

## Laser-Induced Nuclear Orientation of $1\text{-}\mu\text{s}$ $^{85}\text{Rb}^m$

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Frequency-resolved laser-induced gamma-ray anisotropy has been achieved and used to measure the  $D_1$  hyperfine structure of the  $1\text{-}\mu\text{s}$  isomer  $^{85}\text{Rb}^m$ . The magnetic dipole moment obtained is  $(6.046 \pm 0.010)\mu_N$  and the isomer shift relative to  $^{85}\text{Rb}$  is  $-52 \pm 9$  MHz. The experiment was performed with a sealed cell containing radioactive  $^{85}\text{Kr}$  (3 mCi) and natural Rb ( $\sim 10$  mTorr). This method is simple and convenient and promises to be of wide usefulness.

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We report the use of laser optical pumping of atoms with unstable nuclei to orient the  $\frac{9}{2}^+$   $1\text{-}\mu\text{s}$  nuclear level of  $^{85}\text{Rb}$  ( $^{85}\text{Rb}^m$ ) and produce anisotropy in the ensuing 514-keV gamma decay. The  $^{85}\text{Rb}^m$  atoms are produced in a cell via beta decay of 10.7-yr  $^{85}\text{Kr}$ . The atomic hyperfine (hf) structure of the  $D_1$  line is resolved with large signal-to-background ( $S/N$ ) ratio, yielding values for the nuclear magnetic moment of  $(6.046 \pm 0.010)\mu_N$  and the isomer shift, relative to ground state  $^{85}\text{Rb}$ , of  $-52 \pm 9$  MHz. The lifetime of this nucleus is a thousand times shorter than that of any previously studied by optical methods, and the average density of  $^{85}\text{Rb}^m$  atoms is less than  $1/\text{cm}^3$ , demonstrating the potential of the technique. Furthermore, this experiment provides a test system for many on- and off-line studies proposed or in progress based on laser interaction with short-lived radioactive species.

The technique, laser-induced nuclear orientation (LINO),<sup>1</sup> is one of the several optical methods being used to study unstable nuclides.<sup>2-4</sup> Of all these techniques, LINO is capable of studying species with the shortest lifetimes. Optical pumping of vapor-phase "isomeric" atoms with tunable laser radiation orients both the atoms and their unstable nuclei. Anisotropic emission of the gamma rays (or other decay products) occurs when the laser frequency is resonant with an hf transition of the isomeric atom. Thus, the profile of anisotropy versus laser tuning gives the atomic hf splittings, from which nuclear moments can be obtained.

Several optical-pumping-anisotropy experiments, performed using lamps, have studied nuclides with lifetimes  $> 1$  s.<sup>5-8</sup> Also, two LINO-type experiments have been performed,<sup>9,10</sup> both on-line at accelerators, both using relatively long-lived (ms) nuclides, and both giving anisotropy profiles with small  $S/N$  ratios; and an experiment on  $^{134}\text{Ba}^m$  is

under way.<sup>11</sup> Off-line (cell) experiments are of interest because they eliminate the need to work at a large facility and offer a more convenient and reproducible environment for studying and optimizing the physical processes producing the anisotropy signals. In a cell experiment the short-lived species is produced by a long-lived parent nucleus. One must then thermalize the short-lived daughter, form neutral, ground-state isomeric atoms, and optically pump them, all before the daughter nucleus decays. In addition, wall sticking of both parent and daughter atoms and other detrimental wall effects must be prevented.

In the present experiments, the cell is filled with 4 Torr of Kr, about one-third of which is  $^{85}\text{Kr}$  (3-mCi activity). The  $^{85}\text{Kr}$  decays by beta emission with a half-life of 10.7 yr. The  $\frac{9}{2}^+$   $^{85}\text{Rb}^m$  isomer is formed with 0.4% branching ratio, the remaining  $^{85}\text{Kr}$  decaying to the  $^{85}\text{Rb}$  ground state. The presence of only one decay gamma ray, at 514 keV, makes detection simple and reduces background problems.

The Kr-Rb system is free of cell-wall effects. The  $1\text{-}\mu\text{s}$  half-life of the  $^{85}\text{Rb}^m$  nucleus assures that it decays on average long before the isomeric atoms reach the walls (mean decay distance  $\approx 100 \mu\text{m}$ ). Thus, neither wall sticking nor wall-induced depolarization affects the  $^{85}\text{Rb}^m$  atoms. The chemical inertness of the Kr parent insures that it too is not affected by the walls. We attribute the excellent reproducibility of our results to the absence of cell-wall effects.

Krypton also serves as an effective buffer. An inert buffer gas is needed to thermalize the fast  $^{85}\text{Rb}^+$  ions produced in the beta decay, and to produce velocity-changing collisions (vcc's). The vcc's make the entire Doppler distribution of  $^{85}\text{Rb}^m$  atoms accessible to optical pumping despite the narrow bandwidth of the lasers,<sup>12</sup> and are needed to

produce large gamma anisotropy signals.

Rapid neutralization of the  $^{85}\text{Rb}^{m+}$  ions requires a collision partner with a large charge-exchange cross section. Resonant charge exchange offers the largest cross sections,<sup>13</sup> and insures that the neutralized atoms are formed in the ground electronic state. Therefore, we placed natural rubidium metal (72%,  $^{85}\text{Rb}$ , 28%  $^{87}\text{Rb}$ ) in the cell, and used an oven to control its vapor pressure. Reference 13 gives a value of  $550 \text{ \AA}^2$  for the Rb-Rb charge-exchange cross section, which yields a mean neutralization time of  $2 \mu\text{s}$  at a background Rb density of  $2 \times 10^{14}/\text{cm}^3$ .

The presence of background Rb vapor introduces additional complications. The  $D_1$  hf absorption lines of natural Rb are a few gigahertz away from the position of the nearest  $^{85}\text{Rb}^m D_1$  hf component [Fig. 1(e)]. These lines are pressure broadened by the 4 Torr of Kr, and resonant Rb-Rb collisions further broaden the lines. These factors produce appreciable absorption by the natural Rb at the  $^{85}\text{Rb}^m$  hf transition frequencies, which attenuates the laser

light available for optical pumping. To make the most effective use of the available light, the cell geometry must be carefully designed to permit substantial optical pumping of atoms everywhere within the cell. Rb-Rb spin exchange also reduces optical pumping, under typical experimental conditions causing a 20% increase in the laser intensity needed to saturate.

The entire experiment is performed on an optical table. The sample cell is a sealed Pyrex cylinder 12 mm in length and 8 mm in diameter. The cell and its oven are placed in a three-axis set of coils which zero the earth's magnetic field and provide a holding magnetic field of 1 G. Two 3-in. NaI gamma-ray detectors positioned 4 in. from the cell measure the anisotropy. One is placed beyond the cell at  $\theta = 0^\circ$  to the laser beam; the other is at the side of the cell at  $\theta = 90^\circ$ .

Two dye lasers tuned to the 795-nm  $D_1$  line, offset in frequency from the  $^{87}\text{Rb}$  Lamb dips by about 3 GHz, are used to optically pump the  $F = 4$  and  $F = 5$   $D_1$   $^{85}\text{Rb}^m$  hf ground state [Fig. 2]. Two

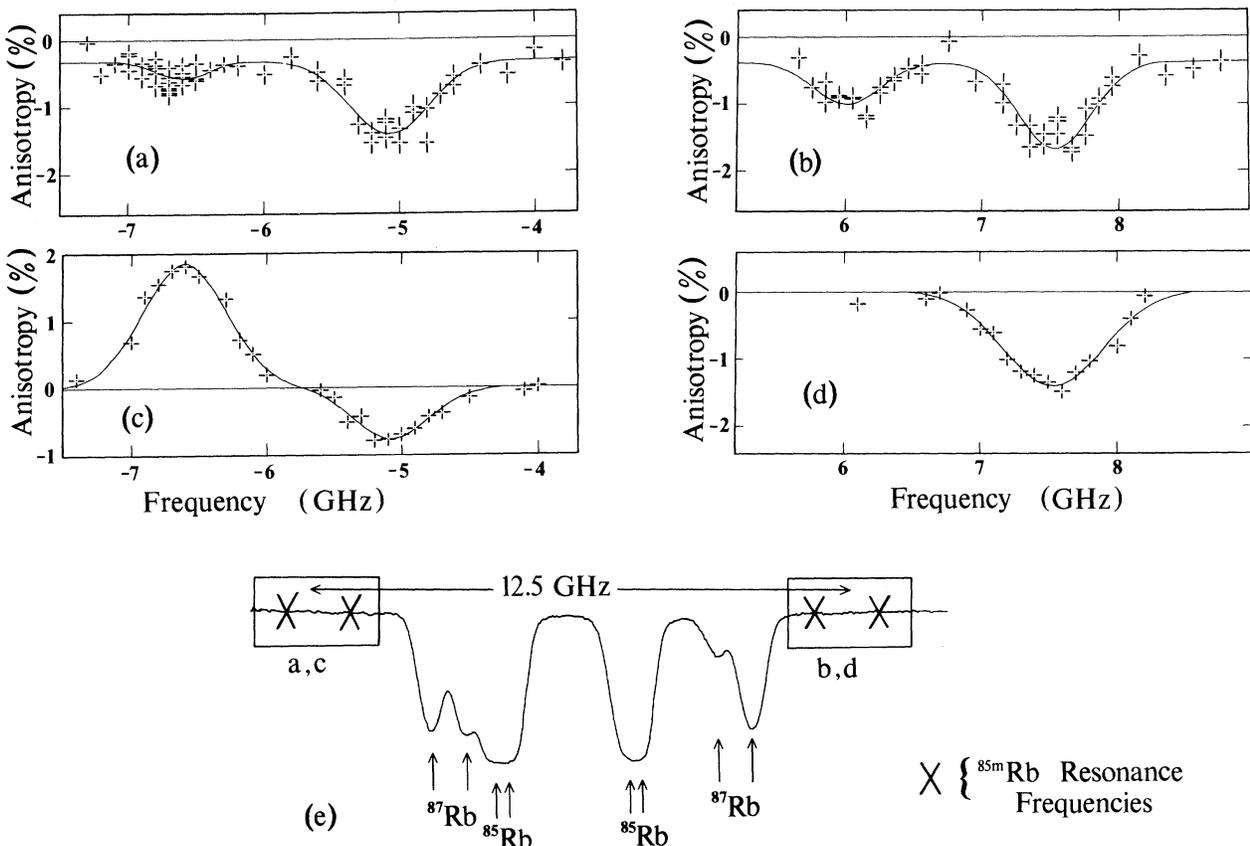


FIG. 1.  $^{85}\text{Rb}^m$  gamma anisotropy resonances, frequencies relative to  $^{85}\text{Rb}$  line center. (a), (b) Circular polarization, both lasers chopped; (c), (d) linear polarization, only scanning laser chopped. (e) Absorption spectrum of natural Rb  $D_1$  hf lines. Positions of the  $^{85}\text{Rb}^m$  gamma resonances are as indicated.

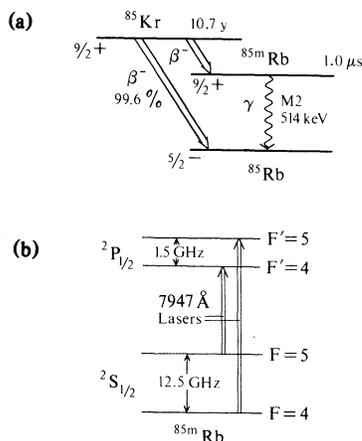


FIG. 2. (a) Nuclear and (b) atomic energy levels. The magnitude and sign of gamma anisotropy is dependent on the optical pumping scheme and laser polarizations used.

lasers are necessary because the ground states are split by 12.6 GHz, which is much larger than the  $D_1$  Doppler width. Therefore, a single laser can pump only one hf ground state, resulting in transfer of population into an unpumped ground state, with a consequent loss of orientation. Such a loss would significantly reduce the gamma anisotropy signal. The two dye lasers are a Spectra-Physics 380A ring laser with Styryl-8 dye, pumped by an argon-ion laser; and a Coherent CR699-21 ring laser with LD-700 dye, pumped by a krypton ion laser. Single-mode powers at the cell are 50–100 mW. Both laser beams are of the same polarization state, either linear or circular.

In the experiments the gamma-ray angular anisotropy,  $A$ , defined to minimize systematic effects, is measured versus laser frequency, with

$$A = \frac{N_{\text{on}}(0^\circ) - N_{\text{off}}(0^\circ)}{N_{\text{on}}(0^\circ) + N_{\text{off}}(0^\circ)} - \frac{N_{\text{on}}(90^\circ) - N_{\text{off}}(90^\circ)}{N_{\text{on}}(90^\circ) + N_{\text{off}}(90^\circ)}$$

Here,  $N_{\text{on}}(\theta)$  and  $N_{\text{off}}(\theta)$  denote the number of counts obtained in the detector oriented at angle  $\theta$  to the laser beam propagation direction with the lasers on and blocked, respectively. The anisotropy is initially maximized by tuning one laser to optimize the signal, and then tuning the second laser to achieve an overall maximum with the first laser frequency fixed. An oven temperature of  $\sim 160^\circ\text{C}$  (Rb atom density  $= 1.5 \times 10^{14}/\text{cm}^3$ ) appears to optimize the trade off between the fast charge exchange and the combined effects of background

rubidium-vapor absorption and spin exchange. The maximum anisotropy is  $A = 2.0\%$ , measured with a count rate of  $\geq 10^3/\text{s}$ , which gives a  $S/N$  ratio of about 20 in a few minutes of counting time (Fig. 1). These results agree with calculations using the known radiative lifetime, the expected charge-exchange cross section, and estimates of the optical pumping saturation intensity and vcc rate.

After the anisotropy is maximized, one laser is scanned in 100-MHz steps to obtain a spectrum. For each frequency  $\sim 7 \times 10^5$  counts are accumulated in  $\sim 10$  min to yield an anisotropy with a standard deviation of  $\pm 0.12\%$ . All frequency detunings are determined with respect to a natural-Rb reference cell which uses a Lamb-dip (saturation resonance) configuration to locate  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  optical resonances with a precision of a few megahertz. Detuning is calibrated using Fabry-Perot interferometer markers. Frequency drift during a counting period is less than 30 MHz in one laser and 10 MHz in the other.

Figure 1 shows spectra obtained by scanning each of the lasers while holding the other one fixed at the frequency for maximum anisotropy. (A small baseline anisotropy is present in the data taken with circularly polarized light, as both beams were chopped and one laser was always on resonance.) All data were fitted to Gaussian line shapes using the  $^{85}\text{Rb}^m$  ground-state hf splitting and  $^{85}\text{Rb}^m$ - $^{85}\text{Rb}$  isomer shift as the two parameters. The raw results are  $12606 \pm 18$  MHz for the ground-state hf splitting, and  $-88 \pm 8$  MHz for the isomer shift. Small corrections must be applied, since the absorption of pump light by the natural Rb varies across the anisotropy-resonance width, causing shifts in the center positions of the anisotropy profiles. Also, the isomer shift must be corrected for the Rb-Kr pressure shift ( $-8$  MHz/Torr). The final result is  $12557 \pm 20$  MHz for the ground-state hf splitting, and  $-52 \pm 9$  MHz for the isomer shift. Assuming zero magnetic hf anomaly, comparison with the ground-state hf splitting of  $^{85}\text{Rb}$  gives the  $^{85}\text{Rb}^m$  nuclear magnetic moment as  $(6.046 \pm 0.010)\mu_N$ . This result agrees with the value obtained by Bartsch *et al.* using the method of perturbed angular distributions,<sup>14</sup> but disagrees with the result of Heubes *et al.*<sup>15</sup> Following the analysis of Thibault *et al.*,<sup>16</sup> we obtain from our measured isomer shift a deformation parameter of  $\langle \beta^2 \rangle^{1/2} = 0.22$ .  $^{85}\text{Rb}^m$  is the only one of seven measured Rb isomers which is more deformed than its corresponding ground state; its mean-square charge radius is very close to that of  $^{81}\text{Rb}^m$ ,<sup>16</sup> the only other  $g_{9/2}$  single-particle Rb isomer studied.

We are currently working to determine the experimental parameters, laser intensities, cell geometry, and pressures needed to optimize the  $S/N$  ratio of our anisotropy signal. We hope to study gamma-ray anisotropy spectra with sub-Doppler resolution. We also plan to measure the splitting of the hf components of the  $D_2$  line, and thus determine the electric quadrupole moment of the  $^{85}\text{Rb}^m$  nucleus. Improved anisotropy signals may also permit a quantitative measurement of the cross section for charge exchange between Rb and  $\text{Rb}^+$  at thermal energies. Because there are no measurements of such charge-exchange cross sections below a few electron volts,<sup>13</sup> this result should be extremely interesting as a check on how well theories of charge exchange extrapolate to such low energy. Further refinements in this experiment may also permit tuning of the 514-keV gamma rays over a 1-eV-energy range.<sup>17</sup>

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