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MEASUREMENT OF THE Σ^{o} LIFETIME*

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ABSTRACT

We propose to use the Primakoff effect to measure the lifetime of the Σ^0 hyperon in the planned neutral hyperon beam at the National Accelerator Laboratory. The experiment requires apparatus essentially identical to that necessary to perform experiments already approved and under construction. We present a brief description of the effect and quantitative estimates of rates and backgrounds.

I. INTRODUCTION

We propose a measurement of the lifetime of the Σ^o hyperon by studying the inverse process $\Lambda^o + \gamma_c \rightarrow \Sigma^o$. The source of the Λ^o's would be the neutral hyperon beam described in Proposal 8.[1] The source γ_c would be the Coulomb field of a heavy nucleus. The process is known as the Primakoff effect,[2] and is characterized by a cross section proportional to Z^2 of the target nucleus and to the decay rate for $\Sigma^o \rightarrow \Lambda^o\gamma$. It has been exploited to measure the rate $\pi^o \rightarrow \gamma\gamma$,[3] and $\eta_o \rightarrow \gamma\gamma$.[4] At the present time only an experimental upper bound $\tau_\Sigma < 10^{-14}$ sec has been placed on the Σ^o lifetime.[5] Theoretical estimates for τ_Σ lie in the 10^{-19} sec range. A calculation using the baryon octet to estimate the transition magnetic moment gives $\tau_\Sigma = 1.4 \times 10^{-19}$ sec.[6] The Σ^o is the only "stable" elementary particle with an unknown lifetime.

The neutral hyperon beam described in Ref. 1 will contain neutrons, Λ^o's, Ξ^o's, and a small number of anti-baryons as well as K^o_S and K^o_L mesons. The four major processes which will produce Σ^o's in a heavy target are therefore: a) $\Lambda^o + \gamma_c \rightarrow \Sigma^o$ (the process of interest); b) $\Lambda^o + A \rightarrow \Sigma^o + A^*$ (coherent or incoherent strong processes in which a Λ^o converts into a Σ^o); c) $n + A \rightarrow \Sigma^o + K^o + A^*$ (incoherent strong processes in which a neutron makes a Σ^o by associated production); and d) $\overline{K}_o + A \rightarrow \Sigma^o + (A-1)$ (a baryon exchange process in which a $\overline{K}$ becomes a forward hyperon). The Λ^o and $\overline{K}_o$ fluxes in the beam are comparable, but the $\overline{K}_o$ spectrum is peaked at a lower momentum. Of the strong processes involving strange particles (b) is expected to be much larger than (d). Therefore only (a), (b), and (c) need be considered in detail. The remainder of this proposal is devoted to careful estimates of the yield of Σ^o's from these sources, the detection of the $\Lambda^o + \gamma$ resulting from the Σ^o decay, and the Ξ^0 decay as a source of non-Σ^o background.

II. Σ^o PRODUCTION BY THE PRIMAKOFF EFFECT

The formula for $\Lambda^o + \gamma_c \to \Sigma^o$ is given in Ref. 2, and can be written at high energy in the form

$$\frac{d\sigma_c}{dt} = \left(233\ \mathrm{mb}/(\mathrm{GeV}/c)^2\right)\left(\frac{Z}{92}\right)^2 \left(\frac{10^{-19}\ \mathrm{sec}}{\tau_\Sigma}\right)\left(\frac{p}{M_\Lambda}\right)^2 \left(\frac{t_o}{t} - \left(\frac{t_o}{t}\right)^2\right) |F(t)|^2. \qquad (1)$$

Here the proportionality of the cross section to the decay rate for $\Sigma^o \to \Lambda^o\gamma$ is explicitly shown. The minimum four-momentum transfer to occurs in the forward direction and is given by $t_o = (M_\Sigma^2 - M_\Lambda^2)^2/4p_\Lambda^2$. At 100 GeV this quantity is $\sim 10^{-6}$ $(\mathrm{GeV}/c)^2$. The cross section is sharply peaked in the forward direction, being contained in an angle region of the order $\theta \sim \sqrt{t_o}/p_\Lambda$, or $\theta \sim 10^{-2}$ mrad at 100 GeV. The nuclear form factor is normalized such that $F(0) = 1$, and it is a satisfactory approximation to assume $F(t) =$ constant $= 1$ from the range of t considered here. Since the angles defined by the collimators for the neutral beam are of the order of 1 mrad, it will not be possible to observe the sharp peak, and Eq. (1) must be integrated to give

$$\sigma_c = (1.4\ \mathrm{mb})\left(\frac{Z}{92}\right)^2 \left(\frac{10^{-19}\ \mathrm{sec}}{\tau_\Sigma}\right)\left(\ln\left(\frac{t_m}{t_o}\right) - 1 + \frac{t_o}{t_m}\right) \qquad (2)$$

Here t_m is the momentum transfer $p_\Lambda{}^2\theta^2$ defined by the beam, or $t_m \sim 10^{-2}$ $(GeV/c)^2$. For uranium, if $\tau_\Sigma = 1.4 \times 10^{-19}$ sec, Eq. (2) gives

$$\sigma_c = 11.6 \text{ mb} \tag{3}$$

Since the total cross section for all processes is about 2400 millibarns, roughly one Λ^o out of every 200 interacting in the target should give rise to a Σ^o through this process.

III. EXPERIMENTAL PROCEDURE

The proposed experimental set-up is shown in Fig. 1. The neutral beam channel and magnetized hadron shield is discussed in detail in Ref. 1. The spectrometer is identical to the one described in Ref. 1. A thin high-Z target will be inserted near the hadron shield and will be surrounded by a veto configuration to suppress multi-particle processes some of which include Σ^o hyperons. Lead and scintillator shower detectors will be used to detect γ rays from Ξ^o decay. The Λ^o will be reconstructed from the $p\pi^-$ decay products passing through the analyzing magnet. The position of the γ rays behind the magnet will be detected by a 3.0 X_{rad} lead sheet followed by a spark chamber. Immediately behind the spark chamber 40 elements of lead glass 12 X_{rad} deep will be used to measure E_γ. Thus within the resolution errors the total momentum $\bar{p} = \bar{p}_\Lambda + \bar{p}_\gamma$ and the invariant mass $M^2 = (E_\Lambda + E_\gamma)^2 - (\bar{p}_\Lambda + \bar{p}_\gamma)^2$ of the Σ^o can be found. The rejection of non-Σ^o associated background depends on the quality of this event reconstruction. The mass resolution will be $\sim$10 MeV (FWHM).

The production angle at the primary target is chosen in the range 5 to 10 mrad rather than the 0 mrad used in Ref. 1 in order to decrease the flux of very high momentum neutrons. Provision has been made in the beam design to vary this production angle. The expected fluxes at the high Z target for 10^{10} 200 GeV incident protons are shown in Table I. To calculate specific yields of Σ^o by the various components of the beam, let the target be 0.01 interaction lengths of uranium sheet, and assume the interaction lengths L (neutron) = $L(\Lambda^o)$ = 8.6 cm, corresponding to σ_{tot} = 2.4 barns. The yield from Eq. (3) at 100 GeV/c is therefore

$$N_{\Sigma^o} / N_{\Lambda^o} = 5 \times 10^{-5}$$

The production of Σ^o has been integrated over our expected spectrum to give the values in Table II.

IV. BACKGROUND

A. Coherent Production

Coherent production of Σ^0 by Λ^0 via one pion exchange with the nucleus is considered in Ref. 2. This cross section is much less sharply peaked at small angles because of the mass of the exchanged π^0, and has a characteristic angle of the order $\theta \sim m_\pi/p_\Lambda$, roughly the same as the inherent angular resolution of the neutral beam. Since the cross section vanishes at $\theta = 0$, its integral from $\theta = 0$ to $\theta \sim m_\pi/p_\Lambda$ is much smaller than the Coulomb term. The interference between coherent Coulomb and coherent OPE vanishes. The result of integrating Eq. (40a) of Ref. 2 is

$$\sigma_{OPE\,(mb)} = \frac{20\pi}{p_\Lambda^2} \left\{ t_m - t_o - \frac{m_\pi^2\ (m_\pi^2 + t_o)}{t_m + m_\pi^2} + m_\pi^2 - (2m_\pi^2 + t_o)\ \ln\left(\frac{t_m + m_\pi^2}{t_o + m_\pi^2}\right) \right\} \tag{4}$$

For $p_\Lambda = 100$ GeV/c and $t_m = m_\pi^2$, this expression becomes

$$\sigma_{OPE} \cong 1.5 \times 10^{-5}\ \text{mb} \tag{5}$$

This contribution is completely negligible with respect to σ_c in Eq. (3) for reasonable values of the Σ^0 lifetime.

B. Incoherent Production of Σ^0

We have used the particle production spectra of Grote, Hagedorn, and Ranft[7] to estimate the background of Σ^0 hyperons from various sources. Numerical integration of the incident beam and particle production spectra was used to give the rates. We assume that the veto configuration surrounding the target will eliminate 90% of the events in which a Σ^0 is produced incoherently. The resultant rates are shown in Table II.

These backgrounds can be determined rather precisely since they have a relatively slow dependence on the momentum transfer, t, and do not depend at all on the Z of the target material if the number of interaction lengths is held constant.

The relative contribution of these backgrounds decreases with higher momentum. Therefore improvements can be made by cutting out low momentum events.

C. Ξ^0 Background

Beam Ξ^0 which decay without target interaction can cause a background. The decay process

$$\Xi^0 \to \pi^0 + \Lambda^0$$
$$\Lambda^0 \to p\pi^-$$
$$\pi^0 \to 2\gamma$$

can give us a Σ^0 trigger if one of the γ's goes undetected. In order to reduce this background we will require a lead-scintillator counter to detect γ-rays which miss the lead glass hodoscope. At

100 GeV the fraction of γ rays which go into the backward hemisphere is of order 10^{-4}. We assume that at least 99% of Ξ^0 decays can be vetoed by detection of the second γ ray.

A precise knowledge of the Ξ^0 decay vertex position would allow us to reject all the remaining Ξ^0 triggers. However, the vertex will not be known and some fraction of the events will reconstruct as Σ^0. We estimate this to be about 10% based on our mass resolution of 10 MeV.

The net result is a background of about 25% which can be measured reliably by target-out runs.

V. CONCLUSION

It appears that a run of 10^{11} to 10^{12} (depending on production angle) interacting protons at 200 GeV would yield about 200 Σ^0 produced by the Primakoff effect. Several sources will contribute a background about equal to the signal. These backgrounds can be determined accurately by running with lighter targets and with target out. Further improvement can be obtained by selecting only higher momentum events. A total of between 10^{12} and 10^{13} protons should yield several thousand Σ^0 under various target conditions, allowing a determination of the lifetime to an accuracy of about 10%. At 10^9 protons/cycle and 400 accelerator cycles/hour, it would take 25 hours to deliver 10^{13} protons.

The rate at which Σ^0 are produced by the Primakoff effect is probably the most soundly based of our calculations. The background estimates come from model-dependent extrapolations of lower energy data. Due to the uncertainties in these estimates, we suggest a short run to test background rates at some intermediate stage of the already approved hyperon beam experiment. If this run indicates that the backgrounds are not excessive, then we will request time for the full experiment.

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TABLE I

Conditions:

10^{10} interacting protons at 200 GeV/c

Solid angle = 10^{-6} steradians

Momentum = 60 to 200 GeV/c

Distance = 8 meters from source

P_{max} = most probable momentum

	Production Angle			
	0.25 deg = 4.36 mrad		0.5 deg = 8.72 mrad	
	Number	P_{max} (GeV/c)	Number	P_{max} (GeV/c)
Neutrons	2×10^7	108	2×10^6	68
Λ^o	5×10^5	90	8×10^4	65
Ξ^o	5000	40	800	40

TABLE II

Σ^0 Rates and Backgrounds (Without Veto)

(Conditions Same as Table I)
Σ^0 Lifetime = 1.0×10^{-19} sec

	Production Angle			
	0.25 deg = 4.36 mrad		0.5 deg = 8.72 mrad	
	Number	P_{max} (Gev/c)	Number	P_{max} (GeV/c)
Σ^0 (Primakoff effect)	18	94	2.7	69
Σ^0 ($n \rightarrow \Sigma^0$)	9	76	0.4	<60
Σ^0 ($\Lambda^0 \rightarrow \Sigma^0$ incoherent)	6	75	0.6	<60
Ξ^0 (reconstructed as Σ^0)	5	40	0.8	40

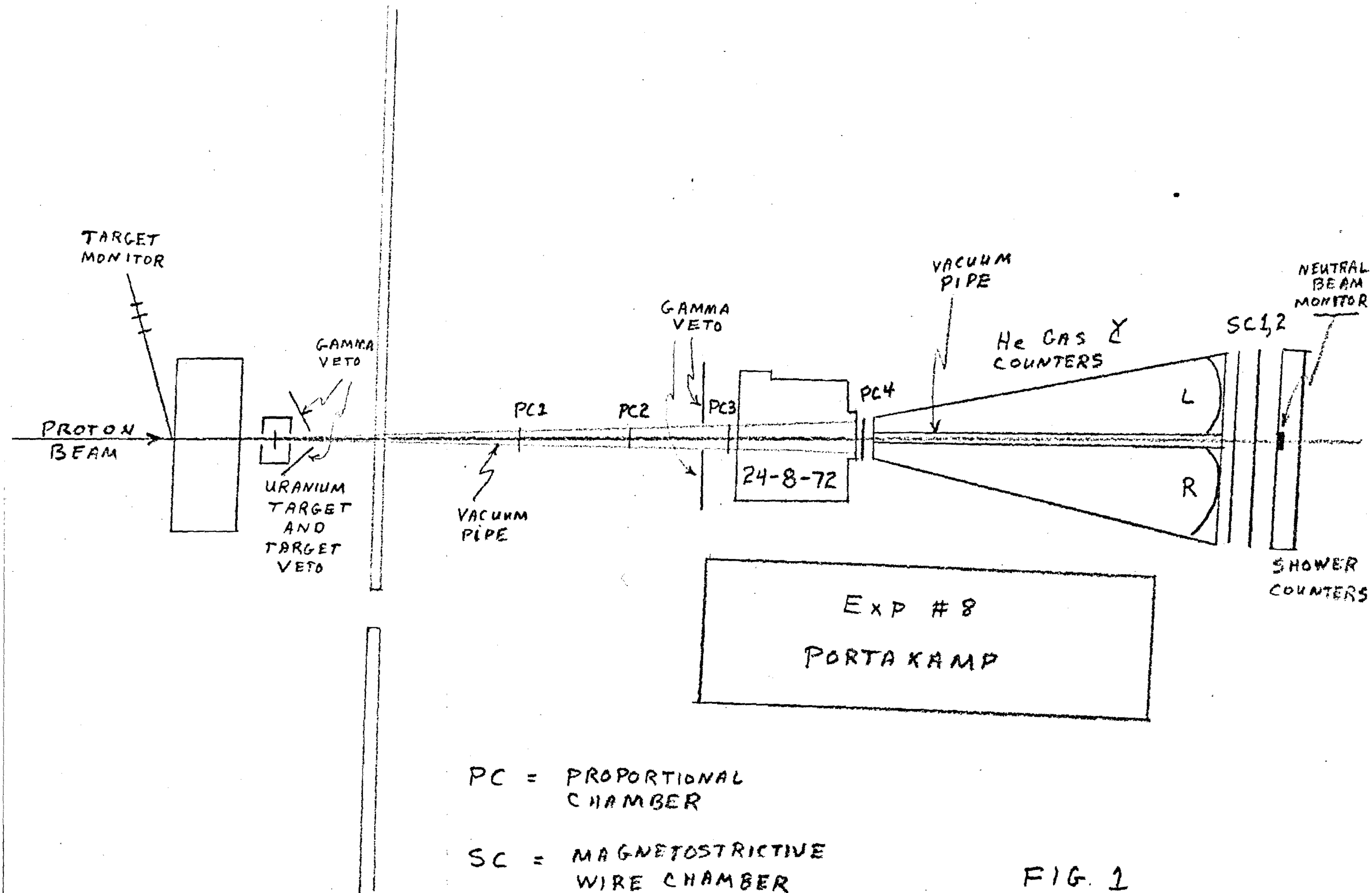

FIG. 1

NOT TO SCALE