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SIGMA MINUS FORM FACTORS AND MAGNETIC MOMENT

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We report results from a Fermilab polarized Sigma minus decay experiment. From a sample of 50,000 beta decays and 10^6 two body decays with polarization parallel to the magnetic field we have extracted the semi-leptonic form factors. From another sample of 21,000 beta decays and 650,000 two body decays where the polarization precessed in the magnetic field we have measured the magnetic moment.

1. INTRODUCTION

Baryon semi-leptonic decay is described by the Cabibbo theory[1] which assumes that: 1. the weak vector current and the electromagnetic current consist of the appropriate components of a common octet current of SU(3); 2. the axial-vector current is the same component of another octet current; and 3. there is a universal suppression factor for strangeness changing decays. Although SU(3) symmetry is known to be broken (e.g., the baryon mass differences), no significant effects have yet been reported in semi-leptonic decays.[2]

2. THEORY

For the decay $\Sigma^- \to n + e^- + \bar{\nu}_e$, the matrix element can be written as

$$M = \frac{G_F}{\sqrt{2}} \langle n | J^\mu | \Sigma^- \rangle \, \bar{u}(e^-)\gamma_\mu (1 + \gamma_5) \, u(\bar{\nu}_e) \qquad (1)$$

where the G_F is the Fermi weak coupling constant. We assume the lepton current is V - A and write the hadron current as

$$\langle n | J^\mu | \Sigma^- \rangle = \sin\theta_c \bar{u}(n) \left\{ f_1(q^2)\gamma^\mu + \frac{f_2(q^2)}{M_{\Sigma^-}} \sigma^{\mu\nu} q_\nu + \frac{f_3(q^2)}{M_{\Sigma^-}} q^\mu + [g_1(q^2)\gamma^\mu + \frac{g_2(q^2)}{M_{\Sigma^-}} \sigma^{\mu\nu} q_\nu + \frac{g_3(q^2)}{M_{\Sigma^-}} q^\mu]\gamma_5 \right\} u(\Sigma^-) \qquad (2)$$

where $\sin\theta_c$ is the Cabibbo angle and q^2 is the momentum transfer squared. The form factors are real if time reversal invariance is assumed. The form factors for semi-leptonic decays within the baryon octet are related to each other (at $q^2 = 0$) by SU(3) Clebsch-Gordon coefficients. For $\Sigma^- \to n + e^- + \bar{\nu}_e$ the ratio $g_1(0)/f_1(0) = F - D$ where D and F are symmetric and antisymmetric couplings of two SU(3) octets to form a third. A recent measurement[2] gave $F = 0.477 \pm 0.012$ and $D = 0.756 \pm 0.011$. In the SU(3) limit $f_2(0)/f_1(0) = \mu_n + \mu_p/2 = -1.017$ where μ_n and μ_p are the neutron and proton anomoulous magnetic moments. A more rigorous analysis by A. Sirlin[3] in the spirit of the Ademollo-Gatto theorem corrects this value to -0.91. Similarly in the SU(3) limit g_2 is second class and has conventionally been ignored. The contributions of f_3 and g_3 are proportional to electron mass squared, hence invisible in hyperon beta decay. The q^2 dependence of the form factors is formulated[2] as:

$$f_1(q^2) = f_1(0) \; (1 + 2q^2/M_V^2) \qquad (3)$$

$$g_1(q^2) = g_1(0) \; (1 + 2q^2/M_A^2) \qquad (4)$$

with $M_V = 0.97$ GeV/c_2 and $M_A = 1.25$ GeV/c^2.

Decay product angular distribution asymmetries in the center of mass can be expressed as

$$\frac{dN_i}{d\Omega} = (1 + \alpha_i P \cdot \hat{\Omega}) \qquad (5)$$

where $i = n, e^-, \bar{\nu}_e$. P is the Σ^- polarization vector. In the case that P points in the y direction, it can be written as $1 + \alpha_i P \cos\theta_y$.

Differential decay rate and α_i's have been calculated by several authors. In our analysis we have used the calculations by Garcia et al.[4]

3. THE SIGN OF g_1/f_1.

For Σ^- leptonic decay, the Cabibbo theory makes the distinctive prediction of a <u>negative</u> g_1/f_1 (i.e., a V + A hadronic matrix element) which is the opposite in sign to neutron beta decay.[5] Thus a V - A interaction on the quark level gives a "V + A"

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matrix element on the hadron level. Consequently the electron asymmetry from polarized Σ^- beta decay would be expected to be large and negative. An entirely analogous phenomenon occurs in nuclear beta decay where a "V - A" interaction on the nucleon level can give rise to "V + A" matrix elements in specific decays; e.g., in tritium beta decay ($H^3 \to He^3 + e^- + \bar{\nu}_e$). Consequently, the electron asymmetry from polarized H^3 decay could be ≈ -1 even though the decay of the "constituent" neutron is V - A and free neutron decay has a very small electron asymmetry. It was therefore disconcerting that experimental measurements prior to 1984 favored a a small, positive electron asymmetry.[6] The situation changed dramatically when Fermilab experiment E-715 reported a precise determination of the electron asymmetry performed with a polarized Σ^- beam.[7] The new value $\alpha_e = -0.56 \pm 0.12$ is in striking agreement with the Cabibbo theory. In contrast with the earlier low energy polarized Σ^- experiments with limited statistics, the high fluxes of polarized Σ^- from the Fermilab hyperon beam (e.g., $\approx$1KHz Σ^- at $\approx$24% polarization) enabled E-715 to collect 5×10^4 beta decays. Moreover, the ability to produce polarized Σ^- in both vertical and horizontal planes and to reverse the sign of polarization gave the hyperon beam experiment a degree of control over systematic effects not available to the earlier low-energy measurements.[8]

4. FORM FACTOR ANALYSIS

4.1 What is Observable in Polarized Beta Decay

We have already noted that f_3 and g_3 are suppressed by $(m_e/m_\Sigma)^2$ and are hence invisible. To better understand the sensitivity to the other form factors we perform a Gordon reduction[9] of the current in Eq. 2 to obtain:

$$\sin(\theta_c)\ \bar{u}(n)\{F_1(q^2)\gamma^\mu + F_2(q^2)P^\mu + F_3(q^2)q^\mu + [G_1(q^2)\gamma^\mu + G(q^2)P^\mu + G_3(q^2)q^\mu]\gamma^5\}\ u(\Sigma) \qquad (6)$$

where $F_1 = f_1 + (1 + m_n/m_\Sigma)\ f_2 \approx f_1 + 1.8f_2$, $F_2 = 2f_2$, $F_3 = f_2 + f_3$, $G_1 = g_1 - (1 - m_n/m_\Sigma)g_2 \approx g_1 - 0.23g_2$, $G_2 = 2g_2$, $G_3 = g_2 + g_3$.

From this, it follows that to leading order we are measuring the ratios f_2/f_1 and $g_1(\text{effective})/f_1$, where $g_1(\text{effective}) = g_1 - 0.23g_2$. It has been past practice to ignore g_2. However, recent theoretical estimates indicate that this may not be a good assumption in strangeness changing decays.[10] In polarized decays, there is sufficient information to be sensitive to g_1 and g_2 separately.

4.2 Measurement of $|g_1(0)|$

We observe that the neutron spectrum in the Σ^- center of mass can be measured independently of the electron energy determination from the relation

$$T_n = [(M_\Sigma - m_n)^2 - q^2]/(2M_\Sigma) \qquad (7)$$

Moreover this spectrum is very sensitive to $|g_1|$ (actually g_1(effective) as discussed in 4.1) and insensitive to f_2. Therefore we can analyze this spectrum to find

$$|g_1(0)| = 0.327 \pm 0.020 \qquad (8)$$

where the error is both statistical and systematic combined. This value agrees well with two previous hyperon beam experiments.[2,11] In this analysis we have provisionally set $g_2 = 0$ to facilitate comparison with previous experiments. A fit to our data is shown in Fig. 1.

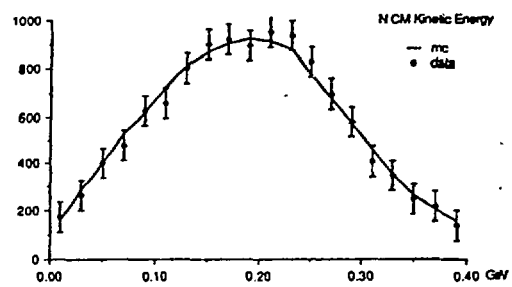

Figure 1.

4.3 Measurement of $f_2(0)$ [weak magnetism].

As is well known, the electron spectrum is sensitive to weak magnetism. However, one must first correct the spectrum for radiative corrections[12] as well as radiation in material. In our case the material contributed (5.94 ± 0.2)% radiation length. We obtain.

$$f_2(0) = 0.96 \pm 0.15 \qquad (9)$$

where the error is both statistical and systematic combined. This agrees with naive SU(3) but somewhat better with the Sirlin value.[3] A fit to our electron spectrum is shown in Fig. 2.

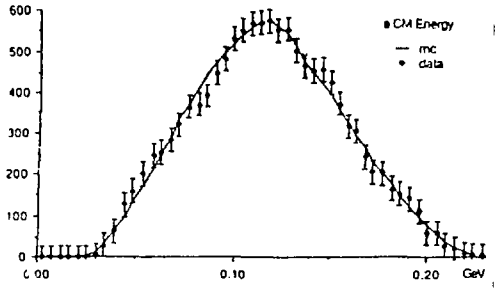

Figure 2.

4.4 Measurement of g_2 [weak electricity].

By combining our center of mass spectra with the correlations of electron, neutrino and neutron with Σ^- polarization we are able to fit separately for g_1 and g_2. In making our fit, we use the two-body α parameter (α = -0.067 ± 0.008) as one of the inputs. We obtain:

$$g_1(0) = 0.18 \pm 0.082$$

$$g_2(0) = -0.67 \pm 0.37 \qquad (10)$$

The x^2 contours in the g_1, g_2 plane for our central value of Σ^- polarization (0.24) is shown in Fig. 3.

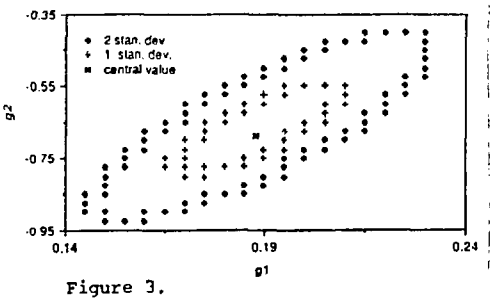

Figure 3.

The statistical power of this experiment is not sufficient to definitively establish a significant contribution from g_2. As we have seen, the effect on the derived values of g_1 is profound and it would clearly be important to pursue the matter in this and other hyperon decays.

5. Σ^- Magnetic Moment

This experiment also collected Σ^- decays with the polarization in the horizontal (x,y) plane perpendicular to the magnetic field of the hyperon channel[13]. By measuring the precession of the polarization in the hyperon channel, the magnetic moment is determined. We collected data at two Σ^- momenta (253 Gev/c and 308 Gev/c) to remove the $2n\pi$ ambiguity. Previous measurements using the spin precession technique made use of the $\Sigma^- \to n\pi^-$ decay mode. We also had the beta decay sample available which has the important advantage of having a much larger α parameter. Table 1 summarizes the results for both two body and three body decay modes and at both Σ^- momenta.

	$\Sigma^- \to ne^-\bar{\nu}$		$\Sigma^- \to n\pi^-$	
	253 GeV/c	308 GeV/c	253 GeV/c	308 GeV/c
αP_x	0.077±0.015	0.117±0.023	-0.0084±0.0034	-0.0166±0.0034
αP_y	0.016±0.014	0.019±0.023	0.0057±0.0034	0.0027±0.0034
αP_z	-0.103±0.022	-0.099±0.034	0.0137±0.0034	0.0077±0.0034
μ_Σ	-1.176±0.024	-1.140±0.028	-1.161±0.038	-1.179±0.027
Events	15,000	6000	310,000	350,000

Table 1. Components of asymmetry, Σ^- magnetic moment in nuclear magnetons, and sample size for each data set.

The data is internally consistent so that we may combine it to obtain:

$$\mu_\Sigma = -1.66 \pm 0.014 \pm 0.011\ \mu_n \qquad (11)$$

where the quoted error is statistical and systematic respectively. This measurement helps to resolve the long standing differences in previous determinations of the magnetic moment by the exotic atom method and the hyperon beam technique.[14]

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