COULOMB EXCITATION OF Λ PARTICLES

B. N. VALUEV

Joint Institute for Nuclear Research

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The electromagnetic transition $\Lambda \rightarrow \Sigma^0$ is examined. This transition is of interest in investigating the possibilities of experimental determination of the Σ^0 lifetime and in testing the validity of charge independence for strange particles (the $\Lambda + He_2^4 \rightarrow \Sigma^0 + He_2^4$ and $\Lambda + d \rightarrow \Sigma^0 + d$ reactions).

THE knowledge of the properties of strange particles is of great importance for any attempt to construct a theory of elementary particles and their interactions. The present paper is devoted to a discussion of the possibilities of an experimental determination of the Σ^0 lifetime, which has not as yet been measured.

As is known,[1] the matrix element corresponding to the electromagnetic transition $\Sigma^0 \rightarrow \Lambda + \gamma$ can be written as follows:

$$\bar{u}(p_\Lambda)\,[f(k^2)\,\sigma_{\mu\nu}k_\nu + g(k^2)\,k_\mu + h(k^2)\,\gamma_\mu]\,a_\pm u(p_\Sigma),$$

where $k = p_\Lambda - p_\Sigma$, $a_\pm = 1$ or γ_5 depending on the relative parity of Σ^0 and Λ. As a result of gauge invariance the term $g(k^2)k_\mu$ drops out and $h(0) = 0$. Consequently the decay probability is determined by the single quantity f, whose dimensions are those of a magnetic moment.

Direct measurement of the Σ^0 lifetime (in flight) may turn out to be inapplicable as a consequence of the very short lifetime of the Σ^0:

$$1/\tau = f^2\omega^3/\pi, \qquad \omega = (M_\Sigma^2 - M_\Lambda^2)/2M_\Sigma;$$

we set $\hbar = c = 1$, $\alpha = e^2/4\pi = 1/137$, i.e. $1/\tau = 4 \times 10^{18}(f/\mu_0)^2\ \mathrm{sec}^{-1}$, where $\mu_0 = e/2M$ with M the nucleon mass ($\hbar/\tau \sim 3(f/\mu_0)^2$ kev).

An estimate of f, analogous to Holladay's[2] estimates of the hyperon magnetic moments, yields $f \sim 2\mu_0$ if the hyperon-pion coupling constants and cut-off momentum are chosen to be the same as for the pion-nucleon interaction. It follows from detailed balance arguments that for small k^2 ($k^2 \lesssim m_\pi^2$) the transition $\Lambda \rightarrow \Sigma^0$ is determined by the same quantity since $f(k^2) \approx f(0)$ and $h(k^2) \approx 0$. It is therefore natural to use for the determination of the Σ^0 lifetime the inverse process, which can be realized through the interaction of a Λ particle with an electron in the Coulomb field of a nucleus. This is analogous to Primakoff's idea for the determination of the π^0 lifetime.[3] This possibility of determination of the Σ^0 lifetime has also been indicated by Pomeranchuk and Shmushkevich.[4]*

Since in nucleon - Λ particle collisions the transition $\Lambda \rightarrow \Sigma^0$ could take place as a result of strong interactions, and the nucleon cross section is of the order of 10^{-26} cm^2,[5] it would be preferable to use collisions with electrons to excite the particle. The relevant differential cross section is given by

$$d\sigma \approx 2\alpha f^2\,dk/k = \alpha f^2\,dT/T,$$

where $T = k^2/2m_e$ is the energy transferred to the electron if the latter is initially at rest. However the threshold for the reaction $\Lambda + e \rightarrow \Sigma^0 + e$ is ≈ 170 Bev.

The differential cross section for the excitation of the Λ particle by a Coulomb center is given by

$$d\sigma^{(\pm)} = Z^2\alpha f^2 S^{(\pm)}k^{-1}\,dk = Z^2\alpha f^2 S^{(\pm)}k^{-2}p_\Lambda p_\Sigma d\cos\theta,$$

$$S^{(\pm)} = 1 + \beta_\Lambda\beta_\Sigma\cos\theta - 2\ (\mathbf{k}\mathbf{p}_\Lambda)(\mathbf{k}\mathbf{p}_\Sigma)/k^2\varepsilon_\Lambda\varepsilon_\Sigma + m_\Lambda m_\Sigma/\varepsilon_\Lambda\varepsilon_\Sigma,$$

$$\beta_\Lambda = p_\Lambda/\varepsilon_\Lambda, \qquad \beta_\Sigma = p_\Sigma/\varepsilon_\Sigma, \qquad \cos\theta = (\mathbf{p}_\Lambda\mathbf{p}_\Sigma)/p_\Lambda p_\Sigma.$$

All quantities are in the laboratory frame of reference and (±) refers to even or odd relative Λ-Σ^0 parities. In the case of a nucleus it is necessary to include in the expression for $d\sigma$ the factor $F^2(k^2)$, where $F(k^2)$ is the nucleon form factor which may be determined experimentally by scattering electrons off the given nucleus.

If we introduce the quantity $\delta = p_\Lambda - p_\Sigma/p_\Lambda = (m_\Sigma - m_\Lambda)m_\Lambda/p_\Lambda^2$ and assume that $\delta \ll 1$, and $\beta_\Lambda = \beta_\Sigma = \beta$, then we easily obtain at small angles (which are precisely the ones that give the main

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contribution to the cross section) the following formulas:

$$d\sigma^{(+)} = Z^2\alpha f^2\beta^2 (\delta^2 + \theta^2)^{-2}\theta^2\, d\theta^2,$$

$$d\sigma^{(-)} = Z^2\alpha f^2 [\theta^2 + \delta^2 (1 - \beta^2)] (\delta^2 + \theta^2)^{-2}\, d\theta^2.$$

It is clear from the derived formulas that $d\sigma/d\theta^2$ ($d\sigma/d\theta^2 = \pi d\sigma/d\Omega$) has a sharp peak at $\theta = \delta$ with a width of the order of δ, and that the total cross section slowly (logarithmically) grows. $(d\sigma/d\theta^2)_{max} = Z^2\alpha f^2/4\delta^2$ grows rapidly with the Λ particle energy and may, in principle, exceed (at $\theta \sim \delta$) the cross section for the transition $\Lambda \to \Sigma^0$ due to strong interactions.

It is not hard to estimate the corresponding Λ particle energy. Let us suppose that the strong transition $\Lambda \to \Sigma^0$ is due to the exchange of a quantum of rest mass m. It is then easy to show that the cross section due to strong interactions is given by

$$d\sigma_s = \sigma_0 \frac{p_\Lambda}{m^2} \frac{d\theta^2}{(1 + p_\Lambda^2\theta^2/m^2)^2},$$

where σ_0 is the total cross section. It is natural to assume that σ_0 does not change rapidly with the energy and remains of the order of the geometrical cross section ($\sigma_0 = 2\pi A^{2/3} \times 10^{-26}$ cm²). Under these assumptions we find that the cross section $d\sigma_e$ (electromagnetic) becomes of the order of $d\sigma_s$ at $p_\Lambda \sim 20$ Bev, $\theta \sim 10^{-4}$ for Z = 90, A = 200; in such a case the nucleus recoil energy is ~ 50 ev (we have set $f = 2\mu_0$, and $m = 2m_\pi$).

It is possible, however, to reduce the contribution due to strong interactions significantly by choosing for the target nucleus one with equal number of neutrons and protons ($I_3 = 0$), since for a system Z with given isotopic spin I and $I_3 = 0$ the transition $\Lambda + Z \to \Sigma^0 + Z$ is forbidden if charge independence is valid. The presence of Coulomb forces results in the nucleus not being in an eigenstate of $\hat{I}^2$, i.e., states with other values of I are admixed. From this point of view the most convenient nuclei are He_2^4 and deuterium. For He_2^4 we may set $|He_2^4\rangle = |I = 0\rangle + \gamma\,|I = 1\rangle$. A rough estimate gives $|\gamma|^2 \lesssim 10^{-3}$.

If we limit ourselves to realistically measurable angles $\theta \sim 0.5°$, corresponding to $p_\Lambda \sim 3$ Bev and a recoil energy ~ 0.2 Mev, then we obtain for He_2^4 with $|\gamma|^2 \lesssim 10^{-3}$ in an analogous manner to what was done above

$$(d\sigma/d\theta^2)_e/(d\sigma/d\theta^2)_s \gg 1.$$

(In these estimates we ignore contributions due to interference. It is an easy matter, however, to write down the general expression for $d\sigma$.) Consequently, under the above outlined experimental conditions the separation of the electromagnetic transition $\Lambda \to \Sigma^0$ is possible in principle, but it does require measuring cross sections of the order of 10^{-30} cm².

In addition to the coherent strong transition $\Lambda \to \Sigma^0$ considered by us, certain incoherent processes will also occur, for example $\Lambda + He_2^4 \to He_2^3 + n + \Sigma^0$. The contribution due to such processes may be reduced by selecting events with low energy recoil nuclei. Further, the angular dependence for such processes will be comparatively smooth, which will also be the case for bremsstrahlung of the Λ particle. The latter, apparently, may be ignored.

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