragments. Each of 50% of peripheral interaction events includes two doubly charged fragments. The channels of the ^{7}Be fragmentation into charged fragments are presented. In 50% of events, the ^{7}Be fragmentation occurs only into charged fragments without the emission of neutrons. The ^{3}He + ^{4}He channel dominates, whereas each of the ^{4}He+d + p and ^{6}Li + p channels constitutes 10%. Two mean free path for the coherent dissociation of relativistic ^{7}Be nuclei into ^{3}He + ^{4}He is equal to (7 ± 1) m. The main features of the fragmentation of relativistic ^{7}Be nuclei in such peripheral interactions are explained by the ^{3}He + ^{4}He two-cluster structure of the ^{7}Be nucleus [13].

3.6. Applied research

The applied research performed at the VBLHE accelerator complex includes the following main activities: radiobiology and space biomedicine, influence of nuclear beams on microelectronic components, radioactive waste transmutation, electronuclear method of energy generation, use of a carbon beam for cancer treatment, and other.

3.6.1. **The Crystal experiment**

An interesting example of applied studies is the first observation of parametric x-ray radiation from moderately relativistic nuclei in crystals.

Experiment was performed in Laboratory of High Energies at Nuclotron with 5 GeV protons and 2.2A GeV carbon nuclei [14]. Layout of the experiment on the study of parametric X-ray radiation can be seen in Fig. 6 and the results are presented in Fig. 7.

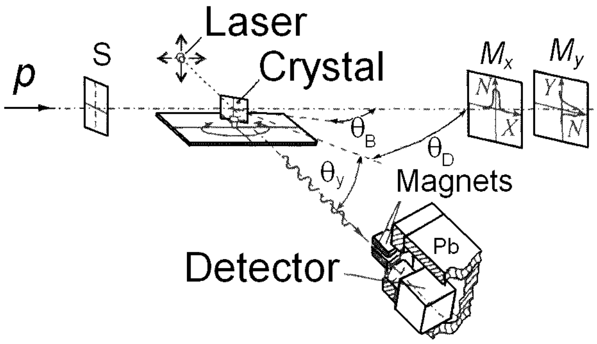

Fig. 6. Layout of experiment on study of parametric X-ray radiation from nuclei at Nuclotron.

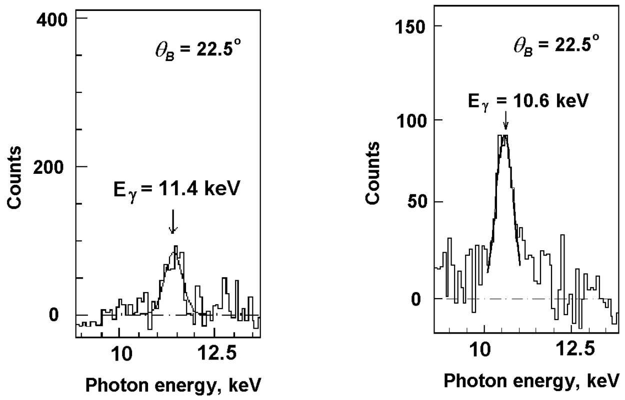

Fig. 7. X-ray spectra registered in the experiment from 5 GeV *protons (left figure) and from* $2.2A$ GeV ^{12}C *nuclei (right figure).*

The yield of the parametric X-ray radiation observed from carbon nuclei is about tens times higher than from protons. Observation of this X-ray radiation opens the possibilities for the parametric X-ray radiation applications in nuclear beam diagnostic.

3.6.2. **Energy plus transmutation experiment**

Another example of the applied use Nuclotron beams are the experiments on the study of transmutation of nuclear waste at the Energy Plus Transmutation setup.

The general scheme of the Energy Plus Transmutation setup, which was built for the investigations of transmutation of spent fuel isotopes is shown in Fig. 8.

The Energy Plus Transmutation setup consists of the following parts:

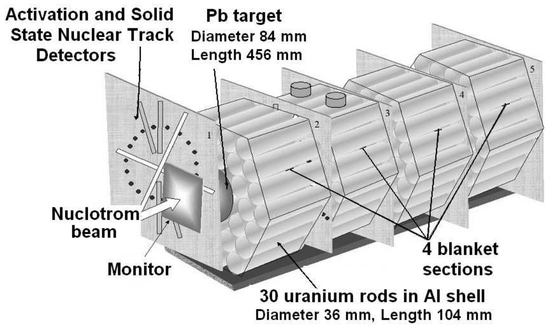

Fig. 8. Scheme of the four-section Energy Plus Transmutation setup with a massive lead target and uranium subcritical blanket. The placement of transmutation samples is presented at the surface of the second section of uranium blanket.

- Lead target divided into four sections (diameter of 8.4 cm and total length of 45.6 cm; weight of 28.6 kg).
- Uranium blanket divided into four sections; each section consists of 30 fuel rods of natural uranium inside an aluminium cover (34 mm diameter, 104 mm length, weight of 1.72 kg). Each section contains 51.6 kg of uranium, so the whole blanket contains 206.4 kg of natural uranium.
- Beam monitoring and adjustment of system of activation and solid state track detectors, proportional ionization chambers and Polaroid films.
- Five polyethylene plates for fixation of activation threshold detectors and solid state nuclear trak detectors (SSNTD).
- Five detection systems based on nuclear emulsions for neutron registration by proton recoil. The results of the first usage of nuclear emulsions technique for investigation of fast electronuclear neutron spectra are presented in our work.
- Shielding box filled with granulated polyethylene with boron carbide, and with a cadmium cover; the outside box is made from wood. The box has dimensions of $100 \times 106 \times 111 cm^3$ and weighs 950 kg.

The study of transmutation of long-lived radioactive waste nuclides from nuclear reactors and industrial setups which use nuclear technologies and nuclear materials into stable or short-lived radioactive nuclides is the main purpose of the project Energy Plus Transmutation.

The values of transmutation rates or velocity of the reaction $R(A_{\mathrm{res}})$ are calculated by the following equation

$$R(A_{\mathrm{res}}) = N(A_{\mathrm{res}})/(n_s \cdot I_b), \tag{4}$$

where $N(A_{\rm res})$ the number of nuclei of isotope $A_{\rm res}$ produced in a sample; n_s is the number of atoms in the activation detector; I_b is beam fluence in the irradiation.

TABLE 2. Preliminary results about product nuclei observed in ^{129}I *and* ^{237}Np *samples.* $R(A_{\rm res})$ *yields resulting from irradiation with proton and deuteron beams.*

Residual nuclei	$T_{1/2}$	Deuterons 2.52 GeV	Protons 2.0 GeV
^{129}I sample, $R(A_{\rm res}) \cdot 10^{29}$			
^{121}Te	16.78 d	4.93 ± 0.94	-
^{124}I	4.18 d	4.38 ± 0.13	4.0 ± 0.5
^{126}I	13.11 d	10.80 ± 0.30	22.5 ± 0.44
^{130}I	12.36 h	816 ± 40	809 ± 33
^{237}Np sample, $R(A_{\rm res}) \cdot 10^{29}$			
^{97}Zr	17.0 h	0.19 ± 0.03	0.16 ± 0.01
^{99}Mo	2.75 d	1.64 ± 0.47	-
^{132}Te	3.26 d	0.217 ± 0.032	0.147 ± 0.011
^{133}I	20.8 d	0.265 ± 0.075	0.182 ± 0.028
^{238}Np	2.12 d	17.0 ± 0.8	13.3 ± 0.3

The radioactive samples of ^{129}I and ^{237}Np and stable ^{127}I were irradiated at the top surface of the second section of the uranium blanket. Transmutation rates of the isotopes (i.e. the yield of product nuclei) were investigated by gamma-spectrometric methods. The data on the absolute reaction rates as an $R(A_{\rm res})$ - parameter, which is the number of product nuclei produced per atom of the sample, per one incident deuteron or proton where obtained [15]. The irradiation of ^{127}I was used for subtraction of a 15% contamination in the ^{129}I sample. Some results of experiment are given in Tab. 2.

3.6.3. **Experiments with a carbon beam for cancer treatment**

Using the carbon beam is rather effective for the treatment of cancer tumours. At VBLHE, experiments with a beam of carbon (^{12}C) have been carried out. In Fig. 9, the curve of energy loss in plexiglass of the Nuclotron carbon beam of the energy of 500A MeV, measured with a diamond detector, is shown. In this figure, the Bragg peak is seen well.

By selecting the beam energy, it is possible to locate the Bragg peak at the depth of the tumour and to concentrate there the maximum of beam energy which destroys the tumour.

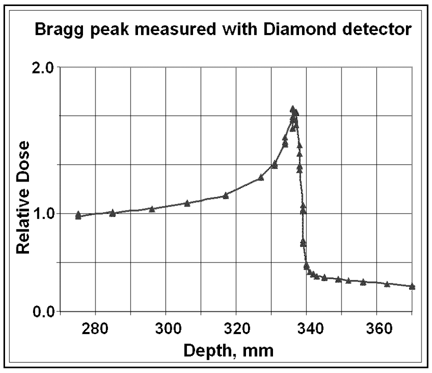

Fig. 9. The energy losses in plexiglass of the Nuclonron carbon beam with energy 500 MeV *as the function of depth of penetration of a beam measured with a diamond detector.*

4. Development of the VBLHE accelerator complex

The new project of the Nuclotron development, named Nuclotron-M, is being prepared. The main goal of the project is the development of the Nuclotron accelerator complex for the acceleration of heavy-ion beams with the energy up to $5A$ GeV and the beam intensities up to 5×10^{10} particles per pulse, and polarized deuteron beams with intensities up to 10^{10} deuterons per pulse. Realization of the project Nuclotron-M will provide also new possibilities for the future development of the Nuclotron to heavy ion (up to uranium) collider facility with energy $\sqrt{S_{\rm NN}} = 9$ GeV and luminosity $10^{27}\rm{cm}^{-2}\rm{s}^{-1}$. Preliminary concept of the new complex was reported at the JINR meeting in October 6 – 7 2006 [16].

The main task of the new complex is the search for and the study of the mixed quark-hadron phase in relativistic heavy-ion collisions [17].

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RELATIVISTIČKA NUKLEARNA FIZIKA U LABORATORIJU ZA VISOKE ENERGIJE ZDRUŽENOG INSTITUTA ZA NUKLEARNA ISTRAŽIVANJA (DUBNA)

Daje se pregled eksperimenata s unutarnjim i vanjskim nuklearnim snopovima Nuclotrona u Dubni. Opisuju se nuklearni snopovi koji se postižu Nuclotronom. Predstavljaju se odabrani ishodi mjerenja suradnika Vekslerovog i Baldinovog Laboratorija za Visoke Energije Združenog Instituta za Nuklearna Istraživanja u Dubni tijekom posljednjih godina. Raspravljaju se planovi budućih istraživanja.