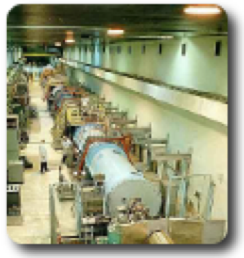
Charge exchange processes in carbon ions fragmentation at 300 MeV/nucleon: a comparison with models of ion-ion interactions


B.M. Abramov, S.A. Bulychjov,
V. V. Kulikov, A. A. Kulikovskaya, M.A. Martemyanov,
M.A. Matsyuk

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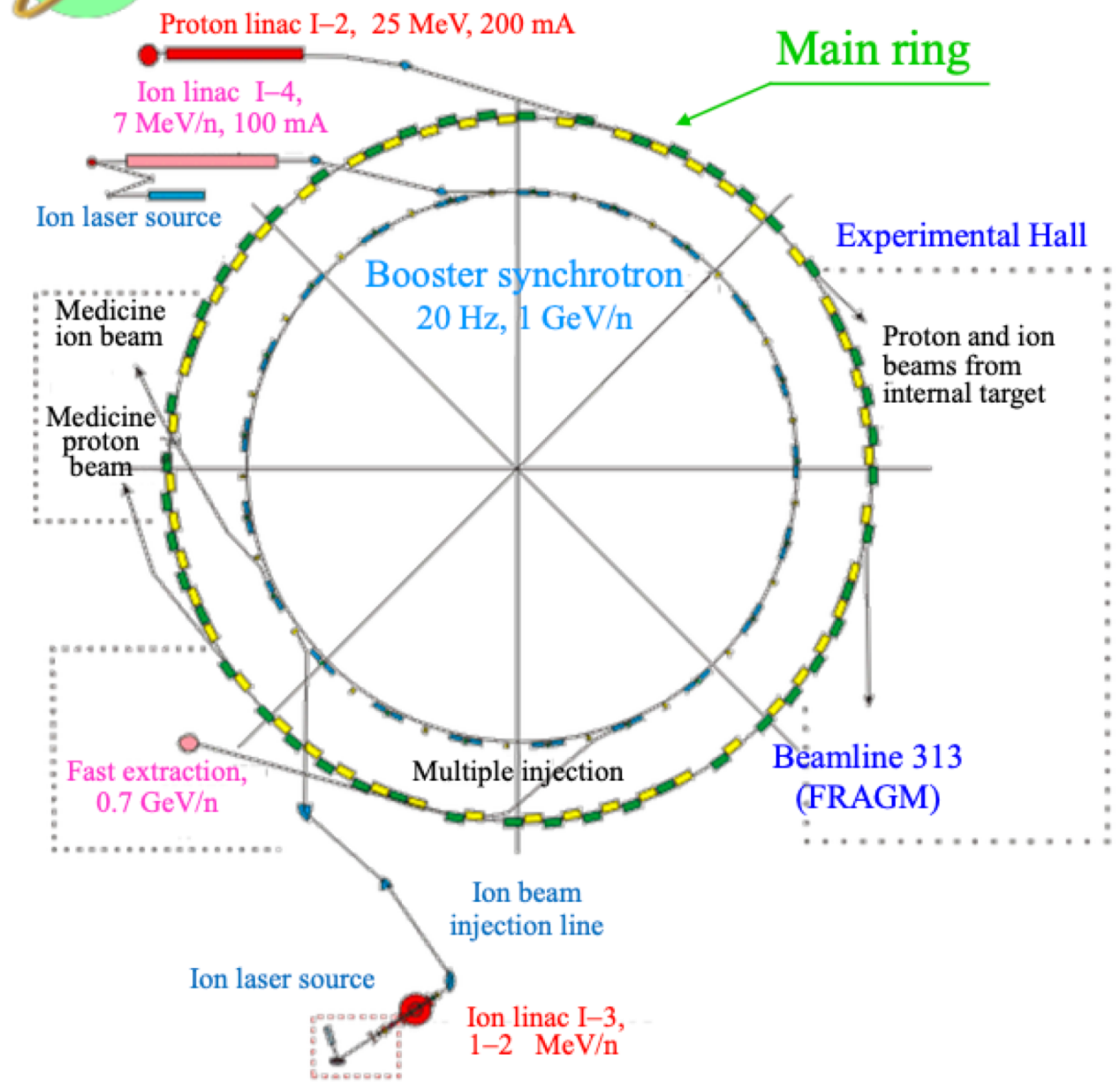
Fundamental problems and applications"

- The aim of the work is to detect for and to measure the processes of fragmentation of carbon ions with charge exchange of nucleons at the energy of the 300 MeV/nucleon
- FRAGM detector was optimized to measure yields of nuclear fragments produced at ion-ion interactions and operated at accelerating-storage complex TWAC at ITEP (Moscow)
- Report is based on the results obtained for reaction : $^{12}C + {}^{9}Be \rightarrow f + X$ where f - proton or nuclear fragment registered with the detector at small angle (~ 3.5^{0}) of kinetic energy at $T_0 = 0.3$ GeV/nucleon
- During the fragmentation of ^{12}C carbon ions after a single nucleon charge exchange, three long-lived isotopes can be formed: ^{11}Be (7 neutrons), ^{12}B (7 neutrons), ^{12}N (7 protons) and two with a double charge exchange of ^{11}Li and ^{12}Be
- Nucleon charge exchange processes during ion fragmentation are poorly studied. There are only a few experiments performed in the energy range 1–2 GeV/nucleon. Such measurements at energy of 300 MeV/nucleon was measured for the first time
- New experimental data can check theoretical models of ion-ion interactions (BC, QMD, INCL, LAQGSM, etc.) and indicate ways to calibrate them.



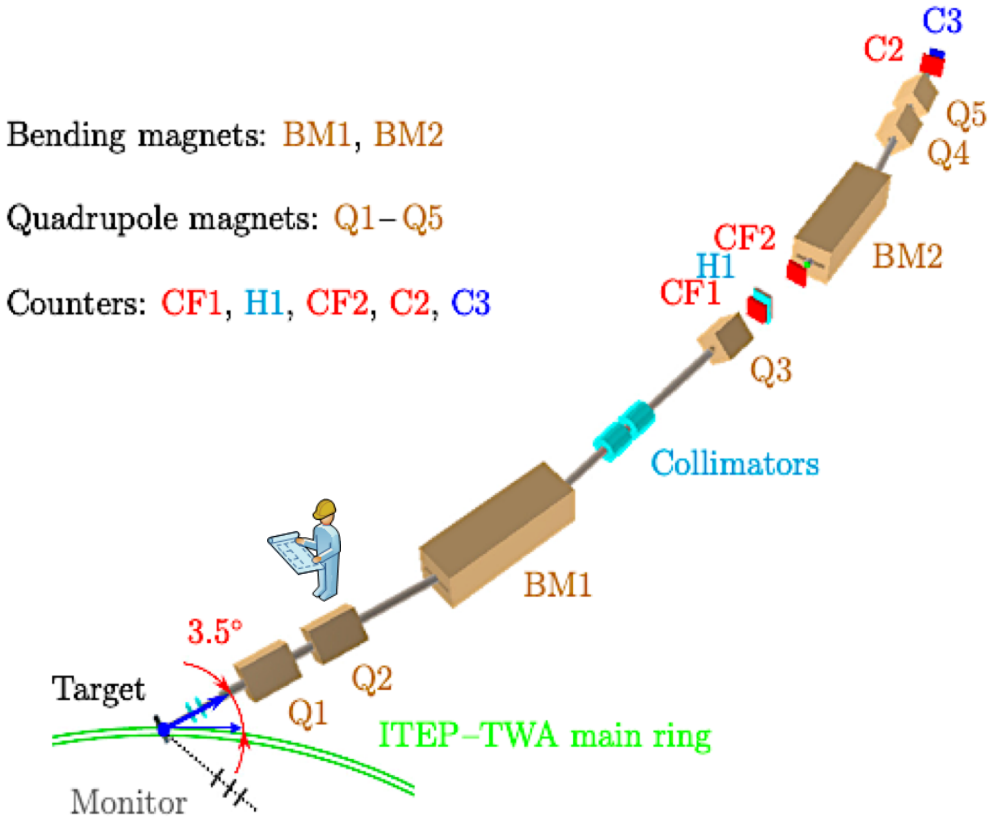
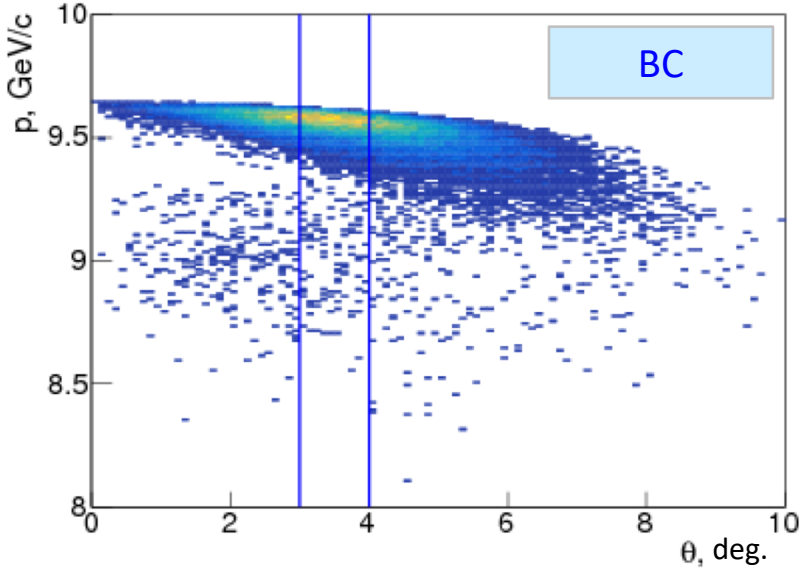


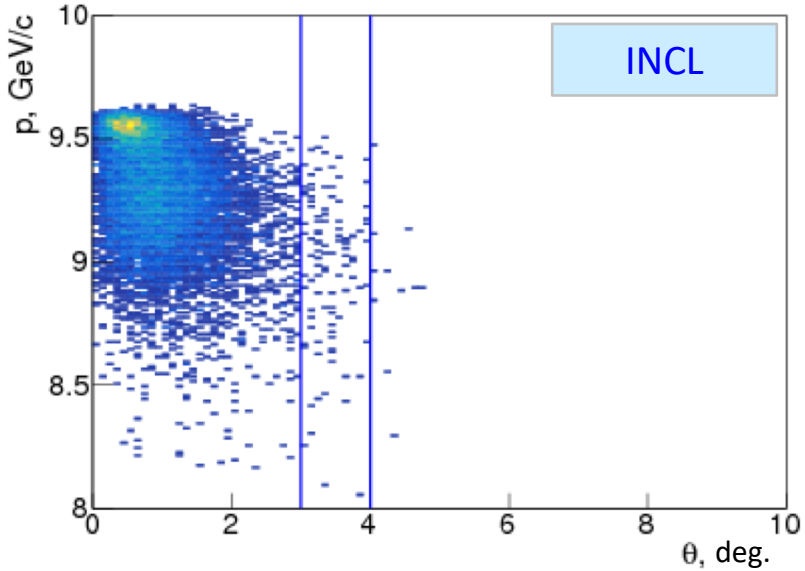
FIG. 1: Experimental setup FRAGM.

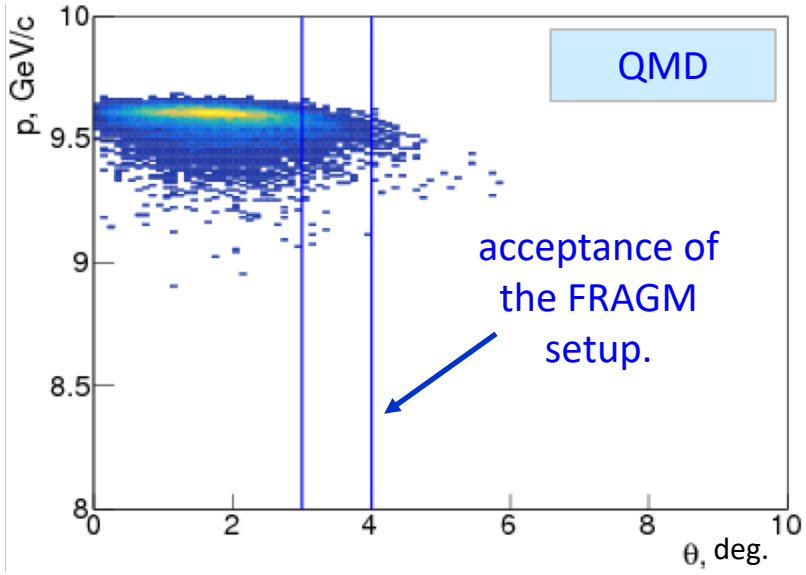
Ion-ion interactions models

- ✓Binary Cascade (BC, GEANT4 toolkit, G. Folger *et al*., EPJA 21 (2004) 407) :
  - ➢ Useable when either projectile or target are light ions. But, it gives a reasonable results for for higher mass ions too
  - ➢ Novel approach of the intra-nuclear cascade is implemented: nucleons distributed in space according to nuclear density; nucleon momenta are distributed assuming Fermi gas model
- ✓Quantum Molecular Dynamics (QMD, GEANT4 toolkit) T. Koi *et al*., AIP Conf. Proc. 896 (2007) 21:
  - ➢ Available for light and heavy ions
  - ➢ All nucleons are considered as participants and are propagated by means of phenomenological nucleon-nucleon potential
  - ➢ Includes a high number of different resonances
- ✓Liege Intranuclear Cascade (INCL++, J. Dudouet *et al*., PR **C**89 (2014) 054616) :
  - ➢ Combines best features of the BC and QMD models
  - ➢ Gives a better agreement with our data by the kinematic parameters of fragments
- ✓Los Alamos version of Quark Gluon String Model (LAQGSM03.03) LA-UR-11-01887, presented by M.I. Baznat (Academy of Sciences of Moldova)
  - ➢ First stage is the intranuclear time-dependent cascade developed initially at JINR
  - ➢ It was tested in a wide energy region up to 1 TeV/nucleon and large number of ions

Charge exchange reaction to the model test

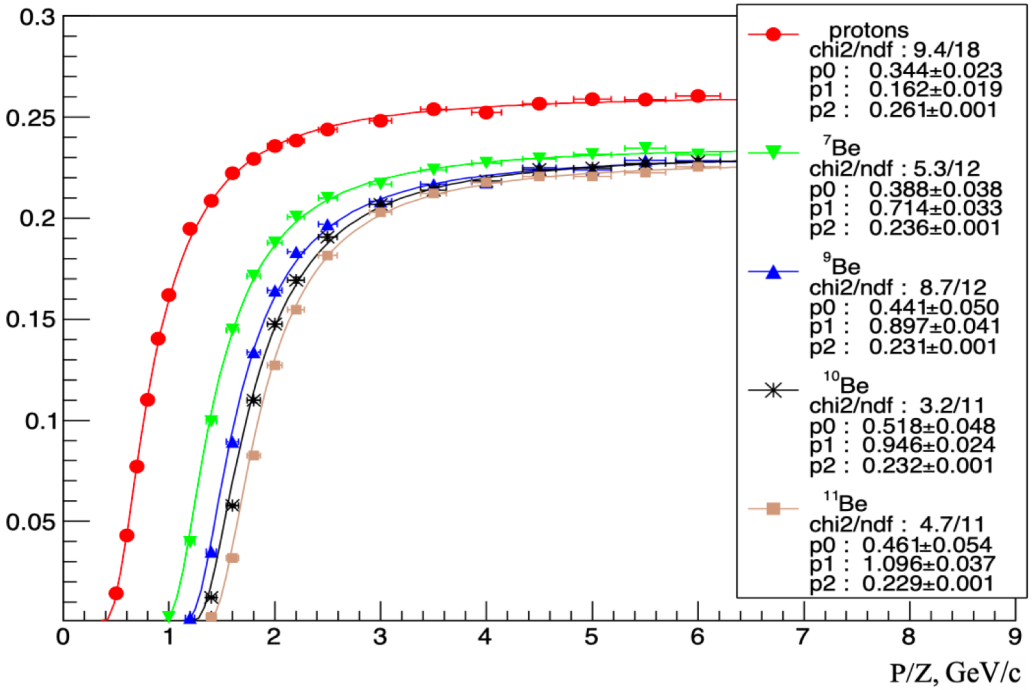


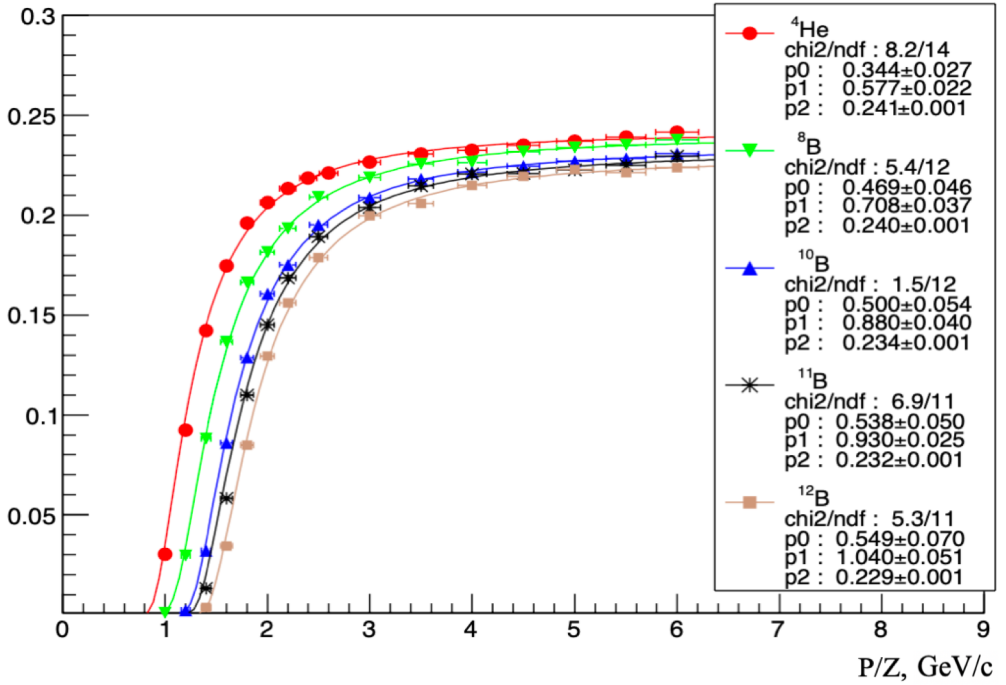




- ✓ BC and QMD models have distributions, but different kinematic descriptions of ^{12}B
- ✓ INCL reproduces the production of ^{12}B, but has an inaccurate angular distribution
- ✓ LAQGSM does not reproduce fragments resulting from the charge exchange reaction

Ions registration efficiency





- Initial simulation conditions:

  dp / p = 3.5 %, dΘ $< 1.0^0$ (corresponds to the impulse and angular grip of the experiment)

- The studied region in terms of rigidity for protons and ions is chosen within the limits: $0.6 < P/Z < 6$ GeV/c

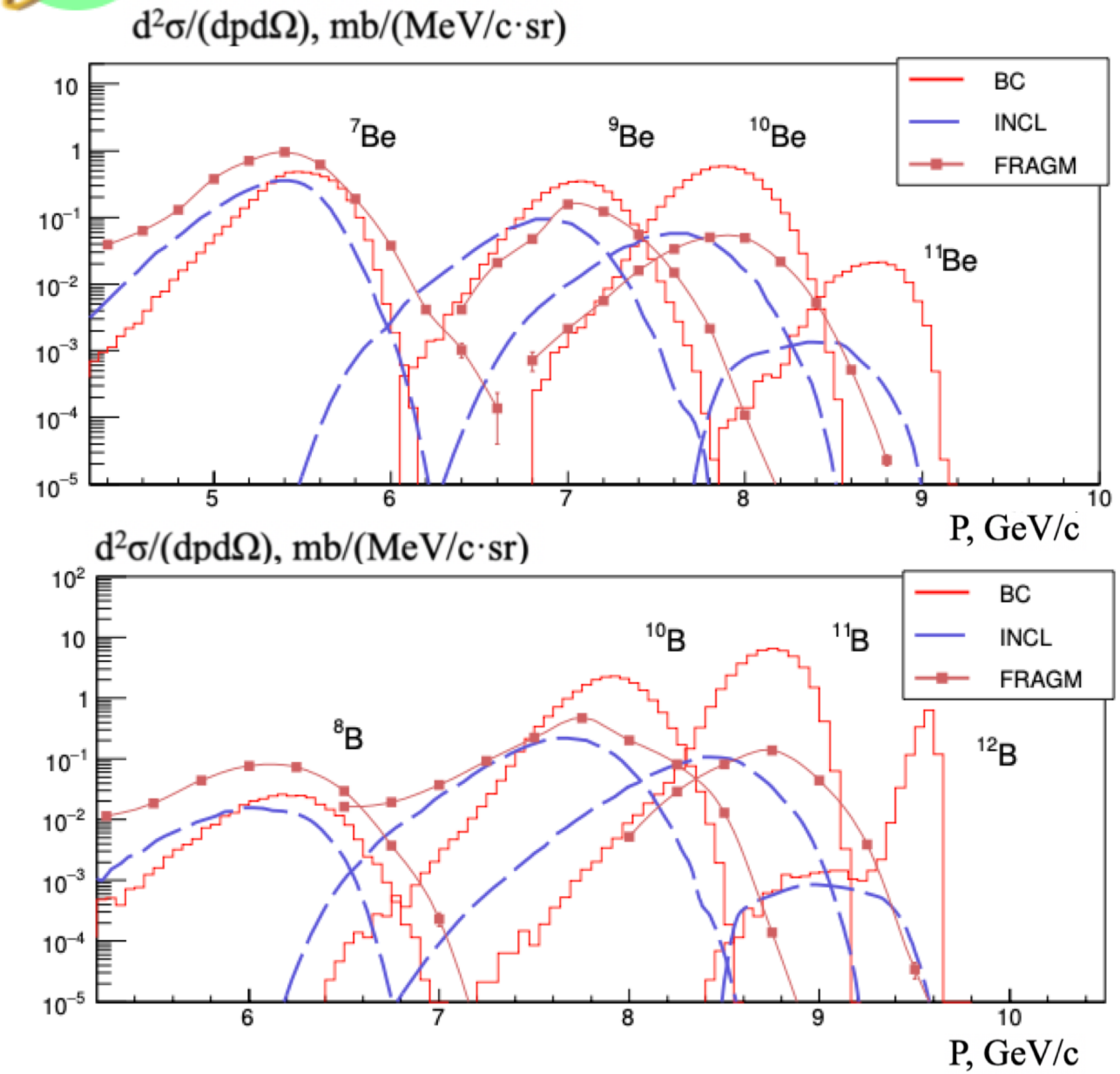
- Fitting function: $f(x) = p_2 \times \exp[-p_0/(x-p_1)^2], x = P/Z$

- Efficiencies for the studied ions ^{11}Be и ^{12}B agree within errors, but lower by about 5% of proton efficiency

- The efficiency correction plays a significant role at rigidity P/Z < 3 GeV/c and can significantly correct the momentum spectrum

- For future analysis, the total cross section value from the LAQGSM model is used: σ = 772.86 mb

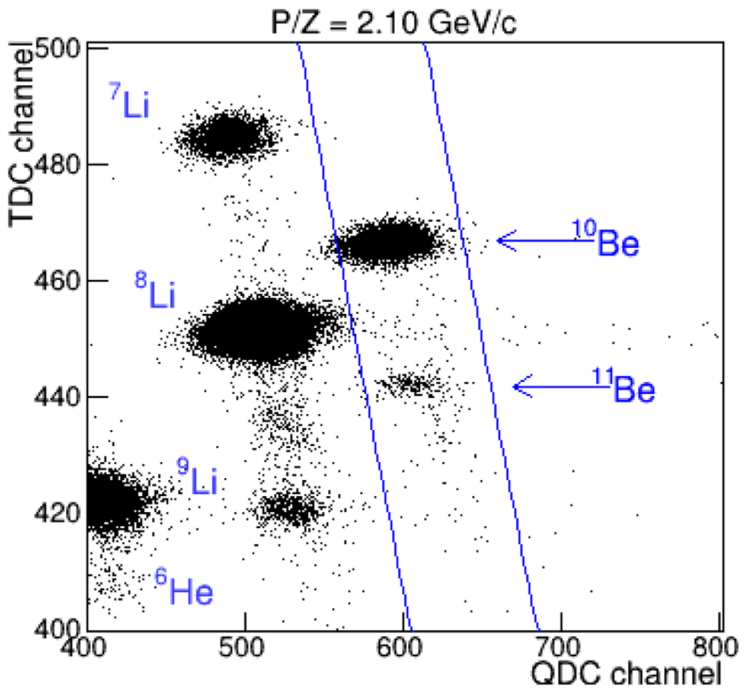
Differential cross section of Be and B production

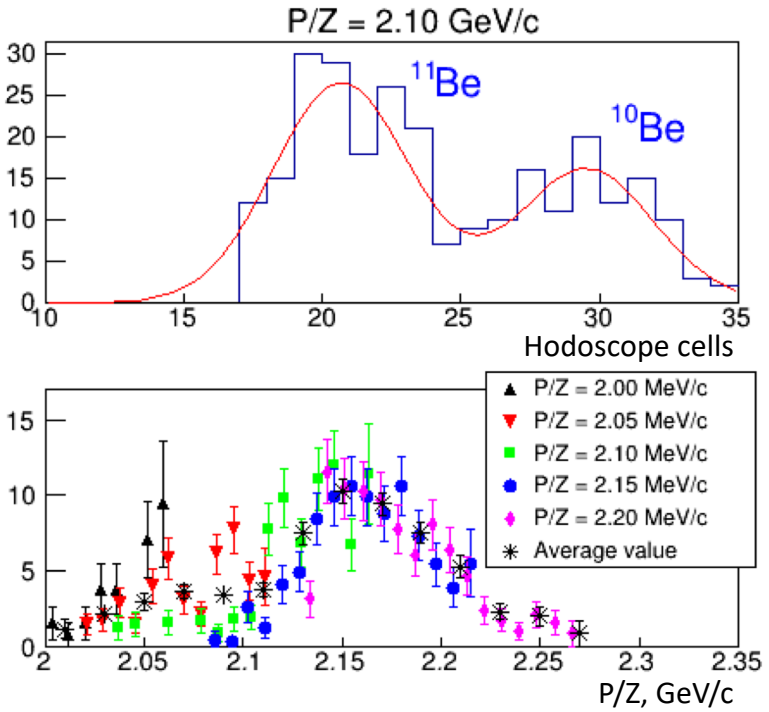


- The charge-exchange reactions over the cross section are suppressed by about an order of magnitude compared to other isotopes
- Binary cascade (BC) model gives the best spectral shapes
- The momentum resolution (dp/p) of most isotopes and the studied ^{11}Be is at the level of ~ 3-4 %
- ^{12}B has a narrow spectrum dp/p ~ 0.5 %.

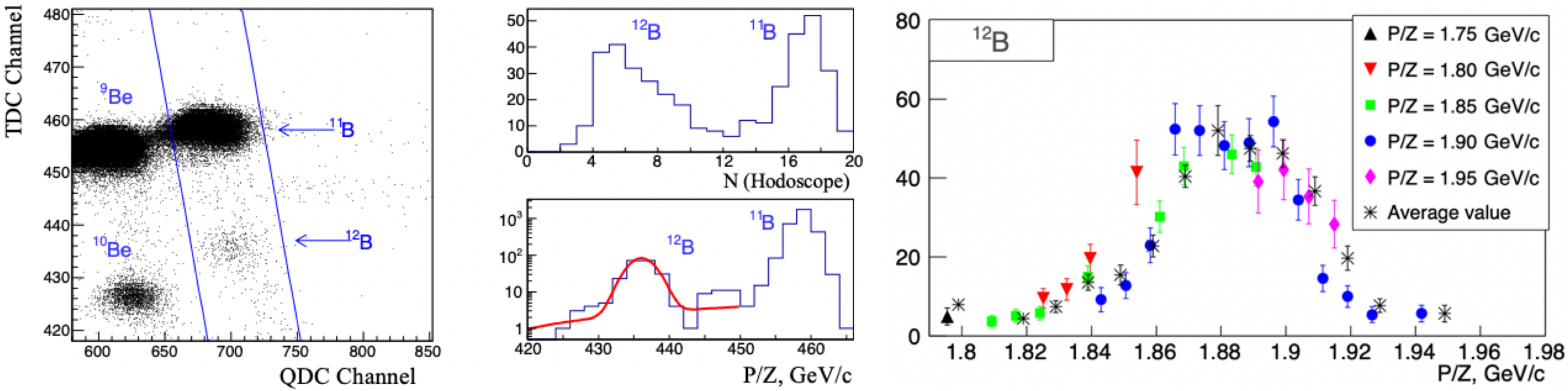
The measurements were carried out with a step of 50 MeV, therefore this method gives only one point. However, information from the hodoscope (H1) will allow us to give a few more points in this range.

Fragment selection by FRAGM setup / ^{11}Be search



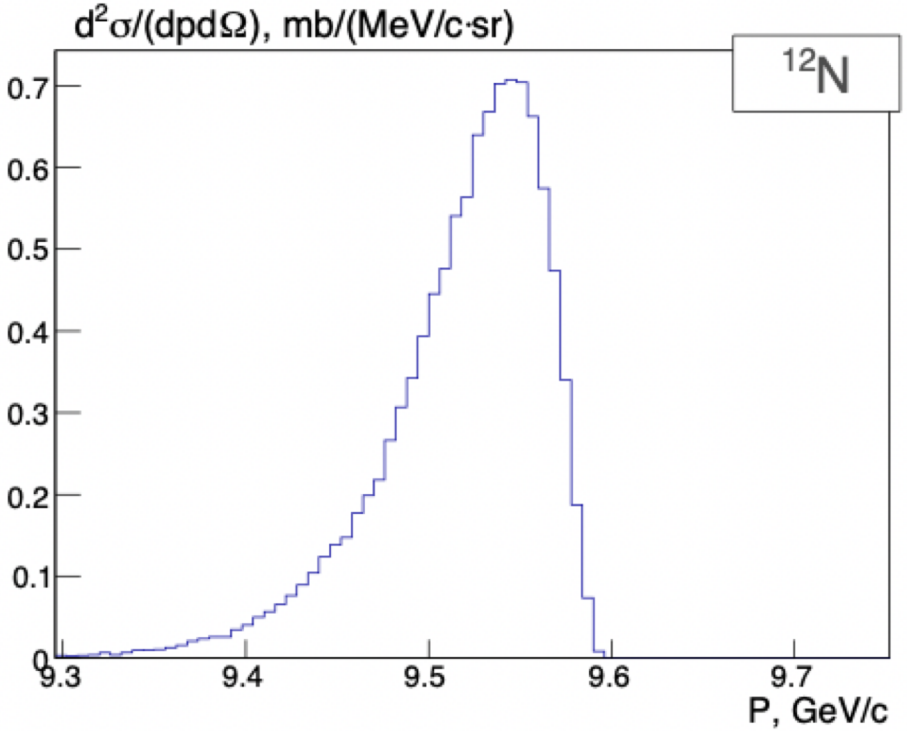


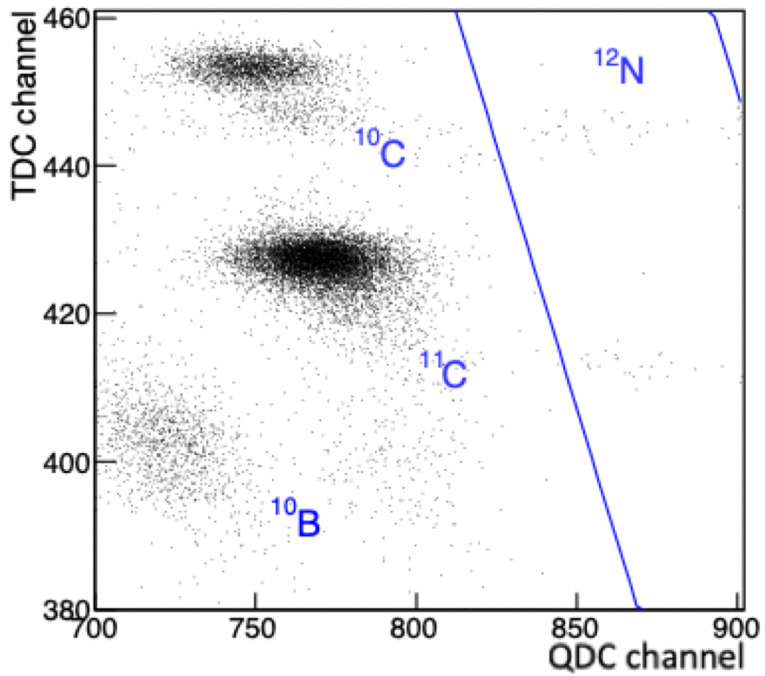
Procedure of the fragments selection: correlation distribution of the time of flight from the time-to-digital converter (TDC) and the signal amplitude from the charge-to-digital converter (QDC) at the rigidity of the magneto-optical channel 2.1 GeV/c (left); distribution of the selected events in the ^{11}Be production region over the hodoscope cell and TDC channel (right plots). For the summation of the ^{11}Be points, a rigidity step of 20 MeV was chosen. Background for ^{11}Be is rejected due to the Gaussian fit.

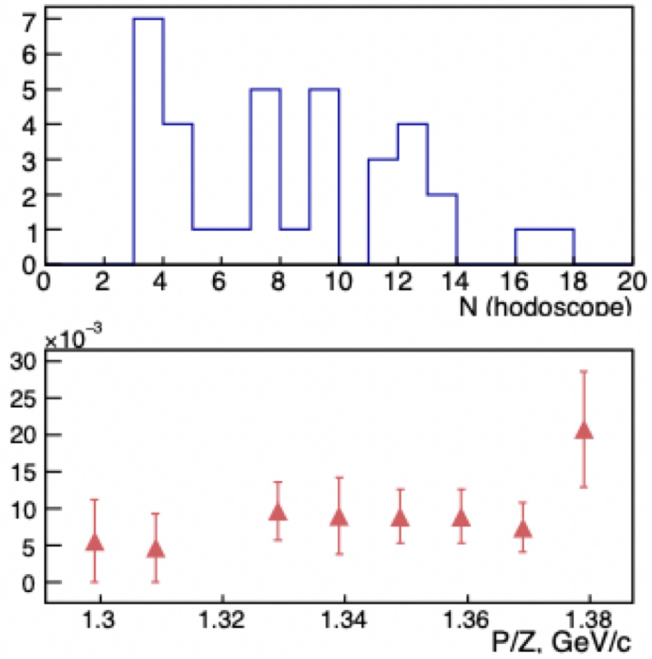


- ^{12}B extraction algorithm at a channel rigidity of 1.8 GeV/c: time-of-flight (TDC) and signal amplitude (QDC) correlation distributions (left); distribution by cell number of the hodoscope counter and by TDC channels (right).
- For the summation of ^{12}B points, a rigidity step of 10 MeV was chosen.

Search of ^{12}N



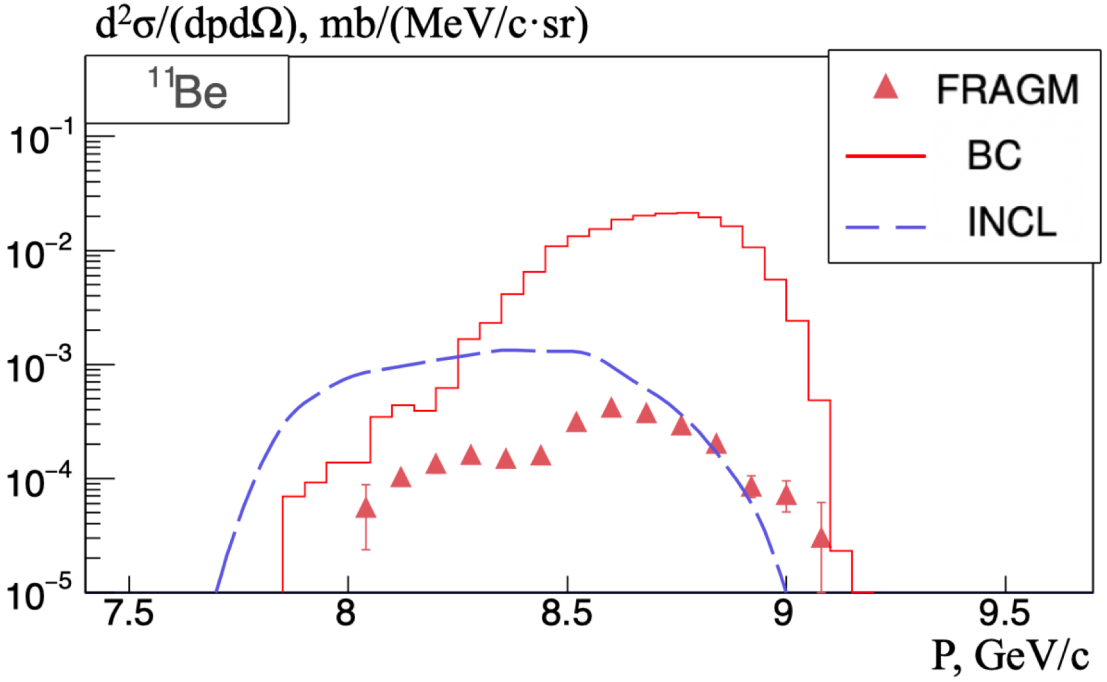


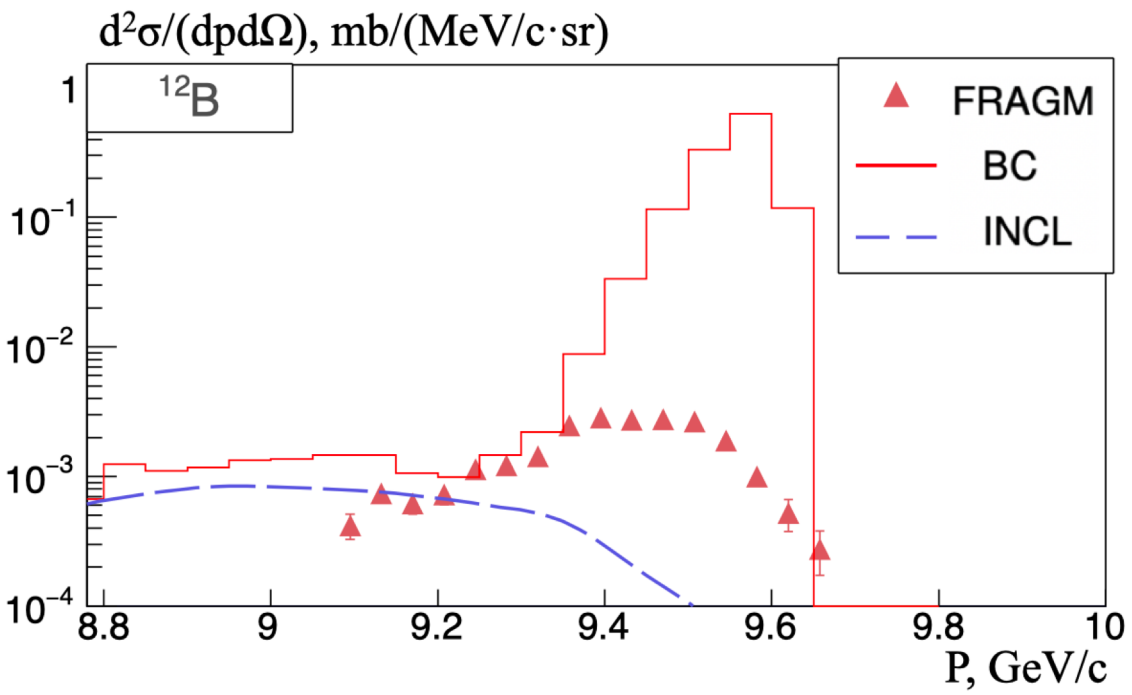


The search for ^{12}N, an isotope mirroring to ^{12}B, did not give a positive result, at the rigidity of the magneto-optical channel from 1.25 to 1.45 GeV/c, which may be due to the effect of the dominance of the formation of short-lived ^{12}N excited states decaying through the p+^{11}C channel in the region of detection angles of the FRAGM setup.

Differential cross section of ^{11}Be and ^{12}B

- The distributions for charge-exchange reactions occurring with the production of ^{11}Be and ^{12}B are given.
- Experimental data and model calculations are quite different relative to each other.
- It should be noted that the experimental data are close to the binary cascade (BC) model in terms of the width and shape of distributions, but diverge from the model in absolute values



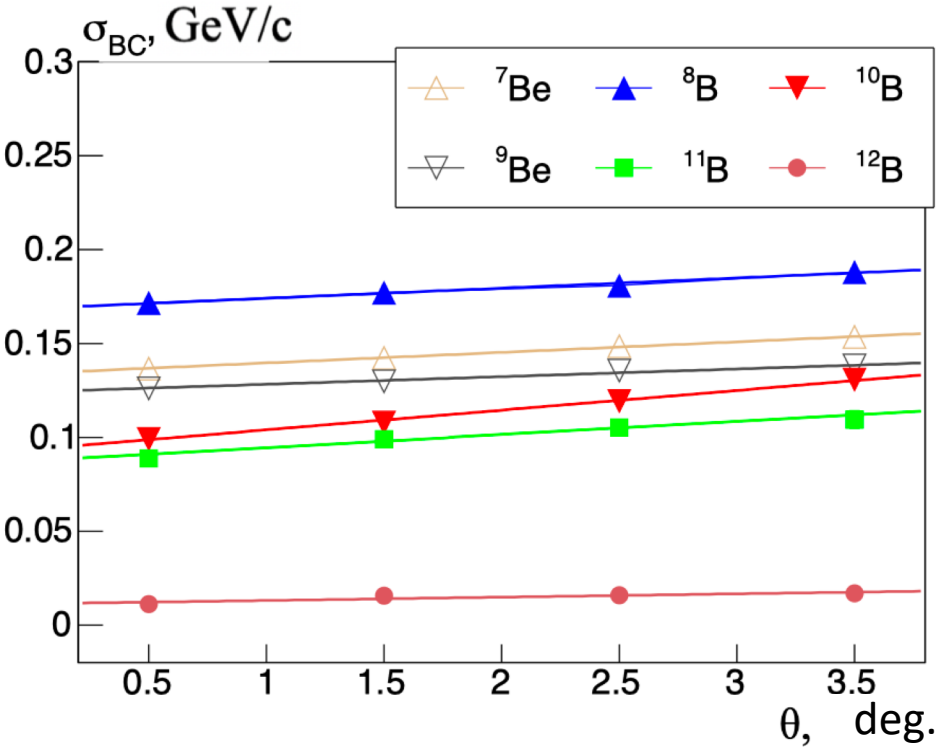


Statistical model and experimental data comparison

$$\sigma_{||}^2 = \sigma_0 \frac{A_F(A_P - A_F)}{(A_P - 1)}$$

Goldhaber formula, where A_p and A_f are the mass numbers of the projectile nucleus and fragment,
$\sigma_0 = P^2_F /5$, P_F is the Fermi momentum
$\sigma_0 = 103$ MeV

- Statistical model means that all nucleons have the Fermi momentum and the momentum widths of this distributions is described by A. Goldhaber formula. The widths in formula is calculated at zero angle.
- To compare the experimental data with model predictions, it is necessary to introduce two corrections for the width of the distributions calculated in the rest frame of the incident nucleus.
- The first correction is related to the momentum resolution of the setup, which is 1.5% in momentum in the case of measurements without using a hodoscope, and 0.5% for charge-exchange reactions obtained using a hodoscope.
- Next correction is related to bringing the experimental width to zero angle. This recalculation was carried out within the framework of the BC model, the correction factor is different for different fragments.



Theoretical and experimental data comparison

For each isotope value of the width σ in the rest frame of the projecting carbon nucleus is measured, which is also reduced to zero angle $\sigma_{||}$, the experimental data at 2.1 GeV/nucleon $\sigma_{||}^{EXP}$ and the theoretical value calculated in the approximation of the statistical model $\sigma_{||}^{theor}$. Values of $\sigma_{||}$ are in good agreement with the widths obtained within the framework of the statistical model.

$\sigma_{||}^{EXP}$ is extracted from [D. E. Greiner et al., Phys. Rev. Lett. 35, 152 (1975).]

Isotope	σ^{FRAGM}, MeV/c	$\sigma_{||}^{FRAGM}$, MeV/c	$\sigma_{||}^{EXP}$, MeV/c	$\sigma_{||}^{theor}$
^{7}Be	202.7 ± 1.8	167.9 ± 5.6	145 ± 2	183.7
^{9}Be	178.5 ± 1.6	136.6 ± 6.6	133 ± 3	161.4
^{10}Be	207.5 ± 0.6	131.3 ± 5.5	129 ± 4	138.9
^{11}Be	148.0 ± 7.9	111.4 ± 13.1	155 ± 40	103.0
^{8}B	213.4 ± 3.3	180.2 ± 5.8	151±16	175.7
^{10}B	206.4 ± 3.6	132.9 ± 6.1	134±3	138.9
^{11}B	162.0 ± 2.0	100.1 ± 7.4	106±4	103.0
^{12}B	91.38 ± 3.0	54.8±4.35	63±9	-

Conslusion

- The report investigated the reactions with a single charge exchange of nucleons.
- During the fragmentation of ^{12}C carbon ions after a single nucleon charge exchange, three long-lived isotopes can be formed: ^{11}Be (7 neutrons), ^{12}B (7 neutrons), ^{12}N (7 protons) and two after double charge exchange: ^{11}Li and ^{12}Be.
- The ^{11}Be and ^{12}B isotopes were detected and their momentum spectra were measured. It was not possible to detect the formation of ^{12}N, which may be due to the dynamic effects of its formation, leading to a very narrow angular distribution.
- Different models of ion-ion interactions were considered from the point of view of their applicability to the description of charge exchange processes.
- The best description of the studied reactions is provided by the binary cascade (BC) model.
- The experimental data are in good agreement with the Goldhaber formula.


Thank You