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Understanding $B \to D^* N\bar{N}$

Chun-Khiang Chua*, **Wei-Shu Hou and Shang-Yuu Tsai**

Department of Physics, National Taiwan University, Taipei, Taiwan 10764, R.O.C.
E-mail: ckchua@phys.ntu.edu.tw

ABSTRACT: The recently measured $\mathrm{Br}(B^0 \to D^{*-}p\bar{n})$ is a few times smaller than $\mathrm{Br}(B^0 \to D^{*-}\rho^+)$. We try to understand this with a factorization approach. The nucleon pair is directly produced from the weak current whose form factors are related by the isospin rotation to nucleon electromagnetic form factors. By using $G_M^{p,n}$ measured from $e^+e^- \to \bar{N}N$ and $p\bar{p} \to e^+e^-$ processes, we are able to account for up to 60% of the observed rate. The remainder is argued to arise from the axial current. The model can be applied to B decays to other mesons plus $p\bar{n}$ modes and D^{*-} plus strange baryon pairs.

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The CLEO Collaboration has recently reported the first observation of $B \to DN\bar{N}X$ modes [1]: $\mathrm{Br}(B^0 \to D^{*-}p\bar{n}) = (14.5^{+3.4}_{-3.0} \pm 2.7) \times 10^{-4}$, $\mathrm{Br}(B^0 \to D^{*-}p\bar{p}\pi^+) = (6.5^{+1.3}_{-1.2} \pm 1.0) \times 10^{-4}$. Although the decay final states are three or four-body, they are only a few times below the corresponding two-body mesonic modes [2] such as $\mathrm{Br}(B^0 \to D^{*-}\rho^+) = (6.8{\pm}3.4){\times}10^{-3}$, $\mathrm{Br}(B^0 \to D^{*-}\pi^+) = (2.76{\pm}0.21){\times}10^{-3}$. Since the creation of D^{*-} carries away much energy, the observed large rate of $B^0 \to D^{*-}p\bar{n}$ supports the suggestion that enhanced baryon production is favored by reduced energy release on the baryon side [3]. Thus, given the large rate of $B \to \eta' + X_s$ decay where $p_{\eta'} > 2$ GeV [4], the $B \to \eta'\Lambda\bar{p}$ decay may be sizable [3] compared to charmless two body baryonic modes. Similar argument holds for $B \to \gamma\Lambda\bar{p}$ as implied by $B \to \gamma + X_s$. With this in mind, a better understanding of the $B^0 \to D^{*-}p\bar{n}$ decay is not only worthwhile in its own right, it can also serve as a first important step towards a more ambitious project on charmless baryonic modes.

In a recent paper [5], we study this subject by proposing a generalized factorization approach. The three-body decay is seen as generated by two factorized weak currents (linked by a W-boson), where one current converts B^0 into D^{*-} and the other creates the $p\bar{n}$ pair, as shown in Fig. 1. In this way, having factorized the $B^0 \to D^{*-}$ transition, we concentrate on the weak current production of the baryon pair.

$$\langle D^{*-}p\bar{n}|\mathcal{H}_{eff}|B^0\rangle = \frac{G_F}{\sqrt{2}}\, V_{ud}V_{cb}^*\, a_1\, \langle D^{*-}|V^\mu - A^\mu|B^0\rangle \times \langle p\bar{n}|V_\mu - A_\mu|\,0\rangle\,. \qquad (1)$$

*Speaker.

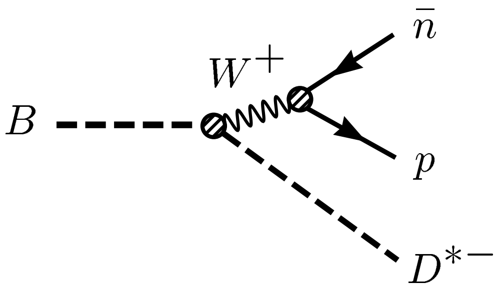

Figure 1: The factorized current model for describing $B^0 \to D^{*-} p\bar{n}$.

The first term is the $B \to D^*$ transition matrix element, while for the second, the nucleon pair is viewed as directly created by the current. The vector part can be expressed as

$$\langle p\bar{n}|V_\mu|0\rangle = \bar{u}(p_p)\left\{F_1^W(t)\gamma_\mu + i\frac{F_2^W(t)}{2m_N}\sigma_{\mu\nu}q^\nu\right\}v(p_{\bar{n}}), \tag{2}$$

where $q = p_B - p_{D^*} = p_p + p_{\bar{n}}$ is the momentum transfer (so $t = q^2$ is nothing but the $p\bar{n}$ pair mass), m_N is the nucleon mass, and $F_{1,2}^W$ are the weak nucleon form factors.

It is well known that the nucleon weak vector form factors are related to isovector electromagnetic (em) form factors through a simple isospin rotation. The matrix element $\langle N(p')\bar{N}(p)|\mathcal{J}_\mu^{em}|0\rangle$ for the em current can be expressed as $\bar{u}(p')\ \times\{F_1(t)\gamma_\mu + i\sigma_{\mu\nu}q^\nu F_2(t)/2m_N\}v(p)$. The experimental data is usually given in terms of the Sachs form factors which are related to F_1 and F_2 through $G_E^{p,n}(t) = F_1^{p,n}(t) + tF_2^{p,n}(t)/(4m_N^2)$, $G_M^{p,n}(t) = F_1^{p,n}(t) + F_2^{p,n}(t)$. Through isospin, the vector portion of the charged weak currents are related to the isovector component of the em currents as,

$$F_i^W(t) = F_i^p(t) - F_i^n(t), \qquad\qquad i = 1,2. \tag{3}$$

With the help of Eq. (3), the matrix element of the vector produced baryon pair can be expressed as $\langle p\bar{n}|V_\mu|0\rangle = \bar{u}(p_p)[\left(G_M^p - G_M^n\right)\gamma^\mu + (p_{\bar{n}} - p_p)^\mu\left(F_2^p - F_2^n\right)/2m_N]v\left(p_{\bar{n}}\right)$. Information on the nucleon em form factors, for which much data exists in the time-like region [6] (e.g. $e^+e^- \to N\bar{N}$ and $p\bar{p} \to e^+e^-$), is then transferred to the nucleon weak form factors by the simple isospin rotation. For other terms of Eq. (1), we use the Bauer-Stech-Wirbel (BSW) [7] and light-front (LF) form factor models [8] for the $B \to D^*$ transition matrix element. The value of a_1 is extracted from the two-body mode $B \to D^{*-}\rho^+$, i.e. $a_1^{\rm BSW} = 0.86 \pm 0.21 \pm 0.07$ and $a_1^{\rm LF} = 0.74 \pm 0.18 \pm 0.06$ [9]. In this approach, $\langle D^{*-}p\bar{n}|\mathcal{H}_{eff}|B^0\rangle$ can be readily obtained once the nucleon em form factors are given.

The so-called QCD quark counting rules [10] give the leading power in the large-$|t|$ fall-off of the form factor $F_1(t)$ by counting the number of gluon exchanges which are necessary to distribute the large photon momentum to all constituents. In the limit $|t| \to \infty$

$$F_i(t) \to (|t|)^{-(i+1)}\left[\ln\left(\frac{|t|}{Q_0^2}\right)\right]^{-\gamma}, \quad \gamma = 2 + \frac{4}{3\beta}, \quad i = 1,2 \tag{4}$$

where $Q_0 \simeq \Lambda_{\rm QCD} = 0.3$ GeV, extra $1/t$ in $F_2(t)$ is due to helicity flip, and γ depends weakly on the number of flavors; for three flavors $\gamma = 2.148$.

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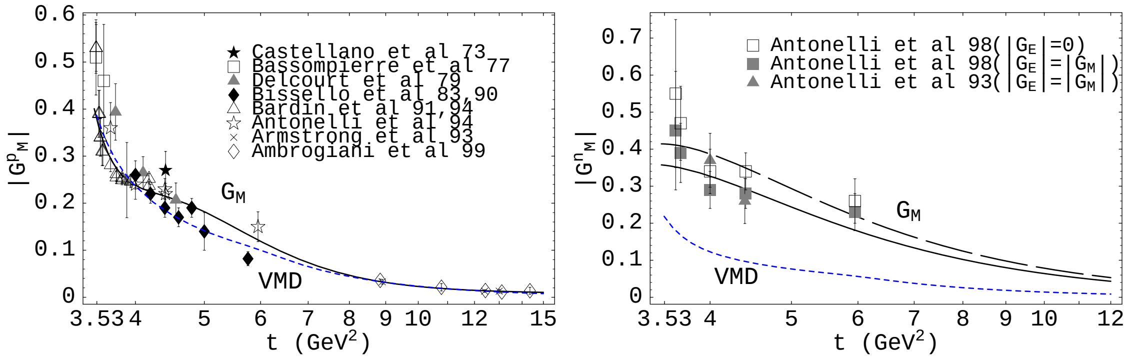

Figure 2: Time-like proton (left) and neutron (right) magnetic form factors fitted (solid) by using Eq. (5). The dashed curves represent the VMD results.

The asymptotic form given in Eq. (4) has been confirmed by many experimental measurements of $G_M = F_1 + F_2$ over a wide range of momentum transfer in the space-like region. The asymptotic behavior of G_M^p also seems to hold in the time-like region, as reported by the Fermilab E760 and E835 experiments [6] for 8.9 GeV$^2 < t <$ 13 GeV^2 and for momentum transfer up to $\sim$ 14.4 GeV^2, respectively.

Most time-like data for the em form factors are extracted by assuming either $|G_E| = |G_M|$ or $|G_E| = 0$ in the region of momentum transfer explored. By assuming $|G_E| = |G_M|$ in extracting G_M from data, the information on F_2 is lost. We should concentrate on the contribution arising from $G_M^p - G_M^n$. The contribution from $F_2^{p,n}$ can be determined only when G_M and G_E can be separated from data with better angular resolution.

We take $|G_M|$ in the following form to make a *phenomenological fit* of the data [6]:

$$|G_M^p(t)| = \left(\sum_{i=1}^{5} \frac{x_i}{t^{i+1}}\right)\left[\ln\left(\frac{t}{Q_0^2}\right)\right]^{-\gamma}, \qquad |G_M^n(t)| = \left(\sum_{i=1}^{2} \frac{y_i}{t^{i+1}}\right)\left[\ln\left(\frac{t}{Q_0^2}\right)\right]^{-\gamma}, \tag{5}$$

where the leading power and log factor are from Eq. (4), and the fewer parameters for G_M^n reflects the scarcer amount of neutron data. The best fit parameters are given in Ref. [5], with the χ^2 per degree of freedom of the fits being 1.47, 0.41 for $|G_M^p|$, $|G_M^n|$, respectively. We show in Figs. 2 the fitted data together with the best fit curves. It was pointed out that the data supports $|G_E^n| = 0$ as well. We therefore perform the fit for the neutron magnetic form factor to the data that is extracted under the assumption of $|G_E^n| = 0$, giving χ^2/d.o.f. = 0.39, and the fit is plotted as the long-dashed line in the right-hand figure of Fig. 2.

We note that there is a sign difference between G_M^p and G_M^n in the space-like region. Analyticity implies continuity at infinity between space-like and time-like t [11] regions. Hence time-like magnetic form factors are expected to behave like space-like ones, i.e. real and positive for the proton, but negative for the neutron.

For both proton and neutron data extracted by assuming $|G_E| = |G_M|$, the predicted branching ratios contributed from the weak vector current are

$$\mathrm{Br}_V^{\mathrm{LF}} = (7.14^{+0.69}_{-0.65}) \times 10^{-4}\left(\frac{a_1}{0.74}\right)^2, \quad \mathrm{Br}_V^{\mathrm{BSW}} = (8.72^{+0.85}_{-0.79}) \times 10^{-4}\left(\frac{a_1}{0.86}\right)^2 \tag{6}$$

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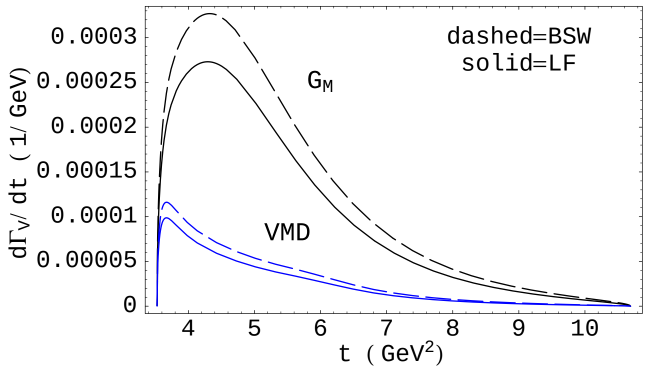

Figure 3: The differential decay rate vs $t = m^2_{p\bar{n}}$ of the vector current induced $B^0 \to D^{*-}p\bar{n}$ decay. The upper curves are from the phenomenological fits to nucleon form factor data assuming $|G_E| = |G_M|$, for the Light-Front (solid) and BSW (dashed) $B^0 \to D^{*-}$ form factor models. The lower curves are for the VMD model.

for the LF and BSW models, respectively. The errors are obtained by scanning through $\chi^2 \le \chi^2_{\rm min} + 1$ of both $|G^p_M|$ and $|G^n_M|$ fits.

Using $|G^p_E| = |G^p_M|$ and $|G^n_E| = 0$ for the proton and neutron data, respectively, we have

$$\mathrm{Br}_V^{\rm LF} = (8.96^{+1.02}_{-0.94}) \times 10^{-4}\left(\frac{a_1}{0.74}\right)^2, \quad \mathrm{Br}_V^{\rm BSW} = (10.94^{+1.25}_{-1.15}) \times 10^{-4}\left(\frac{a_1}{0.86}\right)^2. \tag{7}$$

The larger values for this second set of branching fractions can be understood qualitatively from Fig. 2, where the curve fitted to data assuming $|G^n_E| = 0$ is higher than the one fitted assuming $|G^n_E| = |G^n_M|$, hence the quantity $G^p_M - G^n_M = |G^p_M| + |G^n_M|$ is larger.

Comparing with the central value of the measured $\mathrm{Br}(B^0 \to D^{*-}p\bar{n}) = (14.5^{+3.4}_{-3.0} \pm 2.7) \times 10^{-4}$, our LF (BSW) model results contribute 50 (60)% for the first set and 62 (75)% for the second. If the naive factorization value of a_1 is used, the results are close to the experimental central value, that is $\mathrm{Br}_V^{\rm LF(BSW)} = 12.51\ (13.83) \times 10^{-4}$ for the first set and $15.69\ (17.36) \times 10^{-4}$ for the second set. Since this analysis involves just the factorization hypothesis but is otherwise based on data, it is rather robust. We plot in Fig. 3 the vector current induced differential decay rate $d\Gamma_V\left(B^0 \to D^{*-}p\bar{n}\right)/dq^2$. The lower two curves are from the VMD approach [5]. As seen also from Eqs. (6), (7), the LF form factor model gives results that are smaller than the BSW model case. The $\sim 10\%$ difference can be viewed as an estimate of the uncertainty from $B \to D^*$ form factor models.

From Fig. 3 we see that the differential rate peaks at ~ 4.6 GeV^2, corresponding to $m_{p\bar{n}} \simeq 2.14$ GeV, which is quite close to the threshold of 1.88 GeV. This threshold enhancement effect, consistent with what was suggested in Ref. [3], should be checked experimentally by measuring the recoil D^{*-} momentum spectrum.

Although the axial vector and vector current contributions interfere in the decay amplitude, the interference vanishes when one sums over spin and integrates over phase space. The total rate is therefore a simple sum of the contributions from the vector and axial vector portions of the weak nucleon form factors. Like the vector case, we could in principle

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obtain the axial vector contribution if the nucleon form factors of the axial current were known. Unfortunately, the time-like data is still lacking; hence the contribution from this part remains undetermined. In spite of this, a rough estimate can still be given, which seems to be the right amount [5]. We point out, however, that information on the time-like *nucleon* axial form factor could in fact be obtained in the future via the $B^0 \to D^{*-} p\bar{n}$ decay data. One just has to separate the axial vector contribution from the vector part.

Our analysis is also applied to baryonic modes that contain strangeness. The estimated rates are generally lower than the $p\bar{n}$ mode due to smaller couplings and higher thresholds. The largest mode, $B^0 \to D^{*-}\Sigma^+\bar{\Lambda}$, is predicted at the 1×10^{-4} level [5].

Finally, it is of great interest to estimate the rate of the charmless baryonic mode $B^0 \to \rho^- p\bar{n}$ by replacing D^{*-} in the Feynman diagram depicted in Fig. 1 with ρ^-. We can scale from $B \to \bar{D}^* p\bar{n}$ by $|V_{ub}/V_{cd}|^2$ and phase space, decay constant etc., and again find $B \to \rho^- p\bar{n}$ at 10^{-5} order [12]. Charmless decays are of great current interest.

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