β-decay Anisotropies of the Mirror Nuclei ^{15}O and ^{17}F

N. Severijns, J. Wouters, J. Vanhaverbeke, and L. Vanneste
Department of Physics, Instituut voor Kern- en Stralingsfysika, Leuven University, B-3030 Leuven, Belgium
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Measurements of the β anisotropy of the mirror nuclei ^{15}O and ^{17}F, using on-line isotope separation and low-temperature nuclear orientation, are reported for the first time. Results of this novel approach are discussed in connection with the study of weak interactions in nuclei.

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Precise measurements of the asymmetry coefficient A_1 in the angular distribution of β particles emitted from oriented nuclei are difficult to perform. Even the famous A_1 β asymmetry of ^{60}Co (the first proof of parity violation) has been reported with high precision only recently.[1] Most values tabulated in the literature are of limited accuracy and often conflicting.[2] Still, reliable β-asymmetry measurements, if performed with sufficient accuracy, allow one to obtain new information in many cases. For the mirror nuclei, they could give valuable information on, e.g., the presence of a $V+A$ component in the weak interaction. Up to now, only two A_1 symmetries of mirror nuclei (besides the neutron) have been reported, viz., those of ^{19}Ne (Ref. 3) and ^{35}Ar.[4,5] The difficulties of these measurements are compounded by the short lifetimes and/or absence of a suitable technique.

During the last decade, a large number of short-lived nuclei have become accessible in on-line conditions. At the start of this same period it was proposed to engage in the study of on-line separated nuclei by nuclear orientation.[6] After an initial period described in other papers,[7] we started particle detection in millidegree environments,[8] which makes it possible to study A_1 asymmetries of β transitions. Previously, we have measured β asymmetries of long-lived nuclei off-line, using semiconductor detectors operating at liquid-N_2 temperature.[9] Now the detectors are at liquid-helium temperature[8] without any thermal radiation shield and therefore without any absorbing material between them and the on-line separated source. This eliminates the energy loss and scattering of the β's that would occur in the radiation shields if the detectors were to operate at higher temperatures.

The first on-line β-anisotropy experiments we report here were performed on ^{15}O ($t_{1/2}=122$ sec) and ^{17}F ($t_{1/2}=65$ sec) with the KOOL facility,[7] which is directly coupled to the LISOL mass separator on-line with the cyclotron CYCLONE at Louvain-la-Neuve. ^{17}F was produced by irradiating a mixture of MgO and Al_2O_3 powders, placed inside a forced electron-beam-induced arc-discharge ion source,[10] with 10-MeV deuterons. For ^{15}O, the graphite catcher of the ion source was bombarded with a 32-MeV α beam. Singly charged ion beams of 10^3–10^4 atm/sec could be extracted from the source. After mass separation the nuclei were implanted continuously, at low temperatures (mK region) and low dose, into a polished and magnetized iron foil that was soldered onto the cold finger of a ^3He-^4He dilution refrigerator, and then cryogenically oriented. The temperature was monitored with a calibrated $^{57}CoFe$ source.

The angular distribution of the positrons emitted in the decay of the oriented nuclei was measured as a function of temperature with two detectors, one at 0° or 180° and the other at 90° relative to the external magnetic field. Both 300-mm^2 Si surface barriers (thickness 300 μm) and 300-mm^2 planar high-purity Ge detectors (thickness 2 and 3 mm) were used. All detectors were specially constructed for work at low temperatures. Their energy resolution and stability while working at 4 K are comparable to those achieved in "normal" operating conditions. For detailed information on the performance of semiconductor detectors at 4 K, we refer to Ref. 11. A cross-sectional view of the bottom of the refrigerator, containing the sample holder, the particle detectors, and the polarizing magnet, is shown in Fig. 1.

The intensity and shape of the β spectra depends on the magnitude of the applied magnetic field. Since we are only interested in anisotropies and therefore normalize the cold (anisotropic) spectra with the warm (isotropic) spectra which were taken under identical conditions

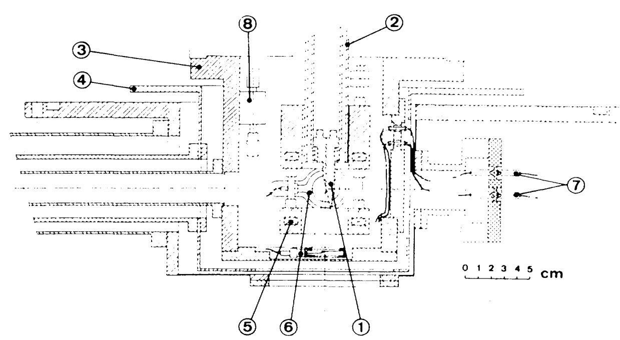

FIG. 1. Cross section of the bottom of the refrigerator. (1) sample holder; (2) 0.6-K shield; (3) 4.2-K shield; (4) 77-K shield; (5) split coil magnet; (6) particle detectors; (7) coaxial signal feedthroughs; (8) 4.2-K baffle driver.

with respect to geometry and external magnetic field, this effect introduces only a higher-order correction. A magnetic field of only 0.093 T was used in order to minimize the error in the emission angle due to the deflection of the β particles, which was calculated to be smaller than the estimated errors in the positioning of the detectors. At energies higher than approximately 1.0 MeV no difference could be detected in the intensity of the β spectra that were obtained in the field of 0.093 T and those obtained in zero field. Scattering and energy loss of the positrons in the source foil was negligible since the most probable penetration depth of 50-kV O and F ions is $\sim 40\ \mu g/cm^2$ and since the foil was tilted 20° towards the axial counter and at the same time rotated over an angle of 13° in the direction of the equatorial counter. Effects of backscattering from the copper-source holder and the walls and interior parts of the experimental chamber were minimized by the relative geometry of the surroundings of the foil. Normalizing the cold spectra with the warm spectra again ensures that eventual effects from scattering can cause errors only in second order. The effect of backscattering from the detectors was limited to $\sim 1\%$ at the midpoint of the spectrum. Finally, we used only the high-energy part of the spectra, where all deviations due to the magnetic field and scattering effects will be minimal. A test measurement on the pure Gamow-Teller (GT) β decay of ^{114}In (end-point energy 2.0 MeV) resulted in a value for the asymmetry parameter A_1 which is in perfect agreement with the theoretical value for this transition, when only the highest-energy tail (100 keV) of the β spectrum was used. A value only 5% smaller was obtained when the last 600 keV of the spectrum were considered. At regular intervals during the experiment the beam was interrupted to take background spectra, which showed no variation with time.

Our experimental anisotropy is given by

$$\frac{W(0 \text{ or } \pi)}{W(\pi/2)} = \frac{[N(0 \text{ or } \pi)/N(\pi/2)]_{\text{cold}}}{[N(0 \text{ or } \pi)/N(\pi/2)]_{\text{warm}}},$$

where $N(\theta)$ is the number of counts detected at an angle θ with respect to the magnetic field and $W(\theta)$ is the normalized angular distribution.[12] The warm counts are taken under isotropic conditions ($T \approx 1$ K). The ratio $N(0 \text{ or } \pi)/N(\pi/2)$ is used to avoid corrections for the short lifetime of both isotopes and for beam instabilities.

Under the assumption of a pure V-A interaction with time reversal invariance, maximal parity violation, and a massless neutrino, the angular distribution for the superallowed β transitions of ^{17}F (1.74 MeV, $\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$) and ^{15}O (1.74 MeV, $\frac{1}{2}^- \rightarrow \frac{1}{2}^-$) can be expressed as[12]

$$W(\theta) = 1 + \alpha \frac{v}{c} A_1 B_1 Q_1 \cos\theta .$$

The asymmetry A_1 of the positrons is written[12,13] as

$$A_1 = \frac{1}{1+y^2} \left(\frac{-1}{[3I(I+1)]^{1/2}} + \frac{2}{\sqrt{3}} y \right),$$

where I is the initial spin of the decay and $y = c_V M_F / C_A M_{GT}$ is the Fermi-Gamow-Teller mixing ratio. The orientation parameter B_1 depends on the magnetic interaction μB, the spin I of the oriented state, and the temperature. Further, Q_1 (=0.989) corrects for the finite solid angle, and v/c is the ratio of the velocity of the emitted positrons to the speed of light. The values used for v/c were always weighted to the actual shape of the spectrum in the energy region under consideration. To take into account the positions of the nuclei in the lattice, we used the two-site implantation model; i.e., α is the fraction of nuclei at good sites, experiencing the full hyperfine field, while the remaining fraction of nuclei is in zero field. Up to now all our on-line nuclear orientation data on sources implanted at low temperatures and low dose can successfully be explained with this model.[14,15]

In the fits of the experimental data points we used for ^{17}F the magnetic-moment value $\mu = +4.7224(12)\mu_N$ (Ref. 16) and the 0-K hyperfine field for fluorine in iron $B_{\text{hf}} = +10.0(1)$ T. This value was extrapolated from a fit of the (substitutional) hyperfine field values obtained for ^{19}F in Fe between 77 and 599 K by Fahlander *et al.*[17] For ^{15}O, the magnetic moment $\mu = +0.7189(8)\mu_n$ (Ref. 18) was used. We observed anisotropies of 25% for both ^{15}O and ^{17}F, at temperatures of 8 and 23 mK, respectively (Fig. 2). The value of the orientation parameter B_1 at these temperatures was 39% and 33%, respectively, of the saturation values. In the ^{17}F experiment the lowest attainable temperature was limited to 22 mK due to the presence of the stable contaminant ^{17}O in the separated beam. Both anisotropies correspond to a normal Boltzmann distribution, indicating a negligible relaxation time. This phenomenon was previously also observed for other nuclei after implantation at low dose into a cold and magnetized iron lattice.[15]

The fits to the ^{17}F data yield $\alpha A_1 = -0.656(56)$. This corresponds to the largest negative value which is theoretically acceptable for spin $I = \frac{5}{2}$ (i.e., -0.683), in-

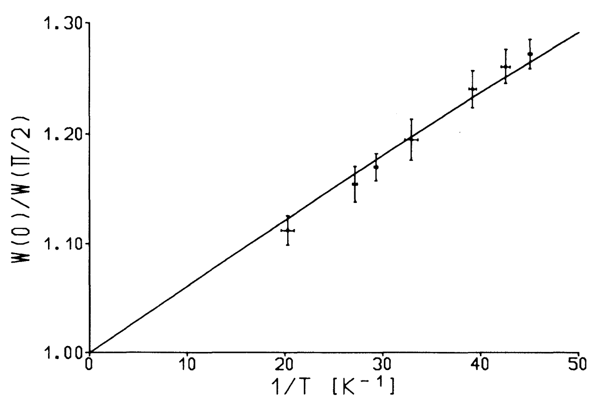

FIG. 2. Experimental β-decay anisotropy for the mirror transition of ^{17}F.

dicating fully substitutional behavior, in agreement with all other isotopes we previously studied under the same experimental conditions.[15] This experimental result is in excellent agreement with the recent large-scale shell-model calculations of Brown and Wildenthal,[19] which lead to an A_1 value of -0.683 using the "effective" GT matrix element.

From the anisotropy measured for ^{15}O, the hyperfine field of oxygen in iron was determined to be +12.4(16) T. Adding this value to the systematics for the 2*sp* elements and comparing this with the theoretical calculations of Akai, Akai, and Kanamori[20] gives support for a substitutional position of the ^{15}O nuclei in the iron lattice.[21] The precision of the hyperfine field value can still be increased significantly (0.1% level) by using the technique of NMR-ON (nuclear magnetic resonance on oriented nuclei), which has recently been shown to be feasible in on-line conditions.[22]

With the setup and analysis method as described, a relative precision of 2% on the asymmetry parameter can be obtained if the interaction μB is known rather accurately (the hyperfine field B is known with a precision better than 0.5% for a large number of elements already). Nevertheless, if one wants to extract limits for the quenching of the axial-vector coupling constant g_A from experimental A_1 values for mirror nuclei, it is in most cases difficult to be competitive with the usually more precise *ft* values, from which these limits can also be obtained. However, the development of this technique provides perhaps the more interesting possibility of a new test for right-handed currents in the weak interaction. Previously, the experimental asymmetry for ^{19}Ne was already used to set limits on the presence of right-handed currents.[23] But, as Deutsch[24] pointed out in a recent paper, there are problems for ^{19}Ne with the sensitivity of A_1 to the parameters δ and ξ (i.e., the mass ratio and the mixing angle of the two eigenstates W_1 and W_2 of the gauge bosons $W_{L,R}$). This sensitivity was recently investigated for all other mirror nuclei up to mass 41,[25] and it turned out that relative precisions for A_1 that are better than 0.5% are needed. However, Quin and Girard[26] recently pointed out that if one could measure the longitudinal polarization of β's emitted by polarized nuclei, the presence of right-handed currents in nuclear β decay can in some cases be tested with up to an order-of-magnitude enhancement in sensitivity compared to measurements for unpolarized nuclei, provided that the asymmetry of the β decay considered is large and that a large nuclear polarization can be achieved. Both ^{17}F and ^{15}O are good candidates for such a polarized nucleus—β polarization correlation experiment. The realization of such an experiment is at present being studied.[27]

With the work presented here, we demonstrated that the A_1 asymmetry of short-lived nuclei can be obtained with reasonable accuracy using on-line nuclear orientation. The case of ^{17}F confirmed the reliability of the technique and good agreement with "complete" shell-model calculations was obtained. Furthermore, the introduction of β-asymmetry measurements in on-line nuclear orientation greatly enlarges the number of nuclei which can be studied with β detection. The method can thus be used to determine numerous nuclear parameters such as, e.g., spins, magnetic moments, and the isospin impurity of medium heavy nuclei with small or no neutron excess. With the determination of the hyperfine field of ^{15}O we showed that, in addition, also solid-state information can be obtained. Finally, the technique creates the possibility for a new and promising test for right-handed currents in the weak interaction.

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[13]Notice that the expression we use for the asymmetry parameter deviates from the one adopted by several other authors, e.g., Refs. 3–5. The difference comes from the fact that they use the formalism of S. R. De Groot, H. A. Tolhoek, and W. J. Huiskamp, in *Alpha-, Beta- and Gamma-Ray Spectroscopy,* edited by K. Siegbahn (North-Holland, Amsterdam, 1968), Vol. 2, p. 1199, to describe the orientation. To be consistent with our definition their values for the asymmetry parameter should therefore be divided by the factor $-(3I/I+1)^{1/2}$.

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