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TITLE NUCLEAR TRANSITIONS INDUCED BY ATOMIC EXCITATIONS

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Nuclear transitions induced by atomic excitations

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ABSTRACT

In the two-step pumping scheme for a gamma-ray laser, an essential step is that of exciting the nucleus from a long-lived storage isomer to a nearby short-lived state that then decays to the upper lasing level. An experiment is in progress to induce this transfer by first exciting the atomic electrons with UV photons. The incident photons couple well to the electrons, which then couple via a virtual photon to the nucleus. As a test case, excitation of the ^{235}U nucleus is being sought, using a high-brightness UV laser. The excited nuclear state, having a 26-minute half-life, decays by internal conversion, resulting in emission of an atomic electron. A pulsed infrared laser produces an atomic beam of ^{235}U which is then bombarded by the UV laser beam. Ions are collected, and conversion electrons are detected by a channel electron multiplier. In preliminary experiments, an upper limit of 7×10^{-5} has been obtained for the probability of exciting a ^{235}U atom in the UV beam for one picosecond at an intensity of about 10^{15} W/cm². Experiments with higher sensitivities and at higher UV beam intensities are underway.

1. INTRODUCTION

In the two-step pumping scheme for a gamma-ray laser,¹ most of the energy required for a population inversion would be stored in long-lived nuclear isomeric states. The isomeric nuclei would be separated and implanted in a solid host to support the Mossbauer effect. To achieve superradiance, the isomers would be "gently" excited to nearby (less than a few hundred eV) short-lived nuclear states (interlevel transfer) that would then spontaneously decay to upper lasing levels. Achieving this interlevel transfer without overheating or damaging the host is a key problem to overcome before demonstrating such nuclear lasing.

For the case of photon excitations, high-intensity sources are available only for relatively low quantum energy, and it is difficult to couple a near-visible-

wavelength photon directly with the relatively much smaller nucleus. A promising solution is to couple the photon energy into the atomic electrons so that the electrons excite the nucleus via a virtual photon.^{2,3,4} The incident photons couple well to the electrons, and since the nucleus is in the near field of the electrons, there is not a wavelength-radius mismatch. With current high-brightness lasers the electric field of the laser beam is of the same order as the electric field binding the electrons to the nucleus. The nonlinear spatial and temporal response of an atom to such laser fields can lead to amplification of the laser field at the nucleus, to production of harmonics of the driving field, and to fields at the nucleus of multipolarity higher than one. It is expected that laser intensities of the order of 10^{17} W/cm² will be required to excite a nucleus with significant probability.

In addition to the possibility of finding an interlevel transfer mechanism (the heating problem may not in the end be resolved), this work may find applications in the search for nuclear states lying close to isomers, another key gamma-ray laser problem. Also, this study initiates new research: multiphoton absorption leading to nuclear excitation.

To investigate laser-atomic-nuclear coupling, we are searching for excitation of the ²³⁵U nucleus via a high-brightness UV laser.⁵ The signature for exciting a metastable state is delayed nuclear radiation. In the first phase of the experiments, the nuclear excitation is sought in a collision-free environment, to facilitate interpretation of the results: the nucleus is to be excited only by electrons of its own atom. The ²³⁵U nucleus was chosen for the first experiment, as it has the lowest known first-excited-state energy of any nucleus, 76 eV. The ²³⁵U ground state has spin and parity $7/2^-$; the first excited state, $1/2^+$. The excited state, having a 26-minute half-life, decays by internal conversion, resulting in emission of an atomic electron. These conversion electrons have a distribution of energies, peaking below 10 eV and extending to 76 eV.

2. EXPERIMENTAL METHOD

One of the difficulties in performing this experiment lies in the short range of these very low-energy internal conversion electrons. After irradiation by the UV laser, the uranium atoms are deposited on a surface. If the deposit is too thick, most of the conversion electrons will not exit the surface. As it is difficult to make an atomic vapor pulse of less than a microsecond in duration, whereas the ultraviolet laser pulse is only 1 picosecond long, it is necessary to select only the atoms that have interacted with the UV beam in order to achieve high sensitivity. The ions

made by the UV beam are swept out of the atomic vapor with an electric field. Little loss of yield results, as essentially all of the atoms that see the intense region of the UV laser beam lose at least one electron.

The scheme of the experiment is thus to bombard a vapor of ^{235}U atoms for about 30 minutes with a high-field ultraviolet laser, collect ions formed, turn off the lasers, and detect delayed electrons from the nuclear decay. Two preliminary measurements have been made, the first at the University of Illinois at Chicago, in collaboration with T. S. Luk, C. K. Rhodes, and their group, the second at the Los Alamos Bright Source. In both cases, measurements were made with vapors of ^{235}U and ^{238}U (as a control).

In the first measurement, the 248-nm high-brightness UV beam was produced by the University of Illinois at Chicago KrF⁺ laser system, operating with a pulse energy of 13 mJ, pulse width of 1 ps, and repetition rate of 10 times per second. This beam was focused into the interaction region with a 25 cm lens. A calibration of the beam intensity was obtained by measuring the distribution of charge states formed by the UV laser in a low-pressure xenon gas, in a separate ion time-of-flight apparatus. This distribution indicated that the intensity was 2×10^{15} watts/cm², in fact over an order of magnitude below that for which we expect the nuclear excitation to be observable.

The ^{235}U vapor was formed by laser vaporization. A 1.5 mm diameter, 6 mm long ^{235}U wire was supported in a small tantalum collet in vacuum. A Nd:YAG (IR) laser with a pulse energy of 100 mJ and a pulse width of 200 microseconds was focused onto the end of the wire and triggered just before the UV laser. The timing between the two beams was optimized by maximizing the number of ions formed. The density of the ^{235}U vapor was estimated by comparing the charge collected with both the IR and UV laser beams on, with that (produced from background gas) collected with only the UV beam on (assuming the average charge state to be the same in the two cases). Background gas pressure, typically 2×10^{-6} torr, was measured with an ion gauge. The uranium pressure during the UV laser pulse was estimated to be 10^{-4} torr.

Two 4 cm diameter plates, spaced 1 cm apart, were centered on the interaction region, one biased at +6 kV, the other at +3 kV. Ions were collected through a 1 mm diameter aperture in the 3-kV plate. A rotatable catcher wheel, at ground potential, was connected to a charge-sensitive preamplifier and amplifier for charge integration. Calibration of this charge collection system was achieved by measuring the output voltage when the preamplifier was connected to a silicon detector looking at alpha particles of known energy. Typical collection from one UV pulse was

2×10^6 charges. Ions collected during the 30-minute laser bombardment were afterwards rotated to a point 6 mm from the front cone of a channel electron multiplier (CEM). The CEM counts were multiscaled to map out the decay curve, using a CAMAC-based scaler system run with an IBM PC-AT. Prior to the laser-based measurements, the systematics of the CEM and data acquisition system were checked by depositing ^{235}U isomers emitted from a ^{239}Pu source onto a catcher that was subsequently positioned in front of the CEM. During the laser-based measurements, continued operation of the CEM was monitored by placing a spare ^{235}U wire in front of the CEM and looking at alpha particles. This wire was mounted on the rotatable catcher wheel, but its radiations were blocked from the CEM during conversion electron measurements.

For the second measurement, at Los Alamos, the UV beam parameters and the vaporization laser parameters were similar, except that the UV repetition rate was 3 times per second, and the vaporization laser was pulsed only once every 15 UV pulses (an optimized IR laser was temporarily unavailable). In this case the rotatable catcher wheel was replaced by a transfer rod that moved the collected ions to a separate vacuum chamber where the CEM was isolated. This configuration is shown in Figure 1. The time-independent background was reduced by a factor of 100 over the Chicago configuration, and the transient background believed to come from exoelectrons⁶ was also greatly reduced.

3. RESULTS

The count rate shows a rapid fall-off with a decay time of a few minutes, and some variation of the background at later times, presumably from exoelectron emission. There is no evidence for a 26-minute component. Control measurements were also made with a ^{238}U wire. No isotopic dependence was observed.

Using the CEM efficiency measured with the ^{239}Pu source, it is found that a ^{235}U atom in a 2×10^{15} W/cm² (peak intensity in the focal volume) laser beam for 1 picosecond has an excitation probability of less than 7×10^{-5} .

4. CONCLUSIONS

An upper limit has been placed on the nuclear excitation probability at a UV laser intensity of the order of 10^{15} W/cm². Higher brightnesses are expected to be required before nuclear excitations are observed, since the excitation probability is anticipated to increase as a high power of the intensity of the laser field.

5. FUTURE WORK

A paraboloid mirror has now been added to the system, designed to attain 10^{17} W/cm², and a 35-microsecond-pulse-length CO₂ vaporization laser that can be pulsed at the UV laser repetition rate has been installed. Measurements are continuing.

6. ACKNOWLEDGMENTS

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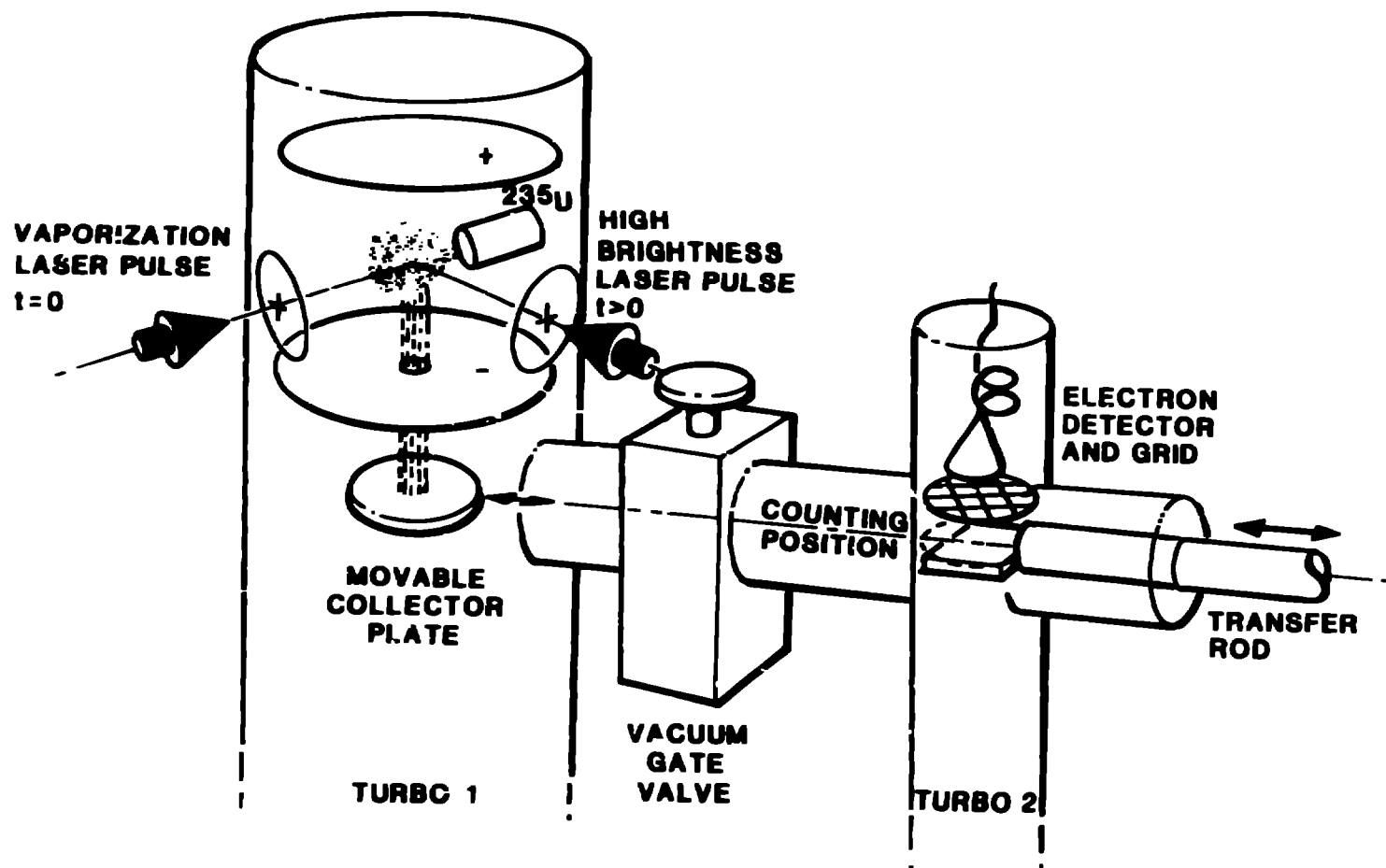


Figure 1. Schematic diagram of the experiment.