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Upper bounds on $|\Delta L|=2$ decays of baryons

Laurence S. Littenberg*
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

Robert E. Shrock†
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794-3840

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From a retroactive data analysis, we derive the first upper bound on a $|\Delta L|=2$ hyperon decay: $B(\Xi^- \to p\mu^-\mu^-) < 3.7\times 10^{-4}$ (90% C.L.). We also comment on the decay $\Sigma^- \to p\mu^-\mu^-$ and $|\Delta L|=2$ decays of charmed and b baryons, in particular, $\Xi_c^+ \to \Xi^-\mu^-\mu^-$. Finally, rough upper limits are given on $B(\Sigma^- \to p\mu^- e^-)$ and $B(\Xi^- \to p\mu^- e^-)$.

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The related issues of the conservation of total lepton number, possible neutrino masses, and possible lepton mixing continue to be of fundamental importance. An interesting class of decays which violate total lepton number L by two units is comprised of

$$B_i \to B_j l^- l'^- \tag{1a}$$

and

$$B_m \to B_n l^+ l^+ , \tag{1b}$$

where the B_i, etc., are baryons, and l and l' denote e or μ. To our knowledge, there have not been any experimental searches for, or bounds on, these decays. In the case $ll'=ee$, this is understandable, since these decay modes are not as sensitive a probe as searches for neutrinoless double β decay, which have yielded very stringent upper limits [1,2]. In the case $ll'=\mu e$, one can set an upper limit on the decay by observing that the leptonic part of the amplitude is related by crossing to the leptonic part of the amplitude for the conversion process $\mu^- + (Z,A) \to e^+ + (Z-2,A)$ (see below). Thus at present the most interesting decays of type (1) are those with $ll'=\mu\mu$, since they are not constrained by either the limits on neutrinoless nuclear double β decay or $\mu^- \to e^+$ conversion [3].

Accordingly, we have carried out a retroactive analysis of data to put an upper limit on this type of decay. In a companion paper [4] we have analyzed $|\Delta L|=2$ meson decays and have put the first upper limit on $K^+ \to \pi^-\mu^+\mu^+$. Figure 1 shows a diagram that contributes to (1a) for B_i a hyperon, together with its crossed graph for the interesting case where $l=l'$ $(=\mu)$. The decays of this type are $\Sigma^- \to p\mu^-\mu^-$, $\Xi^- \to p\mu^-\mu^-$, and $\Omega^- \to \Sigma^+\mu^-\mu^-$. The rates for these decays have the quark mixing matrix dependence $|V_{ud}V_{us}|^2$ for Σ^- and $|V_{us}|^4$ for the Ξ^- and Ω^- decays, respectively, to be compared with $|V_{ud}V_{us}|^2$ for the nonleptonic hyperon decays which dominate the total decay rates. Note that the Ξ^- decay has more than three times the phase space available to the Σ^- decay (172 MeV versus 48 MeV), although it is suppressed in the rate by the factor $|V_{us}/V_{ud}|^2$ relative to the latter decay. Although the Ω^- decay has still more phase space (272 MeV), it is also mixing-angle suppressed and does not provide as powerful a probe since there are far fewer events in the world data sample.

Bubble chamber experiments are the most amenable to a retroactive search such as ours since counter experiments which measured or searched for other decay modes had triggers and cuts which, as far as we can tell, would have excluded the events of interest here. For the Ξ^- decay mode, we have obtained the most stringent limit from a retroactive analysis of a Columbia–SUNY Binghamton experiment using the 31-in. bubble chamber at BNL filled with hydrogen [5]. This experiment searched for a number of rare Ξ^- and Ξ^0 decays (and reported the first observations of the allowed weak decays $\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$ and $\Xi^0 \to \Lambda\gamma$). Among other decays, this experiment searched for the modes $\Xi^- \to p\pi^-\pi^-$ and $\Xi^- \to p\pi^- l^-\bar{\nu}_l$ for $l=e$ and μ. Events due to these decays would appear as a negative prong (the Ξ^-) which branched into three tracks. The main backgrounds were (a) elastic scattering, $K^-p \to K^-p$ followed by the decay $K^- \to \pi^+\pi^-\pi^-$, and (b) events in which the K^-p scattering did produce a Ξ^- which decayed to $\Lambda\pi^-$ with the Λ decaying in a short distance to $p\pi^-$. In order to eliminate background (a), the experiment required that candi-

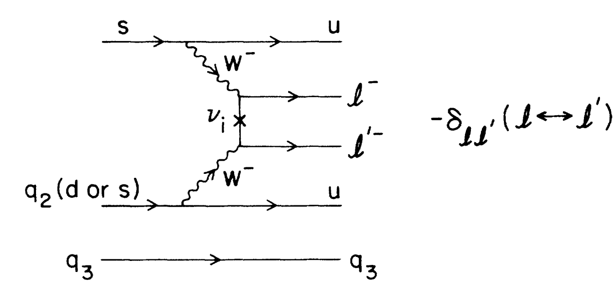

FIG. 1. Graph(s) contributing to $\Sigma^- \to pl^-l'^-$, $\Xi^- \to pl^-l'^-$, and $\Omega^- \to \Sigma^+ l^- l'^-$, for $(q_2,q_3)=(d,d)$, (s,d), (s,s), respectively.

*Electronic address: litt@bnlux1.bnl.gov.

†Electronic address: shrock@dirac.phy.sunysb.edu, shrock@sunysbnp.bitnet.

date events must fail to satisfy the kinematics for elastic scattering. To eliminate background (b), it required that for the final three prongs, if the positive track was interpreted as a proton and each of the two negative tracks as a π^-, then each of the two resultant invariant masses $m(p\pi^-)$ differed by >5 MeV from the Λ mass. No events remained after the imposition of both these criteria. From a simulation of $\Xi^- \to p\pi^-\pi^-$ decay, it was found that 76% of the events would satisfy the second criterion that for either pion $m(p\pi^-)$ would differ by at least 5 MeV from m_Λ. The normalization sample consisted of 8150 $\Xi^- \to \Lambda\pi^-$ events, and Ref. [5] thus obtained the limit

$$B(\Xi^- \to p\pi^-\pi^-) = \frac{\Gamma(\Xi^- \to p\pi^-\pi^-)}{\Gamma(\Xi^- \to \Lambda\pi^-)} < \frac{1.1}{0.76\times 8150} = 1.8\times 10^{-4}, \quad (2)$$

where the factor of 1.1 corresponded to the 68.3% confidence level (C.L.), given zero observed events. For our present purposes, we shall use the more standard 90% confidence-level limit (recall that, given zero observed events, the 90% C.L. limit with Poisson statistics is 2.3). Replacing the 1.1 by 2.3 yields the upper limit $B(\Xi^- \to p\pi^-\pi^-) < 3.7\times 10^{-4}$ (this is rounded off and listed as 4×10^{-4} in Ref. [1]). Of particular importance for our present purposes is the fact that in the search for the $\Xi^- \to p\pi^-\mu^-\bar{\nu}_\mu$ and $\Xi^- \to p\pi^-e^-\bar{\nu}_e$ modes, Ref. [5] stated that "we used criteria similar to the above (for the $\Xi^- \to p\pi^-\pi^-$ mode) and did not require e^- or μ^- signatures." The detection efficiency and effect of the cuts was approximated roughly as being the same for these two latter modes as for the $\Xi^- \to p\pi^-\pi^-$ mode, and hence this experiment obtained the same 68% C.L. limits $B(\Xi^- \to p\pi^-l^-\bar{\nu}_l) < 1.8\times 10^{-4}$, $l=e,\mu$, or, equivalently, the 90% C.L. limit of 3.7×10^{-4}.

Because no specific e^- or μ^- signature was required, we can use this data to obtain an upper limit on the mode $\Xi^- \to p\mu^-\mu^-$. We employ the same approximation as Ref. [5] that the detection efficiency and effect of the cuts to eliminate the backgrounds (a) and (b) above were the same for this mode as for the other three for which the experiment searched [6]. We thus obtain the 90% confidence-level upper limit

$$B(\Xi^- \to p\mu^-\mu^-) < \frac{2.3}{0.75\times 8150} = 3.7\times 10^{-4}. \quad (3)$$

We have also examined the data on Σ^- decays in an effort to extract an upper limit on the decay $\Sigma^- \to p\mu^-\mu^-$. We have again limited our consideration to bubble-chamber experiments, for the same reason as before. These included a Heidelberg experiment using the 80-cm Saclay hydrogen bubble chamber at CERN [7] (yielding about 0.7×10^6 Σ^- decays) and Columbia–Stony Brook [8] and Maryland [9] experiments at BNL using the 30-in. bubble chamber filled with hydrogen (yielding 2×10^6 Σ^- decays). To use the data from these experiments to set a limit on the mode of interest here would require rescanning of the film. Since the proton has a rather low momentum ($|\mathbf{p}_p|_{max}=133$ MeV/c in the Σ^- rest frame, corresponding to a maximum range of 1 cm), the projected range $R_p\cos\delta$ (where δ is the dip angle [10]) would be less than the usual event-selection cutoff of 1–2 mm for a significant fraction of the momentum spectrum of protons emitted. We estimate that if one applied a cut that $R_p\cos\delta > 2$ mm, then about 2% to 10% of the proton tracks would satisfy this cut, depending on the momentum spectrum. (This uncertainty reflects the lack of knowledge of the new physics which might be responsible for the decay, and which would determine the differential decay momentum distribution.) Since for each μ^+, $|\mathbf{p}_\mu|_{max}=104$ MeV/c in the Σ^- rest frame, corresponding to a range $R_\mu \simeq 0.6$ m (and since also the radius of curvature in the magnetic field would be several times larger than the size of the chamber), a significant fraction of the μ^+'s would escape from it. However, their tracks in the chamber should allow reasonably good identification. Thus, if the film could be rescanned for this search, and if no events were observed, then we estimate that one could perhaps set a 90% C.L. upper bound of order 10^{-4} or better on $B(\Sigma^- \to p\mu^+\mu^+)$.

There are several decays of heavy-quark baryons of interest. For the case of $C=1$ baryons, these are of the type (1b). These include $\Lambda_c^+ \to \Sigma^-\mu^+\mu^+$ and $\Xi_c^+ \to \Xi^-\mu^+\mu^+$ (Fig. 2). The rates for these decays have the same V dependence, $|V_{cs}V_{ud}|^2$, as the rates for the dominant nonleptonic charmed baryon decays. In the Λ_c^+ decay, the resultant Σ^- would decay essentially 100% of the time to $n\pi^-$; the presence of the neutron in the final state would make the detection and reconstruction difficult. In the Ξ_c^+ decay, the resultant Ξ^- would decay essentially 100% of the time to $\Lambda\pi^-$; in turn, $\Lambda \to p\pi^-$ about 64% of the time, yielding an observed final state $p\pi^-\pi^-\mu^+\mu^+$. (In about 36% of the decays, $\Lambda \to n\pi^0$, so that the detection and kinematic reconstruction would again be difficult.) As a measure of the current data sample on Ξ_c^+ decays, 23 events corresponding to $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ have been observed by the CLEO Collaboration [11], and it is expected [12] that this group will obtain a sample of order 100–200 events in the next few years. Thus, taking $B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)$ to be a few percent, it follows that one should be able to set an upper limit of 10^{-3} or better on the $\Xi_c^+ \to \Xi^-\mu^+\mu^+$ decay mode with this anticipated data [13]. We suggest that this

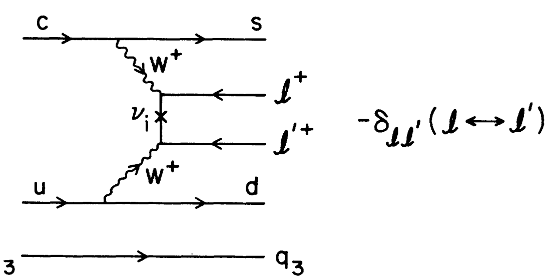

FIG. 2. Graph(s) contributing to $\Lambda_c^+ \to \Sigma^- l^+ l'^+$ and $\Xi_c^+ \to \Xi^- l^+ l'^+$ for $q_3=d$ and s, respectively.

search should be performed.

There are also various possible decays of baryons containing b quarks [of type (1a)] such as $(bdd)\to\Sigma_c^+\mu^-\mu^-$ and $(bdu)_{I=0\text{ or }1}\to\Sigma_c^{++}\mu^-\mu^-$. The rates for these decays have the same V dependence, $|V_{cb}V_{ud}|^2$, as the dominant nonleptonic weak decays of these b baryons. As the world data sample of b baryons increases, it would be worthwhile to search for these decays.

We comment here on the decays (1) with $ll'=\mu e$. Since the leptonic parts of the amplitudes for these decays are related by crossing to the leptonic part of the amplitude for $\mu^-\to e^+$ conversion, one can use the upper limit [14]

$$\sigma(\mu^-\mathrm{Ti}\to e^+\mathrm{Ca}^*)/\sigma(\mu^-\mathrm{Ti}\to\text{capture})<1.7\times10^{-10}$$

to set a limit on the branching ratios for these decays. This is, of course, indirect and model dependent, since the hadronic matrix elements are different. Making reasonable estimates for these matrix elements, including the uncertainties in them, and for differences in the phase space, we infer that

$$\frac{B(\Sigma^-\to p\mu^-e^-)}{B(\Sigma^-\to n\mu^-\bar{\nu}_\mu)}\lesssim10^{-9}\ . \tag{4}$$

From (4) we then infer the rough upper bound $B(\Sigma^-\to p\mu^-e^-)\lesssim10^{-12}$. Since the rate for $\Xi^-\to p\mu^-e^-$ is suppressed by an additional factor of $|V_{us}|^2$ relative to the semileptonic decay $\Xi^-\to\Lambda\mu^-\bar{\nu}_\mu$, we infer by the same method that $B(\Xi^-\to p\mu^-e^-)\lesssim10^{-13}$ [15]. Similar rough upper bounds can be given for the analogous decays of charmed baryons, such as $\Xi_c^+\to\Xi^-\mu^+e^+$.

It should be noted that in the usual extension of the standard electroweak model to include Majorana (and optionally also Dirac) mass terms, given current upper bounds on the admixture of a heavy neutrino mass eigenstate in the weak eigenstate ν_μ, the resultant theoretical estimates of the branching ratios for the strange and heavy-quark baryon decays (1) are much smaller than 10^{-4}. However, we believe that experimental limits on conservation laws such as total lepton number are of intrinsic and fundamental value. They are analogous to bounds on, e.g., $\mu\to e\gamma$ or $K_L^0\to\mu^\pm e^\mp$, where the same extension of the standard model again yields branching ratios much smaller than experimental limits, or to bounds on, e.g., electric charge nonconservation, nonzero photon mass, or *CPT* violation, where the theoretical expectation is that the effect would be exactly zero. Thus, we believe that further efforts to extract upper limits on $|\Delta L|=2$ decays of baryons yielding $\mu^-\mu^-$ or $\mu^+\mu^+$ leptonic final states should be undertaken.

Note added: For upper bounds on $D^+\to(\pi^-$ or $K^-)l^+l'^+$ and $B^+\to(\pi^-$ or $K^-)l^+l'^+$ with $ll'=ee,\mu e,\mu\mu$, see Mark II Collaboration, A. J. Weir *et al.*, Phys. Rev. D **41**, 1384 (1990).

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[10] The dip angle is defined in the usual manner, so that if the particle velocity $\hat{\mathbf{v}}$ is directly toward (orthogonal to) the camera(s), $\delta=90°$ (0°). The ranges are taken from Ref. [1].
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[13] Note that, e.g., for the data taken at $\sqrt{s}=10.55$ GeV, since the Ξ_c is produced with significant velocity, it follows that, although $|\mathbf{p}_\mu|_{max}=0.82$ GeV/c in the Ξ_c rest frame, some of the decays would have Lorentz boosted μ^+'s with sufficient momenta (>1.2 GeV/c) to penetrate the iron absorber and be counted in the CLEO detector. For example, this experiment was able to set the upper limit $B(D^0\to\rho^0\mu^+\mu^-)<0.81\times10^{-3}$ [P. Haas *et al.*, Phys. Rev. Lett. **60**, 1614 (1988)], although $|\mathbf{p}_\mu|_{max}=0.72$ GeV/c in the D^0 rest frame.
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[15] We recall that an indirect limit, based on similar reasoning, was given in Ref. [4] on $B(K^+\to\pi^-\mu^+e^+)$.