References

1. B Holstein preprint 1974 to be published in Rev of Mod Phys.

2. B T Chertok, et al, Phys Rev C8, 23 (1973).

3. E Spamer, et al., Proc of Int. Conf. on Nuclear Electron Scattering and Photoreactions, Sendi, Japan, ed. by Shoda and Ui, Tohoku Univ. 1972.

4. C S Wu, Rev of Mod Phys 36, 619 (1974).

5. D H Wilkinson, Phys Letts 31B, 447 (1970).

6. R E McDonald, et al. preprint.

7. I Towner, Nuc Phys A216, 589 (1973). It should be noted that these considerations do not disturb the existing consistency between the $0^+ \rightarrow 0^+$ transitions.

8. D H Wilkinson and D E Alburger, Phys Rev Letts 26, 1127 (1971).

9. B R Holstein and S B Treiman, Phys Rev, C3, 1921 (1971), B R Holstein, Phys Rev C4, 730, 4 764 (1971); 5 1529 (1972).

10. R E Tribble and G T Garvey, Phys Rev Letts 32, 314 (1974), R E Tribble, Princeton Univ Ph D Thesis 1973.

11. M E Nordberg, Jr., F B Moringo and C A Barnes, Phys Rev 125, 321 (1962).

12. a) D Kurath, private communication
 b) for eg J P Davidson, Collective Model of the Nucleus (Academic, New York, 1968) The deformation parameter is chosen as β = .3.
 c) F C Barker, Nuc Phys 83, 418 (1966).

13. H Vantine, F Calaprice, S Freedman and W Mead in Nov 1973 Princeton Univ Cyclotron Laboratory Progress Report.

14. F Calaprice, S Freedman and R Baltrusaitis in June 1974 Princeton Univ. Cyclotron Laboratory Progress Report.

15. K Kubodera, J Delorme and M Rho, Nuc Phys B66, 253 (1973).

16. H Lipkin, Phys Letts, 34B, 202 (1971); Phys Rev Letts 27, 432 (1971).

17. E Henley and L Wolfenstein, Phys Letts 36B, 28 (1971).

WEAK INTERACTIONS IN ATOMS AND NUCLEI

C Jarlskog
Inst. Theor. Phys., Goteborg
and CERN

In this talk, I shall be primarily concerned with possible weak interaction effects in atoms. At the end, I shall give a very brief summary of the present status of parity violation in nuclei.

1. ATOMS

Atoms may be subdivided into three classes:

(a) Leptonic atoms. Two such atoms have been observed, viz e^-e^+ (positronium) and $e^-\mu^+$ (muonium).

(b) Semileptonic atoms. This class consists of ordinary (electronic) and muonic atoms.

(c) Nonleptonic or hadronic atoms also referred to as exotic atoms. Examples are pionic and kaonic atoms.

If you are used to thinking in terms of Feynman diagrams the appropriate one describing, eg a semi-leptonic atoms is given in Fig.(1a)

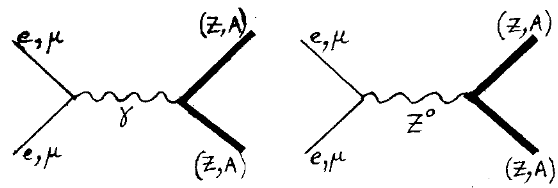

Fig. 1a Fig. 1b

where (Z,A) denotes a nucleus with charge Z and mass number A. Ordinarily the recoil of the nucleus is neglected whereby the nucleus is a source of external field. The $\frac{1}{q^2}$, q = momentum transfer, in the photon propagator gives the $\frac{1}{r}$ potential in the coordinate space. The wave functions and energies are obtained by solving the Dirac equation in the external field ($A_\mu = (\frac{-Z\alpha}{r}, \vec{0})$, α = fine structure constant).

2. NEUTRAL CURRENTS IN ATOMS*

In the presence of neutral currents, we must add to the diagram 1a also those describing the weak interaction of the lepton with the nucleons, eg if such interaction is mediated by a neutral vector boson Z^o the appropriate diagram is as shown in Fig. 1b. Since such a boson is presumably heavy and the momentum transfer is very small $\frac{1}{q^2-M_{Z^o}^2} \simeq \frac{-1}{M_{Z^o}^2}$ giving a $\delta(\vec{x})$ potential in the coordinate space. Putting in the appropriate couplings, we would expect the diagram (1b) to be of the order $G\delta(\vec{x})$, $G \approx 10^{-5}/M_p^2$, as compared to $\frac{1}{r}$ potential of Fig. 1a. Note that in the conventional current-current theory with charged currents the weak interaction corrections to leptonic and semileptonic atoms occur in the order G^2.

Let us assume that neutral currents are vector and axial vector and parameterize the interaction Lagrangian in the form

$$L = \frac{G}{\sqrt{2}} \{\bar{\psi}_e\gamma_\lambda(a_e - b_e \gamma_5) \psi_e\bar{\psi}_p\gamma^\lambda(a_p - b_p\gamma_5)\psi_p + \bar{\psi}_e\gamma_\lambda(a_e - b_e\gamma_5)\psi_e\bar{\psi}_n\gamma^\lambda(a_n - b_n\gamma_5)\psi_n + \ldots\} \quad (1)$$

where a_e, b_e are constants relevant to electronic neutral current, etc. Note that the point-like four fermion form (1) arises if the interaction is mediated by one or more heavy vector bosons. From (1), we may extract an interaction Hamiltonian which consists of parity conserving and parity violating parts $H_1^{p.c.}$ and $H_1^{p.v.}$, viz

$$H_1^{p.c.} = \frac{-G}{\sqrt{2}} \{a_e a_p + b_e b_p \bar{\sigma}_e.\bar{\sigma}_p + \ldots\} \delta(\vec{x}), \quad (2)$$

$$H_1^{p.v.} = \frac{G}{\sqrt{2}} \{b_e a_p \frac{\bar{\sigma}.\bar{p}_e}{m_e} + \ldots \} \delta(\bar{x}), \quad (3)$$

Here $\bar{p}_e$ and m_e are the momentum and the mass of the electron. The dots stand for similar terms for interaction with neutrons, muonic terms, smaller correction terms, etc.

3. EFFECTS OF $H_1^{p.c.}$ (1)

The parity conserving interaction Hamiltonian $H_1^{p.c.}$ gives shifts in the energy levels (primarily s levels) and corrections to hyperfine splitting. From (2) the level shift is given by

$$\delta E_{nl} = \frac{-G}{\sqrt{2}} a_e [Za_p + (A-Z)a_n] |\psi_{nl}(0)|^2, \quad (4)$$

$$|\psi_{nl}(0)|^2 = \frac{Z^3\alpha^3 m^3}{\pi n^3} \delta_{lo}; \; n,l = \text{principal and orbital quantum numbers}$$

where m is the reduced mass (approximately the lepton mass) and we have assumed μ-e universality. Note the appearance of Gm^3 in (4), which is intuitively expected by dimensional arguments. For electronic atoms δE_{nl} is negligible while for muonic atoms $|\delta E| \simeq |a_e[Za_p + (A-Z)a_n]| \frac{Z^3}{n^3} 10^{-6}$ eV thus for a heavy nucleus the energy shift could be of the order of a few eV.

The hyperfine splitting in hydrogen has been measured to a very high degree of accuracy, viz the hyperfine frequency in MHZ is given by[2]

$$(\Delta\nu)_{hfs} = 1420.4057517864(17). \quad (5)$$

From (2), the weak interaction correction is

$$|\Delta\nu| = |4b_e b_p| \; 3 \times 10^{-5} \text{ MHZ} \quad (6)$$

putting $|4b_e b_p| = 1$, as in Weinberg model, we find that the correction is about 10^4 times larger than the experimental accuracy. Unfortunately however, because of our lack of understanding of form factor (size) effects and polarisability (two photon exchange) corrections only the first six digits in (5) are theoretically well understood. Therefore, we conclude $|b_e b_p| < 60$.

4. EFFECTS OF PARITY VIOLATING WEAK INTERACTIONS $H_1^{p.v.}$ (3-7)

Effects of $H_1^{p.v.}$ are expected to be more spectacular than those of $H_1^{p.c.}$ since $H_1^{p.v.}$ can mix states with

* We restrict the discussion to leptonic and semileptonic atoms.

different parity, viz

$$\psi_n = \psi_n^{(0)} + \sum_k \psi_k^{(0)} \eta_{kn} + \dots \qquad (7)$$

where $\psi_n^{(0)}$ is the unperturbed state, η_{kn} is the mixing parameter, $\eta_{kn} = \frac{\langle\psi_k^{(0)}|H_1|\psi_n^{(0)}\rangle}{E^{(0)}-E_k^{(0)}}$, and the dots stand for corrections due to continuum and higher order corrections. The mixing of opposite parity states has two important consequences:

(a) Transitions forbidden by parity become allowed due to mixing. Here the probability of the transition is quadratic in mixing parameter (ie, order G^2). Similar effects in nuclei have already been studied to some extent (see below).

(b) If the states n and k can go to the same final state one may have interference effects to the first order in mixing parameter (first order in G).

In order to get observable effects η_{kn} should not be too small, ie $\langle\psi_k^{(0)}|H_1|\psi_n^{(0)}\rangle$ should be as large as possible while $E_n^{(0)} - E_k^{(0)}$ is as small as possible. By dimensional reasoning $\langle\psi_k^{(0)}|H_1|\psi_n^{(0)}\rangle \sim Gm^3$, where m is the lepton mass. Therefore if the lepton mass were the only scale available one would expect interference effects to be $\left(\frac{m_\mu}{m_e}\right)^2 \sim 4 \times 10^4$ times larger in muonic atoms than in ordinary and leptonic atoms. This argument is invalidated by vacuum polarisation correction (which in muonic atoms depends critically on electron mass) and by finite size effects. Nevertheless, the argument remains partially valid in low Z ions (see below).

Traditionally, the states involved in mixing are chosen to be the $2s_{\frac{1}{2}}$ and $2p_{\frac{1}{2}}$ levels separated only by the Lamb shift energy which is very small. In hydrogen like atoms

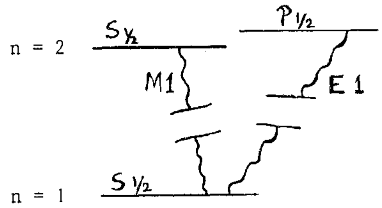

Fig. 2

$$\psi(2s_{\frac{1}{2}}) \approx \psi^{(0)}(2s_{\frac{1}{2}}) + \eta\, \psi^{(0)}(2p_{\frac{1}{2}}),\ \eta = \eta_{2p_{\frac{1}{2}},2s_{\frac{1}{2}}} \text{(see Eq.7)}$$

The states $\psi^{(0)}(2s_{\frac{1}{2}})$ and $\psi^{(0)}(2p_{\frac{1}{2}})$ can both decay to the ground state by one photon emission via M1 and E1 transitions respectively (see Fig. 2). Thus the decay amplitude is given by

$$A(2s_{\frac{1}{2}} \to 1s_{\frac{1}{2}} + \gamma) = M1 + \eta E1.$$

The amplitudes interfere if $\mathrm{Im}\eta \neq 0$*. The consequences of such interference are as follows.

(a) The emitted photon has a circular polarisation P_c^γ

$$|P_c^\gamma| = 2\left|\frac{E1}{M1}\ \mathrm{Im}\ \eta\right|$$

(b) If the initial lepton is polarised, there will be a correlation $\vec{P}.\hat{k}$, where $\vec{P}$ is the polarisation vector of the lepton and $\hat{k}$ is a unit vector along the photon direction.

(c) In muonic atoms, the muon after the transition may decay whereby one could in principle detect parity violation in electron-photon angular correlation.

5. MAGNITUDE OF PARITY VIOLATION IN ATOMS

Parity violation effects are largest in low Z muonic atoms because of two reasons namely the lepton mass is large $Gm_\mu^2 \gg Gm_e^2$ and also the vacuum polarisation and finite size corrections which largely determine the Lamb shift separation tend to cancel for $Z \sim 3$-4. The circular polarisation of the photon in the transition $2s_{\frac{1}{2}} \to 1s_{\frac{1}{2}} + \gamma$ in the Weinberg model for

* η is purely imaginary if time reversal invariance holds.

the extreme as well as 'realistic' values of the Weinberg angle is given by[5].

	$^7Li^{(++)}$	$^9Be^{(3+)}$
$\sin^2\theta_W = 0$	1.4%	-1.3%
$\sin^2\theta_W = .4$	8.1%	-9.6%
$\sin^2\theta_W = 1$	18.2%	-22.1%

It might turn out that the experimental study of low Z atoms is extremely difficult, for higher Z the circular polarisation drops, eg[6]

$$|P_c^\gamma| \approx 10^{-4}, \quad Z \approx 30$$

Note that for electronic atoms the corresponding effects are smaller by three orders of magnitude for $Z \approx 3$-4 and by two orders of magnitude for $Z \approx 30$.

6. PRESENT EXPERIMENTAL SITUATION

Recently it has been pointed out[4] that detection of parity violation in ordinary atoms should be detectable by using a dye laser with adjustable frequency. In this case one could excite an M1 transition; the case chosen is $\gamma + 6s_{\frac{1}{2}} \rightarrow 7s_{\frac{1}{2}}$ in atomic caesium. The signature of the excitation is the observation of photons from $7s \rightarrow 6p + \gamma$. If $6s_{\frac{1}{2}}$ is mixed the number of detected photons is different for right and left polarised laser beams. The experiment is in progress.

7. OUTLOOK

At present the field of study of parity violation in atoms is at its infancy. There are many questions which need to be investigated experimentally. The first step could be to look for M1 transition and study the backgrounds such as the 2γ decay. One would also like to know the population and residual polarisation of the $2s_{\frac{1}{2}}$ levels in muonic atoms. Perhaps transitions other than $2s_{\frac{1}{2}} - 2p_{\frac{1}{2}}$ may be studied[8] more readily. The nice feature of atomic experiments is that, analogous to conventional semileptonic weak interactions, their theoretical interpretation should be simple.

8. PARITY VIOLATION IN NUCLEI[9]

Parity violation in nuclear physics is by now well established although the theoretical interpretation of the results is generally very difficult due to nuclear physics complications. The effects may occur both via charged currents and neutral currents. The charged current terms are presumably given by strangeness conserving part of nonleptonic Cabibbo Lagrangian

$$\frac{G}{\sqrt{2}}\left\{\underbrace{\cos^2\theta_c (V-A)_\lambda^{1+i2}(V-A)^{\lambda\,1-i2}}_{I=0,\,2} + \underbrace{\sin^2\theta_c (V-A)_\lambda^{4+i5}(V-A)^{\lambda\,4-i5}}_{I=0,\,1}\right\}$$

where θ_c = Cabibbo angle and 1 + i2, etc denote the SU(3) structure of the currents. The nature of the neutral current nonleptonic Lagrangian is not known.

Experiments on parity violation in nuclear physics fall into following categories: (a) measurement of circular polarisation of emitted photons or angular correlation between nuclear spin and photon momentum. (b) Observation of irregular parity decays and finally (c) a number of elementary particle type experiments such as $n + p \rightarrow d + \gamma$, $n + d \rightarrow t + \gamma$, etc.

Circular polarisation of γ has been established in several transitions in different nuclei. The largest effect occurs in ^{180}Hf where $P_\gamma \approx -10^{-3}$. There is also some evidence for parity forbidden α decay of a 2^- level in ^{16}O to 0^+ ground state of ^{12}C. Circular polarisation has also been observed in photons from $n + p \rightarrow d + \gamma$. In conclusion parity violation in nuclear forces is established in a large number of experiments. However, in many cases there is serious discrepancy between theory and experiments. The experts agree that more theoretical and experimental work is needed to clarify the situation.

References

1. Effects of possible $H_I^{P.C.}$ in atomic physics have been repeatedly mentioned or discussed in the past. See e.g.,
S D Drell, J D Sullivan., Phys. Lett. 19, 516(1965).
M A B Beg, G Feinberg, preprint COO-2232B-52 (1974).

2. See e.g. the compilation by B E Lautrup, A Peterman, E de Rafael., Phys. Rep. 3C, 193 (1972).

3. Effects of different kinds of $H_I^{P.V.}$ have also been discussed in the past by many authors. See e.g., F Curtis-Michel., Phys. Rev. 138B, 408 (1965).

4. M A Bouchiat, C C Bouchiat., Phys. Lett. 48B, 111 (1974).

5. J Bernabeu, T E O Ericson, C Jarlskog, paper 363, submitted to this conference and Phys. Lett. 50B, 467 (1974).

6. G Feinberg, M Y Chen, preprint COO-2232B-43(1974).

7. A N Moskalev, JETP Lett. (1974)

8. L Simons, private communication.

9. Some recent review articles on parity violation in nuclei are:
B H J McKellar, in Proc. 3rd Int. Conf. High Energy Physics and Nuclear Structure, Ed S Devons, Plenum Press 1970;
R J Blin-Stoyle, Fundamental Interactions and the Nucleus, North-Holland Publishing Company, 1973, Chap. 9;
E Fischbach, D Tadic, Phys. Rep. 6C, 123(1973);
M Gari., Phys. Rep. 6C, 317 (1973).

"NEUTRAL CURRENT AND SIGN OF THE WEAK COUPLING CONSTANT" and "ARE NEUTRINOS ALWAYS LEFT HANDED?"

B Kayser

National Science Foundation

Washington, U.S.A.

Both papers deal with the properties of the neutral weak interaction and their possible use.

1. Neutral current and sign of the weak coupling constant, S. M. Bilenky, N. A. Dadajan and E. H. Hristova (Paper 827)

By measuring the interference of the neutral weak interaction with the electromagnetic interaction, one can determine the relative sign of the corresponding coupling constants. If this is combined with a measurement of the relative sign of the charged and neutral weak couplings, the sign of the Fermi coupling constant G_F can be obtained.

Bilenky et al apply these ideas to the deep inelastic process*:

$$\ell^{\pm}+N \rightarrow \ell^{\pm}+X$$

with ℓ=lepton, N=nucleon and X=hadronic system

The hamiltonian for this interaction is assumed to be:

$$\mathcal{H}(x) = \mathcal{H}_{em}(x) + \frac{G}{\sqrt{2}}\{\bar{\ell}\gamma_\alpha(g_V+g_A+\gamma_5)\ell J_\alpha^{NW} \qquad (1)$$

where J_α^{NW} is the hadronic neutral weak current. If the incoming lepton has a longitudinal polarization λ, the cross section will have the form

$$\frac{d\sigma}{dq^2 d\nu} = \left(\frac{d\sigma}{dq^2 d\nu}\right)_{\lambda=0} (\Lambda+\lambda A)$$

A depends upon Gg_V, Gg_A and the specific form assumed for the relation between J_α^{NW} and its electromagnetic counterpart J_α^{em}. Assuming a definite form for that relation, measurements with leptons and antileptons yield the sign of Gg_V and Gg_A relative to the electromagnetic coupling.

A study of the reaction

$$\nu_e + e \rightarrow \nu_e + e \qquad (3)$$

including a measurement of the electron polarization will give the sign of G_F, the fermi coupling constant relative to the electromagnetic coupling. The form assumed for the interaction hamiltonian is:

---

*Interference effects for this process have also been studied by S. Berman and J. Primack, by M. Suzuki and by others