HYPERON BETA DECAYS AT NAL

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ABSTRACT

Advantages of NAL energies for the study of hyperon beta decays are discussed in some detail.

Many interesting questions concerning hyperon beta decays will remain unanswered when NAL becomes operational. Although decays of Λ, Σ, Ξ, and Ω^- can be studied at lower energy accelerators, the higher yields and larger decay lengths at 200 GeV will enable beams to be constructed which will contain hyperon fluxes of 10^4-10^5 per pulse. An obvious advantage afforded by these hyperon beams for the study of leptonic decays is intensity, since the beta-decay branching ratios are all $\sim 10^{-3}$ or less, and large statistical samples will be required to produce significant results. The higher laboratory energy might not seem beneficial for reconstructing low Q value decays, but in fact fixed momentum and angle resolution in the lab results in fixed uncertainty in the hyperon rest frame, independent of the hyperon lab energy. This is rigorously true as $p_Y/E_Y \rightarrow 1$. Thus the high laboratory energy will not necessarily be a disadvantage and for certain decay studies will prove useful.

Baryon polarization effects in hyperon beta decay could be studied if the hyperons are produced polarized by the strong interactions, if they are daughters from the nonleptonic decay of unpolarized parents (Λ^o's from $\Xi \rightarrow \Lambda\pi$ for example), or if the beta decay under study has a Λ^o in the final state. For these cases the observables $\vec{\sigma}_Y \cdot \hat{e}$ and $\vec{\sigma}_Y \cdot \hat{\nu}$ become accessible. The three independent quantities which could be measured if $\langle\vec{\sigma}_Y\rangle = 0$ are the total rate, the lepton energy spectrum, and the baryon energy spectrum or ℓ-ν angular correlation.

Beta decays of the form $Y \to N\ell\nu$ or $Y \to Y'\ell\nu$ involve four particles but only one charged baryon. The neutral baryon energy must be known to overconstrain the reconstruction fit and lead to a unique solution. The extra constraint would be an advantage in obtaining a pure sample of beta decays for precision measurements. If this energy is unknown, two solutions are obtained corresponding to two components of neutrino momentum along the line of flight of the neutral baryon. If the final-state baryon is a Λ^0, then its energy could be measured by reconstructing $\Lambda^0 \to p\pi^-$, and decays such as $\Sigma^- \to \Lambda^0 e^-\nu$ and $\Xi^- \to \Lambda^0 e^-\nu$ could be overconstrained. If the final-state baryon is a neutron, hadronic calorimeters with resolution of 3 or 4% would suffice to resolve the ambiguity for $\Sigma^- \to ne^-\nu$ if such high-resolution, high-energy devices prove feasible.

Electron-pion discrimination becomes more difficult at NAL energies. Threshold or focusing gas Cerenkov counters seem useless. Two techniques remain: the electrons appear at larger lab angles than the pions from decays $Y \to N\pi$, but this suffers from limited detection efficiency; lead glass total absorption shower counters for the e's might give a factor $\sim 10^{-2}$ suppression of pions at the same energy which might suffice if combined with the extra constraint on the neutral baryon energy.

Muon-pion discrimination is easier at NAL energies. It seems feasible to obtain $\sim 10^{-3}$ suppression of the pions by range techniques after momentum analysis. The remaining π-μ decays in flight can be eliminated by a kinematic cut. Assume only the direction of the neutral baryon to be known, and consider $\Lambda^0 \to p\mu\nu$ for illustration.[1] Let the Λ^0 direction be along the z axis, and let the proton momentum be in the xz plane. Then, $p_{\nu x}$ and $p_{\nu y}$, the transverse neutrino momentum components, are known. Although the maximum allowed value for $\sqrt{p_{\nu x}^2 + p_{\nu y}^2}$ will be nearly the same for $\Lambda \to p\mu\nu$ and $\Lambda \to p\pi$, $\pi \to \mu\nu$, the kinematic boundary in the xy plane for neutrinos from beta decay will be an ellipse of about three times the area of the corresponding ellipse from $\pi \to \mu\nu$ decay. Specifically, neutrinos from the background two-step decay will be confined in $p_{\nu x}$, $p_{\nu y}$ space to an ellipse with semi-minor axis $a = \nu_0$ along y, and semi-major axis $b = \sqrt{1 + (p/m_\pi)^2}\,\nu_0$ along x, centered at $x = (p/m_\pi)\nu_0$, $y = 0$. Here $\nu_0 \approx 30$ MeV, the neutrino energy from $\pi \to \mu$ decay in the pion rest frame, and p is the transverse momentum of the pion. The maximum value of $p = 100$ MeV/c and the average value $\bar{p} = \pi/4 \times 100 = 78$ MeV/c. The area of the average $\pi \to \mu\nu$ ellipse is therefore $\pi\sqrt{1 + (0.56)^2}\,\nu_0^2 = 1.15\,\pi\nu_0^2$. The allowed region for the desired leptonic decays, on the other hand, is approximately circular with radius ~60 MeV/c, giving a ratio of areas leptonic/background = 3.3/1. This type of analysis combined with good π-μ discrimination in the trigger and high-flux hyperon beams make the decays $Y \to N\mu\nu$ seem an attractive field for study at NAL.

The three observables mentioned earlier can be expressed in terms of constant weak interaction form factors using the notation of Watson and Winston.[2] To first order in the nucleon recoil, we have the following expressions:

decay rate

$$\Gamma \sim |f_1|^2 + 3|g_1|^2 - 4\frac{\Delta M}{M}\,\mathrm{Re}\,g_1^* g_2; \tag{1}$$

$\hat{e} \cdot \hat{\nu}$ correlation $\equiv$ a

$$\frac{1-\bar{a}}{1+\bar{a}} = \frac{2|g_1|^2 - 4\frac{\Delta M}{M}\,\mathrm{Re}\,g_1^* g_2}{\left(|f_1|^2 + |g_1|^2\right)\left(1+\frac{\Delta M}{M}\right)}, \tag{2}$$

and lepton energy spectrum

$$\frac{dN_e}{dp_e} \sim p_e^2 (p_{emax} - p_e)^2 \left(1 + \alpha\,\frac{2p_e - p_{emax}}{M}\right), \tag{3}$$

where

$$\alpha = \frac{|f_1|^2 + 5|g_1|^2 + 2\,\mathrm{Re}\,g_1^*(f_1 + 2f_2)}{|f_1|^2 + 3|g_1|^2 - 4\frac{\Delta M}{M}\,\mathrm{Re}\,g_1^* g_2}. \tag{4}$$

In these formulas the bar denotes an average over the electron spectrum; f_1 and g_1 are the ordinary vector and axial vector form factors, f_2 is the weak magnetism term, and g_2 is the weak electricity term, a second-class axial current. If one assumes $g_2 = 0$, then Eq. (2) shows that a is a measure of $|g_1/f_1|$. The term α in Eq. (4) is sensitive to the weak magnetism f_2 if $g_1 \neq 0$. It is instructive to calculate the number of leptonic events required for a given accuracy in α. Let N_1 be the number of leptons with $0 \le p_e \le p_{emax}/2$ and N_2 be the number of leptons with $p_{emax}/2 \le p_e \le p_{emax}$. Integration then gives

$$\epsilon \equiv \frac{N_1 - N_2}{N_1 + N_2} = \frac{5}{16}\,\frac{p_{emax}}{M}\,\alpha.$$

Thus for $\Lambda \to pe\nu$ and small ϵ, we have $\delta\epsilon = (N_1 + N_2)^{-\frac{1}{2}} = 0.05\,\delta\alpha$, or $\delta\alpha \approx 0.1$ would require 4×10^4 events in the lepton spectrum. As expected, the spectrum is predominantly phase space, and a high-statistics experiment is needed to detect the weak magnetism effect. A yield of this type should take only a few days running in a neutral hyperon beam.

The formulas pertinent to a decay like $\Sigma^- \rightarrow \Lambda^o e^- \nu$ and $\Xi^- \rightarrow \Lambda^o e^- \nu$ where the observables $\vec{\sigma}_\Lambda \cdot \hat{e}$ and $\vec{\sigma}_\Lambda \cdot \hat{\nu}$ become accessible can be found in Ref. 2 and in a paper by Desai.[3] These decays are particularly attractive because of the extra kinematic information as well as the information regarding $\langle\vec{\sigma}_\Lambda\rangle$.

In summary, the major advantages anticipated at NAL are a high hyperon flux and the relative ease of working with a collimated beam. Secondary advantages are π-μ separation and neutron detection efficiency and energy resolution.

REFERENCES

[1]This technique is discussed in "ZGS Proposal to Study $\Lambda^o \rightarrow p\mu\nu$" by the ANL, Chicago, and Ohio State group, Argonne National Laboratory Proposal T-296, 1970.

[2]J. M. Watson and R. Winston, Phys. Rev. 181, 1907 (1969).

[3]P. S. Desai, Phys. Rev. 179, 1327 (1969).