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дубна

D1-82-447

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# SPACE RECONSTRUCTION OF A CHARMED $\Lambda_c^+$ BARYON PRODUCTION AND DECAY VERTICES IN NUCLEAR EMULSION

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1982

## INTRODUCTION

In the experiments on measuring charmed particle lifetimes nuclear emulsion chambers [1-4] and bubble chambers [5] as well as semiconductor detectors [6] are used now. Of all these detectors nuclear emulsion has the highest resolving power - down to tenth parts of a micron, while the maximum resolution of small bubble chambers is 35-55 $\mu$m, and that of silicon semiconductor detectors is $\sim$400 $\mu$m.

Emulsion provides a unique opportunity for detection of short-lived particles with decay time $\sim 10^{-15}-10^{-16}$ s. Particle ranges in this case are varying from microns to few tenth of a micron depending on their momentum. The method of measuring such ranges consisting in a geometrical reconstruction of the production and decay vertices by the measured coordinates of track grains has been successfully applied for determination of $\pi^0$-meson lifetime. In the experiment, where a beam of $\pi^-$-mesons with the energy of 3.5 GeV was used, the primary interaction vertex has been reconstructed in XY-plane of the emulsion pellicle with the accuracy better than 0.03 $\mu$m both along the beam and across it [7].

During the search for the short-lived particles produced in high energy interactions the accuracy of the geometrical event reconstruction is limited mainly by small divergence angles of secondary particles. Besides, at a high shower track multiplicity it is impossible to reliably discriminate the required track grains closest to the primary star. In general, the accuracy of the reconstruction of short-lived particle production and decay vertices along the beam is worse than across it.

The measurement accuracy of track grains Z-coordinate is lower than that of X- and Y-coordinates, therefore only track projections in XY-plane are usually analyzed. It has been shown in Refs. [8,9] that a short-lived particle can be detected if at least one track from decay deviates in XY-plane from a primary interaction vertex for more than 0.17-0.20 $\mu$m. A comparative analysis of the reconstruction accuracy for intersection vertices of track pairs in XZ- and XY-planes has been carried out in Ref. [10]. At the equal divergence angles of the measured track pairs the accuracy of the vertex coordinate determination in XZ-plane is few times lower than in XY-plane.

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Emulsion allows not only to detect short-lived particle production and decay vertices, but also to indentify some secondary particles that essentially complements the information obtained from an external detector. In some detected interactions without a visible decay vertex there can be signs of short-lived particle decays: the coincidence of the invariant mass of some tracks with the mass of a charmed or beauty particle along with a reliable identification of particles from a probable decay; detection of a single strange particle, leptons, etc. In these events it is most probable to detect short-lived particles.

In this work the problems of space reconstruction of short-lived particle production and decay vertices are considered on the example of a charmed $\Lambda_c^+$ baryon decay.

DESCRIPTION OF THE EVENT

Among the neutrino interactions detected in FNAL E564 experiment (the experiment was described in Ref. /2/ ) the event shown in Fig.1 has been found. The characteristics of the interaction shower tracks are given in Table 1. When scanning the event we paid attention to a narrow triplet of tracks 5.1,

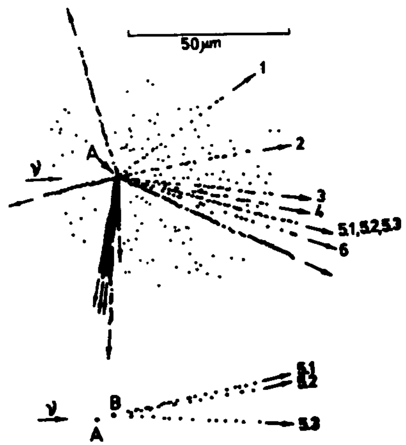


Fig.1. The photomicrograph of the event in emulsion; A - the primary vertex, B - the decay vertex of the $\Lambda_c^+$.

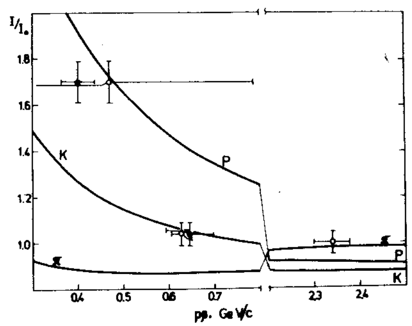


Fig.2. Identification of tracks 5.1 (proton), 5.2 ($\pi^+$ -meson) and 5.2 ($K^-$ -meson) due to measurements of multiple scattering $p\beta$ and ionization $I/I_0$ in emulsion (black circles) and momenta in bubble chamber (open circles).



Table 1

Characteristics of the event shower tracks

| Track | Azimuth angle (deg) | Dip angle (deg) | Momentum (GeV/c) |
|---|---|---|---|
| 1 | $-29.1\pm0.2$ | $-42.1\pm0.9$ | $0.88\pm0.01$ |
| 2 | $-6.9\pm0.2$ | $-11.4\pm0.5$ | $11.76\pm0.24$ |
| 3 | $8.5\pm0.1$ | $12.6\pm0.5$ | $3.36\pm0.20$ |
| 4 | $12.3\pm0.1$ | $18.6\pm0.8$ | $0.94\pm0.02$ |
| 5.1 | $16.2\pm0.1$ | $11.4\pm0.9$ | $0.72\pm0.02$ |
| 5.2 | $16.3\pm0.1$ | $9.5\pm0.9$ | $2.34\pm0.04$ |
| 5.3 | $16.8\pm0.1$ | $-4.5\pm0.3$ | $0.75\pm0.02$ |
| 6 | $19.1\pm0.1$ | $-12.7\pm0.3$ | $1.34\pm0.04$ |

5.2, 5.3 identified reliably as p, $\pi^+$ and $K^-$ respectively due to the measurements of momenta and charges in bubble chamber and multiple scattering and ionization in emulsion (see Fig.2). The bottom of Fig.1 shows a vertical projection of these tracks. The invariant mass of $p\pi^+K^-$ equals $2281\pm12$ MeV and coincides with the mean mass value of the $\Lambda_c^+$ baryon, i.e., $2285\pm3$ MeV /11/.

Azimuth and dip angles of tracks 5.1 and 5.2 are very similar what makes it impossible to measure them separately at distances shorter than 50 $\mu$m. Track 5.3 can be distinguished from tracks 5.1 and 5.2 at a distance longer than 8 $\mu$m. Hence direct reconstruction of a probable decay vertex B by grain coordinates of tracks 5.1, 5.2, 5.3 is impossible. Since the angles between the projections of these tracks in XY-plane are very small, a space reconstruction of primary interaction vertex A has been done, and track 5.3 ($K^-$) deviation from this vertex in XZ-plane has been analyzed.

SPACE RECONSTRUCTION OF THE PRIMARY INTERACTION VERTEX AND ANALYSIS OF TRACKS FOR THEIR BELONGING TO THIS VERTEX

The characteristic features of the considered method are: a space reconstruction of the primary interaction vertex, analysis of tracks from probable decay for their belonging to this vertex on the basis of the likelihood function, and combining of results of various measurements taking into account the correlation among them.

The main source of errors during the space reconstruction of an interaction or decay vertex is an inaccuracy in measuring Z-coordinate of track grains due to an inaccurate focusing, thermal drift of grains and possible shifts of the pellicle.

X, Y, Z -coordinates of track grains were measured on KSM-1 microscope at common magnification 1250X. Before each measurement the microscope with the immobile plate fixed to it was heated for a few hours to reduce thermal drift. After that the thermal drift of track grains was 0.005-0.008 $\mu$m/min in XY-plane, and about 2.5 times greater in XZ-plane. A systematic error in track grain coordinates due to the thermal drift was excluded by the method of "reference grains": before and after measuring each track the coordinates of the reference grain were measured repeatedly. The measurement accuracy for grain coordinates in XY-plane was 0.04-0.05 $\mu$m; that for Z-coordinate was 0.08-0.12 $\mu$m.

An additional factor decreasing absolute accuracy in the reconstruction of the interaction or decay vertex in XZ-plane is a shrinkage of emulsion under development. Inclusion of the shrinkage factor leads to a linear growth of errors, though the relative accuracy remains practically the same.

To avoid influence of multiple Coulomb scattering and possible distortion track lengths of ~60 $\mu$m were measured. In this case the possible track deviations due to multiple scattering do not exceed 0.04-0.06 $\mu$m, what is significantly less than natural spread of grains. On the average the coordinates of 15-17 grains were measured on each track.

Values of the coordinates were approximated by straight lines by means of the least squares method: $y = A(x - \bar{x}) + B$, $z = C(x - \bar{x}) + D$ in XY- and XZ-planes, respectively. Unlike a usual parametrization - $y = ax + b$, $z = cx + d$ - in the above-mentioned approximation the parameter errors are not correlated and do not depend on the origin of the reference frame in the tracks intersection point. Errors $\Delta A$, $\Delta B$, $\Delta C$, $\Delta D$ are unambiguously determined through $\Delta a$, $\Delta b$, $\Delta c$, $\Delta d$ calculated through the spread of grains in a usual way, when $y = ax + b$, $z = cx + d$. They equal

$$\Delta A = \Delta a; \quad \Delta B = (\Delta b^2 - \bar{x}^2 \cdot \Delta a^2)^{1/2};$$
$$\Delta C = \Delta c; \quad \Delta D = (\Delta d^2 - \bar{x}^2 \cdot \Delta c^2)^{1/2}, \qquad (1)$$

where $\bar{x} = \frac{\sum_i^n x_i}{n}$, and $n$ is a number of measured grains.

The coordinates of the tracks intersection vertex were determined as the coordinates of a point in space for which functional

$$\chi_N^2 = \sum_{i=1}^{N} \left[\left(\frac{\lambda_i(x,y)}{\Delta\lambda_i(x,y)}\right)^2 + \left(\frac{\lambda_i(x,z)}{\Delta\lambda_i(x,z)}\right)^2\right] \qquad (2)$$

had a minimum; $N$ is a number of tracks,

$$\lambda_i(x,y) = (A_i(x - \bar{x}) + B_i - y)/\sqrt{A_i^2 + 1}$$

is a minimal deviation of the $i$-th track from the point with $x,y$;

$$\Delta\lambda_i(x,y) = \left[\left(\frac{\partial\lambda_i(x,y)}{\partial A_i}\Delta A_i\right)^2 + \left(\frac{\partial\lambda_i(x,y)}{\partial B_i}\Delta B_i\right)^2\right]^{1/2}$$

is an error of $\lambda_i(x,y)$ deviation. Expressions for $\lambda_i(x,z)$ and $\Delta\lambda_i(x,z)$ are similar. This functional was minimized by means of the FUMILI programme [12]. Coordinates $x_0, y_0, z_0$ of the primary interaction vertex were reconstructed using N tracks, and the deviations $\lambda_{N+1}(x_0, y_0)$, $\lambda_{N+1}(x_0, z_0)$ of the analyzed N+1 track from this vertex were calculated. The number of degrees of freedom $n_D$ for thus reconstructed vertex of N tracks is 2N-3. Then a common vertex for N+1 tracks was reconstructed. Usually, the problem of the existence of the only vertex for all N+1 tracks is solved on the basis of $\chi^2$-criterion [8].

In this work we consider the relative probability of existence of a single vertex for N tracks (hypothesis 1) and for N+1 tracks (hypothesis 2) on the basis of the likelihood function. The problem of comparison of two hypotheses with a different number of degrees of freedom was analyzed in Ref. [13]. In a specific case when $n_{D_2} - n_{D_1} = 2$ a relative probability of the two hypotheses equals *

$$P_2/P_1 = \exp\left(\frac{\Delta\chi^2}{2}\right)\left[\sum_{m=0}^{\infty}\left(\frac{\Delta\chi^2}{2}\right)^m \frac{1}{m!}\right]^{-2}, \qquad (3)$$

where $\Delta\chi^2 = \chi^2_{N+1} - \chi^2_N$; $P_2$ and $P_1$ are probabilities of hypotheses with $n_{D_2}$ and $n_{D_1}$ degrees of freedom, respectively.

To obtained reliable results the event was measured repeatedly. The results of separate measurements were combined, taking into account the correlation between them, since the majority of grains were measured repeatedly. The error of a weighted mean value for the analyzed track deviation after $n$ measurements is

$$\overline{\Delta\lambda} = \frac{\Delta\lambda_0}{\sqrt{n}}\sqrt{1 + (n-1)\rho}, \qquad (4)$$

where $\Delta\lambda_0$ is a mean error in a separate measurement, and $\rho$ is a coefficient characterizing the correlation between measurements. Coefficient $\rho$ is determined through a mean number of grains $\bar{K}_i$, repeated $i$ times in $n$ measurements ($i = 1, \ldots, n$), and a ratio $a$ of square errors in grain measurements to the natural spread of the grains:

* The authors are grateful to Prof. A.A.Tyapkin for derivation of this formula and for useful discussion.

$$\rho = \frac{\frac{n}{1+a}\sum_{i=1}^{n}\bar{K}_i - \sum_{i=1}^{n}\bar{K}_i\frac{i}{i+a}(n-i+1)}{(n-1)\sum_{i=1}^{n}\bar{K}_i\frac{i}{i+a}(n-i+1)} . \qquad (5)$$

The described method allows one to reconstruct both a production vertex and a decay vertex of a short-lived particle, thus making it possible to determine its path and angle of emission. Sometimes it is even possible not only to detect but also to indentify a short-lived particle with a neutral component in the decay.

## ANALYSIS OF THE DETECTED EVENT

The described method was applied to the event shown in Fig.1. Vertex A of the primary interaction was reconstructed by tracks 2, 3, 4, 6 (hypothesis 1), and the deviation of track 5.3 ($K^-$-meson) from this vertex was calculated. Then a common vertex for tracks 2, 3, 4, 6, 5.3 was reconstructed (hypothesis 2). If in case of hypothesis 1 the primary interaction vertex A was reconstructed with confidence level less than 5% ($\chi^2 > 11.3$), the measurement was rejected. The accuracy in the reconstruction of the vertex coordinates was: $\Delta x_0$ =0.17-0.24 $\mu$m, $\Delta y_0$ =0.03--0.04 $\mu$m, $\Delta z_0$=0.10-0.14 $\mu$m*. Table 2 shows calculation results for 5 measurements. As is seen from Table 2 the primary interaction vertex is reconstructed with a good accuracy that indicates the absence of distortion. The deviation of track 5.3 in XY -plane were negligible ($\bar{\lambda}(x,y)$ =0.01$\pm$0.04 $\mu$m). Therefore a spatial deviation of track 5.3 practically coincides with the deviation in XZ-plane. Despite the fact that the value $\lambda$ of track 5.3 in each separate measurement did not exceed three standard deviations, the hypothesis on track 5.3 passing by the primary interaction vertex A in each case was more probable than the opposite hypothesis. The relative probability of hypotheses 2 and 1 obtained through 5 measurements by multiplication of values $P_2/P_1$ is less than 0.02. It means that hypothesis 1 is more than 50 times probable than hypothesis 2. The weighted mean value of deviation $\lambda$ of track 5.3 from the primary interaction vertex equals 0.42$\pm$0.14 $\mu$m. Taking into account additional features of this event, i.e., presence of a single $K^-$-meson and coincidence of the invariant mass of $p\pi^+K^-$ -system with the mass of the charmed $\Lambda_c^+$ baryon, one could affirm that a decay of the charmed $\Lambda_c^+$ baryon is observed in this interaction.

* $\Delta z_0$ and other values of deviations and errors in XZ -plane are given for undeveloped emulsion.



Table 2

Results of the geometrical reconstruction of the event

| Measurement | $\chi_N^2/n_D$ $n_{D1}=5$ | $n_{D2}=7$ | Relative probability $P_2/P_1$ | Deviation $\lambda$ of track 5.3 from vertex A ($\mu$m) |
|---|---|---|---|---|
| 1 | 1.4 | 1.7 | 0.6 | 0.34$\pm$0.26 |
| 2 | 1.1 | 1.5 | 0.5 | 0.68$\pm$0.28 |
| 3 | 1.2 | 2.1 | 0.1 | 0.42$\pm$0.21 |
| 4 | 1.1 | 1.2 | 0.9 | 0.30$\pm$0.22 |
| 5 | 1.4 | 1.6 | 0.7 | 0.45$\pm$0.23 |
| | Weighted mean value | | | 0.42$\pm$0.14 |
| $P_2/P_1$ | obtained through 5 measurements is 0.02 | | | |

Vertex A of the primary interaction belongs to a plane formed with coplanar tracks 5.1, 5.2, 5.3 (coplanarity is equal to $(1.3\pm7.4)\cdot10^{-4}$, i.e., not worse than $1.5\cdot10^{-3}$ at 95% C.L.). Consequently, the presence of a neutral particle in the decay was most unlikely. Thus it was possible to determine the coordinates of the decay vertex B and consequently $\Lambda_c^+$ path. The decay vertex B was determined unambiguously as the intersection point of the vector of momenta of particles 5.1, 5.2, 5.3, directed from vertex A, and track 5.3 passing at distance $\lambda$ from the vertex A. Thus determined decay path of the $\Lambda_c^+$ baryon is equal to 2.07$\pm$0.70 $\mu$m. The invariant mass of the system $p\pi^+$ is 1753$\pm$16 MeV and is not inconsistent with the mass of $\Delta(1690)$-resonance (width ~250 MeV). Hence the following decay mode is possible for the $\Lambda_c^+$ baryon:

$$\Lambda_c^+ \to \Delta(1690)K^-, \quad \Delta(1690) \to p\pi^+ .$$

The $\Lambda_c^+$ baryon momentum being 3.79$\pm$0.05 GeV/c and decay length being 2.07$\pm$0.70 $\mu$m, the charmed baryon decay time is $(0.42\pm0.14)\cdot10^{-14}$ s.

## CONCLUSION

This paper demonstrates the possibility of using the information not only on X and Y, but also on Z-coordinates of track grains for geometrical reconstructuin of events in emulsion.

The space reconstruction of the event which is interpreted as the charmed baryon decay $\Lambda_c^+ \to p\pi^+K^-$ has been carried out.

$\Lambda^+_c$ mass is 2281±12 MeV; the distance between the decay point and primary interaction vertex is 2.07±0.70 $\mu$m; decay time is $(0.42\pm0.14)\cdot10^{-14}$s.

The described method can be applied to the search for new particles, among them beatiful ones, with lifetimes of order $10^{-14}-10^{-16}$s in hybrid experiments in which there is the possibility of selecting events with the characteristic features of the decay.

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Received by Publishing Department
June 11 1982.




Бунятов С.А. и др. Пространственное восстановление вершин образования и распада очарованного $\Lambda^+_c$-бариона в ядерной фотоэмульсии Д1-82-447


Зарегистрирован распад очарованного бариона $\Lambda^+_c \to pK^-\pi^+$, образованного в нейтринном взаимодействии с ядром в фотоэмульсии. Масса $\Lambda^+_c$ равна 2281±12 МэВ, расстояние от вершины первичного взаимодействия до точки распада составляет 2,07±0,70 мкм, время до распада - $/0,42\pm0,14/\cdot10^{-14}$ с. При определении методом геометрической реконструкции пробега $\Lambda^+_c$-бариона до точки распада показана возможность использования информации не только о X- и Y-, но и о Z-координатах зерен следов. Изложенный метод может быть применен при поиске в гибридных экспериментах новых, в частности "прелестных", частиц с временами жизни $\sim10^{-14}-10^{-16}$ с.



Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1982


Bunyatov S.A. et al. Space Reconstruction of a Charmed $\Lambda^+_c$ Baryon Production and Decay Vertices in Nuclear Emulsion D1-82-447


The decay of charmed baryon $\Lambda^+_c \to pK^-\pi^+$ produced in the neutrino interaction with an emulsion nucleus has been observed. The $\Lambda^+_c$ mass is 2281±12 MeV. The distance from the primary interaction vertex to the decay point is equal to 2.07±0.70 $\mu$m. The decay time equals $(0.42\pm0.14)\cdot10^{-14}$s. When determining the $\Lambda^+_c$ decay length by the space reconstruction method the possibility has been demonstrated of using the information not only on X- and Y- but also on Z-coordinates of track grains. The described method can be applied to the search for new particles, among them beautiful ones, with lifetimes of order $10^{-14}-10^{-16}$s in hybrid experiments.



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

Communication of the Joint Institute for Nuclear Research. Dubna 1982