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Estimated Cross Section for the Reaction $p+p \to d+W$*

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The cross section for the reaction $p+p \to d+W$ has been recalculated in a relativistic form. The new estimate of the cross section is considerably higher than the one given previously by Bernstein.

THE study of the reaction $p+p \to d+W^+$ to search for the W-meson has been proposed by Bernstein.[1] We carry out here a relativistic form of the calculation of the cross section for this process. However, the present calculation remains within the approximation of Bernstein's work in that the only diagrams considered are the neutron exchange diagrams (Fig. 1).

In evaluating these diagrams the n-p-W vertex function is assumed to be[2]

$$\frac{g}{\sqrt{2}}\bar{u}_p \epsilon\cdot\gamma(1-i\gamma_5)u_n\,, \tag{1}$$

where g is the dimensionless coupling constant defined by $g^2 = GM_W{}^2/\sqrt{2}$ and G is the usual Fermi coupling constant, $Gm^2 = 1.01\times10^{-5}$. ϵ_μ is the spin vector of the W meson, normalized to $\epsilon^2=-1$. Momentum-dependent form factors and induced pseudoscalar interactions are omitted.

The n-p-d vertex has been studied by Blankenbecler *et al.*[3,4] It can be expressed approximately as (neglecting tensor components)

$$\frac{1}{\sqrt{2}}\frac{N}{m}\bar{u}_n \xi\cdot\gamma C\bar{u}_q{}^T\,, \tag{2}$$

where C is the charge conjugation matrix, $C\gamma_\mu C^{-1} = -\gamma_\mu{}^T$, ξ_μ is the deuteron spin vector, $\xi^2=-1$, and N is proportional to the asymptotic normalization of the deuteron wave function. In terms of the deuteron binding energy B, define $\alpha=(mB)^{1/2}$ and N is given by

$$N^2 = 32\pi m\alpha\,. \tag{3}$$

The expression (2) differs from the form of the vertex used in Refs. 3 and 4 in that a projection operator has been omitted, but the results are not altered very much when this simpler form is used.

The matrix element for the process $p+p\to d+W$ is the product of expressions (1) and (2), summed over the spin of the intermediate neutron, and divided by the energy denominator.

$$M = -\frac{1}{t-m^2}\frac{gN}{2m}\bar{u}_p\epsilon\cdot\gamma(1-i\gamma_5)[(d-q)\cdot\gamma+m]\xi\cdot\gamma C\bar{u}_q{}^T + \frac{1}{u-m^2}\frac{gN}{2m}\bar{u}_q\epsilon\cdot\gamma(1-i\gamma_5) \times[(d-p)\cdot\gamma+m]\xi\cdot\gamma C\bar{u}_p{}^T\,, \tag{4}$$

where $t=(d-q)^2$ and $u=(d-p)^2$.

The differential cross section in the center-of-mass system is given by

$$\frac{d\sigma}{d\Omega} = \frac{1}{(8\pi 2q_0)^2}\frac{|\mathbf{d}|}{|\mathbf{p}|}\frac{1}{4}\sum_{\text{spins}}|M|^2\,, \tag{5}$$

which is

$$\begin{aligned}\frac{d\sigma}{d\Omega} = \frac{|\mathbf{d}|g^2N^2}{m^2(16\pi q_0)^2|\mathbf{p}|}\Bigg\{&\frac{1}{(t-m^2)^2}[q\cdot dp\cdot d - 4m^2q\cdot p + 6m^2 d\cdot p + M_W{}^{-2}(4q\cdot Wd\cdot Wd\cdot p - 2q\cdot Wd\cdot Wq\cdot p - 6(q\cdot W)^2 d\cdot p \\ &+ 2(q\cdot W)^2 q\cdot p + 2q\cdot Wp\cdot Wd\cdot q - 4m^2 p\cdot Wq\cdot W + m^{-2}(q\cdot W)^2 p\cdot dq\cdot d)] + \frac{1}{(u-m^2)^2}[q\cdot dp\cdot d - 4m^2 q\cdot p + 6m^2 d\cdot q \\ &+ M_W{}^{-2}(4p\cdot Wd\cdot Wd\cdot q - 2p\cdot Wd\cdot Wp\cdot q - 6(p\cdot W)^2 d\cdot p + 2(p\cdot W)^2 q\cdot p + 2p\cdot Wq\cdot Wd\cdot p - 4m^2 p\cdot Wq\cdot W \\ &+ m^{-2}(p\cdot W)^2 q\cdot dp\cdot d)] + \frac{1}{(t-m^2)(u-m^2)}[12m^2 p\cdot q - 3q\cdot dp\cdot d + 4m^4 - 4(m/M_W)^2(d\cdot W)^2]\Bigg\} \\ = 1.22\times10^{-35}&(M_W{}^2/q_0{}^2)(|\mathbf{d}|/|\mathbf{p}|)\left\{\begin{matrix}\text{the above}\\ \text{in braces}\end{matrix}\right\}\ \text{cm}^2/\text{sr}\,,\end{aligned} \tag{6}$$

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[1] J. Bernstein, Phys. Rev. **129**, 2323 (1963).
[2] The summation $a\cdot b = a_\mu b_\mu = a_0b_0 - a_1b_1 - a_2b_2 - a_3b_3$ is used here. Nucleon spinors are normalized to $\bar{u}u = 2m$, and m is used throughout for the nucleon mass.
[3] R. Blankenbecler, M. Goldberger, and F. Halpern, Nucl. Phys. **12**, 629 (1959).
[4] R. Blankenbecler and L. Cook, Phys. Rev. **119**, 1745 (1960).

where in the last line above m has been set equal to one. See Fig. 2 for a plot of σ.

The nonrelativistic limit of the above cross section is obtained by setting each four-vector in the braces (except for those in t and u) equal to its rest value $(M,0,0,0)$. The result is in agreement with Bernstein's expression.[1] However, for $M_W \gtrsim m$ the initial protons are always relativistic. This leads to large corrections even near threshold.

At high energies the cross section calculated here increases in the forward direction as the fourth power of the center-of-mass energy.

$$\left.\frac{d\sigma}{d\Omega}\right]_{\theta=0} \sim \frac{g^2N^2}{64\pi^2m^6M_W{}^2}q_0{}^4,$$

and for other fixed angles it varies as $q_0{}^2$. The large discrepancy between the relativistic and the nonrelativistic results comes from the fact that the nonrelativistic formula omits most of the momentum-dependent factors of the relativistic calculation. It seems unlikely, however, that this result can be applied far from threshold.

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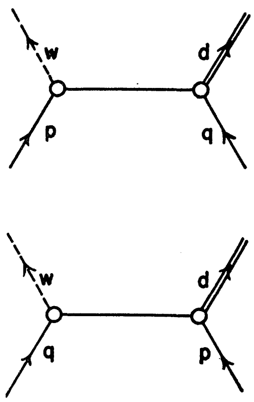

FIG. 1. These diagrams represent the one-neutron-exchange processes in the reaction $p+p\rightarrow d+W$. The letters represent the four-momenta.

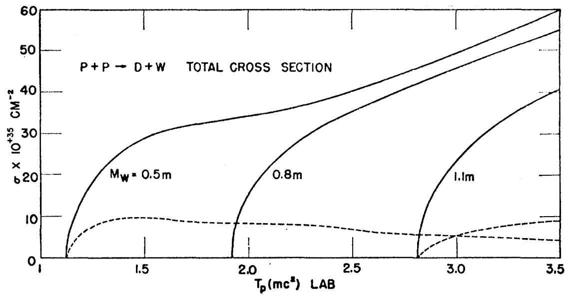

FIG. 2. This figure is a plot of the total production cross section for W mesons as calculated from the relativistic formula (solid curves) together with some of the nonrelativistic results of Ref. 1 (dashed curves). The abscissa is the laboratory kinetic energy.