ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

ДУБНА

E1 - 11202

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OBSERVATION OF THE $^{12}_{\Lambda}C$ HYPERNUCLEUS IN 250 GeV PROTON INTERACTION WITH PHOTOEMULSION NUCLEI

Submitted to ЯФ

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Обнаружение гиперядра $^{12}_{\Lambda}C$ при взаимодействии протонов с энергией 250 ГэВ с ядрами в фотоэмульсии

В фотоэмульсии, облученной протонами с энергией 250 ГэВ, при анализе 150 000 взаимодействий найдено событие, которое интерпретируется как образование и распад основного состояния гиперядра $^{12}_{\Lambda}C$. Заряд гиперядра определен методом измерения зависимости ширины следа от остаточного пробега. Зарегистрирован след позитрона от β-распада ядра отдачи ^{12}N. Значение энергии связи Λ-гиперона B_{Λ} в гиперядре $^{12}_{\Lambda}C$ равно $(11,14 \pm 0,57)$ МэВ. Точность определения величины B_{Λ} улучшена в два раза по сравнению с результатами, полученными методом определения недостающей массы с помощью электроники.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1978

E1 - 11202

Bunyatov S.A. et al.

Observation of the $^{12}_{\Lambda}C$ Hypernucleus in 250 GeV Proton Interaction with Photoemulsion Nuclei

In analysing as many as 150 000 interactions in photoemulsion exposed to the 250 GeV proton beam one event has been found which can be interpreted as the production and the decay of the ground state of the $^{12}_{\Lambda}C$ hypernucleus. The hypernuclear charge has been determined by measuring the track-width dependence upon the residual range. A positron track of the decay of the ^{12}N recoil nucleus has been detected. The Λ-hyperon binding energy B_{Λ} in $^{12}_{\Lambda}C$ has been obtained to be (11.14 ± 0.57) MeV. The accuracy of the B_{Λ} determination has been improved twice as compared to the results determined by the missing mass method employing electronics.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1978

The $^{12}_{\Lambda}C$ hypernucleus has not been identified uniquely in photoemulsion up till now. The indications to the existence of this hypernucleus have been obtained by the missing mass electronic experiment in the $^{12}C(K^-, \pi^-)^{12}_{\Lambda}C$ in the capture of stopped negative kaons /1/ and in the interactions of 390 MeV/c momentum negative kaons /2/ with carbon nuclei. The values of the Λ-hyperon binding energy B_{Λ} obtained in these experiments have turned out to be (11 ± 1) MeV /1/ and (9 ± 2) MeV /2/.

The present experiment has made it possible to identify one event of two-particle π^--mesonic decay of the multicharge hypernucleus followed by the β-decay of the recoil nucleus. This event can be most probably interpreted as a decay of the ground state of the $^{12}_{\Lambda}C$ hypernucleus.

The photomicrograph of this event is shown in Fig. 1. The event has been observed in a NIKFI-BR-2 emulsion stack exposed to the 250 GeV proton beam from the FNAL accelerator (Batavia). The exposure conditions and the scanning procedure have been described in detail elsewhere /3/. The track of the incident particle inducing the disintegration which produced a hypernucleus was scanned up to entering the emulsion stack. The distance from the edge of the stack up to the interaction point is 2.2 cm. Since the particle track has grain density and direction identical to those of primary protons and no other interaction or scattering at large angles have been observed, it can be stated that this particle is a 250 GeV proton.

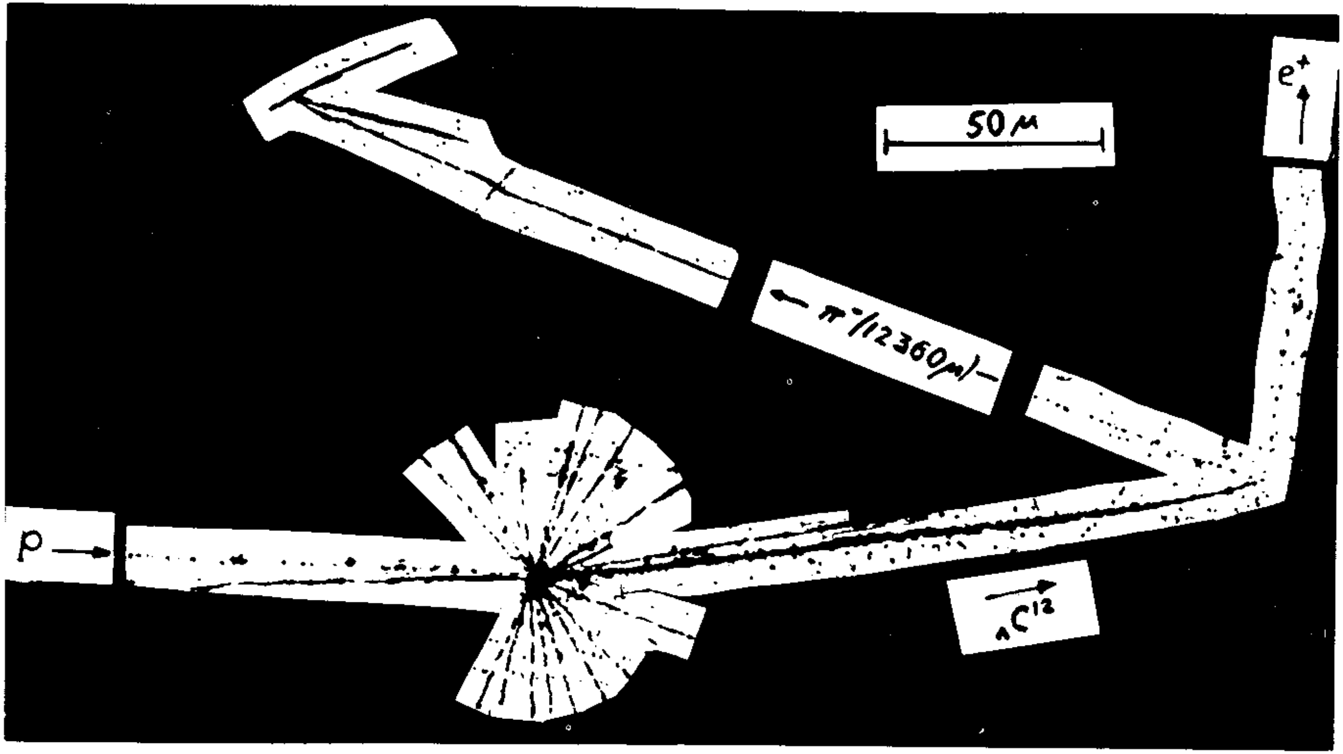

Fig. 1. The photomicrograph of the production and the decay of the ground state of the ${}^{12}_{\Lambda}C$ hypernucleus.

The hypernucleus has been produced in proton interaction with Ag or Br nuclei, since along with a hypernucleus prong 17 "black" and 8 "grey" prongs have been observed in the parent star.

A negative pion from the hypernuclear decay was identified unambiguosly by measuring the relative ionization and a specific configuration of the stopped negative pion capture by the emulsion nucleus.

In addition to the negative pion a beta-particle track from the decay of the recoil nucleus (not seen in the emulsion) was identified. This track has minimal ionization but it is noticeably scattered in emulsion and after passing 7.78 mm is lost in penetrating from pellicle to pellicle; its relative ionization at that point is 1.21 ± 0.05, which coincides with a ~ 0.2 mm residual range /4/. This fact can be explained either by β-particle scattering at a large angle or by its annihilation (if the beta-particle is a positron).

The emulsion stack was calibrated by the muons from the decay of stopped pions $\pi^{+} \to \mu^{+} + \nu$. The mean muon range determined by 46 decays turned out to be $(595.0 \pm 4.3)\ \mu m$, while the range in a standard emulsion is $(602.2 \pm 1.5)\ \mu m$ /5/. As a result, all the ranges were increased by a factor of 1.0121 ± 0.0077. When calculating the ranges correlations for multiple scattering were made /19/. The kinetic energy was determined from the range-energy Tables /4,6/. The characteristics of the hypernuclear, negative pion and beta-particle tracks are given in the Table (the measured ranges are given).

The absence of a visible track of the recoil nucleus indicates that the mass of the recoil nucleus and, hence, that of the hypernucleus are large. The hypernuclear track has a thinning-down typical of the tracks of multicharged nuclei, with decreasing the residual range. Rather a long range of the hypernucleus ($R = 171\ \mu m$) allows the determination of its charge by using track parameters.

Table

Track	Dip angle θ°	Azimuth angle ϕ°	Range R (μm)	Identification	Kinetic energy T (MeV)
HF	9.9 ± 0.5		171 ± 1	$^{12}_{\Lambda}C$	110 ± 2
I	-14.7 ± 0.5	149 ± 1	12360 ± 80	π^-	26.84 ± 0.57
2	-38.8 ± 0.5	65 ± 1	>7780	e^+	>4.6

In order to determine the hypernuclear charge the track-width dependence upon the residual range was measured.

The track widths were measured by using an MBI-9 microscope of 2700X magnification. A measured track was positioned along the X-axis. Its width was measured at equal intervals $\Delta X = 5$ μm. At each step the width was measured three times. The displacement of the referring line located along the upper and lower profile of a track was taken as a measure of the track-width.

The hypernuclear charge was determined from the comparison with the results obtained by Skjeggestad /7/ for ions having Z=3,4,5,6 and 8. The hammer-tracks which may belong to ^{8}Li with great probability were used as calibration tracks. Similar tracks are produced by ^{8}B, however, the probability of ^{8}B production is considerably lower than that of ^{8}Li. Since among 38 hammer-tracks observed in the same pellicle no track had a width significantly larger than the mean width of all the hammer-tracks it can be concluded that all hammer-tracks in this pellicle belong to ^{8}Li.

Calibration measurements were performed in two ^{8}Li tracks having depths in emulsion and dip angles close to those of the hypernucleus.

The properties of the NIKFI-BR-2 and Ilford-G5 (used in ref./7/) emulsions affecting the visible track-width - grain size and sensitivity - are identical. Therefore, when comparing our results with those of ref.[7] we took into account a probable difference in development conditions only.

It should be mentioned that in emulsions developed under different conditions the visible track-widths of nuclei having the same charges differ by a constant λ_0, depending only on development conditions and not depending on the residual range and the nuclear charge [8]. This constant was determined as the mean difference in the values of ^{8}Li track-widths obtained in ref.[7] and by ourselves and turned out to be $(0.14 \pm 0.01)\ \mu m$.

When comparing our results with those of Skjeggestad[7] the values of ^{8}Li track-widths obtained by ourselves (averaged over two tracks) as well as those of the hypernucleus were increased by $\lambda_0 = (0.14 \pm 0.01)\mu m$. The results of comparison are shown in Fig.2. As is seen from Fig.2, the most probable value of the hypernuclear charge is 6 (the relative probability of an alternative hypothesis (Z=5) is smaller than 1% at a 95% confidence level).

The kinematical analysis of the event was performed for if hypernuclei with the charge Z=6 , if the recoil nuclei from the decay of these hypernuclei are beta-active with a maximum beta-particle energy not lower than that of the observed beta-particle:

$$E_{\beta_{max}} \geq 4.6 \text{ MeV}. \quad (1)$$

When determining the value of B_Λ we used the values of nuclear masses from ref.[9]; the values of the Λ-hyperon mass and that of the negative pion from ref.[10]. The data on $E_{\beta_{max}}$ and other properties of recoil nuclei have been taken from Ajzenberg-Selove's papers [11].

Since the values of B_Λ in all unambiguously identified hypernuclei [12,13] are in the interval $(A-3) \leq B_\Lambda\ (\text{MeV}) \leq A$, with A being a mass number of the hypernucleus, it is natural to suppose that the values of B_Λ in the $^A_\Lambda C$ hypernuclei should be in the same interval too. On the other hand, the

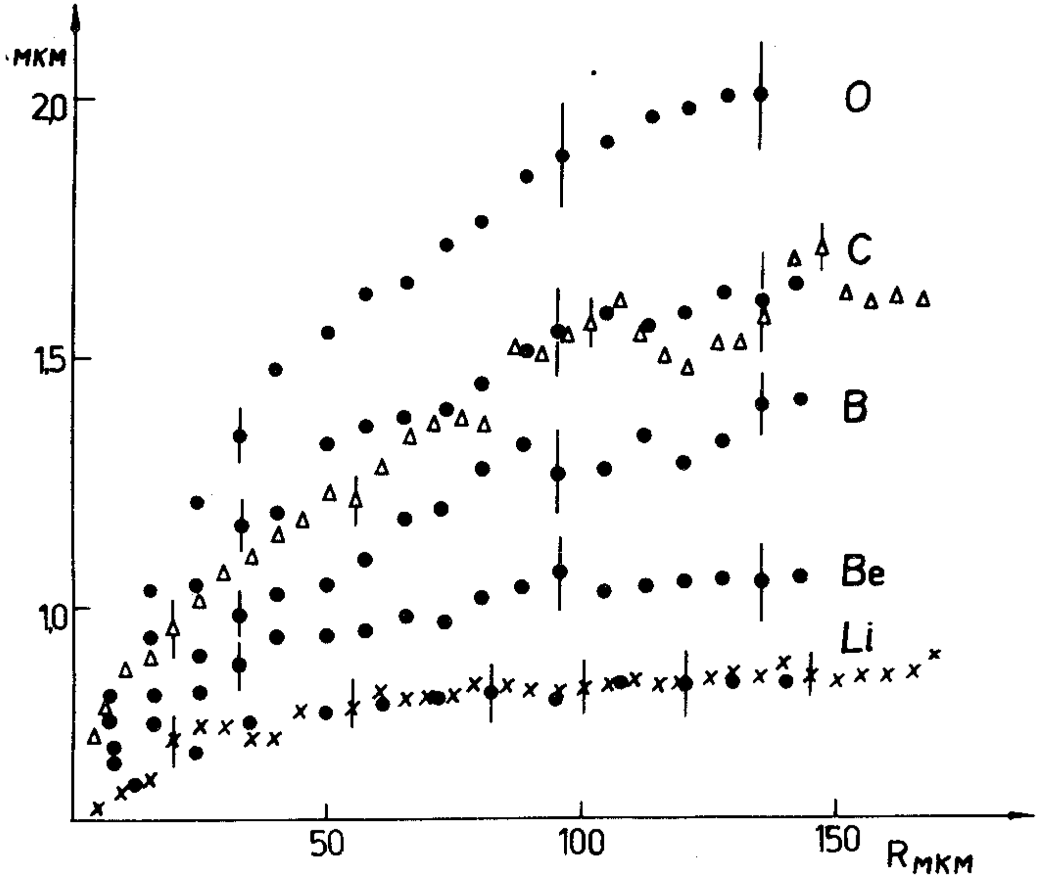

Fig. 2. The determination of the hypernuclear charge from the track-width, λ, dependence on the residual range R : ● – Skjeggestad's data (ref. /7/), × – ^{8}Li track widths (this experiment), Δ – hypernuclear track widths. Our values of ^{8}Li and hypernuclear track widths have been increased by λ_0 = = (0.14±0.01) μm.

upper limit of the B_Λ values in hypernuclei with A = 40 – 100 established experimentally is 22-24 MeV /14/ which indicates to a moderated increase of B_Λ in comparison with A. Therefore, we have assumed less rigid restrictions on the possible values of B_Λ

in ${}^{A}_{\Lambda}C$ hypernuclei with the mass number $A \geq 15$*

$$10 \leq B_{\Lambda}(\text{MeV}) \leq A . \qquad (2)$$

In the case of the decay without neutron emission to the ground state of the recoil nucleus the decay of the ground state of the ${}^{12}_{\Lambda}C$ hypernucleus according to the following scheme:

$${}^{12}_{\Lambda}C \rightarrow \pi^{-} + {}^{12}N \; ; \quad {}^{12}N \xrightarrow{\beta^{+}} {}^{12}C \; ;$$

$$(E_{\beta\, max} = 16.3 \text{ MeV}; \quad B_{\Lambda} = (11.14 \pm 0.57) \text{ MeV})$$

is the only suitable interpretation.

It is worth noting that if the given hypernucleus is ${}^{12}_{\Lambda}C$ its decay in the given case goes quite definitely to the ground state of the recoil nucleus because ${}^{12}N$ even at minimal excitation is unstable with respect to the nucleon decay accompanied by proton emission (the energy of the first excited level of ${}^{12}N^{x}$ is equal to 0.969 MeV /11/ and is higher than the proton separation energy equal to 0.595 MeV /11/).

However, there is no proton track in emulsion, and $E_{\beta\, max}$ of a positron from the ${}^{11}C$ decay is 0.96 MeV /11/, which is considerably lower than the energy of the observed beta-particle.

Either the hypernuclear decays to the excited state of recoil nuclei or the decay with neutron emission (residual nuclei may turn out to be in the excited state too) can form background for this event.

As the analysis has shown, only the decays of ${}^{A}_{\Lambda}C(A \geq 17)$ hypernuclei with neutron emission can satisfy conditions (1) and (2). Therefore, we have estimated the probable background from such hypernuclei.

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* The values of B_{Λ} in ${}^{13}_{\Lambda}C$ and ${}^{14}_{\Lambda}C$ hypernuclei are ~(A–13) and ~(A–1.8) MeV, respectively /13/.

The comparison of data on the yield of uniquely identified hypernuclei produced in K^--meson capture by emulsion nuclei /12/ with the data on the production cross-sections of various fragments by protons from silver nuclei /15/ makes it possible to state that the mass distribution of hypernuclei repeats qualitatively the mass distribution of the proper core nuclei. When comparing these data we took into account that the shape of mass distribution is not practically changed with changing incident particle energy and does not depend noticeably on their type /16/.

Consequently, we can estimate the relative yield of $^{12}_{\Lambda}C$ and $^{17}_{\Lambda}C$ hypernuclei by the production cross-sections of ^{11}C and ^{16}C core nuclei. Since the cross-section of fragment production is sharply decreased with removing from the stability region /16/, the production cross-section of ^{A}C and $^{A+1}_{\Lambda}C (A \geq 17)$ is smaller than that of ^{16}C and $^{17}_{\Lambda}C$, respectively.

According to the data of Table 1, ref. /15/, the ^{11}C production cross-section in 3 GeV proton interaction with silver nuclei is about 13 times greater than that of the ^{16}C isotope (E_p = 2.8 GeV). Since beginning with the energies of incident protons of about 2 GeV, the fragment production cross-section reaches practically a constant value /16/, which can be experimentally observed up to 300 GeV proton energies /17/, at an energy of 250 GeV the order of magnitude of the production cross-section ratio of ^{11}C and ^{16}C isotopes holds *.

Besides, as it has been observed, the energy spectra of neutron-deficient isotopes are much harder than the spectra of neutron-rich isotopes /15/. Thus, the ratio of the production probabilities of

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*If the hypernucleus is produced in proton interactions with the bromine nucleus, this ratio is still larger, since neutron-deficient isotopes are produced with greater probability from more neutron-deficient target nuclei /16/.

^{11}C and ^{16}C isotopes having energies higher than 100 MeV are noticeably gteater than those of the total production cross-sections for these isotopes.

Consequently, it can be stated that the productio cross-section of the $^{12}_{\Lambda}C$ hyperfragment with the energy ≥ 100 MeV is larger than that of $^{A}_{\Lambda}C$ $(A \geq 17)$ hyperfragments more than 13 times. Therefore, the background from the $^{A}_{\Lambda}C$ $(A \geq 17)$ hypernuclei is lowe than $8 \cdot 10^{-2}$. So the most probable interpretation of this event is the production and the decay of the ground state of the $^{12}_{\Lambda}C$ hypernucleus.

The Λ-hyperon binding energy in this hypernucleus is (11.14 ± 0.57)MeV and agrees with two oth estimations - (11 ± 1)MeV /1/ and (9 ± 2)MeV /2/ obtained by the electronics experiments. The value of B_{Λ} obtained by us coincides within errors with that of B_{Λ} in the $^{12}_{\Lambda}B$ mirror hypernucleus which has been found to be (11.37 ± 0.06)MeV /12/. This is in agreement with the hypothesis on Λ-N interaction charge independence.

It is worth noting that up till now the $^{12}_{\Lambda}C$ hypernucleus in the ground state has not been observed in emulsion since the energy and, hence, the ranges of hypernuclei with $A \geq 10$ produced in low energy K^--meson interactions amount to some microns, which impedes the reliable identification of such hypernuclei.

As with increasing incident particle energy the fraction of long-range hypernuclei is increased /18/, in some cases it becomes possible to determine the nature of the hyperfragment by the track parameters. Therefore, when performing photoemulsion experiments with the high energy particles special attention should be paid to a possible identification of rare hypernuclei with $A \geq 10$.

The authors are grateful to M.I.Podgoretsky for helpful advice.

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Received by Publishing Department
on December 26,1977.