Nearly-Degenerate Opposite-Parity Levels in Atomic Dysprosium: A Novel System for the Study of Parity Non-Conservation

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Abstract:

There exists in atomic dysprosium a pair of nearly-degenerate levels of opposite parity. These levels are of potential interest for the study of parity non-conservation because the small energy separation enhances level mixing due to weak-interaction processes. In this paper, we review the unique properties of these levels which make them attractive for measurements of parity non-conservation, and outline the principle of such an experiment now underway.

Introduction

The study of parity non-conservation (PNC) in atoms is now a mature field. Measurements of PNC effects have reached a precision of 2% or better in several elements[1,2,3]. Measurements with higher precision are of interest for several reasons. First, it should be possible to observe the nuclear anapole moment, which arises from PNC in the nucleus and induces a nuclear spin-dependent component of atomic PNC[4]. In addition, if PNC can be measured to high precision in a chain of isotopes of the same element, information can be obtained about neutron distributions in the nucleus[5]. Finally, if some other method of obtaining neutron distributions is available, measurement of PNC in a chain of isotopes can serve as a high-precision test of the standard model of weak interactions[6,7].

Measurement of PNC in the system of nearly-degenerate levels of opposite parity in atomic dysprosium (Z=66) offers the possibility in principle to make such a measurement at a level of precision orders of magnitude better than that achieved so far in other elements. This possibility arises because the small energy splitting enhances the weak-interaction induced mixing between the levels. We describe here the unique properties of this system, and will outline the effort now underway to make a first observation of PNC in dysprosium.

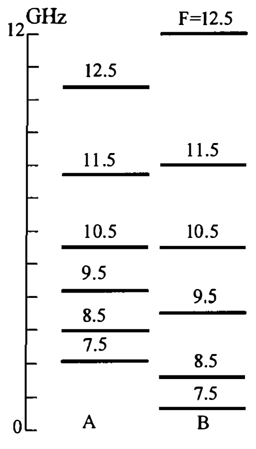

Figure 1: Hyperfine structure of levels A and B for ^{163}Dy.

The nearly-degenerate levels A (even parity) and B (odd parity) both have angular momentum J=10 and lie 19797.96 cm^{-1} above the ground level (J=8). (The level structure of atomic Dy is tabulated in Ref. 8 .) Dysprosium has both even and odd neutron-number stable isotopes ranging from A=156 to A=164. The magnitude of the energy splitting between A and B is of the order typically associated with hyperfine and isotope shifts[9], and thus varies greatly among the various HF and IS components. For the even isotopes (which have nuclear spin I=0, and thus no hyperfine structure) this splitting ranges from 235 MHz for ^{162}Dy to 4200 MHz for ^{156}Dy. The two odd isotopes (^{161}Dy and ^{163}Dy) both have nuclear spin I = 5/2. Fig. 1 shows the hyperfine structure of levels A and B in ^{163}Dy. The hyperfine components with F=10.5 of ^{163}Dy are the closest pair, with a separation of only 3.1 MHz. This pair of levels is used in the current search for PNC.

Outline of the PNC Experiment

In the PNC experiment now underway, we observe Stark-induced quantum beats between levels A and B and look for interference between the Stark amplitude and the much smaller PNC amplitude connecting the two levels. A magnetic field is applied in order to bring Zeeman sublevels of A and B with the same value of m_F to near crossing, and thus to enhance the PNC mixing between them. (Fig. 2 shows some of the Zeeman structure of the ^{163}Dy F=10.5 levels of A and B in a weak magnetic field.) An electric field is applied parallel to the magnetic field to induce ~100% amplitude of the quantum beats. The Stark and PNC amplitudes have a relative phase of $\pi/2$ and so do not interfere if the electric field is DC. In order to adjust the phases in such a way as to produce interference between these two amplitudes, the polarity of the electric field is rapidly (non-adiabatically) switched. This scheme of PNC detection was originally proposed in a slightly different form for use in the 2s-2p system in hydrogen[10].

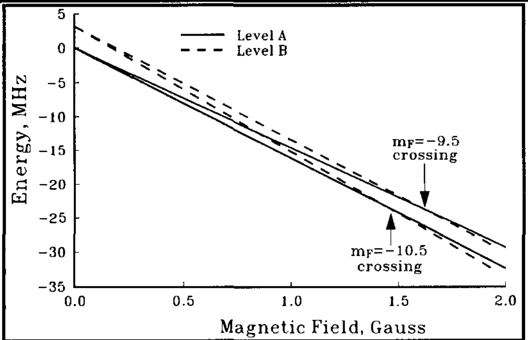

Figure 2: Partial Zeeman structure of the ^{163}Dy F=10.5 sublevels of A and B.

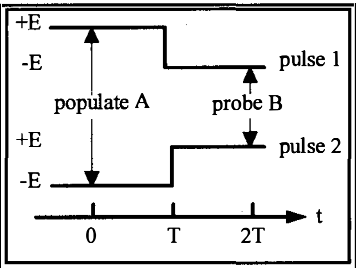

Figure 3: Electric field pulses used in the nonadiabatic switching scheme. The PNC signal is the fractional difference between the signals obtained with these two pulses.

Quantum beats are observed by populating level A instantaneously at time t=0 and probing level B at some later time t=2T. The electric field polarity is switched between the population and probe pulses at t = T (see Fig. 3). Level A is populated by two-step excitation from the ground state via an intermediate odd-parity level with J=9; the corresponding E1 transitions are excited by two consecutive laser pulses at 626 nm and 2614 nm. Level B is probed by excitation to a high-lying even-parity level with another pulsed laser at 571 nm and detection of the subsequent fluorescence. The PNC signal is the fractional difference between the signals from two consecutive population-probe sequences with opposite ordering of the E-field polarity (Fig. 3).

Calculation of the Quantum Beats and the Stark-PNC Interference

The Hamiltonian for the 2-level system formed by the nearly-crossed components of A and B (with the same value of F and m_F) in the presence of an electric field E parallel to the magnetic field is:

$$H = \begin{pmatrix} \frac{-i\Gamma_A}{2} & dE + i\delta \\ dE - i\delta & \Delta - \frac{i\Gamma_B}{2} \end{pmatrix}. \tag{1}$$

Here, $\Gamma_A(\Gamma_B)$ is the natural width of level A(B), Δ is the energy splitting in the absence of mixing (determined by the applied magnetic field), $i\delta$ is the PNC matrix element (pure imaginary due to T-reversal invariance), and d is the electric dipole matrix element between these sublevels. The experimentally determined values of Γ_A, Γ_B and d are[9]:

$$\Gamma_A = 20 \text{ kHz}; \tag{2}$$

$$\Gamma_B < 1 \text{ kHz}; \tag{3}$$

$$|d(F=10.5, m_F=10.5)| = 4 \text{ kHz/ (V/cm)}. \tag{4}$$

In addition, the PNC matrix element δ has been estimated[11] using multiconfiguration Hartree-Fock wavefunctions for Dy:

$$|\delta| = 40 \text{ Hz}. \tag{5}$$

The nonzero value of δ arises from configuration mixing and core-polarization effects: the dominant configurations of A and B differ by the exchange of an f electron for a d electron, whereas the PNC Hamiltonian mixes only s and p states. As a comparison, it can be noted that the PNC matrix element between the $6p_{1/2}$ and $7s_{1/2}$ states of Tl has magnitude $\approx$ 100 kHz. The electric dipole matrix element is also suppressed, because El selection rules are not satisfied in the transition between the dominant terms of A and B; a typical value for an allowed El amplitude is $ea_0 \approx 1$ MHz/(V/cm).

The complex eigenvalues $\lambda_{1,2}$ and corresponding eigenstates $\begin{pmatrix} a_{1,2} \\ b_{1,2} \end{pmatrix}$ of the Hamiltonian in eqn. 1 are found by solving the characteristic equation. The linear combination of these eigenstates which corresponds to state A is excited at time t=0:

$$\psi(t=0) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} = c_1 \begin{pmatrix} a_1 \\ b_1 \end{pmatrix} + c_2 \begin{pmatrix} a_2 \\ b_2 \end{pmatrix}. \tag{6}$$

Just before the electric field switching, the wavefunction has evolved to:

$$\psi(t=T) = c_1 e^{-i\lambda_1 T}\begin{pmatrix} a_1 \\ b_1 \end{pmatrix} + c_2 e^{-i\lambda_2 T}\begin{pmatrix} a_2 \\ b_2 \end{pmatrix}. \tag{7}$$

In the above wavefunction there appears no Stark-PNC interference term, since the PNC matrix element is pure imaginary and the Stark matrix element is real. Non-adiabatic switching of the polarity of the electric field can adjust the relative phases of the PNC and Stark mixing terms to produce interference. After the electric field has been switched, there are new eigenvalues $\Lambda_{1,2}$ and eigenfunctions $\begin{pmatrix} A_{1,2} \\ B_{1,2} \end{pmatrix}$. Thus, just after the switching, the wavefunction can be written in the form

$$\psi'(t=T) = C_1\begin{pmatrix} A_1 \\ B_1 \end{pmatrix} + C_2\begin{pmatrix} A_2 \\ B_2 \end{pmatrix}, \tag{8}$$

where C_1 and C_2 are determined by setting $\psi'(t=T)=\psi(t=T)$. At the time t = 2T of the probe pulse, the wavefunction is:

$$\psi'(t=2T) = C_1 e^{-i\Lambda_1 T}\begin{pmatrix} A_1 \\ B_1 \end{pmatrix} + C_2 e^{-i\Lambda_2 T}\begin{pmatrix} A_2 \\ B_2 \end{pmatrix} \tag{9}$$

Since the probe pulse couples only to state B, the signal has the form

$$S \propto \left| C_1 e^{-i\Lambda_1 T} B_1 + C_2 e^{-i\Lambda_2 T} B_2 \right|^2. \tag{10}$$

Fig. 4 shows the measured and expected dependence of the signal as a function of the applied magnetic field near a level crossing.

For $dE \gg \delta$, The signal asymmetry

$$\mathcal{A} = \frac{S(E+ \to E-) - S(E- \to E+)}{S(E+ \to E-) + S(E- \to E+)} \tag{11}$$

is linear in δ. With T, E, and the magnetic field chosen so that $(1/T) \approx dE \approx \Delta \approx \Gamma_A$, the population of state B at the time of the probe pulse is a considerable fraction of the initial population of state A, and the asymmetry $\mathcal{A}$ is on the order of $(\delta/\Delta) \approx 2\times10^{-3}$. This asymmetry changes sign with the overall applied magnetic field and with the detuning Δ; it has the signature of the P-odd, T-even invariant

$$(\mathbf{E}_i - \mathbf{E}_f)\cdot(\mathbf{B} - \mathbf{B}_c), \tag{12}$$

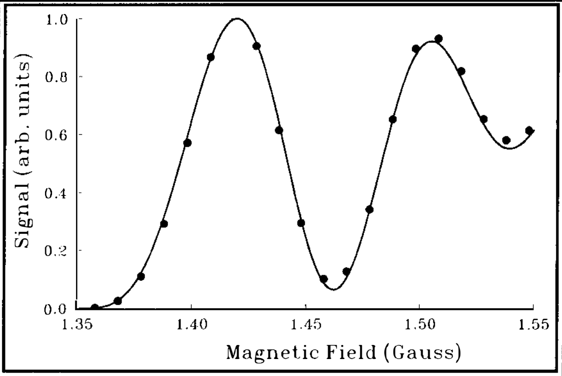

Figure 4: Magnetic field dependence of the nonadiabatic-switching quantum beat signal near the ^{163}Dy F = 10.5, m_F = 10.5 level crossing, which occurs at 1.46 G. The line shows the expected dependence; the points are experimental data. The conditions are: E = ±7 V/cm, T = 4 μs. The lineshape is asymmetric becasue of contributions from the nearby m_F = 9.5 level crossing.

where the subscripts f and i denote final and initial, and $\mathbf{B}_c$ is the magnetic field required to produce an exact level crossing.

Systematics and Sensitivity

A full analysis of possible systematic effects in the PNC measurement is beyond the scope of this paper. Briefly, however, several points can be made. First, it can be noted that the availability of multiple field reversals to change the sign of the asymmetry leads to rejection of systematic effects due to stray and nonreversing fields. In particular, we find that the use of balanced E-field switching (i.e., with both polarities for each pulse, as in Fig. 3) greatly suppresses spurious effects due to nonreversing E-fields. In addition, the presence of spurious fields can be detected and corrected for by means of numerous auxiliary measurements using the Dy atoms themselves. It is also of interest to note that the magnitude of a stray or non-reversing electric field required to produce mixing as large as the expected PNC mixing is macroscopic: $|\delta / d| \approx 10\ \mathrm{mV/cm}$. For these reasons, we believe that systematic effects can be controlled to a high level of precision.

Study of PNC in the nearly-degenerate levels offers the potential for unprecedented levels of statistical precision in the measurement of PNC effects. This potential arises both because the predicted PNC asymmetry for these levels is large ($\mathcal{A} \approx 2\times10^{-3}$) and because this asymmetry is obtained using E1 transitions in every stage of the experiment, which means that high counting rates can be achieved. Both properties are important because, in the shot-noise limit, the fractional uncertainty in the PNC matrix element δ is given by $(\mathcal{A}\sqrt{N})^{-1}$, where N is the total number of detector counts.

Current Status and Conclusion

The current statistical sensitivity of our apparatus to the asymmetry $\mathcal{A}$ is $\sim 5\times 10^{-2}/\sqrt{\mathrm{Hz}}$. This sensitivity is limited by two primary difficulties. First, our laser system is far from optimal for the PNC measurement; the pulsed lasers have a repetition rate of 10 Hz, which gives an effective duty cycle of $\sim 10^{-4}$. Second, pulse-to-pulse fluctuations in the laser intensities and spectral profiles lead to noise far above the shot noise limit. Nevertheless, it should be possible to unambiguously detect PNC at the predicted level with only a few hours of integration time. Before this is attempted, however, we are investigating in detail all possible sources of systematic effects and attempting to reduce the stray and nonreversing fields now present in our apparatus. With control over these fields at levels similar to those obtained in other PNC experiments and with an optimized laser system, it is a reasonable goal to measure PNC in the nearly-degenerate levels of Dy to a precision of 10^{-4} or better.

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