SYMMETRY TESTS IN ATOMIC PHYSICS*

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ABSTRACT

Recent and continuing tests of the discrete space-time symmetries, charge conjugation, spatial reflection, and time reversal, using atomic sytems are reviewed. Particular emphasis is given to investigations searching for the effects of neutral current interactions which are predicted by unified gauge models of weak and electromagnetic interactions. Also the present limits for electric dipole moments of elementary particles are discussed.

INTRODUCTION

There is at the present time a widely-held view that the interactions which we describe as fundamental result from the underlying symmetries of the physical laws. The most recent contribution to the rationale for such a view is the striking experimental support of the unified gauge theory of weak and electromagnetic interactions.[1]

Investigations of atomic systems have made significant contributions to the understanding of symmetry principles. These studies include the analysis which led to the formulation of Laporte's rule, tests of Lorentz invariance and translation invariance in space and time, the accurate measurement of the charge equality of leptons and baryons, tests of charge conjugation invariance, determination of stringent limits on the sizes of intrinsic electric dipole moments of the electron and proton, and searches for the effects of neutral current interactions between electrons and nucleons.

Atomic systems are predominantly electromagnetic in character. Therefore the results of symmetry tests have been taken to have only a limited range of validity. Recent developments have broadened this range of validity. As an example on the technical side, relatively intense stable laser radiation has permitted higher precision measurements down to limits where non-electromagnetic effects are manifest. As an example on the theoretical side, with the advent of the unified gauge models of the electro-weak interaction it appears that a number of atomic physics symmetry experiments will yield more generally applicable results.

The experiments to study parity violating neutral current interactions illustrate the unique characteristics of atomic systems which can be exploited to make accurate tests of symmetry principles. The neutral current interaction is believed to be moderated by the exchange of a vector boson with a predicted mass $M_Z \simeq 90$ GeV. As atomic systems involve extremely small momenta, they should be quite insensitive to the concomitant short-range effects. However, many processes in atomic physics can be significantly perturbed by external electric and magnetic fields. With suitable choices of such perturbations, together with a judicious use of selection rules for electromagnetic transitions, the effects of the short-range interactions can be considerably enhanced. In heavy atoms coherent interactions of optical electrons and nucleons and relativistic effects give further large enhancements. The result is that predicted effects are within modern measurement capability. In the case of heavy atoms, initial measurements from searches for parity-violating neutral current interactions have reached the precision required to test unified gauge models.

The discussion here will be confined to recent investigations in atomic system of the discrete space-time symmetries, C (charge conjugation), P (parity), and T (time reversal). For a review of earlier work on these symmetries as well as other invariance principles,the reader is referred to the articles by Feinberg,[2] Commins,[3] and Sandars.[4]

CHARGE CONJUGATION

Charge conjugation is the operation of changing every particle into its antiparticle. As most atoms comprise electrons and nucleons, it is clear that they are not eigenstates of C. For this reason, this symmetry operation is generally of little consequence in atomic systems. However, of the various neutral systems which are eigenstates of C there is one of particular significance in atomic physics. This is the "exotic" atom positronium (Ps), which is the bound state of a positron and an electron and is unstable against annihilation into photons.

The level structure of the Ps atom is similar to that of hydrogen but with energy level separations a factor of two smaller as a consequence of the smaller reduced mass. As only ground state (n=1) Ps can be produced in suitably large amounts, experiments have been limited to this state. There are two substates of the n=1 level, the singlet $^1S_0$ (para) state and the triplet $^3S_1$ (ortho) state.

The possibly decay modes of these states is restricted by conservation of linear and angular momentum and C-invariance. They can be exhibited by noting that (1) the C quantum number of a state of Ps is

$$C = (-)^{S+\ell} , \tag{1}$$

where S is the total spin angular momentum and ℓ is the relative orbital angular momentum, and (2) the C quantum number of an N photon state is

$$C = (-)^N . \tag{2}$$

Conservation of linear momentum prohibits single photon decay of either state. The $^1S_0$ state can decay into any even number of photons (the primary mode is two-photon decay with a lifetime of 1.25×10^{-10} seconds). Invariance under C forbids decay of the singlet state into an odd number of photons with $N \geq 3$. The $^3S_1$ state can decay into an odd number of photons, $N \geq 3$ (the primary mode of decay for this state is into three photons with a lifetime of 1.38×10^{-7}seconds). Conservation of angular momentum and C-invariance prohibits two-photon decay. Invariance under C alone forbids decay into an even number of photons with $N \geq 4$. From these arguments it can be seen that searches for appropriate forbidden decay modes of the Ps ground state would constitute tests of C-invariance.

There have been two such experiments done, one, carried out by Mills and Berko, searching for decay of the $^1S_0$ state into three photons[5] and the other, carried out by Marko and Rich, searching for decay of the $^3S_1$ state into four photons.[6] In both cases no evidence was found for a C-violation. Defining $\lambda_S^{2\gamma}$ and $\lambda_S^{3\gamma}$ as the respective rates for $^1S_0$ decay into two and three photons, the branching ratio $b_S = \lambda_S^{3\gamma}/\lambda_S^{2\gamma}$ was found to be

$$b_s < 2.8\times10^{-6} \quad . \tag{3}$$

Similarly, defining $\lambda_T^{3\gamma}$and $\lambda_T^{4\gamma}$ as the respective rates for $^3S_1$ decay into three and four photons, the branching ratio $b_T = \lambda_T^{4\gamma}/\lambda_T^{3\gamma}$ was found to be

$$b_T < 8\times10^{-6} \quad . \tag{4}$$

Charge conjugation is a symmetry of the normal electromagnetic interaction. In order to interpret the results (3) and (4) use is made of phenomenological point interactions which are C-violating, P-conserving and either T-conserving or -violating. As an example, for the $^1S_0$ experiment, a phenomenological Lagrangian density

$$\mathcal{L} = g\left(\frac{1}{2m}\right)^8 \bar{\psi}\gamma_5\psi F_{\alpha\beta}F_{\alpha\beta,\gamma\delta}F_{\mu\gamma,\delta} \ , \tag{5}$$

which is T-conserving was employed. Here g is the coupling parameter, ψ the electron field operator and $F_{\mu\gamma}$ the electromagnetic field operator. With m chosen as the electron mass the result (3) yields $g \lesssim 1$. For the $^3S_1$ experiment the simplest C-violating Hamiltonian density is

$$\mathcal{H} = \lambda\left(\frac{1}{m}\right)^8 e^4\partial_\alpha\bar{\psi}\gamma_\beta\psi F_{\alpha\delta}F_{\alpha\beta}F_{\mu\gamma}F_{\mu\gamma} \ , \tag{6}$$

which is P-conserving and T-violating. With m again chosen as the electron mass, the result (4) gives $\lambda < 0.8$. It should be noted that if a C-violation had been detected at the levels of sensitivity obtained in these experiments, the phenomenological descriptions (5) and (6) would lead to anomalous results in high energy e^+-e^- interactions. They are valid only in the low energy regime. The more fundamental structure at high energies should be included and will modify the energy dependence. It is an open question as to whether a suitable theory can be developed which is consistent with the effective couplings to which these C tests are sensitive and also agrees with other low energy experiments.[7]

While experimental results which accurately establish the equality of the masses, magnitudes of charges and gyromagnetic ratios of particles and antiparticles have been quoted as evidence that C is a symmetry of the electromagnetic interaction they are actually a consequence of the stronger invariance under CPT.[8]

PARITY AND TIME REVERSAL

There are two distinct classes of atomic physics experiments designed to test symmetry under spatial inversion. One comprises searches for electron-nucleon interactions which are parity-nonconserving and time reversal invariant, the other searches for interactions which violate both parity and time reversal. Unlike the interpretation of the tests of charge conjugation in positronium, there are rather firm theoretical predictions for the sizes of a number of effects. Further there now exist some data both from high energy and atomic physics experiments which corroborate the existence of an electron-nucleon neutral current interaction which is P-violating and T-conserving, an interaction which was predicted by the unified gauge model of Weinberg and Salam.

P-Violating, T-Conserving Interactions

The discussion of searches for interactions in atomic systems which violate parity but are invariant under time reversal will be given in the context of the weak neutral current interaction. The discovery of unified renormalizable theories of weak and electromagnetic interactions[1] prompted searches for a neutral current interaction which would manifest itself at high energies in neutrino processes or through parity nonconservation in electron-nucleon scattering. The subsequent discovery of such an interaction in the neutrino experiments[9] provided strong motivation to search for weak electron-nucleon interactions in atoms, a motivation which has been enhanced by the observation of the parity nonconserving (PNC) electron-nucleon interactions in the SLAC-Yale experiments.[10]

The simplest unified gauge models predict that there will be weak interactions between electrons and nucleons in atoms via exchange of massive neutral Z^0 bosons as well as the electromagnetic interaction via exchange of photons. The weak interaction can be described as a local interaction characterized by the Fermi constant $G = 2.2\times10^{-14}$ atomic units (a.u.). The small size of G, which would, for example, correspond to shifts in hyperfine structure splittings of only a few Hz, make searches for effects of weak neutral currents in atoms rather difficult.

In order to study such effects it is necessary to have a signature for the weak electron-nucleon interaction which distinguishes it from the dominant Coulomb interaction. The most obvious signature to assume is parity nonconservation. All the designs for existing atomic physics experiments searching for neutral current interactions are based on the assumption that there is a PNC effect at low energies. This, of course, is the same criterion which was used to design the high energy electron scattering experiments.[10]

A PNC weak neutral current interaction will mix atomic states of opposite parity, leading to a violation of Laporte's rule. The interaction is very short range so only the mixing of electronic states with the largest overlap at the nucleus is significant, i.e., that of S and P states. A straightforward estimate, assuming the weak interaction has vector-axial vector (V,A) structure, yields for the mixing matrix element resulting from the electron-nucleon interaction

$$\langle V_w \rangle \sim G\alpha/a_o^3 \approx 10^{-16}\text{a.u.}$$

With a typical level separation of $\Delta E \sim 10^{-1}$a.u. the mixing is

$$\langle V_w \rangle/\Delta E \sim 10^{-15} ,$$

the measurement of which is a formidable challenge.

The current atomic physics experiments are designed to study weak interactions in either heavy atoms ($Z \geq 55$) or hydrogen. Refined estimates of the mixing matrix elements for both these cases can be made by describing the local weak interaction phenomenologically with a non-relativistic PNC electron-nucleon potential. As the range of the potential is order of $\hbar/M_Z c$, it is taken as proportional to a delta function in the relative coordinate, $\delta(\underset{\sim}{r})$. The potential is expanded in powers of p, the relative momentum, with only the leading terms in the electron velocity, p/m, being retained. With these assumptions and that of T-invariance there are only two possible terms of significance in the potential, each of which is linear in p/m,

$$V_1 = -C_1 \frac{G}{\sqrt{8}\,mc} \left\{ \underset{\sim}{\sigma}_e \cdot \underset{\sim}{p}\,\delta(\underset{\sim}{r}) + \text{h.c.} \right\}$$

$$V_2 = +C_2 \frac{G}{\sqrt{8}\,mc} \left\{ \underset{\sim}{\sigma}_N \cdot \underset{\sim}{p}\,\delta(\underset{\sim}{r}) + i\underset{\sim}{\sigma}_N \cdot \underset{\sim}{\sigma}_e \times \underset{\sim}{p}\,\delta(\underset{\sim}{r}) + \text{h.c.} \right\} . \qquad (7)$$

The coefficients C are the dimensionless parameters which are to be measured and which are predicted by the various gauge models, and $\underset{\sim}{\sigma}_e$ and $\underset{\sim}{\sigma}_N$ are the electron and nucleon spins, respectively. There are four coefficients, two characterizing the electron-proton interaction and two, the electron-neutron interaction. In β-decay nomenclature C_1 is the analogue of the Fermi interaction (A^e-V^N) and C_2 of the Gamow-Teller interaction (V^e-A^N). A term analogous to the weak magnetism contribution has been ignored in (7). For multinucleon atoms the C_1 contribution, which is independent of nuclear spin, involves a coherent sum over nucleons. It is to be further noted that the weak mixing matrix elements are imaginary relative to the matrix elements describing the mixing of the same states by the Stark effect. This is a consequence of the assumption of time reversal invariance.

For heavy atoms with a single valence electron the potential V_1 yields a mixing matrix element

$$\langle V_1 \rangle \sim G(Z\alpha)^2 Q_W K_R \ . \tag{8}$$

Here K_R is a relativistic factor of order 5 for cases of interest and Q_W is the weak charge,

$$Q_W = 2\left\{ZC_{1p} + (A-Z)C_{1n}\right\} . \tag{9}$$

The characteristic Z^3 factor in the mixing, which was first pointed out by Bouchiat and Bouchiat,[11] results from the Z dependence of the electron overlap at the nucleus and the coherent sum over nucleons. This enhances the mixing by order of 10^5 and is the main contribution to the sensitivity of the heavy atom experiments. The mixing parameter is then $\langle V_W \rangle/\Delta E \sim 10^{-10}$. The term in C_2 involves no such coherent sum and so the heavy atom experiments are relatively insensitive to such contributions.

In hydrogen there is no such enhancement. However, there is an enhancement resulting from the presence of close-lying parity doublets. All the hydrogen experiments are studies of the mixing of the n=2 S and P states which are nearly degenerate. Here the mixing parameter is

$$\frac{\langle V_W \rangle}{\mathcal{S}} \simeq \frac{10^{-2}\text{Hz}}{10^{-9}\text{Hz}} \simeq 10^{-11},$$

where $\mathcal{S}$ is the Lamb shift. This mixing is further enhanced by reducing the S-P level separation in a magnetic field which results in a mixing parameter comparable to that for heavy atoms.

Any parity experiment involves the measurement of the rate of some process in an apparatus which breaks inversion symmetry. The rate of the process can be written as

$$R(\pm) = |A_{PC} \pm A_{PNC}|^2 \simeq |A_{PC}|^2 \pm (A^*_{PC}A_{PNC} + c.c.) + |A_{PNC}|^2 . \tag{10}$$

Here A_{PC} and $A_{PNC}(<<A_{PC})$ are the parity conserving and PNC parts of the amplitude, respectively. As A_{PNC} is extremely small it is imperative that the interference term, linear in this quantity, be observed. The signs imply that inversion of the symmetry breaking portions of the apparatus will change the relative signs of the two parts of the amplitude. The part A_{PNC} will produce an asymmetry in R

$$A = \frac{R(+)-R(-)}{R(+)+R(-)} = 2\,\frac{|A_{PNC}|}{|A_{PC}|}\cos\psi\ , \tag{11}$$

where ψ is the relative phase of A_{PC} and A_{PNC} which changes sign when the handedness of the apparatus is reversed. It is clear from (11) that if $|A_{PC}|$ can be suppressed, $|A_{PNC}|$ enhanced and if the handedness of the apparatus can be reversed accurately a sensitive experiment will ensue. With all these conditions satisfied it is possible to obtain an asymmetry substantially larger than the parity mixing of the atomic states.

The PC mean rate in (10), $|A_{PC}|^2$, can be expressed in terms of scalar combinations of the physical variables appearing in the rate while the PNC interference term can be expressed in terms of pseudoscalar combinations of the variables. In particle physics the choice of these variables is limited to the spins and momenta of the particles in a reaction. However, in atomic processes, external electric and magnetic fields can result in significant perturbations, so they can also be used as variables. In fact,in a number of existing experiments,all the physical variables involved in the rate terms are external fields. As these fields can be controlled in strength, direction and relative phase, it is possible to adjust amplitudes for optimum sensitivity.

From a somewhat modest effort in 1973, the number of experimental groups pursuing parity experiments in atoms has grown considerably. Details of the various experiments can be found in the proceedings of the 1979 Cargèse workshop.[12] They will be briefly summarized here and the latest results given.

The search for neutral current interactions in atoms was initiated by M. Bouchiat and Pottier[13] following the publication by Bouchiat and Bouchiat[11] of their definitive work on the formulation of such experiments in heavy atoms with single valence electrons. In the Paris experiment the $6S_{1/2}$-$7S_{1/2}$ transition in Cs is driven with circularly polarized λ5400 radiation from a tuneable dye laser (see Fig.1). The circular polarization of the λ13600 fluorescent radiation from the subsequent $7S_{1/2}$-$6P_{1/2}$ decay is monitored. The $6S_{1/2}$-$7S_{1/2}$ transition is a highly suppressed M1 transition. A static electric field $\tilde{E}_0$ is applied to the vapor perpendicular to the propagation direction $\tilde{k}_i$ of the exciting radiation. A (PC) Stark-induced E1 amplitude between the (perturbed) S states results. In the presence of a PNC weak interaction between the electrons and nucleons there is also a weak induced E1 transition amplitude. Interference between these two amplitudes manifests itself in a contribution $\tilde{P}_e$ to the

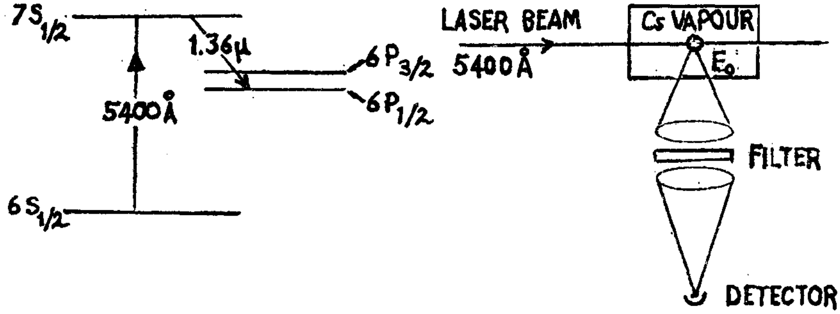

Fig. 1 Cs level diagram and experimental arrangement.

spin polarization of the 7S state. If the fluorescent radiation is observed along a direction $\underset{\sim}{k}_f$ perpendicular to both $\underset{\sim}{k}_i$ and $\underset{\sim}{E}_0$, there is a contribution to the intensity of this circularly polarized radiation proportional to $\underset{\sim}{k}_f \cdot \underset{\sim}{P}_e$. The sense of the polarization reverses with a reversal of the sense of polarization of the exciting radiation and of the direction of the $\underset{\sim}{E}_0$. The excitation rate is enhanced by using a multipass laser beam. The present published result for Cs is $C_1 = Q_W/2A < 6.2$, to be compared to the prediction of the Weinberg-Salam model of 0.29, assuming $\sin^2\theta_W = 1/4$. At present efforts are being made to reduce systematic effects to $\sim$10% of the expected effect, in particular those associated with non-reversing stray electric fields. This experiment promises a sensitivity below the level of the prediction shortly. In addition, the Paris group has given a detailed proposal for experiments involving the use of crossed electric and magnetic fields.[14] This will permit resolution of the various hyperfine components of the $6S_{1/2}$-$7S_{1/2}$ transition, which allows the use of linearly polarized exciting light and observation of the intensity, not the polarization, of the fluorescent radiation. This should lead to a number of technical improvements as well as providing complementary results to those of the present experiment.

Hofnagle and Telegdi have initiated an experiment in cesium of the type being carried out in Paris but looking for interference between the PC M1 $6S_{1/2}$-$7S_{1/2}$ amplitude and the PNC weak-induced E1 amplitude.

Commins and his co-workers at Berkeley are just completing an experiment in thallium which is based on suggestions by Bouchiat and Bouchiat[11] and which is similar to the cesium experiment described above. The PC Stark-induced $6P_{1/2}$-$7P_{1/2}$ transition (see Fig.2) is driven with circularly polarized λ2927 radiation. As in the Cs experiment interference of the Stark-induced amplitude and a weak-induced amplitude results in a polarization of the 7P state in the z-direction perpendicular to the propagation direction of the exciting radiation and the static electric field. While this interference could be detected by analyzing the circular polarization of the subsequent $7S$-$6P_{3/2}$ fluorescence at λ5350, there is significant depolarization of this radiation from several effects. To avoid this loss in sensitivity, a second laser and optical

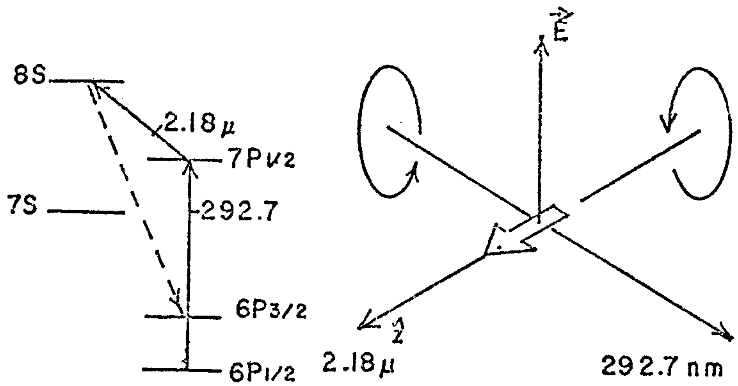

Fig. 2 Tℓ level diagram and experimental arrangement.

system, producing circularly polarized λ21800 radiation propagating in the z-direction, drives the $7P_{1/2}$-$8S_{1/2}$ transition. By observing the intensity of the λ3230 radiation from the $8S_{1/2}$-$6P_{3/2}$ transition while reversing the handedness of the λ21800 radiation the polarization of the $7P_{1/2}$ state can be measured. The Berkeley group has observed circular dichroism consistent with the prediction of the Weinberg-Salam model.[12,15] Their results give a value for the weak charge of $Q_W^{exp} \simeq -280\pm140$, compared to the theoretical value Q_W^{th} = -204 for $\sin^2\theta_W = 0.25$. They have a more recent result with improved statistics which is consistent with this but are making a detailed search for systematic effects similar to those being checked in the cesium experiment.[16] Two other experiments in thallium are in initial stages of construction. One involves measuring circular dichroism in the $6P_{1/2}$-$7P_{3/2}$ transition at λ2844 resulting from the PC M1 amplitude and the weak-induced E1 amplitude. The other is an experiment using the $6P_{1/2}$-$7P_{1/2}$ transition and crossed electric and magnetic fields, similar to that described by Bouchiat et al.[14]

There are currently four experimental groups studying PNC neutral current interactions in atomic bismuth. Each of the experiments is designed to measure the optical rotary power of a vapor sample resulting from the interference of a suppressed PC M1 amplitude and a PNC weak-induced E1 amplitude. Fortson and his group in Seattle are working with the $6S_{3/2}$-$6D_{3/2}$ magnetic dipole transition at λ8757 while Sandars and co-workers at Oxford, Barkov and Zolotorev in Novosibirsk, and Sobel'man and collaborators in Moscow are using the $6S_{3/2}$-$6D_{5/2}$ line at λ6478 (see Fig.3). The Oxford group has also initiated an experiment at λ8757. Figure 3 also shows a typical experimental arrangement, that at Oxford. The latest Seattle experiment employs a laser diode and the others dye lasers. The laser radiation traverses a bismuth vapor which is placed between crossed linear polarizers. The plane of polarization is modulated with a Faraday rotator. Any rotation of the plane of polarization by the bismuth shows up as a change in the transmitted

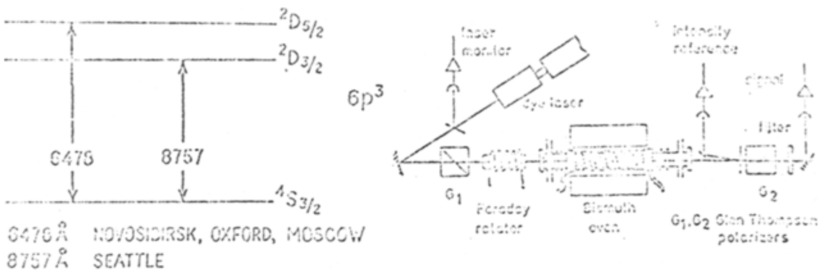

Fig.3 Bi level diagram and experimental arrangement.

light intensity at the frequency of modulation of the plane of polarization. A level of sensitivity corresponding to measurement of an optical rotation angle of $\sim 1\times 10^{-8}$ radians has been attained. The most recent results from Seattle,[17] Novosibirsk,[12] and Moscow[18] are given in Table 1 and compared with the predictions of the Weinberg-Salam model. The quantity $R = \text{Im}(E1^{PV}/M1)$ where $E1^{PV}$ is the weak-induced PNC amplitude and M1 the PC amplitude.

Table I Comparison of R_{exp} and R_{th} for bismuth

	$R_{expt}(\times 10^8)$	$R_{th}(\times 10^8)$
Seattle	-9.5±1.2	-12
Novosibirsk	-20.2±2.7	-18
Moscow	-2.3±1.3	-18
Oxford	-10.3±1.8	-10

The estimated uncertainty in the Seattle result is dominated by possible systematic effects, while the Moscow group has doubled their statistical errors to account for such effects. The quoted error in the Novosibirsk result is purely statistical. The Oxford group also has a preliminary result for the 876 nm line, $R<5\times 10^{-7}$.

While there were several discussions of the effects of weak interactions in atomic hydrogen which appeared subsequent to the discovery of neutral currents,[19] the first practical ideas for experiments exploiting the unique characteristics of the n=2 state were put forth by Lewis and Williams.[20] They pointed out that the four coupling constants C_{1p}, C_{2p}, C_{1n} and C_{2n} could be measured if studies were made of the effects in both hydrogen and deuterium. Experimental work was initiated in Ann Arbor. This was followed by the proposals of Hinds and Hughes[21] and the Michigan group to use microwave transitions in the n=2 state. The details necessary to the general formulation of such experiments have been given by Dunford, Lewis and Williams.[22]

Hydrogen experiments are being carried out at Michigan, Washington and Yale with intense atomic beams. As mentioned above they are searches for a weak mixing of the nearly degenerate states of the $2S_{\frac{1}{2}}$-$2P_{\frac{1}{2}}$ parity doublet. The Michigan apparatus is operating but because of the background problems no attempt has yet been made to obtain limits on the coupling constants. The experiments at Washington and Yale are still under construction.

In the Michigan experiments[23] a beam of hydrogen atoms in one of the hyperfine substates of the $\alpha(m_J=+\frac{1}{2})$ component of the metastable 2S state (Fig.4) passes through a microwave cavity in which there are also static and magnetic ($\underset{\sim}{B}$) and electric ($\underset{\sim}{E}$) fields. The orientation of the oscillatory electric field ($\underset{\sim}{\varepsilon}$) and the static fields (Fig.5) provides a transition region which breaks inversion

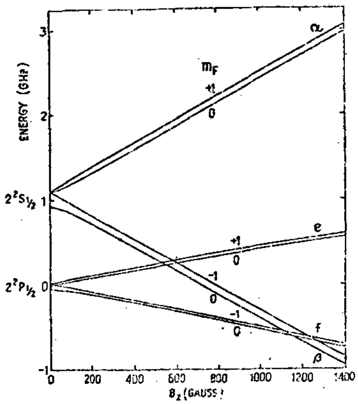

Fig.4 Zeeman diagram for H,n=2.

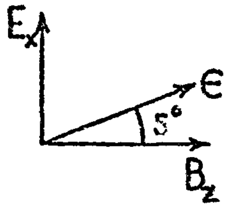

Fig.5 Field configuration for Michigan experiment.

symmetry. The PC mixing of the 2S and 2P levels by the static electric field permits driving a Stark-induced microwave E1 transition from an α substate to one of the hyperfine substates of the $\beta(m_J=-\frac{1}{2})$ component of the 2S state. Similarly there will be a PNC weak-induced microwave E1 amplitude. The experiments are designed to detect interference between these two amplitudes by measuring the dependence of β-state population on the handedness of the transition region. The contribution to the rate from this term changes sign under reversal of $\underset{\sim}{E}$, $\underset{\sim}{B}$ or ε_x; most of the possible PC terms in the rate are even under these reversals. With the present design the asymmetry A (see(11)) will be $\sim$1 ppm. The PNC mixing is to be studied in the vicinity of the crossings of the β and $2P_{\frac{1}{2}}$ substates ($\sim$550G and 1100G). Although the magnetic field does not directly enhance the sensitivity,[24] it plays a significant role in a number of ways. For a particular value of the field the states which cross are specific mixtures of hyperfine states and the contribution to the mixing will involve a definite linear combination of C_1 and C_2. Measurements of the mixing near the β-e and β-f crossings in hydrogen and deuterium determine the four coupling constants characteristizing the electron-nucleon interaction. As a consequence of the strong damping of the 2P state, the real part of the energy denominator can be made zero and the phase difference between the Stark-induced and weak-induced amplitudes varies through π about the crossing. This variation yields a characteristic line-shape which provides further discrimination against systematic effects. The use of a magnetic field also provides an external physical variable which can be used to construct invariant terms in the transition rate. In the present experiment the $\alpha(m_F=0)-\beta(m_F=0)$ transition is being studied near the $\beta(m_F=0)-e(m_F=0)$ crossing. This will determine C_{2p} and C_{2n}. The PC transition, which is detected by observing Lyman-α radiation from selective Stark-quenching of the β-state atoms, is of the expected size. There is a spurious background about five times as large. The immediate effort is to circumvent the deleterious effects of it.

The investigations at Washington and Yale will use multiple transition regions. The Washington experiment will comprise a study of the parity mixing near the β-e crossing. It too is designed to observe interference between Stark- and weak-induced microwave E1 amplitudes in the α-β transition, but will measure a pseudoscalar invariant which is different from that in the Michigan experiment. There will be two cavities in which there are microwave and static electric fields oriented along the direction of the static magnetic field.[25] This approach combines features of the sharp α-β resonances discussed by Lamb[26] and of the Ramsey separated oscillating fields technique.[27] The phase shift necessary to effect the desired interference is obtained by externally controlling the phase difference between the microwave fields in the two cavities. This contribution to the rate can be identified by the reversal of the directions of the static electric and magnetic fields and of the sign of the phase difference. A suitable atomic beam is being generated and the solenoid for the static magnetic field is in operation. Prototype cavities have been tested and the versions to be used are being built now.

The Yale experiment will be carried out in zero magnetic field.[28] To lowest order it is sensitive only to C_2 and eliminates systematic effects from motional ($\tilde{v}\times\tilde{B}$) electric fields. The hydrogen 2S beam will be selected to contain atoms in either the F=1 or F=0 hyperfine structure states (see Fig.4) using microwave Stark quenching through the 2P state. This beam will pass through two consecutive radiofrequency regions operating at the F=1-F=0 separation (∿177 MHz). The regions generate, respectively, oscillatory magnetic and electric fields which are parallel to one another. A PNC interaction manifests itself as a contribution to the transition rate from interference of a PC M1 amplitude with a PNC E1 amplitude. The asymmetry can be optimized by the appropriate choice of the relative phase of the oscillatory fields. The interference term reverses sign relative to the PC rate terms when the sign of the phase is reversed. Further the sign is different depending on whether the transition is driven from the F=0 state to the F=1 state or vice versa. The hydrogen beam is in operation and the state selection apparatus built. The transition region is under construction.

Robiscoe[29] has proposed an intriguing three cavity experiment to operate near the β-e crossing. It has three symmetry breaking reversals, two phases and the static magnetic field, while avoiding the technical problems associated with the use of static electric fields. It promises asymmetries comparable to those in the experiments discussed above as well as higher transition rates.

P-Violating, T-Violating Interactions

There are several possible sources for parity-violating, time reversal-violating electron-nucleon interactions in atomic and molecular systems. Among these are intrinsic electric dipole moments (edm's) of the electron, proton or neutron, which would give rise to long-range interactions, and weak neutral currents, which would result in short-range interactions. The same experiments which were designed to search for the effects of intrinsic electric dipole moments in atoms and molecules are interpreted to limit the strengths of neutral current interactions.

All experiments to search for intrinsic edm's are based on studying the interaction of a (necessarily) neutral system with an external electric field. The present limits on the edm of the neutron result from searching for shifts of the magnetic resonance frequency when ultra-cold neutrons are subjected to external electric fields. The present limits for the edm range from $1.6\text{-}3\times10^{-24}$e-cm.[30] These can be compared with the present estimate from gauge theory of $\sim10^{-25}$e-cm, although it should be noted that the range of theoretical predictions is large and that experiment has continued to press the theoretical estimates to lower and lower values.

Investigations of the effects of an intrinsic edm of a charged particle are much more difficult. This results from a theorem[31] which shows that for a system of charged, point electric dipoles in an arbitrary external electrostatic potential, there is no term in the interaction energy linear in the edm's, i.e., there is complete shielding. The theorem breaks down, however, when a particle has a charge distribution different from the distribution of the edm or when it has a magnetic dipole moment. In either case there results an interaction between an effective electric field in the direction of the applied external electric field and the edm. For hydrogen, calculations[31,32] show that the shielding results in an effective electric field which is $\sim10^{-4}$ times the applied field for an electron edm and $\sim10^{-7}$ times the applied field for a proton edm. However, Sandars has pointed out that by studying the appropriate atom or molecule the interactions can be significantly enhanced. He has shown that the effective field depends on Z to such an extent that in the case of an electron edm it can be larger than the applied field.[33] As a result the edm of the cesium or xenon atom is ∿100 times the edm of the free electron. The effective field for the edm of a bound proton is significantly less than the applied field, even for high Z. Sandars discovered that this could be overcome to a large extent by exploiting the large electric fields in polar molecules which can be polarized by relatively small applied fields.[34]

The best available upper limit on the size of the electron edm comes from the experiment with xenon of Player and Sandars.[35] A polarized beam of xenon atoms in the metastable $^3P_2$, m_J=+1 state undergoes two-quantum radiofrequency transitions to the m_J=-1 state in a Ramsey-type separated field region (it is necessary to observe transitions in which $\Delta|m_J|=0$ to avoid inhomogeneous broadening of the resonance line as well as severe systematic effects). The transitions take place in a region with parallel static electric ($\underset{\sim}{E}$) and magnetic (B) fields. As in the experiments searching for a neutron edm, the presence of an atomic edm would result in a shift of the resonance line which is proportional to $\underset{\sim}{E}\cdot\underset{\sim}{B}$. This yields a characteristic signature under reversal of $\underset{\sim}{E}$ or $\underset{\sim}{B}$ which can discriminate against systematic effects which might mimic that of an atomic edm. They obtain as a limit on the size of the edm of the electron $|d_e| = (0.7\pm2.2)\times10^{-24}$e-cm. It should be noted that the electron edm is expected to be about m/M $\sim 10^{-3}$ times that of the neutron.

The recent results of Hinds and Sandars [36] provide the most stringent limit on the possible size of a proton edm. The experiment, which is similar in concept to that in xenon, searches for the effects of a proton edm in the ground state of TℓF in a molecular beam. It exploits the enhancement of the effective field in polar molecules mentioned above. Again shifts of a resonance line (in this case that of a Δm=-1 nuclear magnetic dipole transition) in an external electric field are studied. The Ramsey technique is used to reduce the observed linewidth. The limit on the size of the proton edm from this experiment is $d_p = (-1.4\pm6)\times10^{-21}$e-cm.

These experimental limits on the sizes of d_e and d_p can be interepreted to give limits on the strengths of short-range P-and T-violating neutral current interactions between electrons and nucleons.[37] The two possible interactions are a scalar and a tensor interaction described phenomenologically by

$$H_S = iC_S \frac{G}{\sqrt{2}} \bar{\psi}_e\Gamma_S\psi_e\bar{\psi}_N\Gamma_S\psi_N\delta(\underset{\sim}{r})$$

$$H_T = iC_T \frac{G}{\sqrt{2}} \bar{\psi}_e\Gamma_T\psi_e\bar{\psi}_N\Gamma_T\psi_N\delta(\underset{\sim}{r}) \quad . \qquad (12)$$

Here C_S and C_T are, respectively, the coupling constants characterizing the scalar and tensor interactions, and Γ_S and Γ_T are the usual scalar and tensor combinations of the Dirac matrices. The xenon experiment provides a limit on the scalar coupling constant,

$|C_S| \lesssim 3\times10^{-4}$. The thallium fluoride measurements yield $|C_T| \lesssim 6\times10^{-5}$. These particular P- and T-violating interactions are at least three orders of magnitude smaller than the P-violating - T invariant interactions predicted by the Weinberg-Salam theory.

SUMMARY

Investigations of atomic and molecular systems has provided considerable information about fundamental symmetry principles. Studies of the discrete space-time symmetries, C, P and T, have been reviewed here. Results from experiments on weak neutral current interactions or searches for intrinsic electric dipole moments of elementary particles will provide important input to theoretical formulations. The interpretation of the results of the C tests in positronium is at present unclear.

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DISCUSSION

FICK: How do you detect the transitions in hydrogen?

WILLIAMS: The $2S_{\frac{1}{2}}M_J = -\frac{1}{2}$ state leaves the interaction region and enters a region of strong electric field where it decays with emission of Ly-α radiation. We detect this radiation as a measure of the transition rate.

MUKHOPADHYAY: Could you once again summarize the status of the comparison of the Weinberg-Salam type theories and the atomic parity-violating experiments, taking conservatively all the thoretical uncertainties inherent in such calculations?

WILLIAMS: The experiments at Berkeley (Te), Seattle (Br), Oxford (Bi) and Novoaihinsk (Bi) agree with the local calculation. There is a spread in the theoretical values of about 40%. Moscow (Bi) has a result in disagreement with the other Bi experiments. While I am skeptical about the ability of the heavy atom experiments to check theory well, I believe parity nonconservation has been observed.