Production and decay of relativistic hydrogen hypernuclei

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Relativistic hypernuclei have been detected and reliably identified for the first time. The cross section for the production of ${}^4_\Lambda$H by α particles with a momentum of 18 GeV/c in a CH_2 target is $0.4^{+0.4}_{-0.2}$ μb. The average momentum and average lifetime of ${}^4_\Lambda$H are 16.7 ± 0.2 GeV/c and $(2.2^{+0.5}_{-0.4}) \times 10^{-10}$ s, respectively.

Two groups have reported observing relativistic hypernuclei. Nield *et al.*[1] reported a study of the reaction ${}^{16}O + CH_2 \rightarrow {}^{16}_\Lambda O + K^+ + \ldots$ at an ^{16}O-nucleus energy of 2.1 GeV/nucleon. In Refs. 2–4, the observation of six cases of the production and decay of ${}^4_\Lambda$H hypernuclei by an emulsion method was reported.

In the experiments which we are reporting here, which were carried out in a beam of helium nuclei accelerated to 18 GeV/c, we measured the cross section for the production of relativistic ${}^4_\Lambda$H hypernuclei, and we determined their lifetime. A trigger system consisting of three groups of scintillation counters and fast electronics generated a signal which triggered a streamer channel when the following conditions were satisfied: a) A doubly charged particle entered the target. b: There were no doubly charged particles among the particles leaving the target. c) A doubly charged particle reappeared beyond the decay volume. Decays of hypernuclei were detected in a streamer chamber filled with neon to atmospheric pressure and immersed in a magnetic field ~0.9 T. The trigger logic was intended to select cases in which ${}^4_\Lambda$H and ${}^3_\Lambda$H hypernuclei were produced, and there were subsequent decays in the sensitive volume of the chamber, by the mechanisms ${}^4_\Lambda H \rightarrow {}^4He + \pi^-$, ${}^4_\Lambda H \rightarrow {}^3He + \pi^- + n$, and ${}^3_\Lambda H \rightarrow {}^3He + \pi^-$.

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In principle, a physical background might be generated during detection of the decay ${}^4_\Lambda H \to {}^4He + \pi^-$ in the chamber by the decay of ${}^3_\Lambda H$ and ${}^4_\Lambda H$ hypernuclei (a mechanism involving a neutron) and also by a charge-exchange reaction with the gas in the chamber, ${}^3H + Ne \to {}^3He + \pi^- + ...$ (tritons may form in the target as products of ${}^4_\Lambda H$ fragmentation). The latter reaction also meets the conditions for the selection of events by the trigger. The following criteria were imposed in order to distinguish cases of the production and two-particle decay of ${}^4_\Lambda H$: First, the charge-exchange reaction usually generates some additional tracks (fragments of the target nucleus) or a bright streamer, because of an ionization of neon by the recoil nucleus, at the interaction point. Second, the momentum of the ${}^3He$ produced through charge exchange should be above 13 GeV/c, like the momenta of the ${}^3He$ produced in the decay ${}^3_\Lambda H \to {}^3He + \pi^-$ or ${}^4_\Lambda H \to {}^3He + \pi^- + n$. The momenta of the ${}^4He$ from the ${}^4_\Lambda H$ decay, in contrast, should be concentrated near 16 GeV/c. For this reason, the events which satisfy the selection conditions—a clean vertex and a momentum of the doubly charged particle above 14 GeV/c—are, with a high probability, ${}^4_\Lambda H$ decays. In our experiments, 15 (of the 17) events satisfied both of these conditions, and all had an effective mass for the ${}^4He + \pi^-$ system which agreed within a few MeV (the resolution of the apparatus in terms of the effective mass) with the mass of the ${}^4_\Lambda H$ hypernucleus. In 11 (of these 15) events, the primary tracks had a length sufficient for a reliable visual evauation of the difference between the ionization of the primary track ($Z = 1$) and that of the secondary track ($Z = 2$). Only two of the events, whose vertices were not seen because of high-voltage breakdown events (spots), were identified on the basis of the following criteria: the He momentum and the effective mass.

The cross section measured for the production of ${}^4_\Lambda H$ in the CH_2 target turned out to be $0.4^{+0.4}_{-0.2}$ μb, in good agreement with the result (0.29 μb) of a calculation carried out by Bando *et al.*[5] An interesting point is the substantial difference between this result for the cross section and the data of Ref. 1, where a cross section of 28 ± 14 μb for the production of an oxygen hypernucleus was reported for the reaction ${}^{16}O + CH_2 \to {}^{16}_\Lambda O + K^+ + ...$ (which we mentioned earlier) at 2.1 GeV/nucleon. Both qualitative considerations and direct calculations[5] show that the cross sections for these two processes should be on the same order of magnitude. We do not rule out the possibility that the data of Ref. 1 contain a significant impurity of background processes, since some rather weak criteria were used in the identification of events.

The problem of identifying hypernuclei in the emulsion studies reported in Refs. 2–4 was solved in a totally unsatisfactory way. Furthermore, it follows from the description of the single event, which was reported in Refs. 2–4, that the case under consideration could not possibly be a decay of a ${}^4_\Lambda H$ hypernucleus, since the π^- emission angle (50.3°) was substantially greater than the kinematically allowed value (about 15°).

The ${}^4_\Lambda H$ lifetime found from our experiments is $(2.2^{+0.5}_{-0.4}) \times 10^{-10}$ s. This figure is slightly greater than the value found by taking an average over the earlier experimental results: $(1.6 \pm 0.3) \times 10^{-10}$ s (see the review in Ref. 6). Furthermore, our result is quite different from the calculated result $(1.3 \times 10^{-10}$ s) reported in Ref. 7. All of the previous data on the ${}^4_\Lambda H$ lifetime were obtained in experiments with slow hypernuclei, which were produced through the capture of K^- mesons by helium nuclei or emulsion nuclei. In that case there are several complex methodological problems (see, for example, the review in Ref. 8), which stem from both the very small fraction of in-flight decays and the identification of the hypernuclei which have decayed in flight.

In our experiments the average momentum of the ${}^4_\Lambda H$ was 16.7 ± 0.2 GeV/c, and the mean free path before the decay was 28 cm. The latter figure is at odds with the data of Refs. 2–4, where, incidentally, a methodological error was made in the calculation of the mean free path (the experimental data yield only a lower limit on the mean free path), and the ratio of the lifetime to the mean free path was calculated from a nonrelativistic formula (at $v/c = 0.97$).

An interesting situation has arisen in connection with ${}^3_\Lambda H$ hypernuclei. Working from the ratio of the ${}^4_\Lambda H$ and ${}^3_\Lambda H$ production cross sections according to the calculations of Ref. 5, the fraction of two-particle decays which have a negatively charged pion (according to the data of Ref. 9–13), and the simulated ratio of efficiencies, we conclude that we should have had about ten ${}^3_\Lambda H$ decays for the 17 ${}^4_\Lambda H$ decays which were detected. Experimentally, we detected only a single case of the former decay. If this is not an instrumental effect (the ratio of efficiencies was simulated on the basis of a rather crude model, described in Ref. 14), and if it is not the result of fluctuations, then the small number of ${}^3_\Lambda H$ decays detected experimentally might indicate some unexpected properties for this hypernucleus (e.g., a short lifetime or a binding energy of the Λ particle in the hypertriton which is substantially smaller than 0.1 MeV; Ref. 8). A Coulomb dissociation of the hypertritons in the CH_2 target (at $v/c \sim 1$ and at a Λ-particle binding energy above 0.01 MeV) could not explain the decrease in their yield, although Coulomb dissociation is important at low velocities and large target Z values.[15]

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