HYPERON BETA DECAY AND THE CKM MATRIX

PHILIP G. RATCLIFFE

Dip.to di Scienze CC.FF.MM.
Univ. degli Studi dell’Insubria—sede di Como *)
via Valleggio 11, 22100 Como, Italy

Received 10 January 2004;
final version 31 January 2004

I shall present a pedagogical discussion of hyperon semileptonic decays, covering some of the historical background, the basics notions of hyperon semileptonic decays, deeply inelastic scattering and the CKM matrix, and the description of SU(2) and SU(3) breaking. I shall also present a prediction for a process under current experimental study.

PACS: 13.30.Ce, 12.15.Hh
Key words: hyperon, beta decay, CKM matrix

1 Preamble

This workshop is dedicated to the memory of Vernon Hughes, who had such a determining role in the development of spin physics. I wish to take this opportunity to recall a brief but memorable (for my part at any rate) first encounter with Vernon. As a young post-doc, I had been asked to make a plenary review presentation on transverse spin at the 1984 International Spin Symposium. Being my first talk at a major conference, I was more than a little nervous, as a very shaky pointer made plain to all present. Moreover, as the talk proceeded I sadly realised that it was far too technical (note that transverse spin was then still a somewhat esoteric subject even for such a specialised audience) and would indeed have been impervious to all but a very few cognoscenti. Later in the day, quite spontaneously, Vernon, whom I did not know personally, approached me and congratulated me on a “fine talk”. I was sure his words were only intended as encouragement for a new-fledged and inexperienced researcher, but was nevertheless very happy to have received them from someone of his stature. I should, however, note in this write-up that immediately after concluding this talk I was gently reprimanded by Miriam Hughes: her “husband would never have made such a remark, had he not meant it”.

2 Introduction

Let me now briefly examine the historical background, from both theoretical and experimental viewpoints. In particular, I wish to stress the significance of the subject not only for extraction of Cabibbo–Kobayashi–Maskawa (CKM) elements, but also for deep-inelastic spin-dependent structure-function analysis.

*) The Insubri were a Celtic tribe originally from across the Alps, who in the 5th. century B.C. settled roughly the area now known as Lombardy.
2.1 The Cabibbo–Kobayashi–Maskawa matrix

The three-family model of the weak interaction describes the ‘up’-type to ‘down’-type quark transitions in terms of the CKM 3×3 unitary matrix \[1, 2\]:

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}.
\]

(1)

Unitarity applied to the first row then implies that

\[|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.\]

(2)

Given the measured value of \(V_{ub} = 0.0036 \pm 0.0011\), for hyperon semileptonic decay (HSD) purposes, the third generation may be safely neglected. Thus, unitarity is conveniently imposed simply by writing \(V_{ud} = \cos \theta_c\) and \(V_{us} = \sin \theta_c\). Alternatively, one may also try to extract \(V_{ud}\) and \(V_{us}\) separately as independent parameters.

2.2 Hyperon semileptonic decay experiments

In the early eighties a series of experiments at the CERN SPS by Bourquin et al. \[3\] vastly improved the picture. Shortly after, Hsueh et al. \[4\] added high-precision measurements for \(\Sigma^{-} \to n e^{-} \bar{\nu}_e\). In 1997 and 1999 the Fermilab experiment KTeV \[5\] collected data on \(\Xi^{0} \to \Sigma^{+} e^{-} \bar{\nu}_e\) (~600 + 600 events), the second set has still to analysed and new results are in the offing. NA48 (CERN) also has data on this decay (~20 k events), but the analysis has still to be performed \[6\].

2.3 Proton spin phenomenology

In 1988 the EMC \[7\] published measurements of the proton spin structure function \(g_1(x)\). The early value of its \(x\) integral (0.114 ± 0.012 ± 0.026) was a little over half the celebrated 1974 predicted by Ellis and Jaffe \[8\]. Since then an enormous amount of experimental and theoretical effort has gone into studying the baryon spin. In short, we now know that the gluon contribution, via the ABJ triangle anomaly, is crucial to reconciling theory and experiment. However, many attempts to “repair” the naive Ellis–Jaffe sum rule turned to the HSD input, in the form of the \(F\) and \(D\) parameters—SU(3) breaking is known to be order 10%. Indeed, as experimental precision improves, it will be necessary to improve on the \(F–D\) parameter extraction from HSD.

3 Basics

3.1 Hyperon semileptonic decay theory

The baryon octet \((p, n, \Lambda^0, \Sigma^{\pm, 0}, \Xi^{0, -})\) admits, in principle, a number \((11 + 6)\) of \(\beta^\pm\)-type (electronic and muonic) decays:

\[B \to B' + \ell^\pm + \nu_\ell (\bar{\nu}_\ell) \quad (\ell = e \, \text{or} \, \mu).\]

(3)
Such decays may be described in terms of 6 currents and their form factors:

\[
\langle B | J^\alpha | B' \rangle = C \bar{u}_{B'}(p') \left[ f_1(q^2) \gamma^\alpha + f_2(q^2) \frac{i q_\beta \sigma^{\alpha\beta}}{M} + f_3(q^2) \frac{q^\alpha 1}{M} \\
+ g_1(q^2) \gamma^\alpha \gamma_5 + g_2(q^2) \frac{i q_\beta \sigma^{\alpha\beta} \gamma_5}{M} + g_3(q^2) \frac{q^\alpha \gamma_5}{M} \right] u_B(p),
\]

The different types of current involved are:

- \( f_1 \): \( \gamma^\alpha \) vector current (often denoted \( g_V \))
- \( f_2 \): \( \frac{i \sigma^{\alpha\beta} q_\beta}{M} \) induced tensor (“weak magnetism”)
- \( f_3 \): \( \frac{q^\alpha}{M} \propto \frac{m^2}{M^2} \) vector mass parameter
- \( g_1 \): \( \gamma^\alpha \gamma_5 \) axial current (often denoted \( g_A \))
- \( g_2 \): \( \frac{i \sigma^{\alpha\beta} \gamma_5 q_\beta}{M} \) induced pseudotensor
- \( g_3 \): \( \frac{q^\alpha \gamma_5}{M} \propto \frac{m^2}{M^2} \) axial mass parameter

The two non-leading, but non-negligible structure functions are: \( f_2 \), which (see below) may be estimated even for broken SU(3) [9], and \( g_2 \), which is often set to zero in experimental analyses, but which may be important for broken SU(3).

The relevant phase-space integrals were long ago accurately tabulated by García and Kielanowski [10]. Moreover, all radiative corrections have been calculated and are typically less than a few percent. As to the \( q^2 \) variation of the form factors, the following dipole form is usually assumed, with corresponding vector and axial mass parameters for strangeness-conserving (-changing) decays:

\[
f_i(q^2) = f_i(0) \left( 1 - \frac{q^2}{m_i^2} \right)^{-2} \quad \text{with} \quad \begin{cases} m_V = 0.84 \ (0.97) \ \text{GeV}, \\ m_A = 1.08 \ (1.25) \ \text{GeV}. \end{cases}
\]

Fit results are insensitive to the mass parameters; the tabulation by García and Kielanowski [10] includes the first term in a simple power expansion in \( q^2 \) while \( q^2 \) dependence is not included (nor is it necessary to present accuracy) for the second-class currents.

In the CVC hypothesis, the Ademollo–Gatto theorem [11] guarantees \( f_1(0) = 1 \) while the ratio \( g_1(0)/f_1(0) \) is given by the following reduced matrix elements:

\[
\frac{g_1(0)}{f_1(0)} = C_F F + C_D D \quad \text{with} \quad \begin{cases} C_F = \text{Tr} \left( \lambda_W \{ B', B \} \right), \\ C_D = \text{Tr} \left( \lambda_W \{ B, B' \} \right), \end{cases}
\]

where \( \lambda_W \), \( B \) and \( B' \) are the (octet) matrix representations for the weak-interaction flavour structure, initial and final baryons respectively. For the weak magnetism in
broken SU(3), Sirlin [9] gives
\[ f_2(0) = \frac{m_B}{m_p} \left[ C_F \left( \frac{1}{2} \mu_p + \frac{1}{2} \mu_n \right) - C_D \frac{3}{4} \mu_n \right]. \] (7)

### 3.2 Polarised deeply-inelastic scattering phenomenology

Ignoring QCD radiative corrections (typically of order 10% or less) for simplicity and neglecting heavy quarks, the integral of the spin structure function \( g_1(x_B) \) is

\[ \Gamma_{p1} \equiv \int_0^1 dx g_1^p = \frac{1}{2} \left[ \Delta U + \frac{1}{2} \Delta D + \frac{1}{9} \Delta S \right] = \frac{1}{12} a_3 + \frac{1}{36} a_8 + \frac{1}{9} a_0, \] (8)

where

\[ \Delta U = \int_0^1 dx \left[ \Delta u(x) + \Delta \bar{u}(x) \right] = \frac{1}{2} a_3 + \frac{1}{6} a_8 + \frac{1}{3} a_0 = 2F + \Delta S \]

\[ \Delta D = \int_0^1 dx \left[ \Delta d(x) + \Delta \bar{d}(x) \right] = -\frac{1}{2} a_3 + \frac{1}{6} a_8 + \frac{1}{3} a_0 = F - D + \Delta S \]

\[ \Delta S = \int_0^1 dx \left[ \Delta s(x) + \Delta \bar{s}(x) \right] = -\frac{1}{3} a_8 + \frac{1}{3} a_0, \] (9)

or

\[ a_3 \equiv \Delta U - \Delta D = F + D \]

\[ a_8 \equiv \Delta U + \Delta D - 2 \Delta S = 3F - D \]

\[ a_0 \equiv \Delta U + \Delta D + \Delta S = \Delta \Sigma. \] (10)

As a function of the popular ratio \( F/D \), which is precisely 2/3 in exact SU(6):

\[ \Gamma_{p1}^p = \frac{1}{36} g_A \left[ 6 + 4(1 + F/D)^{-1} \right] + \frac{1}{9} a_0 \]
\[ = \frac{1}{18} g_A \left[ 9 + 10(1 + F/D)^{-1} \right] + \frac{1}{4} \Delta S. \] (11)

This has been expressed on terms of \( g_A \), exploiting the fact that the measured precision of \( g_A \) is well beyond what is necessary here. Put simply, the Ellis-Jaffe hypothesis is that \( \Delta S = 0 \) or, equivalently, \( a_0 = a_8 \). Thus, given the experimental determination of \( \Gamma_{p1}^p \), one sees that a mere 15% reduction in the ratio \( F/D \) from its accepted value (~0.58) is sufficient to entirely remove the discrepancy between polarised DIS data and the Ellis-Jaffe sum rule [12].

### 3.3 Baryon magnetic moments

It is perhaps important to stress that although baryon magnetic moments are, in some way, related to spin densities, the connection is not useful here. This may be
seen from the following standard definition:

\[
\mu_B = \frac{1}{2} \langle B | \sum_f \frac{Q_f}{2m_f} \bar{\psi}_f \gamma_5 \gamma^3 \psi_f | B \rangle
\]

\[
= \frac{1}{2} \sum_f \mu_f \int_0^1 dx [\Delta q_f(x) - \Delta \bar{q}_f(x)],
\]

(12)

\[
\Gamma_1^B = \frac{1}{2} \sum_f Q_f^2 \int_0^1 dx [\Delta q_f(x) + \Delta \bar{q}_f(x)].
\]

(13)

Note the differing charge-conjugation properties. Moreover, the quark magnetic moments themselves are not known and the SU(3) description of baryon magnetic moments is rather poor (in comparison with that of HSD).

3.4 CKM-matrix unitarity

Over the years various discrepancies have occurred in regard of neutron \(\beta\)-decay data. For a long period the neutron lifetime (combined with \(f t\) values for super-allowed nuclear transitions) disagreed with the directly measured value of \(g_A/g_V\). The effect on \(\cos \theta_c\) was to reduce the quoted precision. However, since this last is around 0.1\%, the absolute size of the discrepancy was much smaller than the general precision attained in HSD and so it was not relevant here; and, happily, it went away! More important is the independent determination of \(\sin \theta_c\) or \(V_{us}\). Unitarity is a problem at present: \(|V_{ud}|^2 + |V_{us}|^2 < 1\). N.B. the value of \(V_{us}\) used here is that obtained from so-called \(K_{\ell3}\) decays, which is typically smaller than that from HSD. Recent precise measurement by Abele \textit{et al.} \cite{13} put the discrepancy at the level of almost three standard deviations. The question then arises as to the source of the discrepancy: new physics or uncertainty in \(K_{\ell3}\)-decay analysis?

3.5 Hyperon semileptonic decay data

A number of hyperon semileptonic decays have been measured with varying degrees of accuracy and depth of information; Fig. \ref{fig1} depicts the full set of experimental data presently available. Note that several of the rates and asymmetries have now been measured to better than 5\%. A complete summary of present global HSD rate and angular-correlation data \cite{14} is provided in Table. \ref{table1}.

4 SU(3) Breaking

There have been many approaches to accounting for SU(3) breaking effects in this sector; I shall briefly mention here only those that have been applied in a coherent, comprehensive and self-consistent fashion. It is important to appreciate that while some early results here pointed to a very small value for \(F/D\), they were often performed superficially and with the explicit aim of showing that \(F/D\) could indeed be smaller than was commonly held.
Fig. 1. The SU(3) scheme of the measured baryon-octet \(\beta\)-decays: solid lines—decays where both rate and asymmetry are known; short dash—rates only; long dash—\(f_1 = 0\) decays; dotted line—KTeV and NA48.

Table 1. Present world HSD rate and angular-correlation data [14]. Numerical values marked \(g_1/f_1\) are as extracted from angular and spin correlations.

| Decay          | Rate\((10^6 \text{s}^{-1})\) | \(g_1/f_1\) | \(g_1/f_1\) |
|----------------|------------------------------|-------------|-------------|
| \(A \rightarrow B\ell\nu\) | \(\ell = e^\pm\) | \(\ell = \mu^-\) | \(\ell = e^-\) |
| \(n \rightarrow p\) | 1.1291 ± 0.0010 | 1.2670 ± 0.0030 | \(F + D\) |
| \(\Lambda^0 \rightarrow p\) | 3.161 ± 0.058 | 0.60 ± 0.13 | 0.718 ± 0.015 | \(F + \frac{1}{4} D\) |
| \(\Sigma^- \rightarrow n\) | 6.88 ± 0.23 | 3.04 ± 0.27 | -0.340 ± 0.017 | \(F - D\) |
| \(\Sigma^- \rightarrow \Lambda^0\) | 0.387 ± 0.018 | \(-\frac{\sqrt{2}}{4} D^\dagger\) |
| \(\Sigma^+ \rightarrow \Lambda^0\) | 0.250 ± 0.063 | \(-\frac{\sqrt{2}}{4} D^\dagger\) |
| \(\Xi^- \rightarrow \Lambda^0\) | 3.35 ± 0.37 | 2.1 ± 2.1 | 0.25 ± 0.05 | \(F - \frac{1}{4} D\) |
| \(\Xi^- \rightarrow \Sigma^0\) | 0.53 ± 0.10 | \(F + D\) |
| \(\Xi^0 \rightarrow \Sigma^+\) | 0.876 ± 0.071 | 0.012 ± 0.007 * | 1.32 ± 0.21 | \(F + D\) |

* KTeV data [3]—not included in the fits presented here.

\(\dagger\) The absolute expression for \(g_1\) is given, not \(g_1/f_1\) (as \(f_1 = 0\)).

4.1 Centre-of-mass corrections

Donoghue, Holstein and Klimt [15] described SU(3) breaking using so-called recoil, or centre-of-mass, corrections. This approach (denoted \(A\) here) accounts for the extended nature of the baryon via momentum smearing in the wave function. For \(B \rightarrow B'\ell\nu\), the resulting corrections to \(g_A\) take a one-parameter (linearised) form:

\[
g_A = g_A^{SU(3)} \left[ 1 - \frac{(p^2)}{3m_B m'_B} \left( \frac{1}{4} + \frac{3m_B}{8m'_B} + \frac{3m'_B}{8m_B} \right) \right]. \tag{14}
\]

N.B. This is essentially the same mechanism that is assumed responsible for the reduction of \(g_A\) from its naïve SU(6) value of 5/3 to the experimental \(~5/4\).
4.2 Effective Hamiltonian formalism

A rather similar approach \((B)\) relates the breaking to mass-splitting in an effective interaction Hamiltonian via first-order perturbation theory \([16, 17]\). The correction here then takes on the following simple form:

\[
g_A = g_A^{SU(3)} \left[ 1 - \epsilon (m_B + m'_B) \right].
\] (15)

In this (as too in the previous) approach the corrections are normalised to a common reference point, \(g_A^{n \rightarrow p}\), and depend on a single parameter, \(\langle p^2 \rangle\) or \(\epsilon\). Note, however, that Donoghue et al. actually calculated \(\langle p^2 \rangle\) in a bag model. Furthermore, corrections to \(g_V\) are found negligible in \(A\) and assumed to be so in \(B\), in accordance with the Ademollo–Gatto theorem \([11]\).

I should stress that any further global normalisation correction specifically for the \(|\Delta S=1|\) rates (due, \(e.g.,\) to wave-function mismatch) is disfavoured. Donoghue et al. used their bag-model calculated value of \(\sim 8\%\); such a large correction, while acceptable with the data at that time, is completely excluded by present-day data. Adding such a renormalisation as a free parameter does not improve fits and it is always returned as zero within the errors. Moreover, there is at present no particular theoretical justification for this correction. Note that with their full calculation, Donoghue et al. obtained a particularly low value of \(F/D\) (\(\sim 0.53\)).

Table 2 displays the fit results: \(S\) — exact SU(3) symmetry, \(A\) and \(B\) — broken SU(3). \(V_{ud}\) is determined by the super-allowed nuclear \(ft\) data and \(V_{us}\) is then fixed via CKM unitarity. When \(V_{ud}\) and \(V_{us}\) are extracted from HSD data alone (with or without imposing unitarity), all parameter values remain essentially unchanged. Thus, unitarity appears to be well respected while the extraction of \(F\) and \(D\) is very stable (variation \(\sim 1\%)\).

| Fit | \(V_{ud}\)  | \(F\)     | \(D\)     | \(\chi^2/\text{DoF}\) |
|-----|------------|-----------|-----------|---------------------|
| \(S\) | 0.9748 (4) | 0.466 (6) | 0.800 (6) | 2.3                 |
| \(A\) | 0.9740 (4) | 0.460 (6) | 0.808 (6) | 0.8                 |
| \(B\) | 0.9740 (4) | 0.459 (6) | 0.809 (6) | 0.8                 |

4.3 The \(1/N_c\) expansion

The \(1/N_c\) expansion approach naturally suffers strong model dependence. Moreover, in the analysis by Dai et al., data outside the baryon octet has an important role: both octet and decuplet data are simultaneously fit (with extra parameters). The overall resulting \(\chi^2\) is rather poor. However, when only the octet data are fitted similar results to those presented here are obtained. I should also remark that Flores-Mendieta, Jenkins and Manohar, again using the \(1/N_c\) expansion but in a less model-dependent manner, perform a fit effectively similar to that presented here and (obviously) obtain similar (though not identical) results.
4.4 Other analyses

Note however, that all other analyses generally have one (or both) of two defects: either strong model dependence or “selective” use of the data. An example of a fit obtaining a very low value of $F/D$ (with also a very large error) is that of Ehrnsperger and Schäfer [20]. They only use $g_A/g_V$ data, which are very limited, there being only three good points, and through an extreme lever-arm effect, their breaking parameter is totally determined by random fluctuations.

On the other hand, Roos [21] noted that the large $\chi^2$ in SU(3)-symmetric fits comes mainly from one particular data point ($\Sigma^- \to \Lambda^0 e^- \bar{\nu}_e$ with $\chi^2 \sim 16$). He thus explored excluding it and/or using earlier values, more in line with SU(3)-symmetric fits. This, of course, improves the fits dramatically. However, it turns out that in the final SU(3)-breaking fits shown here, no single data value is extremely discordant (or, to be more objective, the $\chi^2$ distribution is as expected). The point is that for the different dependence on $F$ and $D$ and also mass variations, some decays are affected more than others in an unobvious and non-trivial pattern.

5 SU(2) breaking

While, in general, isospin-violating effects are obviously small, their influence in HSD could, in fact, be significant: due to SU(2) breaking there can be $\Lambda^0$ and $\Sigma^0$ mixing. Indeed, Karl [22] has pointed out that the isospin-violation induced mixing between $\Lambda^0$ and $\Sigma^0$ and described via

$$\Lambda^0 = \cos \phi \Lambda_8 + \sin \phi \Sigma_8,$$
$$\Sigma^0 = -\sin \phi \Lambda_8 + \cos \phi \Sigma_8,$$

could affect HSD, in particular, the $\Sigma^\pm \to \Lambda^0$ transitions.

The suggested phenomenological mixing angle is around $\phi = -0.86^\circ$. Consider now, e.g., the $\Sigma^\pm \to \Lambda^0$ decays: in exact SU(2) $f_1$ for these decays vanishes identically. Thus, angular and spin correlations are normally expected to be absent there. If, however, $\Lambda^0$ contained a small admixture of $\Sigma^0$, this would no longer be true. While there is no strong signal in the fits for such mixing, intriguingly, the values returned are around $-0.8^\circ \pm 0.8^\circ$, in both SU(3) symmetric and broken fits. Note that, unfortunately, the decays in question are relatively poorly measured.

6 A Prediction for $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$

A prediction for the KTeV and NA48 measurements can now be made: in Fig. 2 we show a comparison of the KTeV data point [5] for $g_A$ vs. $g_V$ with the predictions of the effective Hamiltonian approach [17] and the $1/N_c$ expansion [19]; also shown is the prediction obtained from pure Cabibbo theory and exact SU(3) [1].

7 Comments and Conclusions

I shall now close with schematic set of comments and conclusions.
7.1 Comments

- No existing analysis simultaneously obtains both a good fit of all the HSD data and a low value for \( F/D \); thus, the typical values used in polarised deeply-inelastic scattering analysis seem safe.
- Unlike present \( K_{\ell 3} \) decay data, HSD data are in good shape with respect to CKM unitarity; thus, one might argue for reinstatement as a source for \( V_{us} \).
- SU(3) breaking effects are very small in this sector and are definitely well under control in any sensible approach.
- The goodness of present-day fits makes it almost impossible to proceed any further theoretically in a meaningful or useful manner.

7.2 Conclusions

HSD data analysis has manifold importance: it

- is vital input to nucleon spin structure function analysis;
- could prove a useful alternative to \( K_{\ell 3} \) decay for \( V_{us} \);
- provides insight, in its own right, into baryon structure.

However, it needs more

- theoretical work—more reliable/general models;
- experimental data—improved precision (both \( \Gamma \) and \( g_A \)).
References

[1] N. Cabibbo, *Phys. Rev. Lett.* **10** (1963) 531.

[2] M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49** (1973) 652.

[3] M. Bourquin *et al.*, *Z. Phys.* **C12** (1982) 307; *ibid.* **C21** (1983) 1; 17; 27.

[4] S.Y. Hsueh *et al.*, *Phys. Rev. Lett.* **54** (1985) 2399.

[5] A. Affolder *et al.*, KTeV E832/E799 Collab., *Phys. Rev. Lett.* **82** (1999) 3751.

[6] M. Piccini, NA48 Collab., in Proc. of the *Int. Europhys. Conf. on High Energy Physics—HEP 2003* (Aachen, July 2003), eds. M. Beneke *et al.*; *Eur. Phys. J. Direct C* [Topical Volume] (2004) PS 05.

[7] J.G. Ashman *et al.*, EMC, *Phys. Lett.* **B206** (1988) 364.

[8] J. Ellis and R.L. Jaffe, *Phys. Rev. D* **9** (1974) 1444; *erratum, ibid.* 1669.

[9] A. Sirlin, *Nucl. Phys. B161* (1979) 301.

[10] A. García and P. Kielanowski, *The Beta Decay of Hyperons*, no. 222 in Lect. Notes in Phys. (Springer–Verlag, 1985).

[11] M. Ademollo and R. Gatto, *Phys. Rev. Lett.* **13** (1964) 264.

[12] F.E. Close and R.G. Roberts, *Phys. Lett.* **B316** (1993) 165.

[13] H. Abele *et al.*, *Phys. Rev. Lett.* **88** (2002) 211801.

[14] K. Hagiwara *et al.*, Particle Data Group, *Phys. Rev. D**66** (2002) 010001.

[15] J.F. Donoghue, B.R. Holstein and S.W. Klimt, *Phys. Rev. D**35** (1987) 934.

[16] P.G. Ratcliffe, invited plenary talk in Proc. of the *2nd Topical Workshop on Deep Inelastic Scattering off Polarized Targets: Theory Meets Experiment* (Zeuthen, Sept. 1997), eds. J. Blümlein *et al.* (DESY 97-200, 1997), p. 128.

[17] P.G. Ratcliffe, *Phys. Rev. D**59** (1999) 014038.

[18] J. Dai, R. Dashen, E. Jenkins and A.V. Manohar, *Phys. Rev. D**53** (1996) 273.

[19] R. Flores-Mendieta, E. Jenkins and A.V. Manohar, *Phys. Rev. D**58** (1998) 094028.

[20] B. Ehrnsperger and A. Schäfer, *Phys. Lett. B**348** (1995) 619.

[21] M. Roos, *Phys. Lett. B**246** (1990) 179.

[22] G. Karl, *Phys. Lett. B**328** (1994) 149; *erratum, ibid.* 449.

[23] E. Monnier, KTeV Collab., in Proc. of the *5th Int. Conf. on Hyperons, Charm and Beauty Hadrons—BEACH 2002* (Vancouver, June 2002), eds. C.S. Kalman *et al.*; *Nucl. Phys. B (Proc. Suppl.) B**115** (2003) 45.

Czech. J. Phys. 54 (2004)