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Decay-lepton distributions from photoproduced heavy leptons*

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We discuss heavy-lepton pair production via the reaction $\gamma + Z \rightarrow L^+ + L^- + Z$ followed by the decays $L^\pm \rightarrow \mu^\pm + \nu + \bar{\nu}$ or $L^\pm \rightarrow e^\pm + \nu + \bar{\nu}$. Particular attention is given to the energy and angular distributions of the final detected leptons. The only reasonable signal for heavy-lepton production seems to be the detection of μe pairs in relatively quiet events. In the case of $\mu\mu$ pairs the signal from the decay of the heavy-lepton pairs is much smaller than the background due to regular Bethe-Heitler production for both the cross section and for all the differential spectra.

Recently, Perl *et al.*[1] have seen μe events produced in the e^+e^- colliding-beam facility SPEAR at the Stanford Linear Accelerator Center. Although the μe signal has several possible explanations, the authors have continually stressed that the best fit to the data comes from the reaction $e^+e^- \rightarrow L^+L^- \rightarrow \mu^\pm e^\mp +$ missing energy. In other words, new heavy spin-$\frac{1}{2}$ leptons (denoted by L) are being seen for the first time through the observation of their decay products.[2] Since the announcement of the μe events several calculations of heavy-lepton production and decay have been made,[3] in attempts to clarify the situation. Also, potential backgrounds from regular quantum-electrodynamic reactions have been calculated,[4] and they turn out to be too small to account for the known signal. The latter calculations have demonstrated that the $\mu\mu$ and ee signals observed in the experiment are too large to be explained away by quantum-electrodynamic processes. Thus it is reasonable to assume that all the dilepton channels seen, including μe, $\mu\mu$, and ee, arise from the decays of new charged heavy leptons with masses around 1.8 GeV/c^2. The information on the relative numbers of μe, $\mu\mu$, and ee events has been used to test the type of neutrino[5] emitted when the heavy lepton decays. At present the relative number of events is compatible with the decay of a sequential heavy lepton, i.e., one associated with its own neutrino ν_L.

The discovery of hadronic states[6] at 1.86 GeV/c^2 casts an element of doubt on the interpretation of the μe events because these new states have almost the same mass as the proposed heavy leptons. Maybe the μe events are really connected to the decays of hadronic states, rather than leptonic states. It is difficult to separate these effects in e^+e^- colliding-beam experiments because there is a hadronic background which can only be suppressed by experimental cuts. Further experiments are necessary to either reinforce or destroy the heavy-lepton hypothesis, so it becomes crucial to find signals in other reactions. Our discussion in this paper is limited to the production of charged heavy leptons. Neutral heavy leptons do not seem to be able to explain the dimuon events in neutrino data, so there is no evidence at present that they exist.[7]

Neutrino beams can obviously produce new charged leptons if the heavy leptons couple to ν_μ or ν_e. Present information is rather meagre, so we will not discuss neutrino production but refer the interested reader to some of the latest references on the subject.[8]

Regarding possible production in proton-proton collisions, quark-parton-model estimates have already been made. In general, the production cross section is far too small to be of much interest.[9] Hence we focus our attention on the photoproduction of heavy-lepton pairs, which seems to be a reasonable, if maybe hard, way of producing them. In particular the photoproduction experiment at the Fermi National Accelerator Laboratory, which has already produced evidence for new baryon states,[10] can also produce heavy leptons.

The cross section for the photoproduction of charged-heavy-lepton pairs via the Bethe-Heitler mechanism has already been calculated by Tsai[11] and by Kim and Tsai.[12] In these reactions it is well known that the scale of the cross section is set by the mass of the heavy lepton. The asymptotic cross section[13] for $\gamma + Z \rightarrow L^+ + L^- + Z$ is

$$\sigma(\omega) = Z^2 \frac{\alpha^3}{27 M_L^2}\left[84 \ln\left(\frac{2\omega}{M_L}\right) - 218\right], \qquad (1)$$

where ω is the photon energy, M_L is the heavy-lepton mass, α is the fine-structure constant, and Z is the charge of the nucleus. This result holds for production in the Coulomb field of a heavy nucleus, which is not the dominant reaction for heavy-lepton production at accelerator energies, but gives a good order-of-magnitude estimate. Unfortunately, the cross section is very small for masses around 2 GeV/c^2. In veiw of the fact that the scale is set by the mass of the lepton (neglecting the mass changes in the logarithm) the regular Bethe-Heitler pair production of muons is larger by a factor $(M_L/m_\mu)^2$. However, this is only the production part of the problem.

The signal for detecting heavy-lepton production must be the identification of decay products, because the decay lifetime is expected to be ~10^{12} sec, so we have to consider the branching ratio into various channels. Tsai[14] estimates that for 1.8-GeV/c^2 heavy leptons each leptonic decay constitutes approximately 15% of the decay rate. We assume, therefore, that the signal for observing heavy leptons is the detection of $\mu\mu$ or μe pairs. The detection of e^+e^- pairs seems to be more difficult experimentally, so we do not discuss it. Although two-body semileptonic branching ratios are comparable to the three-body leptonic ones, the identification of these decays is very complicated. Hence the question to ask is whether detection of lepton pairs is possible in experiments at Fermilab, and whether the signal from heavy-lepton decays is larger than the backgrounds from reactions such as $\gamma+Z\rightarrow\mu^+ +\mu^- + Z$, $\gamma+Z\rightarrow\mu^+ +\mu^- +\mu^+ +\mu^- + Z$, and $\gamma+Z\rightarrow\mu^+ +\mu^- + e^+ + e^- + Z$. Fortunately, the latter reactions have been investigated by Brown *et al.*[13] (see also Masujima[15]). The total cross sections are known in the asymptotic region because, using

$$\sigma(\gamma\gamma\rightarrow\mu^+\mu^-\mu^+\mu^-)=\frac{\alpha^4}{36\pi m_\mu^2}[175\zeta(3)-38]$$

$$=1.5\times10^{-34}\ \mathrm{cm}^2 \tag{2}$$

and

$$\sigma(\gamma\gamma\rightarrow\mu^+\mu^-e^+e^-)$$

$$=\frac{2\alpha^4}{27\pi m_\mu^3}\left[7\ln^2\left(\frac{m_\mu^2}{m_e^2}\right)+\frac{103}{3}\ln\left(\frac{m_\mu^2}{m_e^2}\right)+\frac{485}{9}\right]$$

$$\simeq 2.8\times10^{-33}\ \mathrm{cm}^2\,, \tag{3}$$

the Coulomb cross sections are

$$\sigma(\gamma Z\rightarrow\mu^+\mu^-\mu^+\mu^- Z)$$

$$\cong Z^2\frac{\alpha}{\pi}\ln^2\left(\frac{\omega}{m_\mu}\right)\sigma(\gamma\gamma\rightarrow\mu^+\mu^-\mu^+\mu^-) \tag{4}$$

and

$$\sigma(\gamma Z\rightarrow\mu^+\mu^-e^+e^- Z)$$

$$\cong Z^2\frac{\alpha}{\pi}\ln\left(\frac{\omega}{m_\mu}\right)\ln\left(\frac{\omega}{m_e}\right)\sigma(\gamma\gamma\rightarrow\mu^+\mu^-e^+e^-)\,. \tag{5}$$

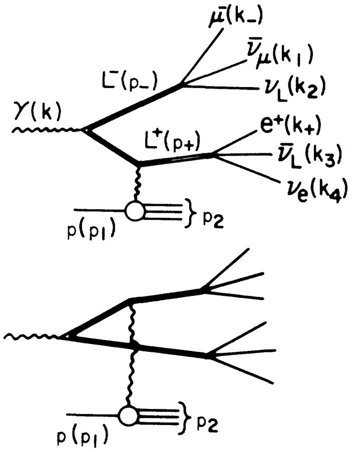

FIG. 1. The Bethe-Heitler diagrams for the production of heavy-lepton pairs followed by their subsequent three-body leptonic decays.

Hence, for a 100-GeV photon beam on a beryllium target, the cross sections are 2.6×10^{-34} cm^2 and 8.8×10^{-33} cm^2, respectively. These numbers are not so large that we anticipate serious problems from these reactions. In particular the invariant mass of the lepton pairs will be very small. One way to eliminate this background is to count the number of opposite-sign charged pairs seen in an experiment and compare it with the number of pairs with the same sign. If both systems are seen in equal numbers then a closer examination of these backgrounds will be necessary. However, the first question to be asked is whether the detection of $\mu^+\mu^-$ pairs from heavy-lepton decays can be seen above the background of $\mu^+\mu^-$ pairs produced via the regular Bethe-Heitler mechanism. If this is *not* the case then can one possibly see $\mu^\pm e^\mp$ pairs and infer that they come from heavy-lepton decays?

To answer these questions we have extended the calculations of Tsai[11] to include the decays of the heavy-lepton pairs. In other words, we calculate the diagrams depicted in Fig. 1 assuming that the heavy lepton is on its mass shell. We introduce the branching ratio B defined by

$$B=B_{L\rightarrow\mu\nu\bar{\nu}}=B_{L\rightarrow e\nu\bar{\nu}}=\frac{\Gamma_{L\rightarrow\mu\nu\bar{\nu}}}{\Gamma}=\frac{G^2M_L^5}{192\pi^3}\frac{1}{\Gamma}\,, \tag{6}$$

in the approximation where we drop the final lepton masses. Then the cross section is factorized into the form

$$\sigma=\frac{4}{\pi^4}\frac{B^2\alpha^3}{\omega M_1 M_L^{12}}\int dM_f^2\frac{d^3p_2}{2E_2}\frac{d^3p_-}{2E_-}\frac{d^3p_+}{2E_+}\delta^4(p_2+p_++p_--p_1-k_1)\int\frac{d^3k_-}{2k_-^0}\int\frac{d^3k_+}{2k_+^0}\theta((p_--k_-)^2)\theta((p_+-k_+)^2)|M|^2\,, \tag{7}$$

where we used energy-conserving δ functions at the decay vertices to eliminate the neutrino momenta. If we also assume that the weak coupling of the heavy-lepton current is $V-A$, then we can use a Fierz transformation together with Lenard's formula to eliminate all dependence on neutrino momenta in the matrix element. We can subsequently write the matrix element in two forms. The first assumes that spin effects are unimportant, so we can factorize the matrix element and calculate the production of a pair of heavy leptons (summed over spin states) followed by the decay of two unpolarized leptons. This is the easiest method to use but it is not completely clear that spin effects in *heavy*-lepton production and decay are really negligible, so we also did the calculation by the exact method of taking the traces along the complete fermion lines. Unfortunately the expression for $|M|^2$ becomes extremely large in this case so it is impossible to reproduce it here. We should mention that the traces in Eq. (7) were done by the algebraic computer program SCHOONSCHIP[16] and the integrations were then done by Monte Carlo methods on the CDC 7600 computer at Brookhaven National Laboratory.

We checked our calculations by comparing our values for the integrated cross sections with the results of Tsai at $B=1.0$. Also, by eliminating the decay part of the program, the production of muon pairs in a Coulomb field could also be handled and we could generate all possible distributions of interest to the experimenter. We should mention that mappings were made in several variables to handle the extreme forward peaking of these reactions. On comparing our numbers with those of Tsai for the production process, we found excellent agreement in general. The only case of disagreement was in our inelastic production. Although we used the same form factors as Tsai for elastic scattering off of a proton (the standard dipole fit), quasielastic scattering (i.e., including the Pauli principle), coherent nuclear scattering, and deep-inelastic scattering, we note that he was only interested in a rough answer for the last reaction so he may have made some approximation. Our numbers for the inelastic reaction are approximately a factor of two larger than his.

For completeness we will give the expressions for the form factors. We decomposed the hadronic part of the matrix element in the standard way using

$$W_{\mu\nu}=-\left(g_{\mu\nu}-\frac{q_\mu q_\nu}{q^2}W_1\right)+\left(p_{1\mu}-q_\mu\frac{p_1\cdot q}{q^2}\right)\left(p_{1\nu}-q_\nu\frac{p_1\cdot q}{q^2}\right)\frac{W_2}{M_1^{\,2}},$$

where W_1 and W_2 are in general functions of q^2 and $M_f^{\,2}$, with $q=p_1-p_2$. Gauge invariance of the electromagnetic interactions allows one to drop all the terms in q_μ and q_ν in the contraction with the trace over the lepton line. The SCHOONSCHIP program punched the algebraic results from traces which multiply W_1 and W_2 onto cards for insertion in the numerical-integration program.

Finally we have to specify the forms used for W_1 and W_2. For elastic scattering we used the dipole proton and neutron form factors, namely,

$$\begin{aligned}
W_1^p&=2M_1^{\,2}\delta(M_f^{\,2}-M_1^{\,2})\frac{(2.79)^2\tau}{(1-t_2/0.71)^4}\,,\\
W_2^p&=2M_1^{\,2}\delta(M_f^{\,2}-M_1^{\,2})\frac{1+(2.79)^2\tau}{(1-t_2/0.71)^4}\,\frac{1}{1+\tau}\,,\\
W_1^n&=2M_1^{\,2}\delta(M_f^{\,2}-M_1^{\,2})\frac{(1.91)^2\tau}{(1-t_2/0.71)^4}\,,\\
W_2^n&=2M_1^{\,2}\delta(M_f^{\,2}-M_1^{\,2})\frac{(1.91)^2\tau}{(1-t_2/0.71)^4}\,\frac{1}{1+\tau}\,,
\end{aligned}\tag{8}$$

with $\tau=-(t_2/4M_1^{\,2})>0$ and $t_2=q^2$. For inelastic scattering we used identical form factors for proton and neutron targets. W_1 and W_2 were taken from the paper by suri and Yennie,[17] namely,

$$\begin{aligned}
W_1^p&=\frac{1}{C}\left[\frac{m_\rho^{\,4}(M_f^{\,2}-M_1^{\,2})97.5}{(m_\rho^{\,2}-t_2)^2}+\frac{250.6M_1^{\,2}(1-x')^4}{1-1.26x'+0.96x'^2}\right],\\
W_2^p&=\frac{1}{1-\nu^2/t_2}\left[W_1^p-\frac{56.3}{C}\,\frac{t_2m_\rho^{\,2}(M_f^{\,2}-M_1^{\,2})^3}{(m_\rho^{\,2}-t_2)^2(M_f^{\,2}-M_1^{\,2}-t_2)^2}\right],
\end{aligned}\tag{9}$$

where

$$x'=t_2/(t_2-M_f^{\,2})\,,$$

$$C=8(19.73)^2\alpha\pi^2M_1\,,$$

$$\nu=(M_f^{\,2}-M_1^{\,2}-t_2)/2M_1\,,$$

$$M_\rho^{\,2}=0.585\,.$$

For the elastic scattering from a Be nucleus we used the experimental results[18]

$$W_1=2M_1^{\,2}\tau G_m^{\,2}\delta(M_f^{\,2}-M_1^{\,2})\,,$$

$$W_2=2M_1^{\,2}\,\frac{G_e^{\,2}+\tau G_m^{\,2}}{1+\tau}\,\delta(M_f^{\,2}-M_1^{\,2})\,,$$

with

$$\begin{aligned}
G_{e,\,\mathrm{Be}}^{\,2}&=16\left(1+\frac{16}{3}t_2\right)e^{32t_2}\,,\\
G_{m,\,\mathrm{Be}}^{\,2}&=1.18^2\times45\times(1+25.6t_2+314t_2^{\,2})e^{32t_2}\,,
\end{aligned}\tag{10}$$

and $\tau=-t_2/4M_1^{\,2}$. The form factors we used for the quasielastic scattering from a Be nucleus were[12]

$$W_1^{\mathrm{QE}}=C(t_2)(4W_1^{p\,\mathrm{el}}+5W_1^{n\,\mathrm{el}})\,,$$

$$W_2^{\mathrm{QE}}=C(t_2)(4W_2^{p\,\mathrm{el}}+5W_2^{n\,\mathrm{el}})\,.$$

$C(t_2)$ is the Pauli suppression factor and is given

TABLE I. Total cross section (in cm^2) for the photoproduction of heavy-lepton pairs. Error estimates are also given. The beam energy is in GeV units. The row marked 100* refers to the photoproduction of regular $\mu^+\mu^-$ pairs by 100-GeV photons and is included for comparison.

E_γ	p elastic	p inelastic	Be coherent	Be quasielastic
50	$(1.97 \pm 0.05) \times 10^{-35}$	$(9.68 \pm 0.10) \times 10^{-36}$	$(6.70 \pm 0.37) \times 10^{-36}$	$(9.60 \pm 0.21) \times 10^{-35}$
100	$(5.53 \pm 0.18) \times 10^{-35}$	$(3.14 \pm 0.05) \times 10^{-35}$	$(9.73 \pm 0.55) \times 10^{-35}$	$(2.08 \pm 0.05) \times 10^{-34}$
100*	$(1.94 \pm 0.05) \times 10^{-31}$	$(1.57 \pm 0.11) \times 10^{-32}$	$(2.63 \pm 0.07) \times 10^{-30}$	$(1.22 \pm 0.04) \times 10^{-31}$
200	$(1.09 \pm 0.03) \times 10^{-34}$	$(6.95 \pm 0.13) \times 10^{-35}$	$(4.22 \pm 0.27) \times 10^{-34}$	$(3.39 \pm 0.08) \times 10^{-34}$
500	$(2.04 \pm 0.05) \times 10^{-34}$	$(1.39 \pm 0.06) \times 10^{-34}$	$(1.33 \pm 0.06) \times 10^{-33}$	$(4.97 \pm 0.13) \times 10^{-34}$

by

$$C(t_2) = 1 \quad \text{if} \quad Q > 2P_F = 0.5 \text{ GeV}$$

and

$$C(t_2) = \frac{3}{4}\frac{Q}{P_F}\left[1 - \frac{1}{12}\left(\frac{Q}{P_F}\right)^2\right] \quad \text{if } Q < 2P_F\,,$$

with $Q^2 = t_2^2/(2M_1)^2 - t_2$.

The integration over M_f^2 was done last and started from $(M_1 + m_\pi)^2$ in the inelastic case. The second-last integral was the t_2 integral and its boundaries were

$$t_2^{\max} = M_1^2 + M_f^2 - [(s + M_1^2)(s + M_f^2 - 4M_L^2) + (s - M_1^2)\lambda^{1/2}(s, M_f^2, 4M_L^2)]/2s\,,$$

$$t_2^{\min} = 4M_L^2[M_f^2 - M_1^2 + M_1^2(4M_L^2 - M_f^2 + M_1^2)/s]/t_2^{\max}\,.$$

Our results are given in Tables I–III and Figs. 2–7. In Table I we give the values of the total cross sections for heavy-lepton pair production for various energies. In all cases the heavy-lepton mass is taken to be 1.8 GeV/c^2. The individual cross sections should be summed according to the formula

$$\sigma(\text{tot}) = \sigma(\text{Be coherent}) + \sigma(\text{Be quasielastic}) + 9\sigma(p \text{ inelastic})$$

because we assume no difference between inelastic production from protons and neutrons. Remember that the results for heavy-lepton production do *not* contain the decay branching ratio into leptons, so there is still a factor of $B^2 \simeq 0.02$ in the cross section for dilepton production.

Now let us turn to discuss the distributions for the leptons produced when the heavy lepton decays. Note that we assume these leptons to be massless, so there is no difference between muons

TABLE II. Average values of the square of the transverse momentum of the final decay leptons [p_T^2 in (GeV/c)^2], their invariant masses (M_{+-} in GeV/c^2), their energies (E_+ in GeV), and the energy transfer to the final hadrons (Δ in GeV).

	E_γ	p elastic	p inelastic	Be coherent	Be quasielastic
$\langle p_T^2 \rangle$	50	0.57	0.55	0.38	0.59
	100	0.63	0.73	0.49	0.73
	100*	0.035	0.190	0.026	0.095
	200	0.81	0.90	0.62	0.93
	500	0.95	1.18	0.73	1.15
$\langle M_{+-} \rangle$	50	1.19	1.17	0.95	1.23
	100	1.30	1.37	1.11	1.41
	100*	0.50	0.80	0.47	0.73
	200	1.53	1.54	1.30	1.63
	500	1.72	1.75	1.43	1.95
$\langle E_+ \rangle$	50	9.0	8.3	8.5	8.9
	100	16.8	16.5	18	17.4
	100*	49	50	50	50
	200	35	33	38	35
	500	88	86	91	89
$\langle \Delta \rangle$	50	0.168	2.7	0.0031	0.192
	100	0.105	4.4	0.0018	0.144
	100*	0.006	3.25	0.0001	0.033
	200	0.074	8.2	0.0010	0.118
	500	0.051	14.0	0.0006	0.099

TABLE III. Values of cross sections, $\langle p_T^2\rangle$, $\langle M_{+-}\rangle$, $\langle E_+\rangle$, and $\langle\Delta\rangle$ for the case of a photon spectrum $N(\omega)=e^{-\omega/49\,\text{GeV}}$. The last row gives the average photon energy in GeV for the different reactions.

	p elastic	p inelastic	Be coherent	Be quasielastic
σ (cm^2)	$(2.77\pm0.11)\times10^{-35}$	$(3.69\pm0.14)\times10^{-36}$	$(4.46\pm0.46)\times10^{-35}$	$(1.10\pm0.05)\times10^{-34}$
$\langle p_T^2\rangle$ [(GeV/c)^2]	0.67	0.72	0.47	0.73
$\langle M_{+-}\rangle$ (GeV/c^2)	1.33	1.38	1.13	1.38
$\langle E_+\rangle$ (GeV)	19.2	18.8	24.5	17.3
$\langle\Delta\rangle$ (GeV)	0.128	0.890	0.0015	0.160
$\langle E_\gamma\rangle$ (GeV)	107	105	149	98

and electrons. The next two tables summarize our results for these distributions by giving the average values of p_T^2, the square of the transverse momentum of the leptons, M_{+-}, the invariant mass of the lepton pair, E_+, the energy of one member, and Δ, the difference in energy between the final hadrons and the target. Table II gives these averages (in units of GeV or GeV^2) for several photon-beam energies. Finally, Table III gives the total cross section and averages when we take a photon spectrum into account. We have assumed an approximate Fermilab spectrum of the form

$$N(\omega)\propto e^{-\omega/49\text{ GeV}}.$$

The last row in Table III gives the average photon energy, i.e., weighted by the cross section and the spectrum.

Figures 2–7 illustrate our results for the various distributions of the decay leptons. We also include the same distributions for muons produced via the regular Bethe-Heitler process. In view of the fact that the latter cross section is much larger than the former, we found it convenient to plot the distributions divided by their respective cross sections in order to get the curves on the same scale. For example, in Fig. 2 we give the angular distributions for the decay leptons produced when heavy leptons decay. The curves I and II refer to the case when the heavy leptons are photoproduced on a proton target using elastic form factors, or in the Coulomb field of a Be nucleus. The curves III and IV refer to the distributions from regular Bethe-Heitler-produced muon pairs in the same two cases. The curves

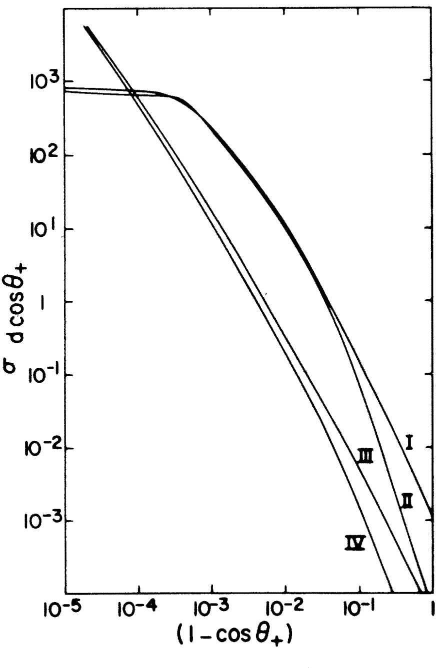

FIG. 2. The angular distribution of the decay lepton for the cases (I) elastic heavy-lepton pair production off of a proton target, (II) heavy-lepton pair production in the Coulomb field of Be nucleus. The direct-muon angular distribution in the Bethe-Heitler process for (III) elastic production off of a proton target, (IV) production in the Coulomb field of a Be nucleus. In all cases the photon energy is 100 GeV.

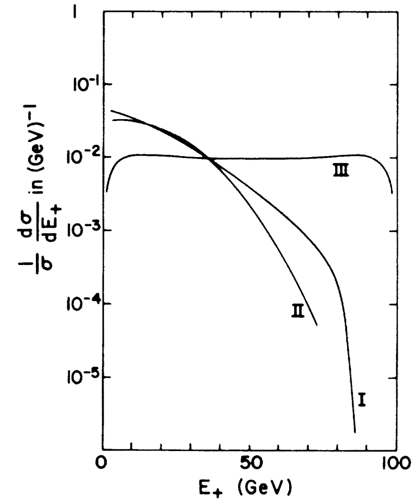

FIG. 3. The energy distribution of the decay lepton for the cases (I) elastic heavy-lepton pair production off of a proton target, (II) heavy-lepton pair production in the Coulomb field of a Be nucleus. The direct-muon energy distribution in the Bethe-Heitler process for (III) production in the Coulomb field of a Be nucleus. In all cases the photon energy is 100 GeV.

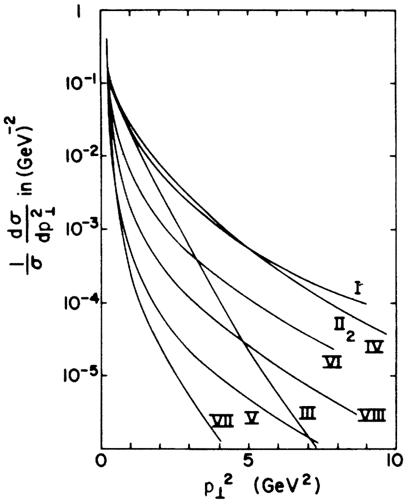

FIG. 4. The distribution in the square of the transverse momentum of decay leptons and direct Bethe-Heitler muons for the cases (I) decay leptons produced elastically off of a proton target, (II) decay leptons produced in inelastic collisions, (III) decay leptons produced in the Coulomb field of a Be nucleus, (IV) decay leptons produced in a quasielastic collisions with a Be nucleus, and (V–VIII) direct leptons produced via the reactions I–IV. Note that curves II and IV are the same within error. The beam energy in all cases is 100 GeV.

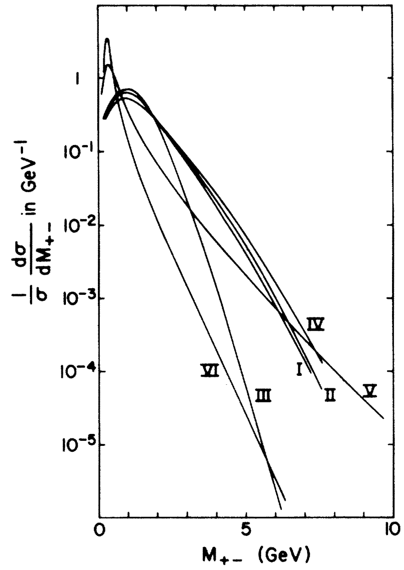

FIG. 6. The invariant mass of the pair of charged leptons produced when the heavy leptons decay. The curves marked I–IV are for the same reactions as in Fig. 4. The curves marked V and VI are the invariant mass distributions for direct muons produced in inelastic collisions with protons and produced in the Coulomb field of a Be nucleus, respectively. In all cases the photon energy is 100 GeV.

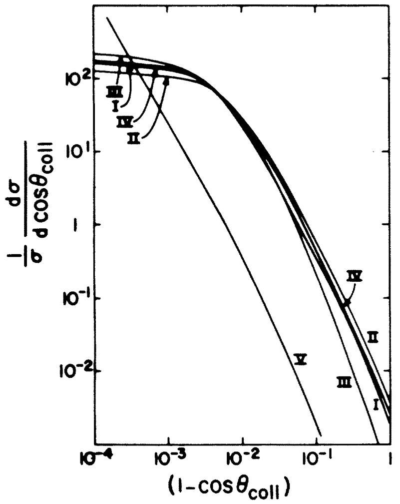

FIG. 5. The opening-angle distribution of the charged decay leptons. The curves marked I–IV are for the same reactions as in Fig. 4. The opening-angle distribution of regular Bethe-Heitler pairs is given in V for coherent production from a Be nucleus. In all cases the photon energy is 100 GeV.

due to production via inelastic collisions or quasielastic collisions on Be are similar to the elastic case. It is obvious that the regular $\mu\mu$ production is larger than the production of the decay leptons at all angles. The same situation holds for the distributions given in all the other graphs. Figure 3 shows the energy distributions and Fig. 4 shows the distributions in the square of the transverse momentum. Finally, Figs. 5–7 show the distri-

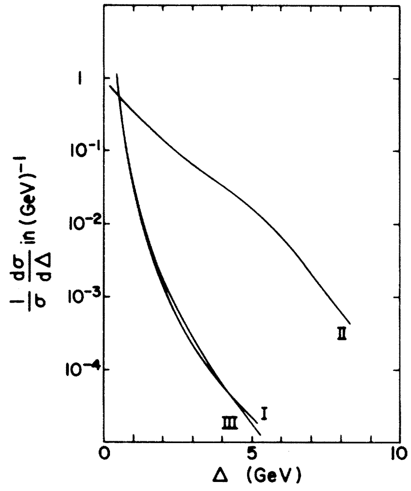

FIG. 7. The distribution in the energy transfer to the hadrons $\Delta = E_{\text{hadrons}} - E_{\text{target}}$. The curves are for decay leptons produced in (I) elastic collisions on a proton target, (II) inelastic collisions on a proton target, (III) quasielastic production on a Be nucleus.

butions in the opening angle of the pairs of leptons, in their invariant masses and in $\Delta = E_{\text{hadrons}} - E_{\text{target}}$, i.e., the difference between the final hardon energy and the initial target mass. It is difficult to give error estimates on these curves. The error estimate on the total cross section probably gives some idea of the error magnitude on the distributions. The multidimensional-integration routines do show some slight scatter in the distributions.

The difference between our two methods of doing the calculation for the decay pairs is not visible at these energies. This leads us to conclude that spin effects are really quite small at energies of 100 GeV, but are probably significant at much lower energies. The fact that we did the calculation by two different methods allowed us a check on this. However, the main problem of seeing these effects is not so much the algebraic difference but rather the usual problem of getting enough accuracy on the multidimensional-integration routines.

We conclude by making the following observations. The production of regular Bethe-Heitler pairs is too large to see any effects due to the decays of 1.8 GeV/c^2 heavy leptons into muon pairs. This is true for all distributions. However, the detection of μe pairs seems possible, depending on beam intensity, heavy-lepton branching ratios, etc. The possible contamination due to other Bethe-Heitler reactions is small. Hence detection of relatively quiet μe events in photoproduction experiments could indicate that heavy leptons are being pair produced. Hadronic reactions can lead to μe events but these would be noisy, with much larger energy transfer to the hadrons.

Note added. Our disagreement with Y.-S. Tsai on the size of the cross section for incoherent production of Bethe-Heitler pairs is due to an error in his computer program. Tsai now agrees that our numbers are the correct ones.

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