THE POLARIZATION OF THE WEAK CHARGED CURRENT IN SEMILEPTONIC b DECAYS *,**

M. Dittmar

Eidgenössische Technische Hochschule,
8093 Zurich, Switzerland

AND

Z. Wąs

TH Division
CERN, 1211 Geneva, Switzerland
and
Institute of Nuclear Physics
Kawiory 26a, 30-055 Kraków, Poland

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A method to measure the structure of the weak charged-current in semileptonic b–hadron decays using the energy spectrum of the neutrinos is presented. This method allows to distinguish experimentally between the V–A×V–A, V×V–A and V+A×V–A form of the charged current interaction. First result of such a measurement have now been obtained by the L3 collaboration, a brief summary of their results is also given. Their results allow to exclude the exotic V+A structure in b–decays.

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Gronau and Wakaizumi have pointed out that until recently no experimental justification was existing, which could exclude even the exotic V+A×V–A structure for the b–quark decay [1]. Beside the exotic possibility of a V+A contribution in the b decay, we want to point out that the experimental data on well measured semileptonic $K^{\pm}$ decays, almost

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completely saturated by $K^{\pm} \to \ell^{\pm}\nu\pi^0$ decay, are described with matrix elements calculated from the chiral Lagrangians, where a reference to the underlying quark structure (see *e.g.* [2]) is not necessary.

The semileptonic weak decays of hadrons containing c and b quarks are often modelled according to the so-called "spectator model", which describes the charm and beauty hadron decays with the weak charged current at the quark level [3, 4] see also [5]. This ansatz uses the assumption that the light quarks present in charm and beauty hadrons do not play an active role in the decay dynamics. Within this approach, the quark level V–A×V–A structure is assumed for the matrix element calculation of b–hadron decays. Later QCD and non-perturbative corrections are incorporated.

In the decay of s-quarks ($K^{\pm}$), the structure of the interaction is described at the level of particles with a matrix element of the form V×V–A instead of the V–A×V–A that one would use for the decay of a free s-quark. This completely different form of the matrix element can be explained with the small mass of the s-quark, relative to the confinement scale. Therefore, by changing the quark content of the hadrons from b to c and s, some kind of transition must take place in the phenomenological picture of weak semileptonic hadron decays, since hadron structure corrections start to dominate over the free quark picture. Consequently, one might ask to which degree the semileptonic B and D hadron decays can be described with the free-quark level matrix elements, and how these matrix elements are modified by perturbative QCD corrections and by the confinement (hadron structure) effects. A detailed theoretical discussion of the above points within the QCD framework can be found in the literature, see *e.g.* Refs [6, 7] and further references therein.

In a review on physics of heavy flavours [8], semileptonic decays involving $b \to c$ transitions were called the showpiece of the heavy quark effective theory (HQET) [9, 10]. This approach has the goal to obtain a systematic derivation of the properties of heavy-flavour hadrons from QCD. HQET is made in two steps. First, one considers the limit for the infinite heavy quark mass and corrects the results afterwards for the finite mass of the heavy quark. For the process $\overline{B} \to D^* l \overline{\nu}$, which is normally used to determine the V_{cb} entry in the quark mixing matrix, these finite mass corrections have been estimated and were found to be very small [11].

We will leave these discussions aside because our aim is different. We will first present a method [12], which allows in semileptonic b–hadron decays to probe *experimentally* the polarization of the virtual W, which is sensitive to the structure of the interaction. Secondly we discuss the results of such a measurement as performed by L3 [13].

To perform such a measurement it is necessary to find observables, which distinguish between the quark level V–A×V–A, V+A×V–A and chiral Lagrangian form of the matrix element (as in case of $K^{\pm} \to \ell^{\pm}\nu\pi^0$ decay). The simplest effect is an energy asymmetry between the charged lepton and the neutrino in semileptonic c−hadron and b−hadron decays, which occurs because of the polarization of the virtual W, which "decays" into a lepton and a neutrino. In the case of the $K^{\pm} \to \pi^0 e^{\pm}\nu$ decay, the virtual W is unpolarized, whereas for infinitely heavy b quarks, where the V−A×V−A interaction is expected, the virtual W would be 100% polarized. It is thus natural to expect that, in the case of b−hadron decays, the experimental results should be found somewhere in between these two extreme cases.

The exact knowledge of the beam energy in e^+e^- experiments allows to obtain the neutrino energy, which corresponds to the difference between the beam energy (half the Z^0 mass at LEP) and the observed jet energies[1]. In this paper, we show how one can use the measurement of the missing energy (the neutrino energy) to distinguish between the possible theoretical descriptions of semileptonic b−hadron decays.

The neutrino energy spectrum from semileptonic b−baryon decays can be used for other purposes as well. In Ref. [14] the neutrino momentum spectrum is proposed as a particularly good method to study the b−quark polarization and, in Ref. [15], the energy asymmetry between the charged lepton and the neutrino energy has been proposed as a quantity, which is sensitive to the b−baryon polarization in Z^0 decays.

For a free semileptonic b−quark decay (assuming no fragmentation, no hadronization and no QCD corrections) it is straightforward to calculate from the matrix element the distributions of the charged lepton and the neutrino. In *spectator approach* [3] of semileptonic B−meson decays, two classes of corrections must be added to these results : QCD corrections and corrections arising from the bound-state structure of the B meson. The description of the K-meson decay $K^{\pm} \to \pi^0 e^{\pm}\bar{\nu}$ is diametrically opposite to this [2].

The matrix element for the decay $b(p_b) \to c(p_c)\ell(p_\ell)\bar{\nu}(p_{\bar{\nu}})$ averaged over spin can be written as:

$$|M^b_{\rm f.q.}|^2 = p_b \cdot p_{\bar{\nu}}\, p_\ell \cdot p_c\,, \qquad (1)$$

where p_b, p_c, p_ℓ, $p_{\bar{\nu}}$ denote respectively the four-momenta of the decaying free quark b and the decay products: the c quark, the charged lepton ℓ and the (anti)neutrino $\bar{\nu}$. Similarly for the c−quark decay, $c(p_c) \to s(p_s)\ell(p_\ell)\nu(p_\nu)$ the matrix element takes the form

$$|M^c_{\rm f.q.}|^2 = p_c \cdot p_\ell\, p_\nu \cdot p_s\,, \qquad (2)$$

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[1] This is especially convenient for experiments operating at the top of a resonance, as in the case of the Z^0 at LEP, where events with missing energy along the beam pipe due to initial-state photons are damped by the resonance.

where as before p_c, p_s, p_ℓ, p_ν denote respectively the four-momenta of the decaying c quark and its decay products: the s quark, the lepton ℓ and the neutrino ν.

In the case of [2], the point-like (p.l.) matrix element for $K(p_K) \rightarrow \pi(p_\pi)\ell(p_\ell)\nu(p_\nu)$ reads:

$$|M_{\text{p.l.}}|^2 = 2\, p_\ell \cdot p_K \; p_\nu \cdot p_K - p_K^2 \; p_\ell \cdot p_\nu\,, \tag{3}$$

where again p_K, p_π, p_ℓ, p_ν denote, respectively, the four-momenta of the

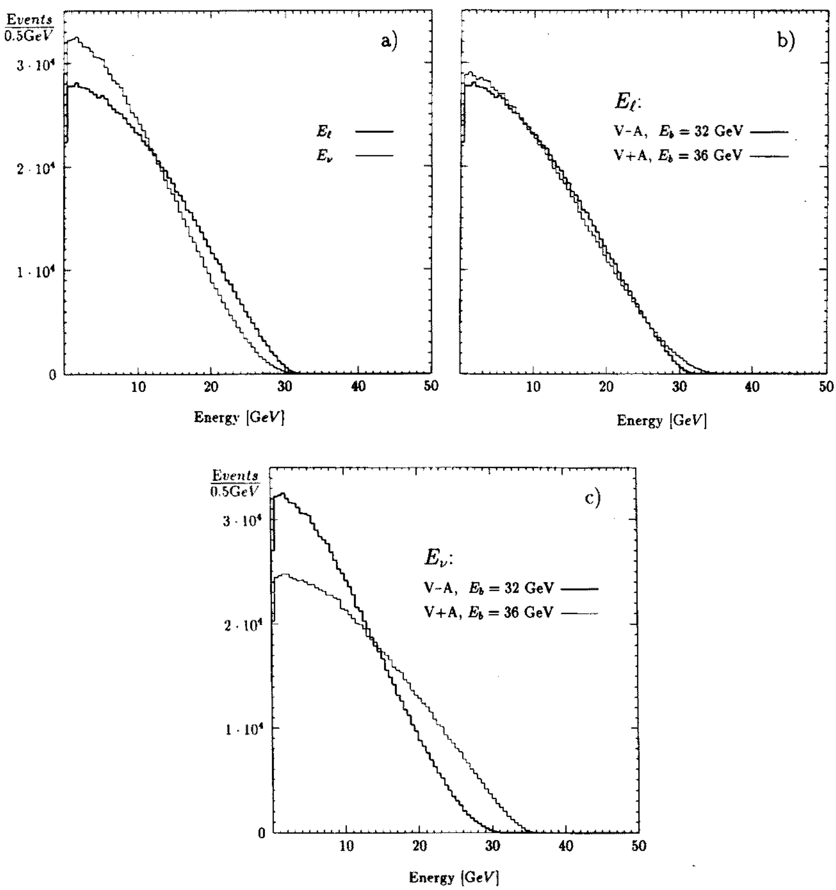

Fig. 1. a) — The energy spectra of the charged lepton and the neutrino for V–A×V–A with a b–hadron energy of 32 GeV. b) — The energy spectra of the charged lepton for V–A×V–A with a b–hadron energy of 32 GeV and for V+A×V–A and a b–hadron energy of 36 GeV. c) — The energy spectra of the neutrino for V–A×V–A with a b–hadron energy of 32 GeV and for V+A×V–A and a b–hadron energy of 36 GeV. (The masses for the B meson (b quark) and the D meson (c quark) were fixed to 4.8 and 1.45 GeV, respectively.)

decaying K meson and its decay products: π, charged lepton ℓ and neutrino ν. We will use this form of the matrix element also for the $B(p_B) \to X(p_X)\ell(p_\ell)\nu(p_\nu)$ decay as an extreme choice with respect to the free-quark one.

It should be realized (see Fig. 1) that, because of the V–A couplings of the W to leptons, the energy of the charged lepton is larger than that of the neutrino from the decay of the b quark, because the W coupling to the b quark is also V–A. For the decay of the c quark, where its coupling to the W is V+A, the neutrino should obtain more energy than the charged lepton.

In the case of point-like (and spin-zero) c and b mesons, identical energy spectra for the neutrino and the charged lepton should be observed for the V×V–A assumption. Furthermore in this case, both the spectra of the charged lepton and the neutrino are essentially the ones obtained for the neutrino in the V–A×V–A case. Therefore, also the energy difference between the charged lepton and the neutrino should be smaller than the one calculated for the free-quark decay.

The lepton energy spectra, discussed later, are obtained with the appropriately modified KORALZ [16] and TAUOLA [17] Monte Carlo programs.

The average energy of b–hadrons in Z^0 decays has been measured, using mainly the observed p and p_t spectra of electrons and muons[2]. With the assumption of the pure V–A×V–A coupling, an average b–hadron energy of about 32 GeV, or about 70% of the beam energy, has been estimated [18].

To demonstrate the influence of the structure of the weak charged current on the charged lepton and the neutrino, we have used a fixed b–hadron energy of 32 GeV, and 36 GeV for the quark-level simulation with the modified KORALZ and TAUOLA Monte Carlo. For the simplification of the comparison, the B–meson (b–quark) and D-meson (c–quark) masses were fixed to the "pole" quark masses [19] of 4.8 and 1.45 GeV, respectively. The semileptonic b decays, $b \to \ell\nu c$, are then simulated, using always the V–A assumption for the leptonic side and the V–A, V and V+A assumption for the quark side. The resulting energy spectra for the charged lepton and the neutrino for a b–hadron energy of 32 GeV are shown in figure 1a for the V–A×V–A matrix element. For the V+A×V–A matrix element the charged lepton and the neutrino spectra are simply exchanged. For the V×V–A one finds that the charged lepton and the neutrino energy spectrum are identical, and also that they are essentially identical to the neutrino energy spectrum obtained with the one for the V–A×V–A matrix element.

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[2] Charged leptons

Figure 1b shows the charged lepton energy spectrum (thick line histogram) for the V–A×V–A coupling and a b–hadron energy of 32 GeV. The thin line shows the charged lepton spectrum, for the V+A×V–A assumption, but now with a b–hadron energy of 36 GeV; a very similar spectrum is found. The different energy spectrum for the charged lepton, due to the assumed coupling, as well as its average energy, can thus simply be compensated by a small change of the b–hadron energy, which in fact is within its experimental uncertainty[3]. This is the main reason why the charged lepton energy spectrum alone does not allow a distinction to be made between the V–A×V–A, V×V–A and the V+A×V–A assumption. However, if also the neutrino energy spectrum can be measured, a significant difference of the mean neutrino energy for the above extreme cases is found. The obtained neutrino energy spectra for the V–A×V–A assumption and a b–hadron energy of 32 GeV, and for the V+A×V–A assumption with a b–hadron energy of 36 GeV are shown in Fig. 1c.

The different energy spectra of the charged lepton and the neutrino are the result of virtual W polarization. The difference in the energy spectra should be largest if the polarization of the W in the b–hadron rest frame is parallel to the direction of the boost in the laboratory system. If this polarization is transverse to the direction of the boost, essentially identical energy spectra and different p_t spectra should be found. Once the energy of the W (the energy sum of the charged lepton and the neutrino) exceeds half the average energy of the b–hadron (roughly 16–17 GeV at the Z^0 peak) the W should be substantially polarized along the b direction, which can be approximated by the direction of the thrust axis of the event, and thus enhance the observable effects.

As described above, we have proposed to measure the neutrino energy spectrum (the missing energy) in semileptonic b–hadron decays, that is b decays with an identified electron or muon. Measurements of b–hadron decays, based on the identification of electrons and muons have become a standard experimental technique.

The exact knowledge of the beam energy in e^+e^- experiments allows to obtain the neutrino energy, which corresponds to the difference between the beam energy (half the Z^0 mass at LEP) and the observed jet energies. For not too hard gluon radiation, the hadronic events can be well separated into two hemispheres, defined for example by the thrust (or the sphericity) axis. Due to energy and momentum constraints, the original energy in each hemisphere has to be the beam energy. The difference between the beam

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[3] In Ref. [18] this uncertainty is calculated, using the observed charged lepton energies and the V–A×V–A matrix element assumption, to be of the order of 1 GeV. Once this assumption is released, we expect an increase in the estimated uncertainty.

energy and the visible energy in one hemisphere corresponds approximately to the energy of the neutrino produced in the semileptonic decays. Thus, the neutrino energy and momentum can be measured with an accuracy, that is essentially identical to the jet energy and momentum resolution.

Indeed such measurement has now been performed by the L3 collaboration. Let us quote here only their main results. We address the reader to Ref. [13] for details and explanations. As one can see from Table I and Fig. 2 the experimental data agree well with the results of a complete Monte Carlo simulation if V–A×V–A form of the matrix element is chosen. In other cases large discrepancies between data and Monte–Carlo estimates are seen for the energetic neutrinos.

TABLE I

The observed number of events for different neutrino energy regions in the data and the difference between the data and the different models. The errors given for the difference include the estimated statistical and systematic errors due to background, energy scale and the assumed accuracy of the neutrino measurement. This table was taken from Ref. [13]

			$N_{\rm Data}-N_{\rm MC}$	
ν–energy range [GeV]	$N_{\rm Data}$	(V–A)×(V–A)	(V+A)×(V–A)	V×(V–A)
		b→ X$e\nu_e$ candidates		
< 0.0	960	–27 ± 39 ± 47	83 ± 39 ± 42	42 ± 39 ± 44
0.0–6.0	1782	11 ± 53 ± 101	97 ± 53 ± 96	39 ± 53 ± 99
6.0–16.0	2106	58 ± 58 ± 107	60 ± 58 ± 107	60 ± 58 ± 107
> 16.0	518	–42 ± 29 ± 21	–241 ± 31 ± 28	–140 ± 30 ± 24
		b→ X$\mu\nu_\mu$ candidates		
< 0.0	1897	–76 ± 55 ± 119	37 ± 55 ± 112	–16 ± 55 ± 116
0.0–6.0	3245	–132 ± 71 ± 78	65 ± 71 ± 73	–54 ± 71 ± 76
6.0–16.0	3694	119 ± 75 ± 79	152 ± 75 ± 78	132 ± 75 ± 78
> 16.0	904	85 ± 37 ± 46	–258 ± 39 ± 65	–67 ± 38 ± 54

In this presentation, we have concentrated on the energy spectra of the charged lepton and of the neutrino, which depend strongly on the longitudinal W polarization in semileptonic b–hadron decays. We have shown that the energy spectra of the charged lepton and the neutrino are sensitive to details in the structure of the weak charged current. The considered V–A, V and V+A structure on the hadron side of the semileptonic b–hadron decays represent respectively:

- the Standard Model predictions for the free $b-$quark decay in the infinite $b-$quark mass approximation,
- the experimentally confirmed matrix element used to describe the $K^{\pm}$ semileptonic decay, where the quark interaction is completely dominated by the hadronic structure and,
- the exotic — but experimentally to be excluded — possibility that the $b-$quark decay would be described by the matrix element, used for the Standard Model prediction for a free $c-$quark decay.

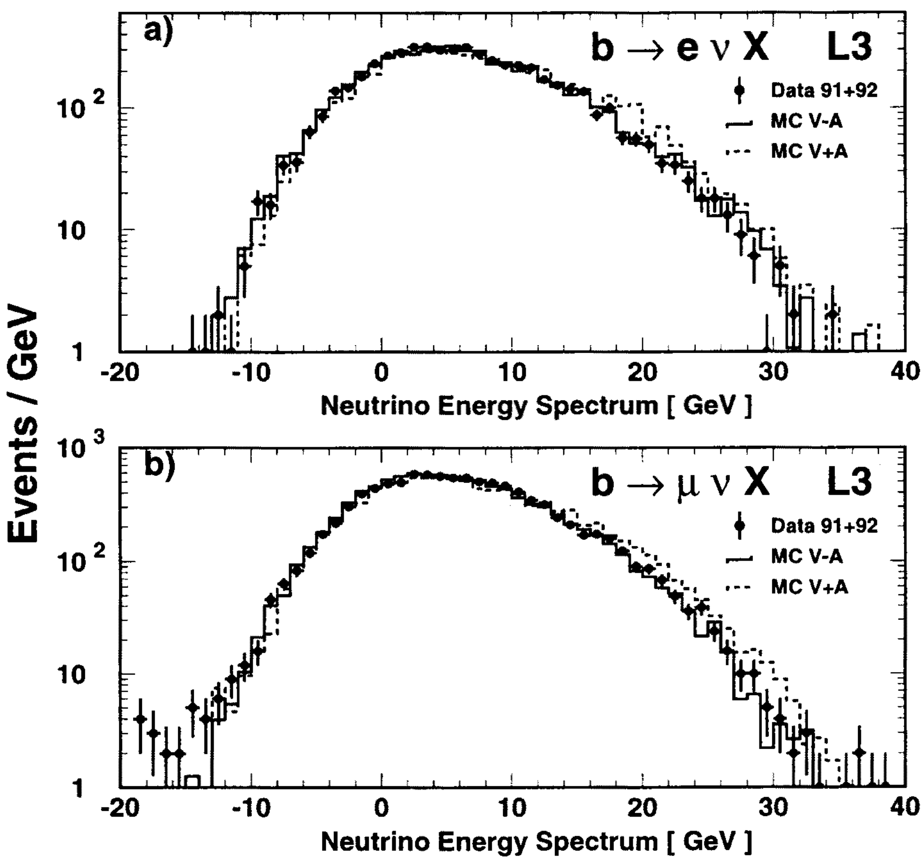

Fig. 2. The missing energy spectrum of b→X$\ell\nu$ candidates in the data and in the Monte Carlo with a (V+A)×(V−A) and a (V−A)×(V−A) b–hadron decay structure, (a) is for ν_e candidates and (b) for ν_μ candidates. The systematic uncertainties due the ν energy resolution and the background are not included. This plot is taken from Ref. [13].

A first measurement based on the above principle was performed by the L3 collaboration leading to the best, so far, measurement of the coupling. It is in good agreement with the W–polarization expected from the V–A free quark model. The exotic V+A×V–A structure was excluded with more than 6 standard deviations and the V×V–A form of the matrix element was disfavored [13].

Future improvements of such measurements can be expected allowing to investigate more details of the current structure, like the mass and energy spectrum of the W. Finally, we would like to remark that a similar analysis can be performed also for semileptonic c–hadron decays. In this case one can expect a sizeable discrepancy, due to the somewhat lower mass of the c quark, between the quark level matrix element and the experimental distributions. Such a deviation in the case of the c–hadron decays would fit nicely into the picture of a phenomenological transition, when going from the semileptonic K decays, which are described by the point-like matrix element, to the heavier charm and beauty hadrons that are usually described by the free quark matrix elements.

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