Proceedings of ICRC 2001: 1371 © Copernicus Gesellschaft 2001

ICRC 2001

Isotopic cross sections of ^{12}C beam fragmentation on hydrogen measured at 1.87 and 2.69 GeV/n

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Abstract. As a completion of our previous results at 3.66 GeV/n, we present new data from the experiment in which ^{12}C beam fragmentation on liquid hydrogen has been studied. The experiment was performed at the Dubna Synchrophasotron at projectile energies 1.87 and 2.69 GeV per nucleon, using the magnetic spectrometer ANOMALON. The isotopic and elemental cross sections of the ^{12}C fragmentation have been obtained. Our results are compared with semi-empirical (Silberberg and Tsao) and parametric model (Webber, Kish and Schrier) predictions.

1. Introduction

The task to measure fragmentation cross sections of ^{12}C and ^{16}O on hydrogen has been undertaken by the Polish-Russian collaboration some years ago. It was to provide more (and hopefully – better) data for studies of cosmic ray propagation in the Galaxy. The energy region around 2 GeV/n is particularly important as it is there that the ratio of secondary to primary cosmic ray nuclei (e.g. boron to carbon) starts to decrease with energy. Thus, the good knowledge about the energy dependence of fragmentation cross sections of primaries (such as ^{12}C and ^{16}O) in this energy region is necessary to draw sensible conclusions about the behaviour of the cosmic ray escape path length.

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The first part of our results (^{12}C fragmentation at 3.66 GeV/n) has been already published (Korejwo et al., 1999 and 2000). Here we present the results for two remaining energies – 1.87 and 2.69 GeV/n.

2. Experiment

The experiment has been performed using the Anomalon set-up (Zarubin et al., 1993; Borzunov et al., 1997) at the Synchrophasotron's slow extraction beam VP-1 (Joint Institute for Nuclear Research in Dubna, Russia). Layout of the spectrometer is nearly the same as in our measurements of isotopic cross sections at 3.66 GeV/n. Some changes of the location of detectors have been done in order to optimise the measurement conditions.

The principal components of Anomalon magnetic spectrometer (Fig. 1) are, first of all, a system of multiwire proportional chambers (MWPC) and an analysing magnet SP-40. The spectrometer also includes a Cherenkov hodoscope for determination of fragment charges, a trigger system consisting of scintillation and Cherenkov counters, and a beam monitor. The target consists of a 0.94 g cm^{-2} liquid hydrogen contained in a mylar tube with total wall thickness of 0.067 g cm^{-2}. The chambers and the liquid hydrogen target have been designed and produced at JINR.

The multiwire proportional chambers constitute a coordinate detector destined for determining track parameters. The chambers in the first group (MWPC 1 – 3)

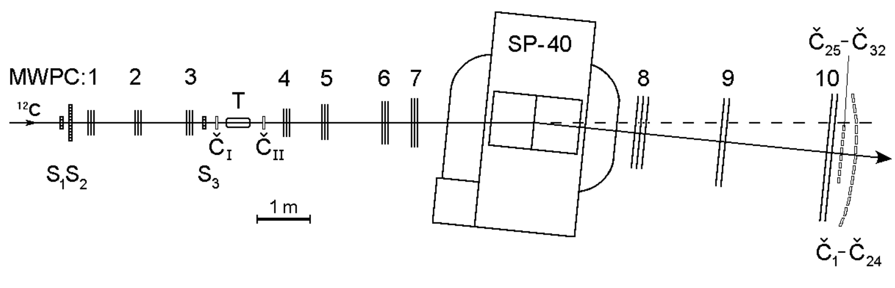


Fig. 1. Layout of the spectrometer. MWPC 1 – 10: multiwire proportional chambers, $S_1 – S_3$: scintillation counters, $\check{C}_I$, $\check{C}_{II}$, $\check{C}_1 – \check{C}_{32}$: Cherenkov counters, T: liquid hydrogen target, SP-40: analysing magnet.

measure the primary beam coordinates. The fragment coordinates are measured in front of and behind the magnet by MWPC 4 – 7 and 8 – 10, respectively. MWPC 8 – 10 and the Cherenkov hodoscope are aligned at 80 mrad deflection angle relative to the main axis of the spectrometer. Cherenkov hodoscope consists of 32 counters with lucite radiators.

The operation voltage for MWPC 4 – 10 has been chosen to correspond to the efficiency plateau for the nuclei from Li to C, so the efficiency of track reconstruction for fragments with $Z < 3$ has been lowered.

All the detectors were handled by trigger system on time intervals of 100 ns with a time delay chosen for each chamber separately. Triggering and beam flux measurements have been performed by scintillation counters S_1, S_2, S_3, and Cherenkov counters $Č_I$, $Č_{II}$. The Cherenkov counters have also been used to separate the pure ^{12}C projectiles and to suppress the events without fragmentation in the target. Total number of registered events in the measurements is about $1.1\cdot10^6$ with the hydrogen target and $4\cdot10^5$ with empty target (for the background calculation) at 1.87 GeV/n and $6\cdot10^5$ at 2.69 GeV/n.

3. Data analysis and results

The charge spectrum, obtained by processing the data from the Cherenkov counters, crossed by all identified trajectories, has been composed and is shown in Fig. 2 (analogous spectra have been made for the 1.87 GeV/n data with target and without target). The experimental data are shown as squares, thin lines represent shapes of individual peaks fitted with Gaussian functions, thick line – the sum of the fitted spectra. The events have been histogramed under condition that tracks of the projectile and fragment are reconstructed. The events without fragmentation (^{12}C peak) have been partially discriminated by trigger while the fragments with $Z < 3$ – by unefficiency of MWPC 4 – 10. The peak at the charge ~ 2.7 e is interpreted as caused by two helium nuclei crossing the same Cherenkov detector simultaneously. The charge resolution of the Cherenkov hodoscope is about 0.28 e for fragments with $2 \le Z \le 5$.

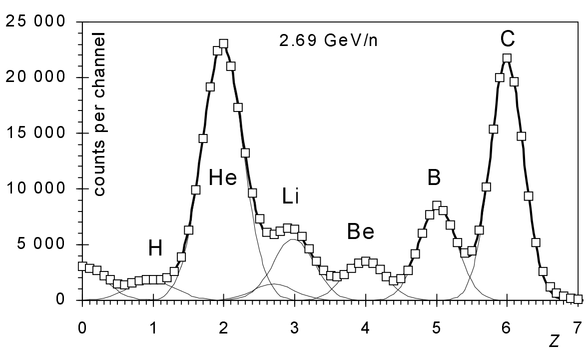


Fig. 2. Charge spectrum of fragments with reconstructed tracks.

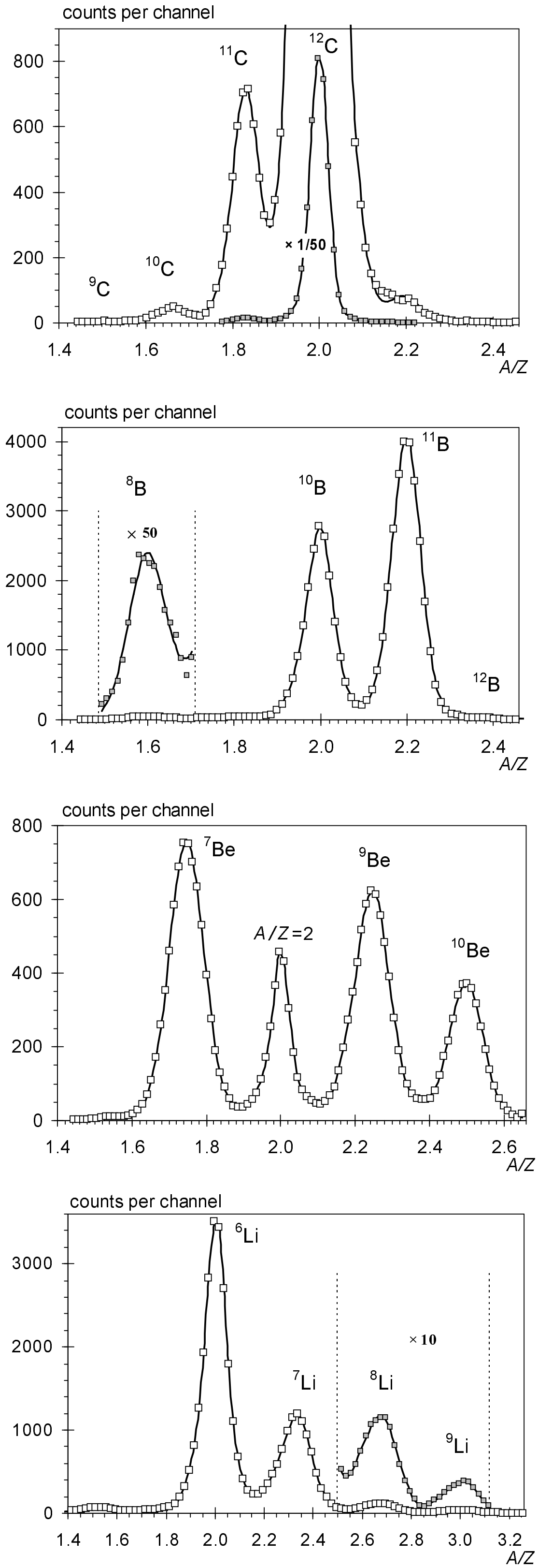


Fig. 3. *A/Z* distributions for $Z \approx 6$, 5, 4 and 3 obtained at 1.87 GeV/n. Similar distributions have been constructed for background data and at 2.69 GeV/n.

Additionally, the charge spectrum without track analysis has been determined – for the calculation of the efficiency of track reconstruction.

In the next step, distributions of the inverse of the deflection angle for tracks corresponding to individual elements have been determined. These distributions have been rescaled to *A/Z* distributions (Fig. 3). Such recalculation is based on the fact, that the fragment momenta per nucleon are approximately the same in laboratory frame, then deflection angle is inversely proportional to *A/Z* (for small angles).

The *A/Z* distributions have been prepared for charges near integer values, for instance $Z = 4.8 - 5.2$, $3.8 - 4.2$, etc. (an exception has been made for carbon nuclei: in this case the upper limit of charge interval is relatively larger). In some cases, however, the contribution of nuclei with charge other than chosen and the same *A/Z* ratio is considerable (in particular, the contribution of ^{12}C nuclei in the ^{10}B peak in the *A/Z* distribution for $Z \approx 5$).

Analogous method of data processing was applied to the background data (no hydrogen in the target vessel).

4. Isotopic cross sections

The method of calculation of fragmentation cross sections is the same as in our previous work in which we measured cross sections at 3.66 GeV/n (Korejwo et al., 2000), where the formula is described. For the value of inelastic cross section for ^{12}C interaction with hydrogen we have adopted $\sigma_{in} = (250 \pm 2)$ mb. This value has been extrapolated from the paper by Bobchenko et al., 1979, from the energy region 4 – 8 GeV/n. In our experiment we have determined the inelastic cross section as well (238 mb and 244 mb at 1.87 and 2.69 GeV/n, respectively), but with smaller precision (relative error is estimated for a few percent).

The results are given in Tab. 1 and Tab.2. Experimental errors of isotopic cross sections at 1.87 GeV/n have been computed separately as statistical (including errors concerning the determination of contributions of isotopes with the same *A/Z*) and systematic ones. The systematic errors are caused mainly by the uncertainty of track reconstruction efficiency (varying with *Z*). For the cross section ratios for isotopes with the same *Z*, only statistical errors should be taken into consideration.

At 2.69 GeV/n the measurement without target has not been performed. For that reason we have taken into account background data from our measurements at 1.87 and 3.66 GeV/n, and estimated total errors only.

Table 1. Isotopic cross sections of ^{12}C fragmentation on hydrogen at 1.87 GeV /n.

reaction $^{12}C \rightarrow$	σ mb	$\Delta\sigma_{stat}$ mb	$\Delta\sigma_{syst}$ mb
^{11}C	26.8 ± 2.2	2.1	0.7
^{10}C	1.4 ± 0.3	0.3	0.1
^{12}B	0.09 ± 0.06	0.06	0.01
^{11}B	19.7 ± 1.2	0.4	1.1
^{10}B	8.2 ± 3.0	2.9	0.5
^{8}B	0.30 ± 0.09	0.08	0.02
^{10}Be	4.1 ± 0.7	0.12	0.7
^{9}Be	6.6 ± 1.2	0.14	1.1
^{7}Be	7.8 ± 1.4	0.15	1.4
^{9}Li	0.36 ± 0.08	0.04	0.06
^{8}Li	1.27 ± 0.22	0.07	0.20
^{7}Li	11.8 ± 2.0	0.2	2.0
^{6}Li	17.7 ± 3.3	0.5	3.2
^{6}He	1.01 ± 0.12	0.06	0.10
^{4}He	156 ± 15	1	15
^{3}He	22.0 ± 2.2	0.24	2.2

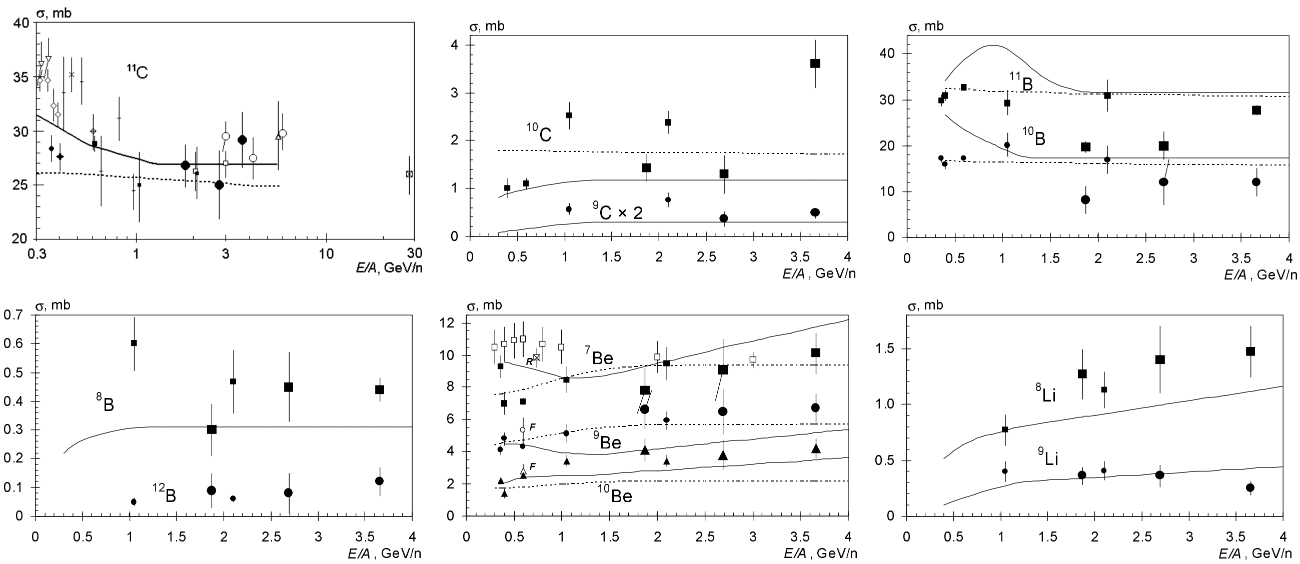
Table 2. Isotopic cross sections of ^{12}C fragmentation on hydrogen at 2.69 GeV/n.

reaction $^{12}C \rightarrow$	σ mb	*reaction* $^{12}C \rightarrow$	σ mb
^{11}C	25 ± 3	^{9}Li	0.36 ± 0.10
^{10}C	1.3 ± 0.4	^{8}Li	1.4 ± 0.3
^{9}C	0.18 ± 0.08	^{7}Li	13 ± 3
^{12}B	0.08 ± 0.07	^{6}Li	19 ± 4
^{11}B	20 ± 3	^{6}He	1.4 ± 0.2
^{10}B	12 ± 5	^{4}He	180 ± 30
^{8}B	0.45 ± 0.12	^{3}He	30 ± 4
^{10}Be	3.8 ± 0.9		
^{9}Be	6.5 ± 1.4		
^{7}Be	9.1 ± 1.9		

5. Comparison with other experimental data and predictions

Isotopic cross sections of ^{12}C fragmentation on hydrogen in the energy region $1 - 3$ GeV/n have been measured for many isotopes by Lindstrom et al., 1975 (also published by Olson et al., 1983), later denoted by L&O. In these papers there were presented experimental data from ^{1}H to ^{12}N, obtained with liquid hydrogen target at 1.05 an 2.1 GeV/n. Some cross sections have been determined in other experiments, practically only for radioactive isotopes with suitable lifetime (in particular, ^{11}C and ^{7}Be). Below 1 GeV/n there are significantly more numerous data, from experiments accomplished at LBL and SATURNE (e.g. Webber and Kish, 1985; Webber et al., 1990; Webber et al., 1998), with liquid hydrogen target or using $CH_2 - C$ subtraction.

Results of the isotopic cross sections for energies above 0.3 GeV/n are presented in Fig. 4. Additionally, in the same figure we present results of calculations of cross sections made with semi-empirical (Silberberg et al., 1998; Tsao et al., 1999) and parametric (Webber et al., 1990) approaches. Calculations have been made with the aid of programmes accessible at Space Physics Data System (SPDS).



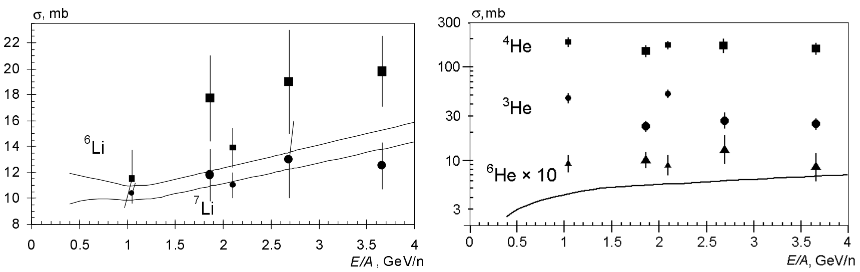


Fig. 4. Isotopic cross sections of ^{12}C fragmentation on hydrogen. Solid line: semi-empirical model calculation (S&T); dashed line: calculation with parametric approach (WKS). Full set of references to experimental data (excluding our new results) is available in our previous paper (Korejwo et al., 2000). Our results are marked by larger points.

6. Conclusions

Our experiment is one of the few measurements of carbon fragmentation with liquid hydrogen target. Using the same experimental set-up and practically the same method of data processing, we have obtained the isotopic cross sections for many final nuclei at three energies (including our previous data). To adopt them to the cosmic ray propagation in the interstellar gas it is necessary to determine the ‘decayed’ σ's (cross sections for production of a given isotope after all possible decays of the radioactive ones, which take place in the Galaxy), which can be easily done from our data.

On the whole, our results are close to those of other experiments and indicate a weak energy dependence of cross sections in the analysed energy region. But, as seen in Fig. 4, in some cases they are significantly different from other experimental data at neighbouring energies or predictions of models. Of particular interest for the cosmic ray escape time from the Galaxy is a determination of production cross section ratios $^{10}Be/^{9}Be$ and/or $^{10}Be/^{7}Be$. There are no measurements yet of the corresponding cosmic flux ratios at the energies considered here, but our $^{10}Be/^{9}Be$ ratios are practically the same as that determined by L&O at an intermediate energy of 2.1 GeV/n. However, our $^{10}Be/^{7}Be$ at 1.87 GeV/n is larger than that obtained by L&O by ~ 1.4 and larger by ~ 2 than those predicted by the phenomenological formulae. At 2.69 GeV/n our result agrees with that of L&O within 17 %, but diverges from the formulae by ~ 1.6.

Because some doubts in our experiment may concern the detector efficiency, for the time being we presume, that the presented results should be treated as preliminary. Assuming, that the efficiency is dependent on *Z* only (not on *A* at given *Z*), there is possible to normalise all isotopic cross sections to the elemental cross section from another experiment, as the isotopic fractions have been determined by us more precisely than the absolute values. Nevertheless, we are planning to check in more detail the dependence of the detector efficiency on isotope mass.

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