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Inelastic photoproduction of charged vector bosons

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A proposal for a photon beam at the Superconducting Super Collider makes Mikaelian's paper on photoproduction of charged vector bosons of current interest. We update that paper to include modern values of the parameters, modern distribution functions, and an electric quadrupole coupling in the three-gauge-boson vertex. The cross section remains large enough that a substantial number of $W^{\pm}$ could be produced. The prospects for determining the three-gauge-boson coupling, however, are not good.

It is possible to convert a proton beam into a beam of photons. Such a photon beam exists at Fermilab and at CERN and Tannenbaum has suggested using the same technology to make a photon beam at the Superconducting Super Collider[1] (SSC). He suggests that a possible use of such a beam would be the photoproduction of W bosons. This would proceed through the diagrams shown in Fig. 1 and would be particularly useful if it could be used to study the three-gauge-boson vertex of Fig. 1(c).

Photoproduction of charged intermediate vector bosons was studied some years ago by Mikaelian.[2] The elastic processes $\gamma+p\to W^{+}+n$, $\gamma+n\to W^{-}+p$ proposed by Tannenbaum were also studied by one of us.[3] In this brief note we discuss the inelastic processes $\gamma+q\to W^{\pm}+q$ of Tannenbaum's proposal. Unlike the elastic processes the inelastic reactions were carefully studied by Mikaelian; we have checked his formulas and agree with them completely. We will only update his work and then discuss the possibility of using these processes to fix the three-gauge-boson vertex. The update consists of the following: (1) including an electric quadrupole moment for the W's in the three-gauge-boson vertex (Mikaelian included only an anomalous magnetic moment); (2) using modern values for the parameters such as the W mass and the Weinberg angle (Mikaelian used M_W equal to 70 GeV); (3) using more modern distribution functions including a dependence on the momentum transfer. The range of center-of-mass energies considered by Mikaelian includes that given by the proposed 9-TeV photon beam of SSC.

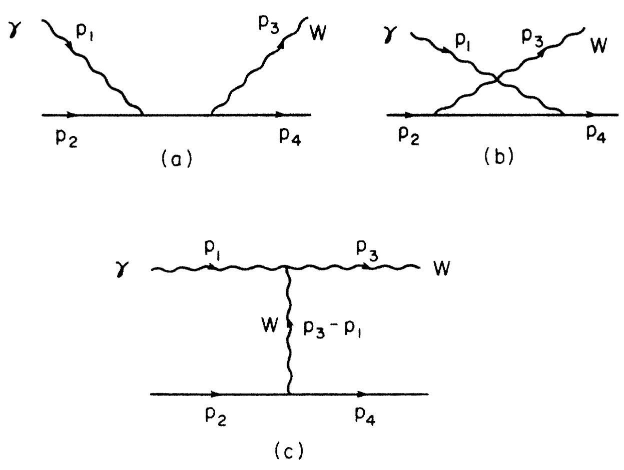

FIG. 1. Feynman diagrams for the reaction $\gamma+q\to W^{\pm}+q$.

In terms of the momenta shown in Fig. 1 the three-gauge-boson vertex, for the present case with one W off shell, is given by[4] $\epsilon^{*}_{\alpha}(p_3)\epsilon_{\mu}(p_1)V^{\mu\nu\alpha}$ where

$$V^{\mu\nu\alpha}=g^{\alpha\mu}p_1^{\nu}(1+\kappa)-2p_3^{\mu}g^{\nu\alpha}-g^{\mu\nu}p_1^{\alpha}(1+\kappa)-2\frac{\Delta Q}{M_W{}^2}p_1^{\nu}(p_1^{\alpha}p_3^{\mu}-g^{\alpha\mu}p_1\cdot p_3)\ . \quad (1)$$

κ is the anomalous magnetic moment and ΔQ is the electric quadrupole moment defined so as to agree on shell with Bardeen, Gastmans, and Lautrup.[5] Of course, in the standard model κ must be one and ΔQ must be zero.[6]

The square of the matrix element given by Fig. 1 is the $T(\kappa,Q,s,t)$ given by Eq. (5) of Ref. 2. To include the ΔQ dependence we must add

TABLE I. The cross section $\sigma(\kappa,\Delta Q)$ for $\gamma+p\rightarrow W^{+}+X$ in units of 10^{-35} cm^2. In each case the top number comes from using set 1 ($\Lambda=0.2$ GeV) of the distribution functions of Duke and Owens, the bottom number (in parentheses) comes from set 2 ($\Lambda=0.4$ GeV) of Duke and Owens.

s (10^4 GeV^2)	$\sigma(0,0)$	$\sigma(1,0)$	$\sigma(-1,0)$	$\sigma(0,1)$	$\sigma(1,1)$	$\sigma(0,-1)$
1.0	2.40×10^{-3}	2.58×10^{-3}	2.26×10^{-3}	2.59×10^{-3}	2.80×10^{-3}	2.25×10^{-3}
	(2.01×10^{-3})	(2.16×10^{-3})	(1.89×10^{-3})	(2.17×10^{-3})	(2.34×10^{-3})	(1.89×10^{-3})
1.5	4.73×10^{-2}	5.36×10^{-2}	4.36×10^{-2}	5.39×10^{-2}	6.25×10^{-2}	4.32×10^{-2}
	(4.20×10^{-2})	(4.74×10^{-2})	(3.88×10^{-2})	(4.77×10^{-2})	(5.51×10^{-2})	(3.84×10^{-2})
2.0	0.138	0.163	0.126	0.165	0.202	0.126
	(0.126)	(0.148)	(0.115)	(0.150)	(0.182)	(0.115)
2.5	0.252	0.307	0.231	0.313	0.399	0.231
	(0.232)	(0.282)	(0.213)	(0.286)	(0.364)	(0.213)
3.0	0.380	0.473	0.350	0.484	0.638	0.353
	(0.353)	(0.437)	(0.325)	(0.447)	(0.584)	(0.328)
3.5	0.516	0.654	0.478	0.673	0.906	0.488
	(0.482)	(0.607)	(0.447)	(0.624)	(0.835)	(0.456)
4.0	0.658	0.844	0.613	0.874	1.198	0.634
	(0.619)	(0.789)	(0.576)	(0.815)	(1.109)	(0.595)
4.5	0.803	1.041	0.753	1.084	1.506	0.790
	(0.760)	(0.978)	(0.712)	(1.017)	(1.401)	(0.745)
5.0	0.951	1.242	0.896	1.300	1.826	0.952
	(0.905)	(1.173)	(0.853)	(1.225)	(1.706)	(0.901)

$$\Delta T(\kappa,Q,s,t,\Delta Q)=-8\left[\frac{\Delta Q}{M_W{}^2}\right]^2\hat{s}\hat{u}+16\left[\frac{\Delta Q}{M_W{}^2}\right]\left[Q\frac{M_W{}^2(\hat{u}-\hat{s})}{M_W{}^2-t}-\kappa\frac{\hat{s}\hat{u}}{M_W{}^2-t}+\frac{\hat{s}M_W{}^2}{M_W{}^2-t}-\frac{\hat{s}\hat{u}(M_W{}^2+t)}{(M_W{}^2-t)^2}\right], \quad (2)$$

where $\hat{s}=x(s-m_p{}^2)$ with s and t the usual Mandelstam variables. m_p is the nucleon mass, x is the usual scaling variable, and $\hat{u}=M_W{}^2-\hat{s}-t$. Q is the charge of the initial quark and must be replaced by $-Q$ for W^- production.[2]

Since the cross section is at most quadratic in κ or ΔQ, its value for any values of κ and ΔQ can be written in terms of the cross sections for six distinct combinations of κ and ΔQ. For example,

$$\begin{aligned}\sigma(\kappa,\Delta Q)=&\sigma(0,0)[1-\kappa^2+\kappa\Delta Q-(\Delta Q)^2]+\tfrac{1}{2}\kappa[\sigma(1,0)-\sigma(-1,0)]+\tfrac{1}{2}\kappa^2[\sigma(1,0)+\sigma(-1,0)]\\&+\kappa\Delta Q[\sigma(1,1)-\sigma(1,0)-\sigma(0,1)]+\tfrac{1}{2}\Delta Q[\sigma(0,1)-\sigma(0,-1)]+\tfrac{1}{2}(\Delta Q)^2[\sigma(0,1)+\sigma(0,-1)]\ . \quad (3)\end{aligned}$$

TABLE II. The cross section $\sigma(\kappa,\Delta Q)$ for $\gamma+p\rightarrow W^{-}+X$ in units of 10^{-35} cm^2. The numbers are as in Table I.

s (10^4 GeV)	$\sigma(0,0)$	$\sigma(1,0)$	$\sigma(-1,0)$	$\sigma(0,1)$	$\sigma(1,1)$	$\sigma(0,-1)$
1.0	1.49×10^{-3}	1.54×10^{-3}	1.44×10^{-3}	1.54×10^{-3}	1.59×10^{-3}	1.44×10^{-3}
	(1.26×10^{-3})	(1.31×10^{-3})	(1.22×10^{-2})	(1.31×10^{-3})	(1.35×10^{-3})	(1.22×10^{-3})
1.5	5.03×10^{-2}	5.31×10^{-2}	4.80×10^{-2}	5.32×10^{-2}	5.65×10^{-2}	4.79×10^{-2}
	(4.45×10^{-2})	(4.69×10^{-2})	(4.25×10^{-2})	(4.70×10^{-2})	(4.99×10^{-2})	(4.24×10^{-2})
2.0	0.182	0.196	0.172	0.196	0.213	0.172
	(0.164)	(0.176)	(0.155)	(0.176)	(0.192)	(0.155)
2.5	0.369	0.401	0.346	0.403	0.446	0.346
	(0.333)	(0.363)	(0.313)	(0.365)	(0.404)	(0.313)
3.0	0.580	0.640	0.543	0.643	0.725	0.543
	(0.529)	(0.583)	(0.495)	(0.587)	(0.661)	(0.495)
3.5	0.802	0.894	0.748	0.901	1.031	0.750
	(0.736)	(0.820)	(0.687)	(0.827)	(0.945)	(0.689)
4.0	1.025	1.155	0.955	1.166	1.352	0.961
	(0.947)	(1.066)	(0.883)	(1.076)	(1.247)	(0.888)
4.5	1.247	1.416	1.160	1.432	1.681	1.170
	(1.159)	(1.314)	(1.079)	(1.330)	(1.559)	(1.088)
5.0	1.463	1.674	1.360	1.697	2.014	1.377
	(1.367)	(1.562)	(1.272)	(1.584)	(1.876)	(1.288)

Of course this expression is equally true for a differential cross section such as $d\sigma/dt$. In what follows, therefore, we will present results only for the six combinations of $\kappa,\Delta Q$ used on the right-hand side of (3).

Results for the total cross section for W^+ production from protons are shown in Table I in units of 10^{-35} cm^2. The first numbers given use the distribution functions given by set 1 of Duke and Owens.[7] The numbers in parentheses below each value are the cross sections given by set 2 of Duke and Owens. In both cases the square of the momentum transfer was fixed at $M_W{}^2$. The magnitude of the cross sections seems large enough to give reasonable production rates even at the low s values ($\sim 1.8\times 10^4$ GeV^2) of the SSC. The differences between cross-section values for different choices of κ and ΔQ are small, however, and this seems to make a measurement of κ and ΔQ impossible. Surprisingly the cross section for the preferred values, $\kappa=1$, $\Delta Q=0$, is almost exactly equal to that for $\kappa=0$, $\Delta Q=1$. The same is true for $\kappa=-1$, $\Delta Q=0$ compared to $\kappa=0$, $\Delta Q=-1$. Eventually, as s increases, all cross sections with $\kappa\neq 1$, $\Delta Q\neq 0$ will grow with energy,[8] while $\sigma(1,0)$ will be well behaved, but s will need to be an order of magnitude greater at least before this can be seen. Equally disturbing is the fact that the uncertainty in the distribution functions, as seen by comparing the results of set 1 with those of set 2, is larger in many cases than the difference between different κ, ΔQ values.[9]

Except at small s values the cross sections for W^- production are uniformly larger than those of W^+ and they differ by more than the 10% difference found by Mikaelian. All the comments above about the small differences for different $\kappa,\Delta Q$ values and the relatively large error due to the uncertainty in the distribution functions still hold. The near equality of $\sigma(1,0)$ and $\sigma(0,1)$ and of $\sigma(-1,0)$ and $\sigma(0,-1)$ persists to even larger energies. Values of the total cross section for W^- production are shown in Table II.

The modern expressions for the distribution functions make the cross sections smaller than those given in Ref. 2 but they are still large enough for a reasonable number of $W^\pm$ to be produced. However, the error in the calculated cross section due to the uncertainty in the distribution functions and the still relatively small center-of-mass energy make a detailed study of the three-gauge-boson vertex impossible.

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[6]For us it is sufficient to ignore the possibility that the W may be composite. For a study of the three-gauge-boson vertex from other reactions, including a composite W, see J. A. Robinson and T. G. Rizzo, Phys. Rev. D **33**, 2608 (1986).

[7]D. W. Duke and J. F. Owens, Phys. Rev. D **30**, 49 (1984).

[8]For $\kappa\neq 1$, Mikaelian shows that the cross section grows as $\ln s$ for large s

$$\sigma\rightarrow\frac{\alpha G_F}{4\sqrt{2}}(\kappa-1)^2\ln\frac{s}{M_W{}^2}\ .$$

For $\Delta Q\neq 0$, (2) can be easily integrated to see that the cross section now grows linearly with s

$$\Delta\sigma\rightarrow\frac{\alpha G_F}{4\sqrt{2}}\left[(\Delta Q)^2\frac{s}{M_W{}^2}+4(\kappa-1)\Delta Q\ln\frac{s}{M_W{}^2}\right]\ .$$

Note that the cross section is independent of the charge Q in this large-energy limit.

[9]We also tried the distribution functions (set 2) of E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984), and found numbers for $\sigma(\kappa,\Delta Q)$ which, for small s, were smaller than the smallest of the two sets in Table I, but which increased more quickly with s so that, for the larger s values of Table I, were comparable to the larger values of the two sets.