Additional neutral Z' boson in deuteron disintegration

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An impact of additional neutral gauge boson on neutral channel of deuteron disintegration was considered for low energy antineutrino spectrum. We derive analytic expression for Z′ contribution to $\tilde{\nu}_e D \rightarrow \tilde{\nu}_e pn$ reaction and to $\frac{\sigma\ (\tilde{\nu}_e D \rightarrow e^+ nn)}{\sigma\ (\tilde{\nu}_e D \rightarrow \tilde{\nu}_e pn)}$ ratio. The correction can be described by the renormalization of coupling constant of axial-vector interaction and for the considered energies less than 15 MeV does not depend on antineutrino energy. The influence of additional neutral gauge boson can be as much as 5-10% at the physical mass range of neutral boson greater than 250 GeV. The calculated Z′ impact is substantial for neutrino oscillation experiments with $\tilde{\nu}_e D$ reaction.

The two-channel reaction $\tilde{\nu}_e D \rightarrow \tilde{\nu}_e pn$ or $e^+ nn$ of deuteron disintegration is a sensitive tool for neutrino oscillations search. In extensions of standard model, however, $\tilde{\nu}_e$ interacts with hadron current not only by Z exchange but also by Z′. In exclusive group E_6, which results after compactification of $E_8 x E_8'$, an additional neutral gauge boson Z′ appears in three variants according to the scheme with additional U(1) symmetry factors after the break of E_6 supersymmetric model

$$
\begin{aligned}
&E_6 \rightarrow SU_C(3) x SU_L(2) x U_Y(1) x U_\eta(1) \text{ or}\\
&E_6 \rightarrow SO(10) x U_\psi(1) \\
&\qquad\downarrow \\
&SU(5) x U\chi(1)
\end{aligned}
\qquad (1)
$$

On an intermediate energy scale $M_{int} \sim 10^{10} \div 10^{11}$ GeV one of the fields Z_ψ or Z_χ get a mass ~ M_{int}. As a result there is one light additional gauge boson in the second variant too. The E_6 breaking schemes with additional Z_ψ, Z_χ or Z_η boson can be homogeneously described by the combination of U(1) symmetry generators

$$
Q_6 \equiv Q(\theta_6) = Q_\psi \cos\theta_6 + Q_\chi \sin\theta_6 \qquad (2)
$$

The values $\theta_6 = 0^\circ$, 90°, $142{,}24^\circ$ of mixing angle, which is the parameter for E_6 breaking scheme, correspond to Z_ψ, Z_χ , Z_η bosons. This reaction has a selective sensibility to the structure of hadron neutral currents. We will assume that antineutrinos in interaction with D nuclear system have characteristic energies of nuclear reactor antineutrino spectrum $E_\nu \leq 15$MeV, when nucleons can be considered point like.

Let us denote Z' correction R to $\tilde{\nu}_e d \rightarrow \tilde{\nu}_e pn$ reaction as

$$
R = \frac{\sigma^{Z+Z'}(\tilde{\nu}_e D \rightarrow \tilde{\nu}_e pn)}{\sigma^{Z}(\tilde{\nu}_e D \rightarrow \tilde{\nu}_e pn)} \qquad (3)
$$

Taking in account that Z' doesn't interfere in charged channel we can write

$$\left(\frac{\sigma^c}{\sigma^n}\right)(\text{without } Z') = R\left(\frac{\sigma^c}{\sigma^n}\right)(\text{with } Z') \tag{4}$$

To calculate Z' contribution we confine ourselves by impulse approximation (IA). This means that the calculations of σ^c and σ^n cross sections in IA for two channels of $\tilde{\nu}_e D$ reaction will be about 8% less then in a theory with $\pi\rho A_1$ meson exchange currents, nucleon excitations. We neglect these corrections because our primary aim is to find Z' contribution to the ratio of cross sections when these effects are practically canceled.

The neutral channel cross section $\sigma^n \sim g_A^2$ in IA, where the constant of axial-vector week interaction is $g_A \sim 1{,}254$. The Lagrangian for $\tilde{\nu}_e d \to \tilde{\nu}_e pn$ reaction in impulse approximation when transferred impulses are small ($|q^2| << m_Z^2$) is

$$L_{int} = \frac{G}{\sqrt{2}} \bar{\nu} O^\mu \nu J^h_\mu \tag{5}$$

In the case of two neutral gauge bosons it is possible to introduce an effective neutral current, which preserve an outlook of above low energy Lagrangian

$$L_{int} = \frac{G}{\sqrt{2}} \bar{\nu} O^\mu \nu J^{h\,eff}_\mu \tag{6}$$

Actually the Lagrangian of interaction of the sums $J_\mu = j^\ell_\mu + J^h_\mu$, $J'_\mu = j'^\ell_\mu + J'^h_\mu$ lepton and hadron currents with gauge fields Z_μ and Z'_μ is

$$L_{int} = \frac{g}{\cos\theta_W} J_\mu Z^\mu + g' J'_\mu Z'^\mu \tag{7}$$

The renormgroup analysis shows an equality of the coupling constants $g = g'$. The currents j'^ℓ_μ and J'^h_μ interacting with Z'_μ can be defined in terms of quantum numbers $Q_{\psi,\chi \text{ or } \eta}$ of generators for additional $U(1)_{\psi,\chi \text{ or } \eta}$ symmetry. The quantum numbers of E_6 27 multiplet are

$$\begin{aligned} &Q_\psi(u_L) = Q_\psi(d_L) = Q_\psi(\nu_L) = 1/6\sqrt{5/2} \\ &Q_\chi(u_L) = Q_\chi(d_L) = -1/3 Q_\chi(\nu_L) = -1/2\sqrt{1/6} \\ &Q_{\psi,\chi}(\psi_R) = -Q_{\psi,\chi}(\psi_L^c);\ Q_{\psi,\chi}(\nu_R) = 0 \end{aligned} \tag{8}$$

The "L,R" indices denote left and right chiral states of corresponding elementary gauge fields, "c" is charge conjugation symbol. The neutrino current then

$$j'^\ell_\mu = \bar{\nu} Q_6 \nu \tag{9}$$

where $Q_6^\nu = 1/6\sqrt{5/2}\cos\theta_6 + 1/2\sqrt{3/2}\sin\theta_6$. Omitting the effects of heavy quarks the hadron current is

$$J_\mu'^h = \sum_{q=\bar{u},d} \bar{q}\gamma_\mu Q_6 q \qquad (10)$$

Being not related to the mass states, the gauge fields Z_μ, Z'_μ are defined in terms of physical gauge fields $Z_{1,2}$ by mixing matrix with indefinite angle θ

$$\begin{pmatrix} Z_{1\mu} \\ Z_{2\mu} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} Z_\mu \\ Z'_\mu \end{pmatrix} \qquad (11)$$

Taking an average on physical vacuum $Z_{1,2}$ of neutral gauge bosons in lowest theory perturbations order yields an effective low energy Lagrangian

$$L_{int} = \frac{G}{\sqrt{2}}(\alpha J_\mu J^\mu + \beta J_\mu J'^\mu + \gamma J'_\mu J'^\mu) \qquad (12)$$

By placing the sums of currents interacting with fields Z_μ, Z'_μ into (12) and using (11) leads to an effective Lagrangian of type (5) with effective current (thereafter an index “h” will be omitted)

$$J_\mu^{eff} = (\alpha + \beta Q_6^\nu)J_\mu^h + (\beta + \gamma Q_6^\nu)J_\mu^{h\prime} \qquad (13)$$

where α, β and γ are functions of physical masses m_{Z_1}, m_{Z_2} of additional gauge bosons and mixing angle Z-Z′

$$\begin{cases} \alpha = \left(\frac{m_Z}{m_{Z_1}}\cos\theta\right)^2 + \left(\frac{m_Z}{m_{Z_2}}\sin\theta\right)^2 \\ \beta = \cos\theta_W \cos\theta\sin\theta\left[\left(\frac{m_Z}{m_{Z_1}}\right)^2 - \left(\frac{m_Z}{m_{Z_2}}\right)^2\right] \\ \gamma = \cos^2\theta_W\left[\left(\frac{m_Z}{m_{Z_1}}\sin\theta\right)^2 + \left(\frac{m_Z}{m_{Z_2}}\cos\theta\right)^2\right] \end{cases} \qquad (14)$$

where $\sin^2\theta_W$=0,232 and m_Z=91GeV. In a model with two neutral gauge bosons the value m_Z becomes the non-physical parameter of the standard model.

In the limit $\theta \to 0$, $m_{Z_1} \to m_Z$, $m_{Z_2} \to \infty$ the current and Lagrangian of the standard model can be obtained. In the private case $\theta \to 0$

$$J_\mu^{eff} = J_\mu + \cos^2\theta_W\left(\frac{m_Z}{m_{Z_2}}\right)^2 J'_\mu \qquad (15)$$

It is convenient to use the next isotop-space-time parameterization of hadron currents

$$J_\mu = \alpha^Z V_\mu^3 + \beta^Z A_\mu^3 + \gamma^Z V_\mu^S + \delta^Z A_\mu^S \qquad (16)$$

The same expression with own constant set $\{\alpha^{Z'},...,\delta^{Z'}\}$ is appropriate for current J'_μ. In expression (16) V, A - are vector and axial-vector formfactors, symbols “3” and “s” are denote isovector and isoscalar formfactor properties accordingly. The constants $\{\alpha^{Z'},...,\delta^{Z'}\}$ can be defined by direct comparison (16) with the outlook of hadron current expressed in terms of quark fields in the standard model, and also by (8), (10).

Because $\sigma^n \sim g_A^2$ in IA or in essence ~ $(\beta^Z g_A)^2$, β^Z=1 it is obvious that in order to get Z′ correction it is necessary to perform a substitution corresponding

$$\beta^Z \to (...)\beta^Z + (...)\beta^{Z'}, \beta^{Z'} = -2\sqrt{2/3}\sin\theta_6 \qquad (17)$$

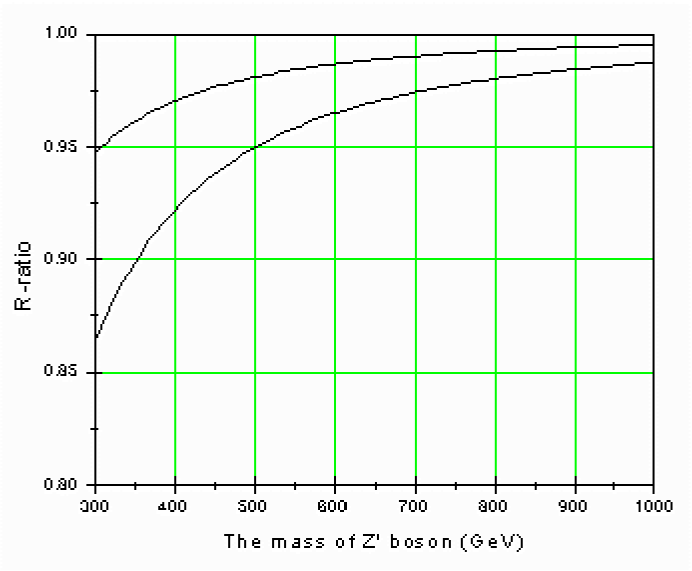
This substitution let us immediately write an expression for R as

$$R = [\alpha + \beta Q_6^v - \sqrt{1/6}\sin\theta_6(\beta + 4\gamma Q_6^v]^2 \qquad (18)$$

In a definite realization of E_6 breaking three-parameter R dependence reduces to two- parameter dependence $R = R(m_{Z_2}, \theta)$ if taking in account functional connection

$$tg^2\theta = \frac{m_Z^2 - m_{Z_1}^2}{m_{Z_2}^2 - m_Z^2} \qquad (19)$$

imposed by the requirement that mass matrix must be diagonal.



This additional connection leads to growing of cross-section $\sigma^n|_{\theta=const}$ when m_{Z_2} increasing. This is an important interference feature of this reaction cross section dependence in a model with more then one Higgs boson. **Figure 1** shows a particular case θ=0 with curves for Z_ψ (R≡1), Z_η and Z_χ from top to bottom. This influence is negative in opposite to positive contribution at non zero mixing angles.

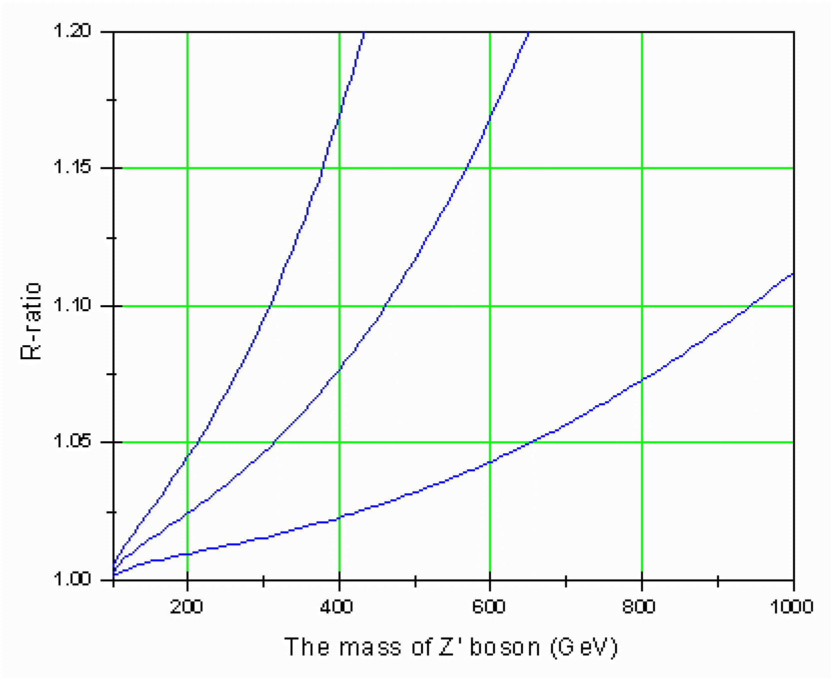


Figure 2: Shows how the theoretically calculated $R = \frac{\sigma_n^{Z+Z'}}{\sigma_n^{Z}}$ value depends on the Z'mass. The variant with Z' corresponding to Z_ψ is shown. For the allowed small Z-Z′ mixing angles θ the ratio is characterized by rapid growth of R when Z' mass increasing.

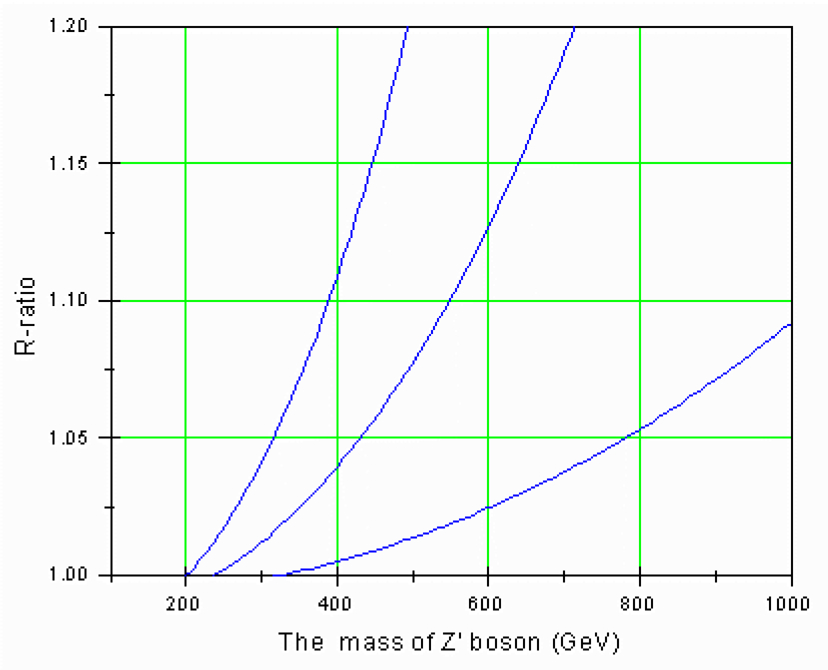


Figure 3: The same dependence as on figure 2, but for negative set of mixing angles accordingly.

Conclusion: We derived in this paper an analytic expression (18) for the contribution of additional neutral gauge boson to the neutral channel of deuteron disintegration. Due to interference effects the cross-section of reaction $\tilde{\nu}_e D \to \tilde{\nu}_e pn$ is not decreasing $\sim 1/m^4$ as in common, but grows $\sim m^2$ in a wide range of Z' mass due to interference terms and specific relation (19). We shown that for permitted θ values Z' contribution to neutral channel of deuteron disintegration attains 5-10%, depending on Z' mass and mixing angle. Figure 2 represents results for Z_ψ boson at fixed positive mixing angles θ. Figure 3 shows the identical dependence but for negative set of θ. Qualitatively the results for Z_χ and Z_η boson are close. The specific growth of cross section is a feature for all possible realizations Z_ψ , Z_χ or Z_η of additional gauge boson depending on a particular E_6 breaking scheme. At small parameters $\theta, \left(\frac{\theta m_2}{m_z}\right)^2, \left(\frac{m_Z}{m_2}\right)^2 \ll 1$ expansion of (19) gives the next simple behavior of Z′ contribution

$$\begin{cases} R_\psi \approx 1 + \frac{\theta}{2} + 2\left(\frac{m_{Z_2}\theta}{m_Z}\right)^2 \\ R_\chi \approx 1 + \theta + 2\left(\frac{m_{Z_2}\theta}{m_Z}\right)^2 \\ R_\eta \approx 1 + 2\left(\frac{m_{Z_2}\theta}{m_Z}\right)^2 \end{cases} \tag{20}$$

The calculated contribution to the ratio $\overline{\sigma}^c/\overline{\sigma}^n$ is higher then modern experimental precision ~1% of σ^c/σ^n measurements in reactor experiments for neutrino oscillations search. We presented the calculations that show that the contribution of additional Z′ boson is higher that this precision and therefore should be taken into account.