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Role of Damping and T Invariance in Induced Transitions in H(2S)

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An interference term has been observed in an induced transition between damped substates of $2S_{1/2}$ atomic hydrogen which is formally odd under time reversal. The magnetic-field dependence of this term through the $2S_{1/2}$-$2P_{1/2}$ level crossing provides a distinct characterization of the interaction of the atom and the radiation field. The results are central to the design and interpretation of the hydrogen parity experiment.

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There is a considerable literature concerning the behavior of unstable particles in external fields.[1] Of recent interest has been the 2S state of hydrogen and hydrogenic ions in the context of investigations of parity nonconservation[2,3] and of the diverse interference phenomena in the angular distribution of Lyman-α radiation from quenching in electric fields.[4] We present here the results of a novel experiment with atomic hydrogen bearing on the role of time-reversal (T) symmetry in induced transitions between damped $2S_{1/2}$ substates.

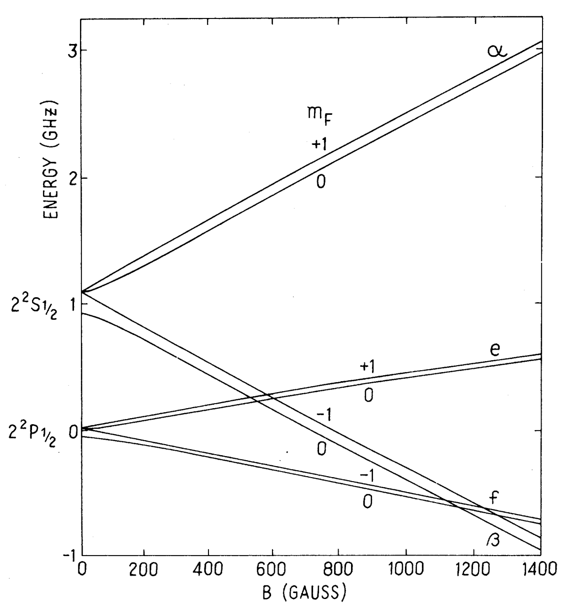

FIG. 1. Zeeman diagram of the $2S_{1/2}$ and $2P_{1/2}$ states of hydrogen.

The initial motivation for this work was to demonstrate experimentally the validity of the formulation of our experiment to investigate parity-nonconserving (PNC) weak interactions in atomic hydrogen.[5] This experiment is based on observation of a pseudoscalar interference term in a suppressed microwave electric dipole transition between the (initial) α_0 and (final) β_0 substates[6] of the metastable $2S_{1/2}$ state in a dc magnetic field, $\vec{B}$, set near the crossings of the β substates and the substates e of the strongly damped $2P_{1/2}$ state (Fig. 1). The transition is induced by mixing of β_0 and e_{+1} with a small applied dc electric field, $\vec{E}$, perpendicular to $\vec{B}$, and of β_0 and e_0 by the putative PNC interaction. The microwave electric field, $\vec{\epsilon}$, and $\vec{E}$ and $\vec{B}$ are arranged in a configuration which breaks inversion symmetry (Fig. 2 with $\psi = 0$). As a consequence

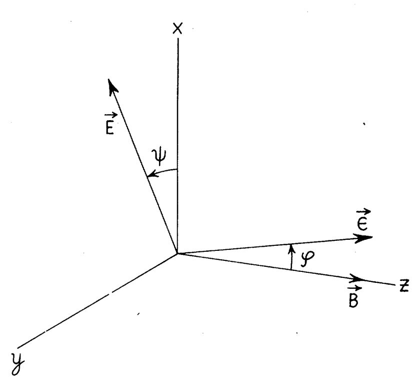

FIG. 2. Field configuration in the transition region.

of T invariance[7] and angular momentum rules, the Stark- and weak-mixing matrix elements are relatively imaginary. The desired P-odd term in the transition rate, resulting from interference of the Stark- and weak-induced amplitudes, is $\mathrm{Re}C\,\vec{\epsilon}\cdot\vec{E}\,\vec{\epsilon}\cdot\hat{B}$, where C is a function of the microwave frequency, ω, and $|\vec{B}|$, but not of $\vec{\epsilon}$ or $\vec{E}$.

That this interference term is formally T odd naturally raised the question of its observability. Theoretical considerations[8,9] of transitions between atomic states in external fields, which states are unstable against photon emission, but in which transitions photon emission does not occur, show that time-reversal invariance leads to the following conclusions. The existence of a T-odd term is possible only as a result of the induced damping of the $2S_{1/2}$ substates. Such a term cannot be present in the probability for the atom to remain in the initial state α_0. It can occur in the transition probability to the observed final state β_0, if the initial populations of α_0 and β_0 are different. These probabilities do not sum to unity even on resonance where β_0 is the only significant final state. Probability balance is maintained by the existence of a corresponding T-odd term of opposite sign in the sum over the other final states. In the experiment described here and in the parity experiment this term belongs to the radiative and not the atomic sector.

The configuration of fields in the experiment discussed here were as shown in Fig. 2. Invariant analysis of the scalar terms in the transition rate gives

$$R_{\alpha_0\to\beta_0}=a\{\vec{\epsilon}^{\,2}-(\vec{\epsilon}\cdot\hat{B})^2\}\vec{E}^2+b(\vec{\epsilon}\cdot\vec{E})^2+c(\vec{\epsilon}\cdot\vec{E})(\vec{\epsilon}\cdot\vec{E}\times\hat{B})=\epsilon_x{}^2\vec{E}^2\{(a+\tfrac{1}{2}b)+(\tfrac{1}{2}b)\cos2\psi+(\tfrac{1}{2}c)\sin2\psi\}\,. \qquad (1)$$

The first two invariants are formally T even. The third is formally T odd and results from interference between Stark-induced amplitudes from dc electric fields in the x and y directions. Angular momentum rules and T invariance result in the corresponding Stark matrix elements being relatively imaginary, in analogy to the relative phase of Stark and weak matrix elements in the parity experiment.

Detailed analysis of the transition rate can be carried out using nonperturbative techniques.[9] However, as confusion concerning the observability of a formally T-odd pseudoscalar term lay in misuse of perturbative techniques, we present the results of this approach used correctly. We consider the projection of the complete Zeeman Hamiltonian onto the atomic sector and introduce an effective Hamiltonian, H_{eff}, according to the Bethe-Lamb formulation[6] to account for radiation reaction. First-order perturbation theory suffices to understand our results. The conventional prescriptions apply provided transition moments are calculated between right and left eigenvectors of H_{eff}.[10] We may ignore states other than those of $n=2$, the $2P_{3/2}$ state, and the natural decay rate of the $2S_{1/2}$ substates. The first-order Stark-perturbed β_0 state function is

$$|\beta_0'\rangle=|\beta_0\rangle+\frac{V\cos\theta e^{-i\psi}}{\Delta E(\beta_0-e_{+1})+i(\frac{1}{2}\Gamma)}|e_{+1}\rangle-\frac{V\sin\theta e^{i\psi}}{\Delta E(\beta_0-f_{-1})+i(\frac{1}{2}\Gamma)}|f_{-1}\rangle\,. \qquad (2)$$

Here $|\,\rangle$ denotes a right eigenvector of H_{eff} in the Zeeman basis, $V=\sqrt{3}ea_0E$, θ is the hyperfine mixing angle ($\theta\cong\frac{1}{20}$ in the vicinity of the β-e crossings and goes to zero in the Paschen-Back limit), $\Delta E(\,)$ is the real part of the magnetic-field–dependent energy difference of the indicated substates, and Γ is the natural decay rate of the $2P_{1/2}$ state. The corresponding left eigenvector is

$$\langle\tilde{\beta}_0'|=\langle\tilde{\beta}_0|+\frac{V\cos\theta e^{i\psi}}{\Delta E(\beta_0-e_{+1})+\frac{1}{2}i\Gamma}\langle\tilde{e}_{+1}|-\frac{V\sin\theta e^{-i\psi}}{\Delta E(\beta_0-f_{-1})+\frac{1}{2}i\Gamma}\langle\tilde{f}_{-1}|\,. \qquad (3)$$

The state function (3) is not the conjugate of (2), as H_{eff} is not Hermitian. The transition rate is

$$R_{\alpha_0\to\beta_0}=\tfrac{1}{4}L(\omega,t)|\langle\tilde{\beta}_0'|\vec{\epsilon}\cdot\vec{r}|\alpha_0'\rangle|^2,$$

where $L(\omega,t)$ describes the transition line shape. Evaluation of this rate and comparison with (1) yields

$$a=\tfrac{1}{4}k|\Delta_1{}^{-1}+\Delta_2{}^{-1}|^2,\quad b=-k\,\mathrm{Re}(\Delta_1\Delta_2{}^*)^{-1},\quad c=k\,\mathrm{Im}(\Delta_1\Delta_2{}^*)^{-1},$$

where

$$\Delta_1{}^{-1}=[\Delta E(\beta_0-e_{+1})+\tfrac{1}{2}i\Gamma]^{-1}-[\Delta E(\alpha_0-f_{-1})+\tfrac{1}{2}i\Gamma]^{-1},$$

$$\Delta_2{}^{-1}=[\Delta E(\beta_0-f_{-1})+\tfrac{1}{2}i\Gamma]^{-1}-[\Delta E(\alpha_0-e_{+1})+\tfrac{1}{2}i\Gamma]^{-1},$$

and $k=\frac{9}{4}(ea_0)^4\sin^2 2\theta$. The coefficient c vanishes for $\Gamma=0$, exhibiting explicitly that the existence of the formally T-odd invariant in the transition rate is possible only through interaction with the radiative sector.

The sign of the T-odd invariant changes for $\vec{B}\rightarrow-\vec{B}$, $E_x\rightarrow-E_x$ $(\psi\rightarrow\pi-\psi)$ or $E_y\rightarrow-E_y$ $(\psi\rightarrow-\psi)$, providing characteristic signatures for the presence of this term. Each reversal induces an asymmetry in the transition rate which is maximum for $\psi\cong 45°$:

$$A_1=c/(2a+b).$$

Measurement of A_1 provides a determination of c.[11] The magnetic-field dependence of A_1 through the β-e level crossing gives a distinct characterization of the interaction of the atomic and radiative sectors.

The integrity of the measurement of A_1 was checked by measurement of the magnetic-field-dependent asymmetry in the $\alpha_0\rightarrow\beta_0$ transition rate resulting from the sign change of the second (T-even) term of (1) when $E=E_x$ $(\psi=0)\rightarrow E=E_y$ $(\psi=\pi/2)$:

$$A_2=b/(2a+b).$$

The experimental arrangement was identical in all important respects to that of the parity experiment.[9,12] An H(2S) beam polarized in the α substates passed through a transition region comprising the field configuration of Fig. 2. The $\alpha_0\rightarrow\beta_0$ transition was induced therein. The resulting β_0-state atoms were selectively detected downbeam from the transition region as a measure of the transition rate. The dc electric fields were motional fields ($\cong$ 1.5 V/cm) produced by application of small (~ 4-G) magnetic fields transverse to the main (~ 550-G) magnetic field.

Spurious asymmetries in the $\alpha_0\rightarrow\beta_0$ transition rate are generated by interferences between Stark-induced amplitudes when the various modulations to obtain A_1 and A_2 were effected. These result from misalignments of the fields in the interaction region, misalignment of $\vec{B}$ and the atomic beam axis, and modulation of the direction of the resultant magnetic field.[13] Asymmetries resulting from misalignments are accurately reflected in the line shape of the allowed Stark-induced α_{+1}-β_0 transition[9] which is $\cong 10^4$ times as strong as the α_0-β_0 transition. The strong transition does not exhibit the interference terms given in (1) and was expeditiously used to obtain the requisite alignment to eliminate these asymmetries, albeit with more difficulty than in the parity experiment, where accurate orientation of only one electric field is necessary. Modulation of the direction of the resultant magnetic field when either of the dc electric fields was modulated resulted from use of motional fields. This leads to a spurious asymmetry to which the α_{+1}-β_0 transition is insensitive. However, use of a multichannel phase-sensitive detection scheme[9] to analyze the detailed symmetry properties of the three terms in (1) permitted unambiguous extraction of A_1 and A_2. Systematic time-dependent interferences were reduced to a negligible level by integration of the asymmetries in the transition probability over the entire $\alpha_0\rightarrow\beta_0$ resonance line shape.

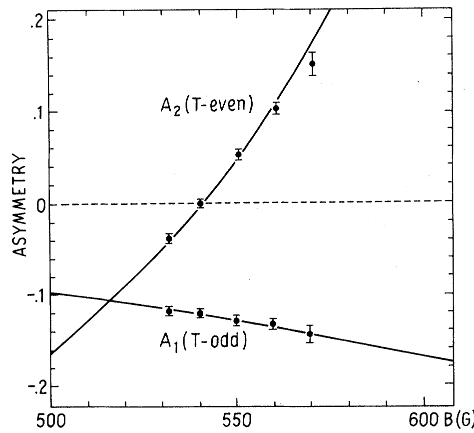

FIG. 3. Comparison of the experimental (solid circles) and theoretical (solid lines) values of the asymmetries A_1 and A_2. The errors are one standard deviation.

The experimental results (solid circles) for A_1 and A_2 are compared with the calculated values (solid lines) in Fig. 3. There are no free parameters in the calculated asymmetries. Of especial note is that had A_1 been calculated using the perturbation methods for undamped states the opposite sign would have been obtained. The negative sign of the asymmetry explicitly confirms the validity of the formulation of our parity experiment.

Alternatively, the assumption that the use of an effective Hamiltonian as discussed above is correct allows us to obtain from the measured value of A_1 an experimental value of the decay rate of the $2P_{1/2}$ state, $\Gamma=99.3\pm1.0$ MHz, comparable in accuracy to those from beam-foil experiments.[14]

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