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Communications

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Magnetic moments of $^{125}Te^{m}$, $^{127}Te^{m}$, and $^{129}Te^{m}$

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Nuclear magnetic resonance measurements on oriented nuclei have been performed for $^{125}Te^{m}$, $^{127}Te^{m}$, and $^{129}Te^{m}$ using low temperature nuclear orientation and conversion electron detection. The magnetic moments of the $11/2^{-}$ isomeric states have been extracted as $\mu = -0.985(6)$ for $^{125}Te^{m}$, $\mu = -1.041(6)$ for $^{127}Te^{m}$, and $\mu = -1.091(7)$ for $^{129}Te^{m}$.

[NUCLEAR STRUCTURE $^{125}Te^{m}$, $^{127}Te^{m}$, and $^{129}Te^{m}$: magnetic moments.]

In this paper we report the first magnetic moment determinations with nuclear magnetic resonance measurements on oriented nuclei (NMR/ON) using conversion electron detection as resonance indication. The application of this technique to long-lived isomers has been delayed because these are often associated with strongly converted transitions.[1] Although we introduced, in an early stage, continuous dilution refrigeration to the integral determination of g factors of tellurium isomers,[2] the very low gamma counting rate did not allow resonance detection even in periods of weeks. Therefore, we developed a technique combining continuous low temperature refrigeration, magnetic resonance destruction of orientation, and detection of conversion electrons emitted by samples at millidegree temperatures.

Magnetic moment measurement of tellurium isomers requires much higher accuracy, than is obtainable by integral measurements, especially for two reasons. First, the sample preparation, i.e., implantation by means of isotope separation, has been shown to be a possible source of errors, since it was assumed in earlier work that tellurium sits exclusively on substitutional sites exclusively on substitutional sites in the lattice.

Evidence has been given from Mössbauer experiments,[3] that several sites are present. In principle one could try to account for the distribution of sites on basis of the Mössbauer results, but this introduces such large uncertainties that the moment determination itself becomes somewhat meaningless. These complications can be circumvented through nuclear magnetic resonance on the substitutional site, provided the internal field associated with this site is known.

The second main reason, which calls for higher experimental accuracy is connected with developments in the theoretical calculation of these moments. Although the accuracy of a nuclear structure calculation compres often unfavorably with the high accuracy from a NMR/ON measurement, there is reason to believe that one could reproduce now even small variations in the moments of these isomers. The tellurium isotopes are especially interesting in this view, since they allow a large amount of configuration mixing, while occupation coefficients for most low-lying levels can be inferred from (d,p) reactions.[4] Since the spin polarization mechanism is extremely successful in explaining the magnitude of moments, it is to be expected that even the small relative variations of a series of these isomers can be predicted in this way. Therefore, we concentrated on a series of three isomers $^{125}Te^{m}$, $^{127}Te^{m}$, and $^{129}Te^{m}$, on which we report accurate g factors as well as improved calculations. At the same time, the increased accuracy allows us to reconsider the nature of the anomalous coupling states as studied through their g factors. The experimental method is described

in detail in another paper, which is mainly concerned with the technique of electron detection.[5] For these measurements Kevex detectors of 2 to 3 mm thickness and a resolution of 2.1 keV for the 1063 keV transition in ^{207}Bi have been used. In the cryostat it proved possible to resolve the K and L lines even in the case of lowest energy, the 56.5 keV K line of ^{127}Te^m. One serious cause of concern in these measurements is the external magnetic field, which one must apply in order to define an orientation axis. High magnetic fields may deteriorate the detector performance. They can also lead to apparently vanishing electron asymmetry through magnetic deflection and focussing of electrons emitted at all angles. However, during a NMR run one normally tries to work with as small a magneitc field as possible, for maximum hyperfine enhancement of the rf amplitude. Also, since the g factor is calculated from a frequency reading, the absolute magnitude of the anisotropy does not matter as long as it remains large enough to allow NMR detection. Hence the following procedure was adopted: After initial magnetization in a large field (10 kG) and cool down to about 15 mK, the magnetic field is reduced to the minimum value (800–1000 G) which indicates no measurable loss of magnetization in the sample. It turns out that the experimental electron anisotropy alway agrees, within errors, with the theoretically expected one for the corresponding temperature. This shows that quantitative studies of conversion electron anisotropy in low temperature nuclear orientation are possible, as was shown also in previous attempts, reported in Refs. 6 and 7. In our setup the experiments have become straightforward due to increased detector stability and decreased scattering corrections. The latter are minimal in this work for several reasons. First of all, the sample preparation (implantation at 70 keV) ensures that all activity is contained within a few hundred Å of the surface. Hence, scattering in the source can be neglected. Also, the high resolution of the detectors allows for descrimination of nearly all other scattering events. Finally, care was taken to have any wall at relatively large distance (e.g., a 6 cm bore magnet) and cover it with materials which suppress scattering as effectively as possible.

The geometry of the set up makes simultaneous gamma detection possible; this was used for monitoring temperature stability throughout the run, by detecting the axial anisotropy of a $^{57}\overrightarrow{Co}\underline{Fe}$ thermometer source with a Ge-Li detector. The change in intensity of the electron detector—also in the axial direction but at 180° with respect to the gamma detector—was recorded at the same time as a function of frequency. The standard procedure was to compare two counting periods at the same frequency, one with and one without modulation. A time interval of 120 s was left between counting periods, of the order of the estimated spin-lattice relaxation time of tellurium in iron. Each NMR scan could thus carefully be checked for any drift in temperature or detector stability. ^{125}Te^m, ^{127}Te^m, and ^{129}Te^m have been produced separately by irradiation of enriched isotopes at the high flux channel of BR2 reactor (SCK Mol), and implanted in iron foils with the Leuven isotope separator at an acceleration voltage of 70 keV. The respective implantation doses are quoted in the second columns of Table I. After cooling of the samples to temperatures between 15 and 20 mK, the electron anisotropy ranged from 12% to 16% for optimized magnetic fields, quoted in the third column of Table I. This anisotropy is only slightly reduced by rf heating, and with count rates usually around 1000 c/s the conditions for a successful NMR search are easily fulfilled. The frequency region of 80 to 120 MHz was first covered in a rough scan with a frequency step of 2 MHz and a modulation width of 2 to 3 MHz. At first, the relaxation time being unknown, an arbitrary waiting time of 120 s was left in between counting periods of 300 s. A later measurement indicates that relaxation times for these Te isomers in iron are indeed relatively large. In the frequency region, which gives indications of a resonance, more intensive scanning was performed using a frequency step and a modulation width of 0.5 MHz.

The results of these repeated scans are shown in the two last columns of Table I as the resonance frequency ν_R (corrected for the external field) and Γ the corresponding FWHM: These quantities have been extracted from the resonance curves through a fit of a Gaussian curve with the experimental modulation width fold in. The resonance curves obtained are displayed in Figs. 1 to 3, respectively, for ^{125}Te^m, ^{127}Te^m, and ^{129}Te^m. Typical fractions of anisotropy destroyed calculated from these curves are 30% to 40% which exclude any other assignment than the substitutional site.[8] In the case of ^{129}Te^m additional measurements of

TABLE I. Characteristics of the samples and the resonance lines.

Isotope	Dose (at. cm^{-2})	B_{ext} (G)	ν_R (MHz)	Γ (MHz)
^{125}Te^m	1×10^{15}	850	93.05 ± 0.04	1.35 ± 0.11
^{127}Te^m	4×10^{14}	920	98.37 ± 0.10	1.45 ± 0.22
^{129}Te^m	1.4×10^{15}	1250	103.18 ± 0.07	2.29 ± 0.16

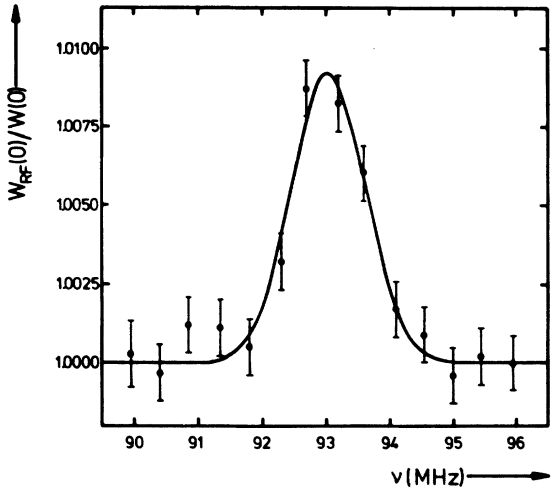

FIG. 1. The resonance line obtained for $^{125}Te^m$: The modulated to unmodulated counting rate is plotted as function of frequency.

the relaxation time have been performed, resulting in a Korringa constant $C = 2.8(6)$ Ks. This result confirms the empirical relation $TTg^2H_{eff}^2 = \text{constant}$, where g is the gyromagnetic ratio and H_{eff} the effective field acting upon the nucleus. The small g ratio made one expect a rather long relaxation time, which was the reason for leaving 120 s intervals between measuring periods in the NMR search. Finally, in the case of $^{127}Te^m$, a measurement of the saturation destruction gave a result of $(85 \pm 10)\%$. This agrees—within errors—with the Mössbauer results[8] and confirms again the substitutional assignment.

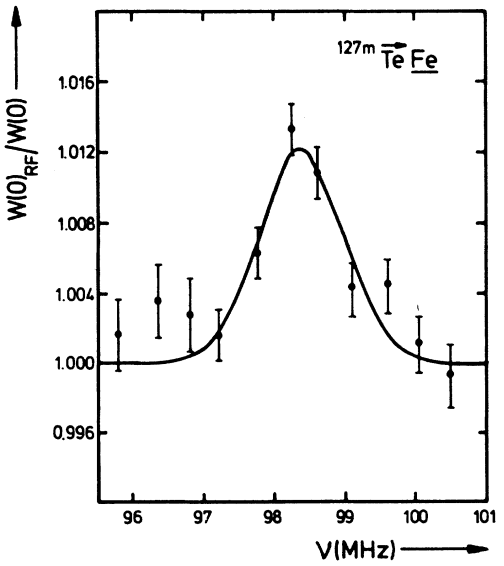

FIG. 2. Resonance curve obtained for $^{127}Te^m$.

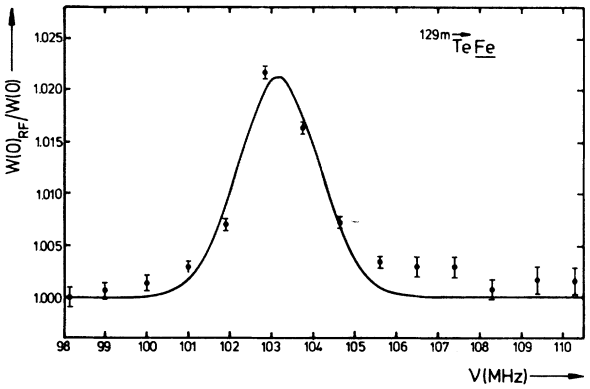

FIG. 3. Resonance curve obtained for $^{129}Te^m$.

In order to extract moments from the quoted frequencies, the hyperfine field of Te in iron on a substitutional site has to be fixed first. Several values have been reported from Mössbauer measurements on diffused as well as on implanted samples.

We used the value 68.1(4) T, for the field corresponding to the substitutional site.[8] Using this, the moments quoted in the second column of Table II have been derived. Comparing these values with calculations based on pairing-plus-quadrupole theory,[2] it is clear that this theory gives a trend as a function of mass number opposite to experiment. These moments are quoted in the third column as μ_{QP}. Therefore, we repeated the calculations putting in experimental single-particle energies as well as experimental occupation coefficients.[4] These results are quoted in the last column of Table II. The only parameter in the calculations is the interaction strength parameter C, for which we took $C = 27.5$ MeV. The choice of this parameter only weakly influences the relative variation of the moments. To stress the power of this approach in reproducing even small variations of the moments, we give in Fig. 4 a survey of all accurately known $\frac{11}{2}^-$ moments in this region, i.e.,

TABLE II. Comparison of moments between experiment and theory.

Isotope	μ_{exp}	μ_{QP}	μ_{QPE}
$^{123}Te^m$	−1.00(5) [a]	−0.99	−1.036
$^{125}Te^m$	−0.985(6) [b]	−0.90	−1.020
$^{127}Te^m$	−1.041(6) [b]	−0.85	−1.087
$^{129}Te^m$	−1.091(7) [b]	−0.81	−1.075

[a] Integral value from Ref. 2, subject to corrections as explained in the text.

[b] From this work.

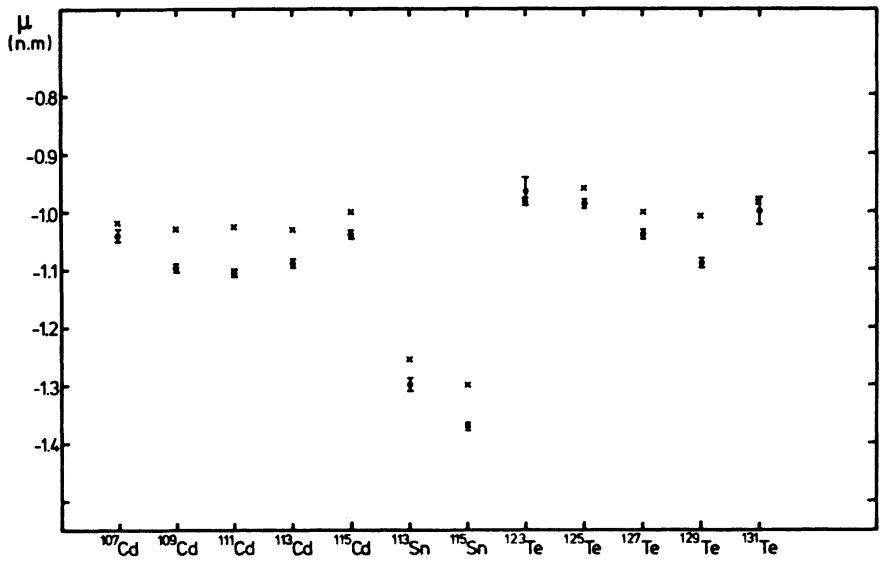

FIG. 4. Comparison between theory (crosses) and experiment (circles) for all accurately known moments of neutron $\frac{11}{2}^-$ isomers in this mass region.

for five Cd isomers, two Sn isomers, and the three Te isomers reported here. Two older values for $^{123}Te^m$ (Ref. 2) and $^{131}Te^m$ (Ref. 13) measured only with integral NO so far, have been included for completeness. For the calculated values, C was deliberately kept at $C = 30$ MeV—although a slightly lower value of C gives better agreement in magnitude—for better visual control of relative variations. Not only the variations between the group of Te, Sn, and Cd moments is borne out, but even the small variations within the same group. Considering the sensitivity of nuclear moments to small mixing of seniority three wave functions as well as the large possible number of excitations between spin-orbit partners, expecially in the case of Te, this is a remarkable success for the spin polarization theory of moments.

The explanation of the "intruder" states in the tellurium isotopes has also attracted considerable attention. Since their explanation by Kisslinger[9] as anomalously low-lying $(j-1)$ states obtained by coupling three quasiparticles built on the $\frac{11}{2}^-$ state, much effort has been devoted to the verification of this theory. One of the major tests consists in measuring the g factors of the $\frac{9}{2}^-$ and the $\frac{11}{2}^-$ states. Following the original theory, they should be identical. This was indeed borne out in the case of ^{125}Te, where several measurements have been reported for the $\frac{9}{2}^-$ state (see Ref. 10 and references quoted therein), leading to a value of $\mu = -0.918(32)$. Compared to the relative inaccuracy with which the $\frac{11}{2}^-$ moment was previously known, only rough agreement could be stated. In a more recent theoretical approach, however, the "intruder" states are to be identified with "dressed" three-quasiparticle states.[11] Both theoretical descriptions result in similar predictions for the electromagnetic properties, such as an enhanced $E2$ transition from the $(j-1)$ state to the j state. In the latter approach, however, the strong interaction of the phonon with the "intruder" state, introduces a small difference in g factors. Indeed, using the value of the moment reported here for the $\frac{11}{2}^-$ state, a difference in g factors results, the $g(\frac{9}{2}^-)$ factor being 14% larger than the $g(\frac{11}{2}^-)$ factor, with a combined error of 4%. This difference is in the sense and of the magnitude predicted by the dressed three-quasiparticle theory: It is one of the rare occasions where the predictions of g factors can be tested with sufficient accuracy both for the j and the $(j-1)$ state.

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