Beams of relativistic nuclear fragments at the Nuclotron accelerator facility

P.A. Rukoyatkin*), L.N. Komolov, R.I. Kukushkina, V.N. Ramzhin

Veksler and Baldin Laboratory of High Enegries, Joint Institute for Nuclear Research, 141980 Dubna, Russia

Relativistic beams of light nuclei slowly extracted from the Nuclotron and a developed beam line system of the facility constitute a good base for exotic nuclear beams forming in-flight. A resent years activity in the field at the Laboratory of High Energies is briefly reviewed in the paper.

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1 Introduction

The relativistic nuclear physics phenomena are studied at the Laboratory of High Energies (LHE) since 1970 when deuterons had been accelerated at the Dubna Synchrophasotron. Now a basic facility provided the investigations is the Nuclotron, a supreconducting accelerator of nuclei. An injection subsystem including four ion sources and a 20 MeV linac yields a wide set of nuclei for acceleration in the main ring. Accelerated beams are used for experiments both at an internal target and are slowly extracted out of the machine and transported through a broad experimental area to external physical setups. Due to the superconducting realization of the ring it is possible to have practically continuous extracted beam: 10 seconds extraction duration has been obtained[1].

Table 1. Operating intensities of slowly extracted nuclear beams at resent Nuclotron runs.

Nuclei	d	α	$\vec{d}$	^{7}Li	$^{10,11}B$	^{12}C	^{24}Mg	^{14}N	^{40}Ar	^{56}Fe
Inten.	$5\cdot10^{10}$	$3\cdot10^{9}$	$2\cdot10^{8}$	$4\cdot10^{9}$	$1\cdot10^{8,9}$	$2\cdot10^{9}$	$1\cdot10^{8}$	$1\cdot10^{7}$	$2\cdot10^{6}$	$1\cdot10^{6}$
Ion src.	*Duoplasmotron*		*ABS*	*Laser*				*ESIS*		

A developed infrastructure of external beam lines[2] at the Nuclotron facility provides opportunities to form various secondary beams. In particular, it is widely used to create secondary beams of unstable ("exotic") nuclei or nuclei which can not be directly accelerated by some technical reasons. The beams forming is based on the peripheral nucleus fragmentation reactions or the charge-exchange reactions. In the first case a picture of an interaction at relativistic energies is quite clear and easy to apply for a beam simulation: in a projectile frame a produced fragment is

*) Corresponding author. E-mail: rukoyat@sunhe.jinr.ru

described by an isotropic momentum distribution with a small (comparing to the fragment mass M_1) momentum r.m.s. σ. In the laboratory frame r.m.s. of a plane angle θ and of relative momentum δ are given by

$$\sigma_\theta \simeq \frac{\sigma}{A_1 p_0}, \qquad \sigma_\delta \simeq \frac{\sigma}{\beta_0 M_1}, \tag{1}$$

where A_1 - fragment mass number, p_0 and β_0 - momentum per nucleon and velocity of primary nuclei. A good practical approach of the value σ except the extreme cases of the lightest nuclei can be obtained by means of the formulae[3]:

$$\sigma = \sigma^* \sqrt{\frac{A_0(A_0 - A_1)}{(A_0 - 1)}}, \tag{2}$$

where A_0 - projectile mass number and the parameter $\sigma^* \simeq 90\,\mathrm{MeV/c}$.

Deuterons provide the best way to generate neutron beams with well defined characteristics. A dedicated neutron beam line permanently operates at the facility during the last decade. Details of the subject have been presented at previous Praha meetings. Relativistic secondary tritons were used to study the charge-exchange reactions using a streamer chamber in magnetic field. A short summary on these and others lightest nuclei fragment beams is given below.

Table 2. Beams of the lightest nuclei fragments realized at the LHE.

Beam	*Reaction*	*Target*	*P, GeV/c*	*Intens., ppc*	*Exp.*	*Ref.*
$\vec{n}$	$\vec{d} + A \to \vec{n} + \ldots$	Be, 20 ffi	$1.9 - 4.5$	$10^5 - 10^6$	$\Delta\sigma$ [4]	[5], [6]
n	$d + A \to n + \ldots$	Be, 20 ffi	$2 - 2.8$	$\simeq 10^8$	--- # ---	
$\vec{p}$	$\vec{d} + A \to \vec{p} + \ldots$	Be, 20 ffi	4.5	10^8	*Test*	[7]
t	$\alpha + A \to t + \ldots$	CH, 5 Θ/ffi	6	$5 \cdot 10^5$	$t \to {}^3He$ [8]	[9]

2 Nuclear fragment beams for emulsion experiments

A further activity on the nuclear fragment beam forming at the LHE was connected with an emulsion experiment program[10]. The nuclear emulsion method provides an important advantage for nuclei structure investigation due to its high resolution power and ability to register all secondary charged products practically in a 4π-geometry. Besides irradiations carried out in primary beams (${}^{10}B$, ${}^{11}B$, ${}^{14}N$) according the program a series of emulsion exposures were done in dedicated secondary ones. Beams enriched with ${}^6He + t$, ${}^7Be$, ${}^9C$, ${}^9Be$ and ${}^8B$ nuclei were prepared. All the isotope beams were formed at 1.2 A GeV kinetic energy, except the case ${}^6He + t$ where the energy was 1.9 A GeV. Due to a limited frame of the

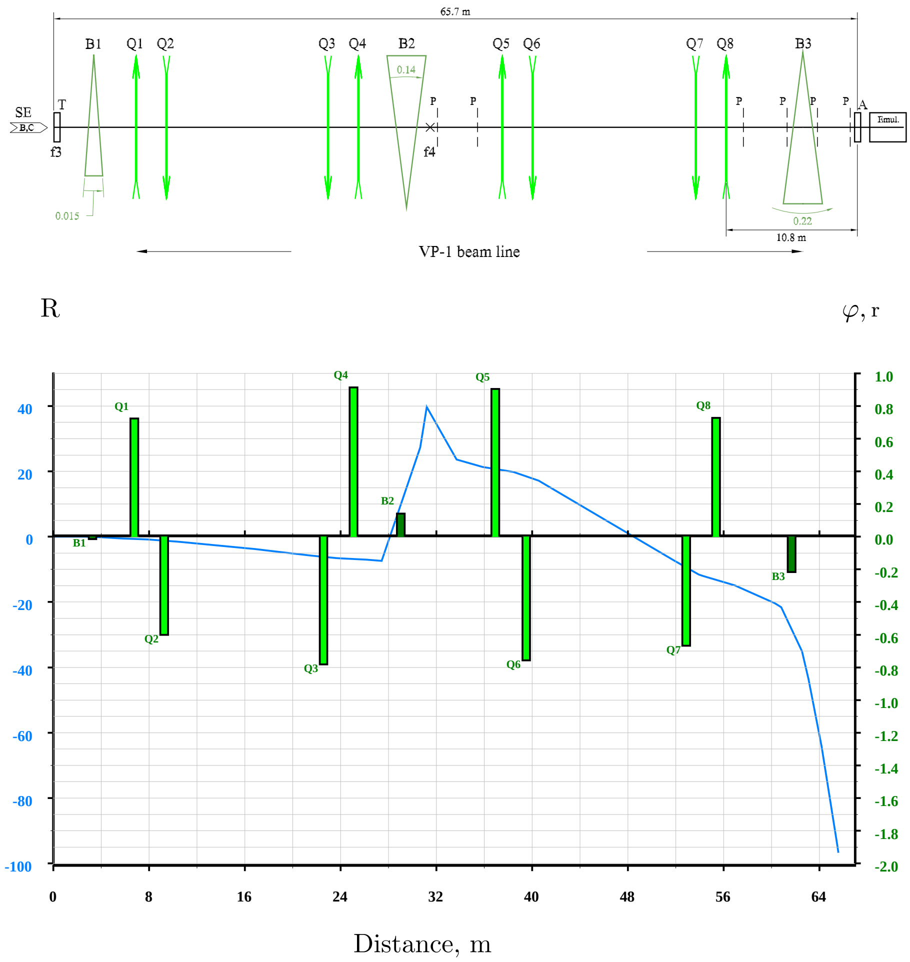

Fig. 1. Above: scheme of secondary nuclear fragment beam forming. Q1...Q8 - quadrupole lenses, B1...B3 - dipole magnets, T - target, A - beam analyzer, P - profilemeters, SE - primary slowly extracted beam. Below: a beam line regime. The vertical bars - states of the magnetic elements, φ: $(eB/pc)\, l_{eff}$ (bend angle) and $\sqrt{eG/pc}\, l_{eff}$ for magnets and lenses correspondingly. The curve - realized resolution function $R(z)$ (see in the text).

paper we stay at some details concerning the three last nuclei formed under the same conditions.

Beams forming was carried out according to a scheme shown in Fig. 1. Interaction of a generating primary nuclei beam slowly extracted from the Nuclotron with a target took place at the slow extraction system exit (f3). The ^9C nuclei were selected from interaction products of the ^{12}C beam. In the ^9Be and ^8B cases ^{10}B nuclei were used as primaries. One should mentioned that direct acceleration of the maim beryllium isotope is currently unavailable at the facility. Both primary beams were extracted at 2 A GeV/c momentum. A 7.8 g/cm^2 polyethylene target was used. The first stage of secondary beam selection was realized by the head part of the VP-1 channel transporting beams to physical setups. This part operated at a standard regime. At the regime the Q1-Q4 lenses polarity in the horizontal plane (analysis plane) was "f-d-d-f" and beam crossovers both in the horizontal and in the vertical planes were formed at the f4 point. At this stage the main contribution to dispersion originated from the B2 magnet with a bend angle $\simeq 140$ mr. Primary selection of a momentum interval was determined by free aperture of the successive Q5,6 doublet. Final dispersive parameters of the system were formed by the Q5-Q8 and B3 elements. Beam line optimization was carried out using a function $R(z)$ defined in the following way:

$$R(z) = \frac{r_{16}(z)}{2\sigma_x(z)}, \tag{3}$$

z - distance along beam line, r_{16} - linear dispersion and σ_x - r.m.s. size of the monochromatic beam in the analysis plane. $R(z)$ was optimized at an emulsion location point ($z \simeq 65.7$ m). A solution of the optimization task was taken as an operating regime base. Further tuning was carried out by means of 6 profilemeters (P in Fig. 1). Each profilemeter was a multiwire ionization chamber measuring beam shapes both in the horizontal and the vertical planes (30X + 30Y channels). At off-line analysis of the experiment information on gradients was corrected and beam envelopes was reconstructed using registered profilemeter data. Finally, a state of the magnetic system was described by a corrected set of gradients in which there were small corrections only for Q6 and Q7 (5% and 2%). A realized resolution function $R(z)$ is shown in Fig. 1. Beams content was monitored by a scintillation counter with a 5 mm thick plastic. The transversal dimensions of the plastic was $10 \cdot 100\,\mathrm{mm}^2$. A calculated momentum throughput FWHM defined by the beam line and the analyzer working area was 2.7%.

Each of primary beams, ^{12}C and ^{10}B, was conducted through the channel twice. At first a low intensity ($< 10^5\,p/s$) beam was passed for calibration of the analyzer. Then beam passed through the production target was conducted at working intensity (10^9, 10^8). After that fields of the channel magnetic elements were strictly changed according to a rigidity ratio of selected secondaries and projectiles. The analyzer was triggered by an additional scintillation counters placed 3 m downstream. In each beam an emulsion package was exposed. A load per a package was about $5 \cdot 10^4$ secondary nuclei. Some preliminary results of the exposures are presented in [11]. An energy deposition spectrum in the analyzer at beam line tuning to the ^8B fragment rigidity is shown in Fig. 2. The data are fitted by a convolution of the Vavilov function with a gaussian. A marked Z=6 component admixture in the beam ($\simeq 10\%$) indicates a practical feasibility to form the ^{10}C beam from the charge-exchange reaction $^{10}B + A \to {}^{10}C + \ldots$. Presence of different components in the secondary beams is summarized in Table 2.

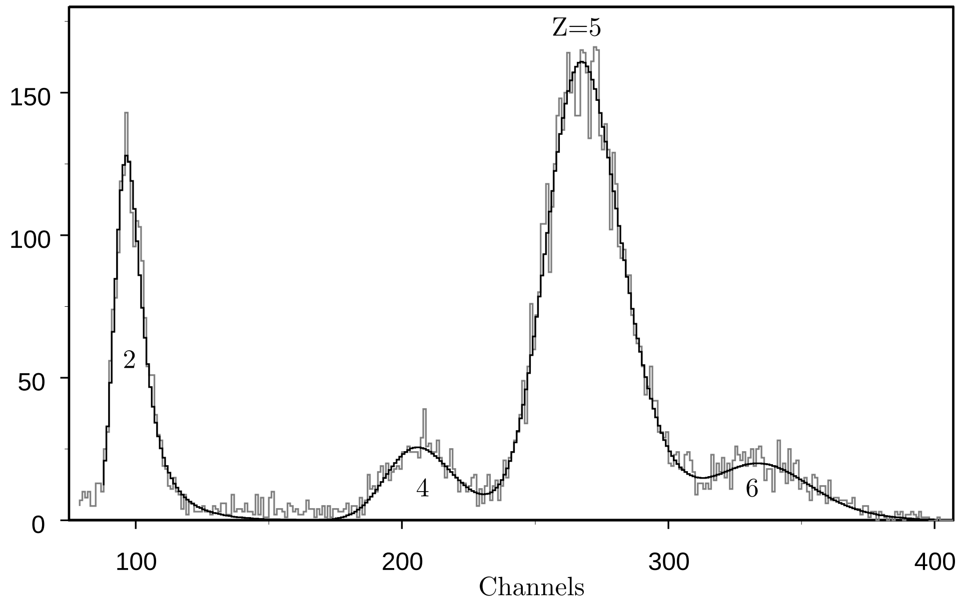

Fig. 2. Energy deposition spectrum in a 5 mm scintillator measured in a secondary beam enriched with ^8B nuclei at 2 A GeV/c momentum. Fraction of the nuclei (Z=5) $\simeq$ 62%.

Table 3. Secondary nuclear beams content.

Ø	Reaction	Component fraction, %				
		Z=2	3	4	5	6
1	$^{10}B + A \to {}^9Be + \ldots$	5.6	19.2	**66.8**	8.4	
2	$^{10}B + A \to {}^8B + \ldots$	19.8		9.1	**61.6**	*9.5*
3	$^{12}C + A \to {}^9C + \ldots$	37.3	2.2	4.0	5.6	**50.9**

3 Summary

In-flight production of relativistic nuclear fragment beams are widely practised at the Nuclotron accelerator facility. Secondary beams of the beryllium, boron and carbon isotopes at 1.2 A GeV were recently formed to study light nuclei clustering by the nuclear emulsion method.

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