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Associated Universities, Inc.
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ACCELERATOR DEPARTMENT
Informal Report

WEAK INTERACTIONS WITHOUT FORM FACTORS
COLLIDING ELECTRON AND PROTON BEAMS

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INTERSECTING STORAGE ACCELERATOR NOTES

WEAK INTERACTIONS WITHOUT FORM FACTORS AT
COLLIDING ELECTRON AND PROTON BEAMS

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Berman and Schwartz,¹ among others, have pointed out that it is conceivable to study weak interactions using colliding beams of electrons (15 GeV) and protons (70 GeV) if you measure the reaction

$$e^- + p \rightarrow \nu_e + X$$

where X is the totality of all hadronic states. The crux of their argument is that the deeply inelastic scattering results² show that inclusive hadronic final state production ($p + X$) appears to have no form factor. Hence, the cross section for the above process will go like

$$\sigma \sim G^2 s$$

and be divergent like purely leptonic weak interactions instead of being cut off by a hadron form factor

$$\sigma \sim G^2 \Lambda^2$$

where

$$F_h(q^2) = \frac{1}{1 + q^2/\Lambda^2}$$

Since the argument hinges on the absence of a hadronic form factor, it was clear to some of us simple minded experimentalists that the reaction

$$p + p \rightarrow X + e^- + \overline{\nu}_e$$

will also have a divergent cross section if we just blast both hadrons into the continuum. This was elegantly elaborated by Berman³ in his recent work.

The main problem with all these arguments is that you have to believe in partons, gluons, seas of anti-partons, light cones and the like to really understand the hadron form factors. As pointed out by Berman, this situation will become much clearer when measurements of the reaction

$$p + p \rightarrow X + e^+ + e^-$$

are made at ISR and NAL.

I wish to point out in this note that there is another [reaction which, in principle, can be studied with colliding electron proton beams and which doesn't have any unknown form factors. In fact, the effect of form factors is negligible. Consider the reaction

$$[e^- + p + \nu_e + \mu^- + \overline{\nu}_\mu + p$$

The momentum transferred to the proton is very small,
on the order of

$$t_{\min} = \left(\frac{m_{\mu}^2}{2E} \right)^2$$

where E is the equivalent lab energy of the reaction

$$E = \frac{s}{2M_p}$$

The weak interaction is purely leptonic, thus having no form factors. In addition, it is the only purely leptonic weak interaction which has been observed in the laboratory. The coupling constants have been measured and even polarization data exist.

The reaction looks very similar to bremsstrahlung except that the electron turns into a muon and the "gamma" is really a pair of neutrinos. The signature is extremely clear and the reaction can be detected even at a machine with poor duty cycle. The forward going muon, which will have energy from that of the incident electron down to

zero, can be detected through a solid iron magnet two meters thick, so that other background will be eliminated. The proton will be essentially unchanged in direction but will lose a few percent of its energy and can be detected in a spectrometer which can in fact be the storage ring itself.

If that doesn't convince you, try to imagine the production of a heavy lepton and its antineutrino by this same reaction. The maximum mass heavy lepton which can be produced is

$$m_{\ell \max} \approx \sqrt{s}$$

let

$$x \equiv \frac{m_{\ell}}{m_{\ell \max}} = \frac{m_{\ell}}{\sqrt{s}}$$

Then if γ_p is the γ of the proton in the colliding beam system (i.e. $\gamma_p = 70$ for PEP), the heavy lepton will come out backward in the colliding beam system if its mass is large enough:

$$m_{\ell} \geq \frac{s}{2M_p \gamma_p}$$

The 4 momentum transfer to the proton will be approximately

$$t_{\min} \approx M_p^2 x^4 \quad \text{if} \quad x \ll 1$$

If we take $t_{\min} = 0.2 \text{ GeV}^2$ as the maximum allowable so as not to have too large an effect from the proton form factor, then $x = \frac{1}{1.5}$

or

$$m_{\ell} \leq \frac{(\sqrt{4200} - 1)}{1.5} = 42.5 \text{ GeV}$$

for form-factor-less production at PEP; and

$$m_{\ell} \leq \frac{\sqrt{12001} - 1}{1.5} = 73.5 \text{ GeV}$$

at a facility like Isabelle where 15 GeV electrons could collide with 200 GeV protons. (See Table I)

I think that this reaction would be easy to detect but I don't wish to discuss it further here since detection involves detailed knowledge of the decay modes of heavy leptons, and the production cross sections. Unfortunately, there have been several calculations relating to the original reaction in question, where the heavy lepton produced is our old friend, the muon. Fujikawa⁴ gave an asymptotic form

$$\sigma = \frac{4Z^2 G^2 \alpha^2}{9\pi^3} \Lambda E \left(\frac{5\pi}{32} \right) \frac{1}{6} [\ln \eta - 3.37]$$

where Λ is the cutoff mass of the target form factor and E is the lab energy. Fujikawa gives $\eta = \frac{2E}{\Lambda}$ which must be wrong since η would increase for heavy nuclei. A more reasonable form from Czyz, Sheppy and Walecka is

$$\eta = \frac{2E\Lambda}{m_\mu^2}$$

Plugging in the numbers

$$\sigma = 5 \times 10^{-41} \text{ cm}^2 \quad \text{at PEP}$$

and

$$\sigma = 1.5 \times 10^{-40} \text{ cm}^2 \quad \text{for Isabelle.}$$

Since the log term varies slowly for any machine in this energy range, a good approximation for heavy lepton production is:

$$\sigma \approx \left(\frac{\alpha}{\pi}\right)^2 \times \sigma_{\text{total weak}}$$

I like doing hard experiments, but the factor $\left(\frac{\alpha}{\pi}\right)^2$ really hurts. Nevertheless, I am writing this note hoping to stimulate the theorists to find ways to increase the cross section. Until that time, these processes, although they have no form factor, also have no appreciable cross section.⁵

While on the subject of heavy leptons, it might be worthwhile to note that there are other types of heavy leptons which could be copiously produced at PEP or Isabelle, if they exist. An electron-like heavy lepton e^* which could decay

$$e^* \rightarrow e + \gamma$$

would be produced by coulomb excitation in the field of the proton. This type of particle was discussed by Low⁶ some years ago. The kinematics are identical to those given above. It would be nice to run this experiment at the highest proton energy for a given s , so that the leptons come out backward in the colliding beam system. The signal is an $e + \gamma$ coming out backward with a large invariant mass. Ordinary bremsstrahlung would not be a background because the brem-photon would always go forward since it is massless ($\beta = 1$). The recoil brem-electron could come out backward, but its energy would be limited to: $(\gamma\beta)_p m_e$ which is only 100 MeV/c even for Isabelle (200 GeV protons). Thus the heavy lepton signal would be quite striking:

(all 3 particles
backward)

(nothing in
forward direction)

The experimental arrangement doesn't involve rooms full of calorimeters.

In conclusion, the "Neutrino Bremsstrahlung" reaction

$$e^- p + \mu^- \nu_e \bar{\nu}_\mu p$$

is a very clean process with which to study weak interactions at electron proton storage rings. However, it appears that the cross section is a factor of about 10^6 too small to be observed at either PEP or Isabelle. On the other hand, an excited electron

$$e^* + e + \gamma$$

could be very easily produced and observed if it exists and its mass is less than or on the order of 75 GeV, What with all the buzzing going on in the corridors now about heavy leptons, it might even become fashionable to look for them.

REFERENCES

1. S. Berman and M. Schwartz, Brookhaven HEDG Meeting, January 1972.
2. Any SLAC Publication during the last 3 years.
3. S. Berman, Brookhaven Seminar, February 29, 1972.
4. K. Fujikawa, Efins Report EFI 70-57; Czyz, Sheppy and Walecka, Nuovo Cimento 34, 404 (1964), J. Smith, private comm.
5. I leave out the obvious suggestion of a factor of 10^3 increase in s or luminosity.
6. F. Low, Phys. Rev. Letters 14, 238 (1965).

TABLE I
SUMMARY OF COLLIDING BEAM MACHINES

<u>Lepton Hadron Kinematics</u>								
<u>PEP</u>								
<u>E_e</u>	<u>E_p</u>	<u>s</u>	<u>√s</u>	<u>γ_{lab}</u>	<u>γ_{cm}</u>	<u>γ_{βcm}</u>	<u>M_ℓ max</u>	<u>E_{lab}</u>
15	70	4201	63.8	70	1.31	-.848	62.9 GeV	2238
		<u>M_ℓ</u>	<u>t_{min}</u>	<u>P_I max</u>	<u>P_I min</u>	<u>P_{lab} max</u>	<u>γ_{lab} M_ℓ</u>	<u>P_{cm}</u>
		.106	~10 ⁻⁶	14.99	- 0.09 GeV	2238	7	-32.4
		6.49	5×10 ⁻³	14.3	- 5.5	2238	420	-32.1
		12.88	1.4×10 ⁻³	12.2	-10.9	2238	900	-31.1
		19.3	7.0×10 ⁻³	8.8	-16.4	2238	1350	-29.5
		38.5	.17	- 9.6	-32.6	2238	2680	-21.0
<u>Electric ISABELLE</u>								
<u>E_e</u>	<u>E_p</u>	<u>s</u>	<u>√s</u>	<u>γ_{lab}</u>	<u>γ_{cm}</u>	<u>γ_{βcm}</u>	<u>M_ℓ max</u>	<u>E_{lab}</u>
15	200	12001	109.5	200	1.96	-1.69	108.6	6395
		<u>M_ℓ</u>	<u>t_{min}</u>	<u>P_I max</u>	<u>P_I min</u>	<u>P_{lab} max</u>	<u>γ_{lab} M_ℓ</u>	<u>P_{cm}</u>
		.106	~10 ⁻⁵	15.0	- .178	6395	20	-54.7
		11.0	10 ⁻³	13.0	- 18.6	6395	2200	-54.2
		21.8	1.4×10 ⁻³	7.1	- 36.8	6395	4360	-52.6
		32.7	8.0×10 ⁻³	- 2.8	- 55.2	6395	6540	-49.9
		65.3	.17	- 56.0	-110.	6395	13060	-35.3

subscripts: cm Center of Mass System
 I Intersecting Storage Ring System
 lab Lab system (proton at rest)