RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 52, NUMBER 2 AUGUST 1995

Laser oriented ^{36}K for time reversal symmetry measurements

A. R. Young, W. S. Anderson, F. P. Calaprice, G. D. Cates, G. L. Jones, D. A. Krieger, and R. B. Vogelaar
Physics Department, Princeton University, Princeton, New Jersey 08544

(Received 29 September 1994)

We have produced very large nuclear alignments in radioactive ^{36}K (half-life 0.34 sec) through laser optical pumping techniques. The ^{36}K was created through (p,n) reactions using a 50 nA, 22 MeV proton beam, and a 3.3 atmosphere ^{36}Ar target. Measurements were made with the target cell at room temperature, when direct optical pumping produces nuclear orientation in the ^{36}K, and at elevated temperatures 160 °C and 180 °C) where the ^{36}K is oriented through a combination of direct optical pumping and spin exchange. The fraction of the maximal nuclear alignment for the 180 °C data was determined to be 0.46 ± 0.07 stat±0.05 syst through measurements of the γ-ray anisotropy following positron decay. Roughly 10^5 or more decays of oriented ^{36}K occurred each second. The application of the superallowed decay of ^{36}K to measurements of time-reversal symmetry in β decay is discussed.

PACS number(s): 29.25.Pj, 23.40.Bw, 24.80.Dc, 27.30.+t

In this paper we report the first production of large nuclear alignment (tensor polarization) in ^{36}K through laser optical pumping techniques. In particular, we explore both direct optical pumping and orientation primarily through spin exchange with optically pumped natural K. Our choice of ^{36}K is motivated by its suitability for tests for time reversal (T) invariance in β decay as well as its amenability to laser orientation techniques. We demonstrate that laser oriented sources of ^{36}K can be produced with large alignment and source strength, in spite of its extremely short half-life (0.34 sec).

Improving the sensitivity of experimental tests of time reversal (T) invariance in nuclear β decay is important because the phenomenon of CP violation is not yet well understood, and the observation of a violation of T symmetry in nuclear systems would signal new physics beyond the standard model [1]. A simplified decay scheme for ^{36}K and a sample spectrum from our intrinsic Ge detectors is depicted in Fig. 1. We suggest that the superallowed decay branch to the 6.61 MeV, 2^+, $T=1$ level is potentially a good candidate for tests of T invariance. Decays to this branch result in the prompt emission of several γ rays, enabling one to measure the fivefold angular correlation proportional to (for an $E1\gamma$ transition) $E\mathbf{J}\cdot(\mathbf{p}_e\times\mathbf{k})(\mathbf{J}\cdot\mathbf{k})$, where $\mathbf{J}$ is the nuclear spin, $\mathbf{p}_e$ is the electron momentum vector, $\mathbf{k}$ is the photon momentum vector, and E is a coefficient characterizing the size of the T noninvariant effect [2]. The appearance of $\mathbf{J}$ twice in the above vector formula indicates that this correlation is proportional to the alignment of the nuclear spin substates. Because this is a β decay between isobaric analog states, such a measurement provides an effective method for detection of a T noninvariant phase through the interference terms between the Fermi and Gamow-Teller amplitudes present in this decay. The strong β decay branch to the 1.97 MeV, 2^+ level in ^{36}Ar is a pure Gamow-Teller decay, which results in γ emission as well. This branch, which is expected to be relatively insensitive to T violation [3], can serve as a test of angular correlations measurements designed to detect a T noninvariant phase.

The experimental apparatus is depicted in Fig. 2. A 50 nA, 1 mm diam, 22 MeV proton beam is passed through a spherical glass target cell, 2.5 cm diam, containing 3.3 atm of ^{36}Ar, a few milligrams of natural K, and about 500 Torr of nitrogen. An important feature of this paper is that the beam-generated radioactive ^{36}K is effectively trapped at the location at which it is created because of the high pressures in the target cell. The characteristic time for a K atom created at the center of the cell to diffuse to the cell wall is many ^{36}K half lives. The cell is placed in a glass oven, designed to provide heating by immersing it in a flow of hot air. Data were taken at temperatures of 33 °C, 160 °C, and 180 °C.

In this paper we have exploited two mechanisms to orient radioactive ^{36}K: direct optical pumping and spin exchange with polarized natural K. At 33 °C, the direct optical pumping rate is about 6×10^4 Hz per ^{36}K atom, and the spin exchange rate is negligible (see Table I for the natural K densities in the cell). At 180 °C, the direct optical pumping rate is only about 2×10^4 Hz because the laser radiation is attenuated by the natural K in the cell, whereas the spin exchange rate is about 9×10^4 Hz. Thus, for a reasonably high K polarization (certainly attained in this paper), the orientation of the ^{36}K should proceed predominantly by spin exchange. The inclusion of natural K to effect ^{36}K—natural K spin exchange also helps neutralize ^{36}K ions by resonant charge exchange [4] and virtually guarantees the establishment of a well-defined spin temperature. The presence of a well-defined spin temperature ensures that large ^{36}K polarization will correlate to large higher rank orientations [5].

Laser photons are produced by a Ti:sapphire laser pumped by an Argon-ion laser. The laser beam is passed through a circular polarizer, expanded to fill the target cell, and directed into the cell parallel to an applied magnetic field of 15 Gauss. The laser is tuned to the $D1$ line (769.9 nm), and the laser linewidth, together with the effects of pressure broadening [6], ensures that all of the K isotopes considered in this experiment are optically pumped. At the cell there is an estimated 2.5 W of laser power available for optical pumping.

Two 80 cm^3 germanium detectors, one placed along the magnetic field axis and one at nominally 90° to the axis, were used to determine the intensities of the γ-ray flux from the ^{36}Ar nuclei. Because of backgrounds while the proton beam is on, we use a data acquisition cycle in which the proton beam is turned on for 0.5 sec, and then, after a 0.02

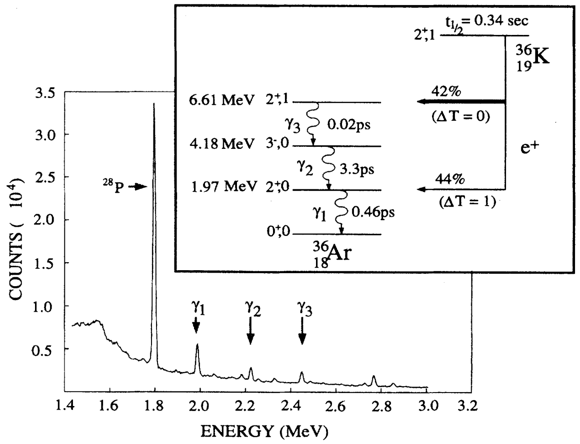

FIG. 1. A portion of the germanium spectrum from our ^{36}Ar target cell is shown, with an inset depicting a simplified decay scheme for ^{36}K. The resolution of the germanium detectors was about 8–10 keV (due primarily to neutron damage) in the region of interest.

sec interval, data are acquired for 0.5 sec. To isolate the effects of the laser induced orientation, the laser beam is modulated as well. An acquisition cycle is performed with the laser on, then with the laser off. Thus, a full data acquisition cycle takes 2 sec to complete.

A typical decay spectrum for ^{36}K measured in our germanium detectors is depicted in Fig. 1. The γ-ray anisotropy for the 180 °C data, or the change in the γ-ray intensity when the laser beam is turned on and off, is depicted in Fig. 3 (corresponding to 18 h of data acquisition). These data demonstrate that a significant degree of nuclear orientation results from illuminating the target cell with laser light. We also note that there was no measurable anisotropy (as expected) in the very strong ^{28}P line (see Fig. 1) at 1.77 MeV which was present because of the ^{28}Si(p,n)^{28}P reaction in the glass walls of the cell. The ratio of the ^{36}K to ^{28}P gamma intensities together with the value for the ^{28}P absolute cross section [7] provides a lower limit to the ^{36}K production of about 10^5 atoms/activation cycle.

The γ-ray emission angular distribution from an oriented sample can be described using the notation of Steffen and Alder [8] (here only dipole and quadrupole gamma transitions are considered):

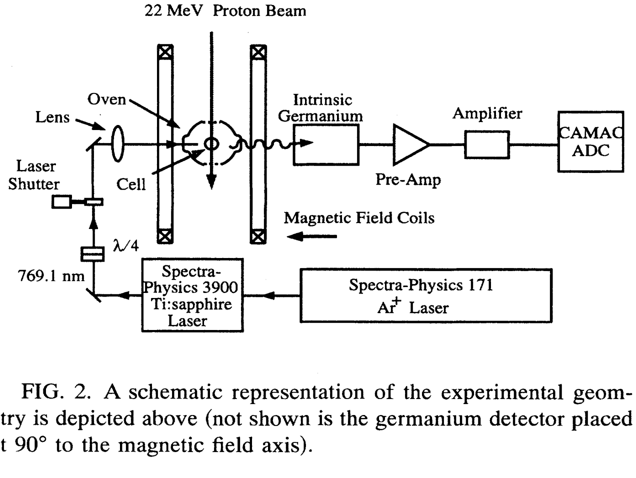

FIG. 2. A schematic representation of the experimental geometry is depicted above (not shown is the germanium detector placed at 90° to the magnetic field axis).

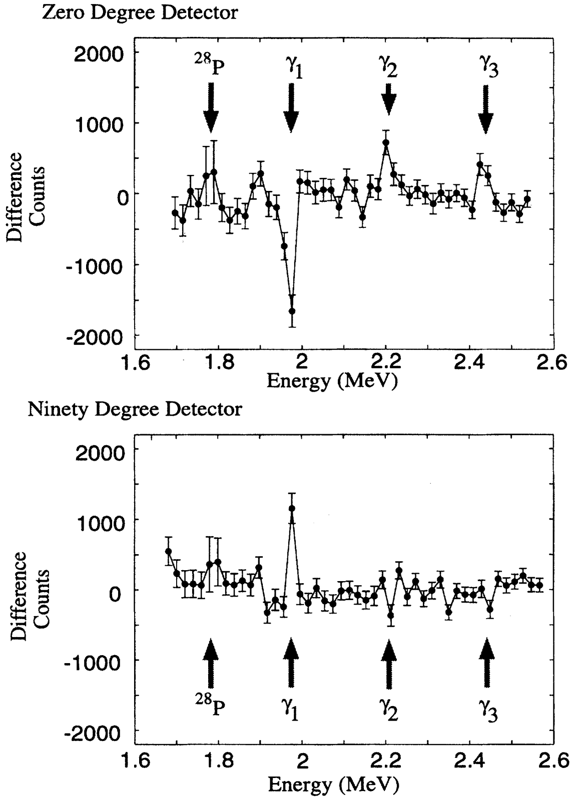

FIG. 3. Shown is the laser on/laser off anisotropy for a portion of the γ spectrum from our target at 180 °C. Labeled is a line from ^{28}P decay, which comes from the glass cell, and lines in the ^{36}Ar daughter of ^{36}K decay. Note that the anisotropies of the ^{36}Ar lines reverse for the 0° and 90° detectors. The line from ^{28}P shows no anisotropy, as expected.

$$W^{\gamma}(\theta)=W_0[1+fB_2U_2A_2Q_2P_2(\cos\theta)+fB_4U_4A_4Q_4P_4(\cos\theta)]. \qquad (1)$$

In the above equation, B_2 is the alignment and B_4 is the "octupole moment" of the nuclear orientation. The factor f is the fraction of the ^{36}K that is in an atomic state which can be optically pumped. A value for f which is less than 1.0 can result, for example, from the possibility that some of the ^{36}K has chemically bonded to the glass walls of the cell or that some of the ^{36}K is in an ionic state. The other terms in the above expression are specific to the given transition: U_n describes the effects of unobserved intermediate β and γ radiation, A_n describes the dependence of the transition on the multipolarity of the gamma ray from the matrix elements, and Q_n describes the effects of finite source and detector sizes ("smear out" effects). The P_n are the Legendre polynomials and θ is the angle between the detector (the gamma-ray's momentum vector) and the quantization axis. Equation (1) was used to compute, for each gamma transition the super-ratio, R_s:

TABLE I. Experimental results.

T °C	K No. density (atoms/cc)	R_s for 1.97 MeV	$\bar{B}_2/\bar{B}_2$ (max)
33 ± 2	1×10^{9}	0.808 ± 0.020	$0.39\pm0.04\pm0.04$
160 ± 2	3×10^{13}	0.822 ± 0.035	$0.36\pm0.08\pm0.04$
180 ± 2	9×10^{13}	0.79 ± 0.026	$0.46\pm0.07\pm0.05$

$$R_s=\left\{\frac{W^{\gamma}_{\text{on}}(0°)}{W^{\gamma}_{\text{off}}(0°)}\right\}\left\{\frac{W^{\gamma}_{\text{off}}(90°)}{W^{\gamma}_{\text{on}}(90°)}\right\}, \tag{2}$$

where $W^{\gamma}_{\text{on(off)}}(\theta)$ is the γ emission rate at $\theta°$ for the laser on(off). R_s is independent, to first order, of the proton beam flux and the detector efficiencies.

The fact that we do not observe complete alignment of the ^{36}K can be attributed to at least two factors: that the spin temperature is not zero (all K atoms in the highest spin state) or that the factor f is less than 1.0. Our strategy is to assume a constant value of f and vary the spin temperature to fit the measured value for R_s. Because f is not determined by this work, we define the quantity $\bar{B}_2\equiv fB_2$, which is effectively the alignment averaged over all the ^{36}K in the cell, including the ^{36}K that cannot be optically pumped. In the limit that the B_4 term in Eq. (1) goes to zero, the value of $\bar{B}_2$ that best fits the data is completely insensitive to the value of f chosen. In our case, the ratio of B_2/B_4 is fixed by the spin temperature. However, for our measurement, the effect of the B_4 term is small (regardless of the value of f), and the systematic uncertainty we observe by allowing f to vary over the entire range permitted by our 180 °C data is less than $\pm7\%$ of the quoted value of $\bar{B}_2/\bar{B}_2$(max). The value of f used was 0.74 ± 0.26, where the uncertainty covers the entire range of f admitted by the 180 °C data.

The two strongest gamma-ray lines (1.97 MeV and 2.43 MeV) in the decay of ^{36}K were used to determine the degree of alignment. The β-decay and γ-decay data in the literature serves to adequately characterize the predicted γ-ray fluxes [10,11], with the notable exception of the ratio $\delta=(M2/E1)$ between $M2$ and $E1$ gamma decay amplitudes in the 2.43 MeV line. The procedure we adopted was to do a least-squares fit to the 180 °C data for both the 1.97 MeV and 2.43 MeV lines while simultaneously varying the spin temperature and the mixing ratio δ in the 2.43 MeV transition. From this procedure we deduce a value of $\delta=0.12\pm0.06$. We note that only the high temperature (180 °C) data were used to determine δ, because it is in this case that the spin-temperature limit is expected to be most reliable.

The Q factors were estimated through a simple computer program based on work by Krane *et al.* [9]. They are very close to one ($Q_2\approx0.99, Q_4\approx0.98$) and show little variation over a very wide range of experimental configurations.

With these values specified we are able to determine the value of $\bar{B}_2$ that best fits our data. The measured values for several temperatures are listed in Table I. The first uncertainty listed is the statistical uncertainty (at the 67% confidence level) and the second is the systematic uncertainty due to the β-decay and γ-ray emission data, the detector geometry f, and the fitting procedure. The largest contributors to the systematic uncertainty were a $\pm7\%$ contribution from a number of small gamma branches which feed the 1.97 MeV line and for which no multipolarity information is known, and $\pm7\%$ from the uncertainty in f. From the data we conclude that we have demonstrated that both direct optical pumping and spin exchange are effective techniques for orienting the short-lived ^{36}K. Our results seem particularly promising when one notes that we have not yet optimized our experimental technique to minimize wall depolarization effects, and yet the measured alignments correspond to polarization of about 70% if $f\approx1$ to nearly 100% if $f\approx0.5$ ($f=0.74\pm0.26$).

We now discuss some of the details of a measurement of T invariance in ^{36}K. The contribution of the E coefficient to the general $\beta-\gamma$ angular distribution has been calculated by several authors [12–14] and the E coefficient itself can be expressed in terms of the decay form factors (with "a" being the Fermi and "c" being the Gamow-Teller form factors) [12]:

$$E=2\left\{\frac{ac}{a^2+c^2}\right\}\sin\phi+\text{higher order terms}, \tag{3}$$

where ϕ is the T noninvariant phase between the decay amplitudes. Using a shell model value [15] of $c=0.13$ for the Gamow-Teller decay strength to the 2^+ state at 6.61 MeV in ^{36}K, one estimates that the $E=0.18\sin\phi$ in ^{36}K decay.

Presently, the most sensitive tests of T symmetry in nuclear β decay have come from studies of the mirror β decays, $n\rightarrow p+e\bar{\nu}$ [16] and $^{19}\text{Ne}\rightarrow{}^{19}\text{F}+e^{+}+\nu$ [17], through measurements of the triple angular correlation $-D\mathbf{J}\cdot(\mathbf{p_e}\times\mathbf{p_R})$, where $\mathbf{J}$ is the nuclear spin, $\mathbf{p_e}$ is the electron momentum vector, and $\mathbf{p_R}$ is the recoil nucleus momentum vector. Here D is now the coefficient characterizing the size of a T noninvariant effect (experiments set a limit of $D<0.6\times10^{-3}$). We note here that $D=-0.52\sin\phi$ for ^{19}Ne decay.

There are several advantages to measurements of the E coefficient in ^{36}K. First, the γ rays resulting from ^{36}K decays are emitted promptly, permitting very high coincidence rates. In contrast, when measuring D coefficients, one measures a slowly recoiling nucleus with a relatively large spread in velocities. Because one must measure β particles in coincidence with these ions, a very long coincidence window is necessary at present, limiting the coincidence rates one can practically attain. Thus, measurements of the E coefficient circumvent one of the technical challenges facing future D coefficient measurements. Second, one can achieve these high coincidence rates (and the necessary nuclear alignment) using the laser orientation techniques demonstrated in this paper and a highly segmented detector array to detect the ^{36}K decays. Finally, ^{36}K is an excellent system from the perspective of evaluating the effects of electromagnetic scattering of the outgoing positron off the fields of the nucleus, also called "final-state" effects. Such scattering can mimic T noninvariance. ^{36}K decays proceed by two main branches; measurements of decays in the mixed branch between isotopic analog states should be sensitive to T noninvariance, while measurements of the pure Gamow-Teller branch should be much less sensitive to T noninvariance. Perhaps more significantly, the final-state effects are also expected to be much smaller (i.e., zero to first order in nuclear recoil amplitudes) in the Gamov-Teller branch [12]. Thus, in one branch, one may effectively measure a "zero," providing the experimenter with a way of evaluating size of spurious effects which can mimic a real asymmetry. We also note that the absolute size of the final-state effects in the mixed branch are favorably reduced by the small size of the weak magnetism form factor (the final-state effects are $\simeq -1.8\times 10^{-4} E_\beta/(E_\beta)_{\max}$) [12].

We conclude by discussing the implications of our work and the work of other authors for T noninvariance measurements. Through the use of high power laser optical pumping, it is possible to create highly oriented, high intensity, low background sources of radioactive nuclei. The use of lasers clearly makes possible what was not practical in the important early work of Otten [18]. In comparing our work with the more recent work of Voytas *et al.* [19] (who performed direct laser optical pumping on beam-generated ^{21}Na), we note that we see a comparable degree of orientation, but we did not observe a reduction in our alignment at early times in our high temperature data (see Fig 4). Even at the earliest times after removing the beam (0–0.125 sec) the measured orientation is consistent with our time-averaged value. The extremely short time required to produce orientation and the high efficiency in producing, orienting, and detecting beam-generated radionuclides make the experimental technique presented here an important alternative to the laser trapping methods pioneered recently [20–22]. Finally, we note that superallowed decays can be studied in a variety of radionuclides using this technique, including ^{20}Na, ^{21}Na, ^{36}K, and ^{37}K.

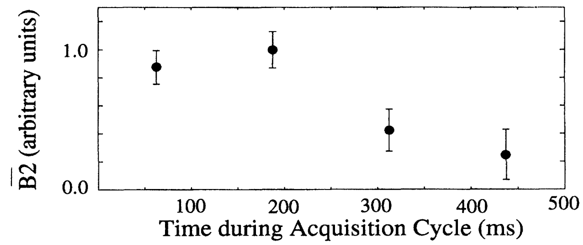

FIG. 4. The time dependence of the alignment for the 180 °C data, binned in 125 ms intervals (no data was acquired during the first 20 ms of the first interval). Convection currents may be partially responsible for a reduction in the alignment seen at longer times.

We are pleased to acknowledge many helpful discussions with Will Happer and the untiring assistance of Steve Kidner and Fred Loeser throughout the work summarized in this paper.

[1] P. Herczeg, in *Precision Tests of the Standard Electroweak Model* (World Scientific, Singapore, 1993).

[2] F. P. Calaprice, S. J. Freedman, B. Osgood, and W. C. Tomlinson, Phys. Rev. C **15**, 381 (1977).

[3] There are several mechanisms which might make heavily hindered Gamow-Teller decays sensitive to T noninvariance [see C. W. Kim and H. Primakoff, Phys. Rev. **180**, 1502 (1968); A. Baroso and R. J. Blin-Stoyle, Phys. Lett. **45B**, 178 (1973)], however the decay in ^{36}K to the 1.97 MeV level is allowed, and therefore E coefficient measurements of this branch should be quite insensitive to T noninvariant phases.

[4] The K-K resonant charge exchange cross section is approximately 3×10^{-14} cm^2 which can be compared to the K-K spin exchange cross section of about 2×10^{-14} cm^2. The charge exchange cross sections are tabulated in S. Sakabe and Y. Izawa, At. Data Nucl. Data Tables **49**, 257 (1991).

[5] W. Happer, Rev. Mod. Phys. **44**, 169 (1972); N. D. Bhaskar, J. Camparo, W. Happer, and A. Sharma, Phys. Rev. A **23**, 3048 (1981).

[6] G. Hull, Phys. Rev. **50**, 1148 (1936).

[7] R. L. Wilson, Phys. Rev. C **13**, 976 (1977).

[8] K. Adler and R. M. Steffen, in *The Electromagnetic Interaction in Nuclear Spectroscopy*, edited by W. D. Hamilton (North-Holland, New York, 1975), p. 552.

[9] K. S. Krane, Nucl. Instrum. Methods **98**, 205 (1972).

[10] C. M Lederer and V. S. Shirley, *Table of Isotopes, Seventh Edition* (Wiley, New York, 1978), pp. 78 and 79.

[11] P. M Endt, Nucl. Phys. **A581**, 360 (1990).

[12] B. Holstein, Phys. Rev. C **5**, 1529 (1972). The weak magnetism form factor for the isobaric analog decay was obtained through private communication with B. A. Brown.

[13] R. B. Curtis and R. R. Lewis, Phys. Rev. **107**, 1381 (1957).

[14] M. Morita and R. S. Morita, Phys.l Rev. **107**, 1316 (1957).

[15] B. A. Brown and B. H. Wildenthal, At. Data Nucl. Data Tables **33**, 347 (1985).

[16] R. I. Steinberg, P. Liaud, B. Vignon, and V. W. Hughes, Phys. Rev. Lett. **33**, 41 (1974).

[17] A. L. Hallin, F. P. Calaprice, D. W. MacArthur, L. E. Piilonen, M. B. Schneider, and D. F. Schreiber, Phys. Rev. Lett. **52**, 337 (1984).

[18] See, for example, E. W. Otten, in *Treatise on Heavy Ion Science*, edited by D. A. Bromley (Plenum, New York, 1989), Vol. 8, p. 517; H. Schweickert, J. Dietrich, R. Neugart, and E. W. Otten, J. Phys. Soc. Jpn. **34**, 164 (1973).

[19] P. Voytas, J. E. Schwew, P. A. Quin, and L. W. Anderson, in *Polarized Ion Sources and Polarized Gas Targets*, AIP Conf. Proc. No. 293, edited by L. W. Anderson and W. Haeberli (AIP, New York, 1994), p. 208.

[20] M. Stephens and C. Wieman, Phys. Rev. Lett. **72**, 3787 (1994).

[21] Z-T. Lu, C. J. Bowers, S. J. Freedman, B. K. Fujikawa, J. L. Mortara, S-Q. Shang, K. P. Coulter, and L. Young, Phys. Rev. Lett. **72**, 3791 (1994).

[22] G. Gwinner, J. A. Behr, S. B. Cahn, A. Ghosh, L. A. Orozco, G. D. Sprouse, and F. Xu, Phys. Rev. Lett. **72**, 3795 (1994).