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Investigation of the E2 and E3 matrix elements in ^{200}Hg using inelastic scattering

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Abstract. A nuclear structure campaign has been initiated to investigate the isotopes of mercury near $A = 199$. Currently ^{199}Hg provides the most stringent limit on an atomic electric dipole moment (EDM). The observation of a permanent EDM would represent a clear signal of CP violation from new physics beyond the Standard Model. Theoretical calculations for ^{199}Hg are very difficult and give varied predictions for the excited-state spectrum. Understanding the E2 and E3 strengths in the neighbouring even-even isotopes of mercury will make it possible to develop a nuclear structure model for the Schiff strength based on these matrix elements, and thereby constrain present model predictions of the contribution of octupole collectivity to the Schiff moment of the nucleus.

1 Introduction

Recently there is a growing interest in particle and atomic electric dipole moments (EDMs) within the nuclear physics community. This interest originates from the desire to understand the fundamental symmetries in the laws of physics and the origin of matter in the universe. All experimental evidence to date supports that CPT is a true symmetry of nature, known as the CPT Theorem [1]. The CPT transformation is the combination of three fundamental symmetries, namely the charge conjugation transformation (C), parity transformation (P), and time-reversal transformation (T). A particle EDM is odd under both the P and T transformations, therefore a permanent EDM for an elementary particle or atom can only arise from parity and time-reversal violating fundamental interactions. A direct violation of the time-reversal symmetry is equivalent to a violation in the charge conjugation and parity symmetry (CP) via the CPT Theorem. CP violating processes are essential for baryogenesis, the physical processes responsible for producing the asymmetry between baryons and antibaryons in the early universe, as first illustrated by Sakharov in 1967 [2]. In the Standard Model there are two mechanisms which incorporate CP violation, namely the weak interaction flavour mixing represented by the complex phase δ_{CKM} of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, and the vacuum expectation value of the QCD gluon field (θ_{QCD}). These sources of CP violation are not sufficient to account for the observed asymmetry between matter and anti-matter in our universe. Additional

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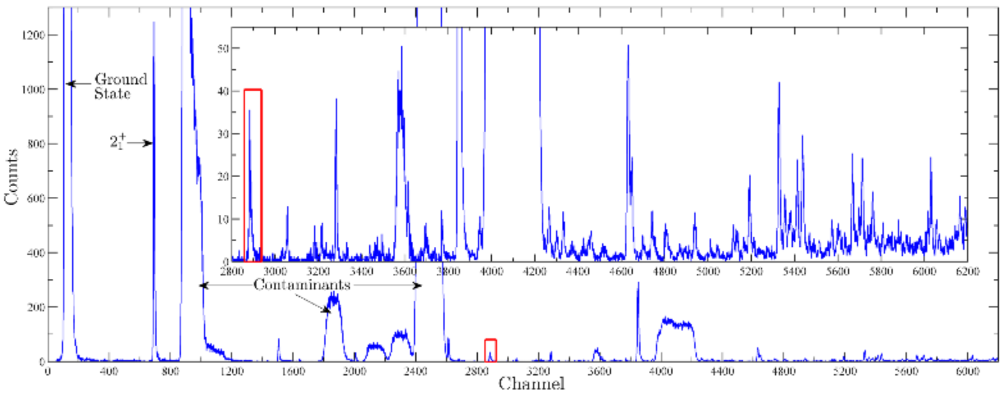

Figure 1. Focal-plane energy spectrum from the inelastic scattering of 22 MeV deuterons on an isotopically enriched target of ^{200}Hg^{32}S at 40°, spanning an excitation energy of approximately 6 MeV.

sources of CP violation are required and provide a strong motivation to search for new CP violating physics beyond the Standard Model.

Despite over half a century of searching with ever-evolving experimental sensitivity, no permanent non-zero particle or atomic EDM has been detected. However, current theories beyond the Standard Model, such as multiple-Higgs theories, left-right symmetry, and supersymmetry (SUSY), generally predict EDMs within current experimental reach [3]. Furthermore, present upper limits on the EDMs or the neutron, electron and ^{199}Hg atom have already significantly reduced the parameter spaces of these models. Currently the upper limit on the EDM of the ^{199}Hg atom provides the most stringent limit on many possible CP-violating terms [4].

Measuring an EDM in a neutral atom is complicated by orbiting atomic electrons, which would arrange themselves to exactly cancel an EDM if the nucleus were a point-like object. Fortunately nuclei have a finite size and the screening effect does not completely cancel the observable atomic EDM. The intrinsic Schiff moment, the lowest order time-reversal odd moment of a nucleus that is measurable in a neutral atom [5], is a measure of the difference between the charge and dipole distributions of the nucleus. It is responsible for inducing the observable atomic EDM in the electron cloud of the atom.

Recent theories and experiments suggest that some of the light actinides have octupole deformed nuclei [6, 7]; the Schiff moment in these systems would be enhanced due to the existence of close-lying parity doublet states [8]. Large E3 strengths between states in ^{199}Hg would also be a signature of enhanced octupole matrix elements. To understand the distribution of Schiff strength in ^{199}Hg we need to know which $\frac{1}{2}^+$ states decay to the $\frac{1}{2}^-$ ground state via E1 transitions. The assumption is that these excited $\frac{1}{2}^+$ states are connected to excited $\frac{5}{2}^+$ states via E2 transitions, and that these states have a strong E3 transition to the ground state. Measuring the E1, E2, and E3 transition strengths would provide detailed set of data to constrain present model predictions of the contribution of octupole collectivity to the Schiff moment of the nucleus.

2 Experimental Program

It is difficult to fully measure these matrix elements in the odd-A ^{199}Hg nucleus due to the high level density. Fortunately, complimentary information is obtainable from the even-even neighbours

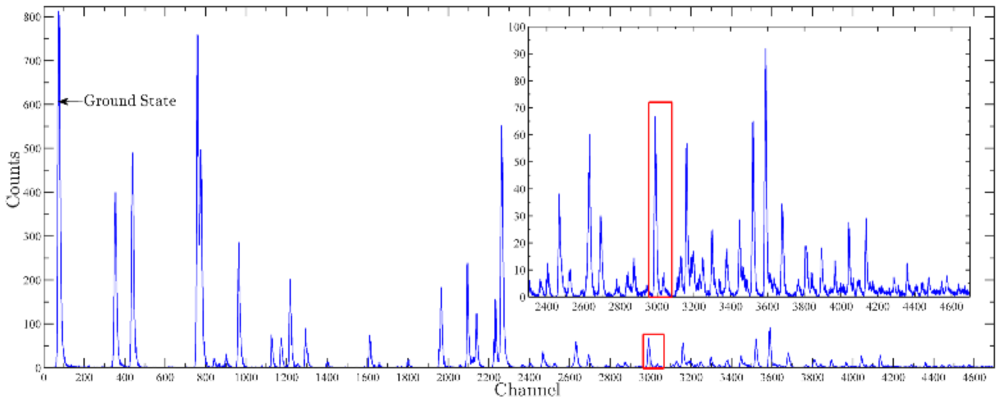

Figure 2. Focal-plane energy spectrum from the (d, t) neutron pickup reaction of 22 MeV deuterons on an isotopically enriched target of $^{200}Hg^{32}S$ at 50°, spanning an excitation energy of approximately 3 MeV.

^{198,200}Hg. The most precise way of measuring E2 and E3 matrix elements which connect the excited states to the ground state is by inelastic hadron scattering and our collaboration is currently pursuing a program of inelastic scattering experiments that will improve on previous measurements. These experiments are being performed using the Q3D spectrograph at the Maier-Leibnitz Laboratory (MLL), a joint facility of Ludwig-Maximilians-Universität München (LMU) and the Technische Universität München (TUM). Additionally, single-nucleon transfer reactions on the even-even isotopes of mercury can yield important information on the single-particle nature of ^{199}Hg. E1 strengths will be determined in experiments at the University of Kentucky using the $(n, n' \gamma)$ reaction.

3 Results and Discussion

The work presented here comprises two experiments using a 22 MeV deuterium beam impinging on an isotopically enriched target of $^{200}Hg^{32}S$. The first experiment is an inelastic deuteron scattering experiment, ^{200}Hg$(d, d')^{200}$Hg, where reaction products were measured at 20 angles ranging from 10° to 115° up to an excitation energy of approximately 6 MeV. The second experiment is a single-nucleon transfer reaction into ^{199}Hg, ^{200}Hg$(d, t)^{199}$Hg, and includes 10 angles from 5° to 50° up to an excitation energy of approximately 3 MeV.

A typical energy spectrum for the inelastic scattering of 22 MeV deuterons on an isotopically enriched target of $^{200}Hg^{32}S$ is shown in Figure 1. The resulting energy resolution for this spectrum is approximately 8 keV FWHM. Figure 2 illustrates a (d, t) neutron pickup reaction from 22 MeV deuterons on the same target. An average energy resolution of 7 keV FWHM is observed. Experimental cross-sections and preliminary distorted wave Born approximation (DWBA) calculations are shown in Figure 3. Figure 3.A. compares experimental cross-sections for the elastic scattering of 22 MeV deuterons on ^{200}Hg to two DWBA calculations using the An and Cai [9], and Daehnick, Childs, and Vrcelj [10] deuteron global optical-model parameter (OMP) sets. Figure 3.B. shows experimental cross-sections for the (d, t) reaction into ^{199}Hg for various L transfers. The experimental data are compared with DWBA calculations using the An and Cai [9] incoming deuteron and Li, Liang, and Cai [11] outgoing triton global OMP sets. The DWBA angular distributions were calculated using FRESCO [12], and reproduce the experimental data very well. The analysis for these experiments is ongoing.

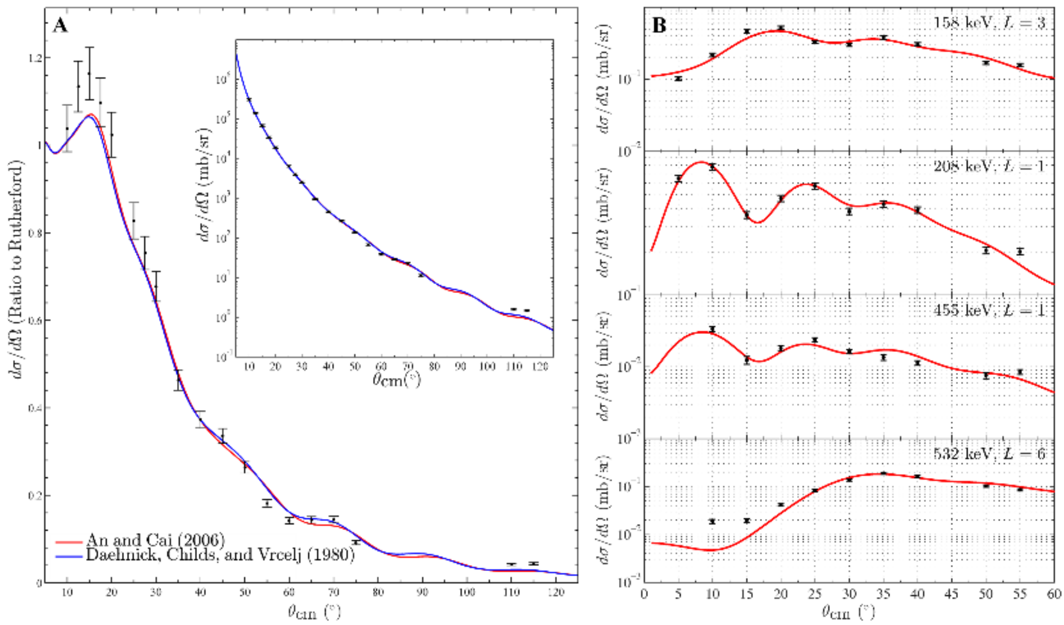

Figure 3. **A**. Experimental cross-sections for the elastic scattering of 22 MeV deuterons on ^{200}Hg compared with two FRESCO DWBA calculations using different global OMP sets. The main figure is plotted as a ratio to Rutherford scattering, whereas the inset figure is plotted on an absolute cross-section scale. **B**. Experimental cross-sections for the (d, t) reaction into ^{199}Hg for various L transfers compared with FRESCO DWBA calculations.

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