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# Measurements of g-Factors of Isomeric States in Fission Fragments[†]

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## Introduction

Spontaneous fission of $^{252}$Cf produces very neutron-rich isotopes falling mainly in three interesting regions of the periodic table: a) the A = 100-120, Z = 38-46 region for which there is evidence of large deformations; b) the isotopes around the double magic $^{132}$Sn where simple configurations coupled to the closed shells Z = 50, N = 82 prevail; c) the region with A = 140-150, Z = 54-60, where there is a smooth transition from spherical to deformed nuclei. Many isomeric γ-rays with half-lives between 10-3000 nsec were found[1,2] to be emitted by fragments in regions (a) and (b).

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Studies of the prompt de-excitation of fission fragments have demonstrated that the fission fragments have their angular momentum aligned normal to the fission direction[3,4]. Angular distributions of γ-rays emitted in the ground state bands of even-even fragments were found to be peaked in the fission direction with an average anisotropy of $N(0^o)/N(90^o)=1.50$[4]. Several transitions in even-odd and odd-odd fragments were also found to be anisotropic with respect to the fission axis[3,4].

In this work we have measured g-factors of isomeric states in fission fragments. Two experiments were carried out. In the first, angular distributions (with respect to the fission axis) of known[1,2] isomeric γ-rays emitted by stopped fragments were found to be anisotropic, thus showing alignment of the angular momentum. In the second experiment, this alignment was used in a time-differential perturbed angular correlation measurement from which g-factors were directly obtained.

Experimental set-up

In both experiments a thin, $10^7$ fissions/min., $^{252}$Cf source, having an active area of about 3 $mm^2$, was used. The source was plated on a 25 $mg/cm^2$ copper backing. The copper was chosen as backing material because: a) it is known to preserve alignment of the angular momentum and b) its relatively low Z minimizes the X-ray background.

The experimental set-up of the angular distribution experiment was described in detail elsewhere[4]. In short, gamma-rays emitted by the fragments stopped in the copper backing were detected in a planar, $2cm^3$, Ge(Li) detector. The fission axis was determined by the complementary fragments which were detected in any one of three surface barrier detectors. These detectors were rotated once during the experiment, and thus gamma-ray intensities at five angles were determined.

The experimental arrangement of the second experiment is presented in Figure 1. The gamma-rays were detected by the Ge(Li) detector of the first experiment. The three fission fragment detectors were placed at $45^{o}$, $0^{o}$, $-45^{o}$ with respect to the source - Ge(Li) detector axis. The experimental chamber was so designed as to allow the fission source to be placed between the conical pole pieces of an electromagnet. The magnetic field was normal to the plane of the detectors and the source. During the whole experiment the magnetic field was maintained at (7.57 ± 0.15) kGauss

In both experiments multiparameter measurements were performed. The kinetic energy of the fission fragments, the gamma-ray energy, and the time difference between detection of a fission fragment and a gamma-ray(in the range 0-620 nsec) were simultaneously recorded on magnetic tape. The time resolution, after correcting in the computer analysis for the experimental walk, was 10 nsec FWHM at 100 keV. This type of experiments require long running periods (17 days for the first experiment and about 120 days for the second). Therefore, digital gain stabilization of the gamma-ray detection system was performed. The energy resolution of the Ge(Li) detector was 0.8 keV FWHM at 100 keV in the first experiment, and about 1.0 keV FWHM in the second.

During the experiments, the fission detectors were cooled to $-30^{o}$C to enable them to withstand $4 \times 10^{9}$ fragments, though with very poor kinetic energy resolution.

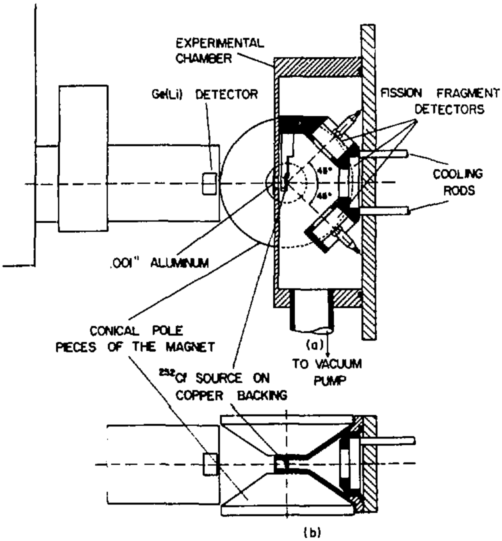


Fig. 1. Experimental arrangement of the g-factor experiment

(a) Side view.

(b) Top view.

## Results

In this work we have studied only gamma-rays which have been assigned to specific fragments by previous authors[1,2], since no mass analysis was possible in our experiments.

The angular distribution of the transitions with respect to the fission axis is expanded as usual:

$$W(\theta) = a_o + a_2P_2(\cos\theta) + a_4P_4(\cos\theta).$$

The coefficients $a_o$, $a_2$, $a_4$ were determined by a least-squares procedure.

In the time-differential perturbed angular correlation measurement[5], g-factors were obtained directly from the oscillations of the gamma-ray intensity as a function of time from fission. The strength of the applied magnetic field, (7.57±0.15)kGauss enabled detection of oscillations for transitions with half-lives between 60-600 nsec. In the following we shall deal with results concerning four transitions, for which oscillations were observed and g-factors determined.

In Table I results of the angular distribution measurements are presented. Also given in the table are the half-lives extracted from our data, and the half-lives and yields measured previously by two independent experiments[1,2]. It is seen that our half-lives are in fairly good agreement with those of the previous experiments, thus confirming the assignment of the respective transitions to the specific isotopes. One exception is the 96.1 keV transition in $^{109}$Ru, where the rather long half-life (550 nsec) relative to the time interval of our measurement (0-600 nsec) is probably the cause for the discrepancy.

Table 1 Results of angular distributions and half-lives of isomeric transitions in fission fragments. For each transition the time interval for which angular distribution results were obtained is given. Half-life and yields obtained by previous authors are shown for comparison.

| Isotope | $E_\gamma$ (keV) | Time interval[a] (nsec) | $A_2$ | $A_4$ | $T_{1/2}$ (nsec) | John et al. (Ref. 1) $T_{1/2}$ (nsec) | John et al. (Ref. 1) Yield[b] | Clark et al. (Ref. 2) $T^{b}_{1/2}$ (nsec) | Clark et al. (Ref. 2) Yield[b] |
|---|---|---|---|---|---|---|---|---|---|
| $^{107}Mo$ | 65.4 | 40-350 | $-0.14\pm0.03$ | $0.01\pm0.03$ | $245\pm15$ | - | - | 238(3) | 895(6) |
| $^{108}Tc$ | 153.9 | 40-350 | $0.26\pm0.05$ | $0.01\pm0.06$ | $100\pm10$ | 110 | 770(7) | 108(25) | 725(6) |
| $^{109}Ru$ | 96.1 | 40-350 | $0.08\pm0.05$ | $0.07\pm0.06$ | $780\pm150$ | 550 | 800(7) | 544(2) | 1155(5) |
| $^{134}Te$ | 115.3 | 20-130 | $0.25\pm0.09$ | $-0.17\pm0.11$ | $161\pm4$ | 162 | 610(7) | 163(2) | 596(5) |

a) Time interval following fission in which angular distributions were measured

b) Percent errors given in parantheses. Yields in photons per $10^5$ fissions.

The angular distributions listed in Table I are shown in Figure 2.

In Figures 3 - 6, the oscillations of the gamma-ray intensity as a function of time from fission are presented for the three different angles. A noted phase difference between the three angles is seen in each case. The normalized difference $[N(45^o)-N(-45^o)]/[N(45^o)+N(-45^o)]$ shows an oscillation which is independent of the half-life of the transition. The solid lines in Figures 3 - 6, were obtained by a least-squares procedure using the exact functional behaviour[5] of the oscillations.

The free parameters which were determined from the fit were: the Larmor frequency of precession of the magnetic moment about the magnetic field direction, the life-time of the transition and a normalization constant. The angular distribution coefficients, which appear in the functional expression of the oscillations[5], were taken from Table I. g-factors were obtained from the Larmor frequencies and the magnetic field causing the precession, and are presented in Table II. In each case the sign was determined from the phase of the oscillations at the different angles. The effective magnetic field at the site of each of the isotopes in the copper lattice was taken to be the applied magnetic field. A small change due to the Knight shift is usually almost cancelled by the diamagnetic shielding. Both effects are of the order of 0.5%[6,7]. Moreover, a measurement of the g-factor of the first excited state of $^{99}$Ru performed with Ru in different hosts[8] showed that no extranuclear effects are observed when a copper host is used.

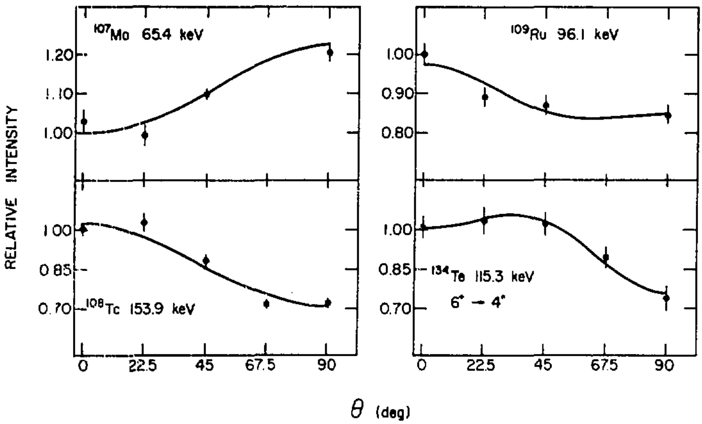


Fig. 2. Angular distributions for four isomeric transitions obtained in spontaneous fission of $^{252}Cf$. The solid lines represent least squares fits to the data with the function $1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$.

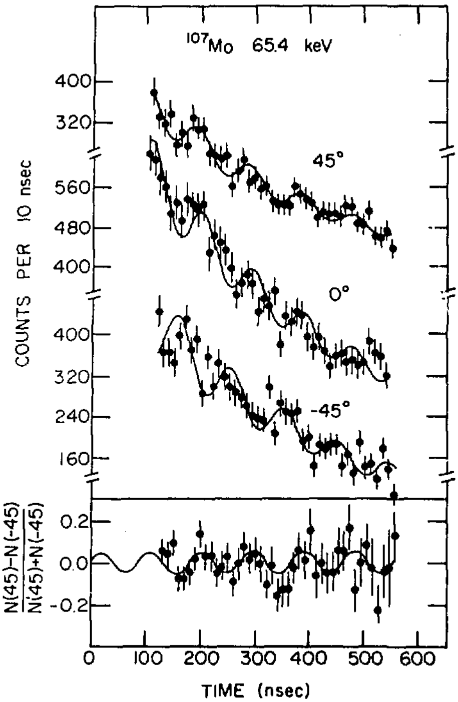


Fig. 3. Time spectra of the 654 keV radiation of $^{107}Mo$ at three angles with respect to the fission direction. Normalized differences between the intensities at 45° and -45° are given in the lower part of the figure. The solid lines were obtained by least squares fits to the data of the functional forms discussed in the text. The average value of $\chi^2$ for the three fits to the time spectra was 1.13.

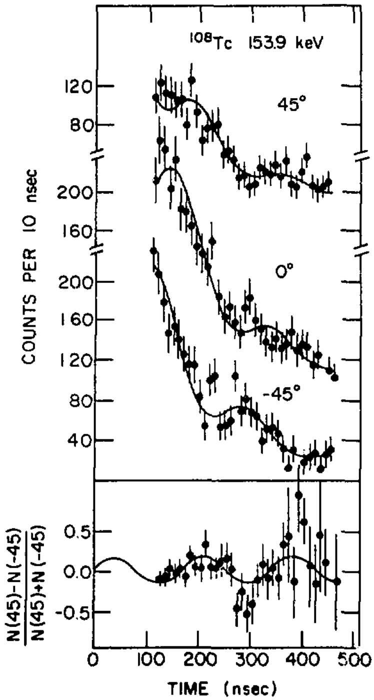


Fig. 4. *Time speccra of the 1539 keV radiation of* $^{108}$*Tc at three* angles with respect to the fission direction. Normalized differences between the intensities at 45° and -45° are given in the lower part of the figure. The solid lines were obtained by least squares fits. The functional forms discussed in the text to the data. The average value of $\chi^2$ of the fits to the time spectra was 0.81.

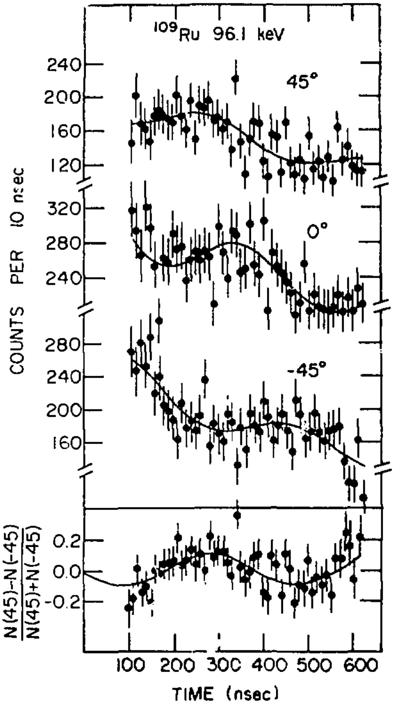


Fig. 5. Time spectra of the 96.1 keV transition of $^{109}$Ru at three angles with respect to the fission direction. Normalized differences between the intensities at 45° and -45° are given in the lower part of the figure. The solid lines were obtained by least squares discussed in the text to the data. The average $\chi^2$ for the three fits to the line spectra was 1.03.

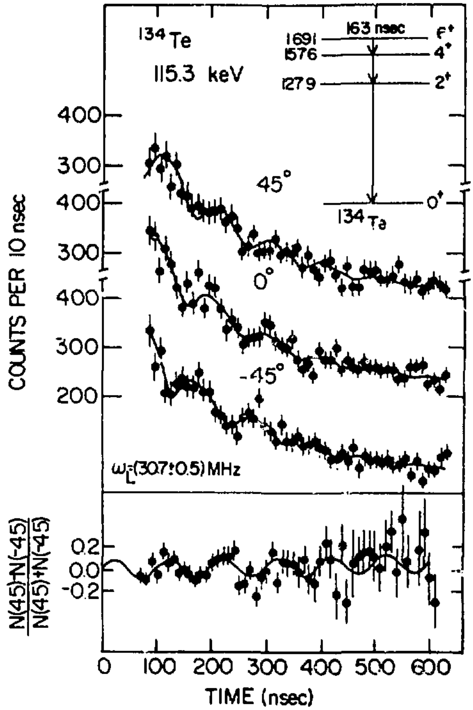


Fig. 6. Time spectra of the 115.3 keV $6^+ \rightarrow 4^+$ transition of $^{134}Te$ at three different angles with respect to the fission direction. Normalized differences between the intensities at 45° and -45° are given in the lower part of the figure. The solid lines represent least squares fits to the functional forms discussed in the text to the data. The average $\chi^2$ of the fits to the time spectra was 0.88.

Table II: Larmor frequencies and g-factors measured in this work. The g-factors were not corrected for extranuclear effects.

| Isotope | $E_\gamma$ (keV) | Larmor frequency (MHz) | g |
|---|---|---|---|
| $^{107}$Mo | 65.4 | 33.3±0.6 | -0.92±0.03 |
| $^{108}$Tc | 153.9 | 18.3±0.5 | 0.50±0.04 |
| $^{109}$Ru | 96.1 | 8.2±0.3 | -0.22±0.01 |
| $^{134}$Te | 115.3 | 30.7±0.5 | 0.846±0.025 |

## Discussion

Of the four cases reported in this work, only in $^{134}$Te the decaying state has an assigned spin and parity. In the other three cases only the identity of the isotope in which the transition occurs is known from previous experiments[1,2].

a. g-factor of the $6^+$ isomeric state in $^{134}$Te.

The decay scheme of $^{134}$Te was studied by Kerek et al.[9] through $\beta$-decay of the mass separated A = 134 chain. A $6^+$ isomeric state ($T_{1/2}$ = 163 nsec) was observed at 1691 keV, decaying by an E2, 115.3 keV transition to a $4^+$ state and subsequently by a $4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade to the ground state (see decay scheme in figure 6). The g-factor of this state is given in Table II. It is believed[10,11] that this $6^+$ state is composed predominantly of two $g_{7/2}$ protons outside the double magic shell $^{132}_{50}Sn_{82}$. The protons are coupled to maximum angular momentum.

The single particle g-factor for a pure $(g_{7/2})^2$ configuration is the same as that of a single $g_{7/2}$ proton, and is equal to

$$g_{s.p.} = 0.491$$

An admixture of the $(g_{7/2}d_{5/2})$ configuration and core polarization of the $^{132}_{50}Sn_{82}$ core by the $g_{7/2}$ protons may enhance the g-factor above the single particle value.

Detailed calculations regarding the structure of the $^{134}$Te levels were performed by Heyde et al.[10] and Wildenthal and Larson[11], who attempted to fit the energy level spacings and transition rates. The first $6^+$ state was calculated by both to be predominantly a

$\pi(g_{7/2})^2$ configuration with an admixture of the $(g_{7/2}d_{5/2})$ configuration of 2.3% (Heyde et al.) and 13.7% (Wildenthal and Larson). These admixtures give an increase of the single particle g-factor of 0.013 and 0.082 respectively.

The effect of the core polarization due to $\pi(g_{9/2}^{-1}g_{7/2})$ and $\nu(h_{11/2}^{-1}h_{9/2})$ excitations on the magnetic moment of ${}^{133}_{51}Sb_{82}$ was evaluated following Arima and Horie[12] who used a δ-interaction, and was found to increase the g-factor by $\delta g_{c.p.}=0.192$.

The calculated g-factor, obtained by adding the above contributions and assuming the $\delta g_{c.p.}$ for the two proton state in ${}^{134}Te$ to be the same as that of the one proton state in ${}^{133}Sb$, is 0.696 for a 2.3% admixture[10] of the $(g_{7/2}d_{5/2})$ configuration and 0.765 for a 13.7% admixture[11]. The latter value is lower by 10% than the experimental result. Altogether configuration admixture and core polarization leave unexplained 42% (for 2.3% admixture) and 22% (for 13.7% admixture) of the difference $g_{exp}-g_{s.p}$. Here it should be emphasized that the above value of $\delta g_{c.p.}$ is due to an admixture of 0.4% of particle-hole states with the pure $g_{7/2}$ proton state. An admixture of 0.9% of particle-hole states would have given $\delta g_{c.p.} = 0.35$, thus accounting for the entire deviation of the experimental g-factor from the Schmidt value.

The experimental value of the g-factor of the $6^+$ state in ${}^{134}_{52}Te_{82}$ is somewhat higher than the g-factors of the $(7/2^+)$ ground states of ${}^{133}_{55}Cs_{82}$ (0.8118) and ${}^{139}_{57}La_{82}$ (0.7952)[13]. This seems to indicate blocking of the core polarization by the presence of additional protons in the $g_{7/2}$ orbit. This fact is illustrated in Figure 7, where the three g-factors are plotted as a function of the number of protons outside the double magic shall ${}^{132}_{50}Sn_{82}$. Such a dependence of the g-factors on the

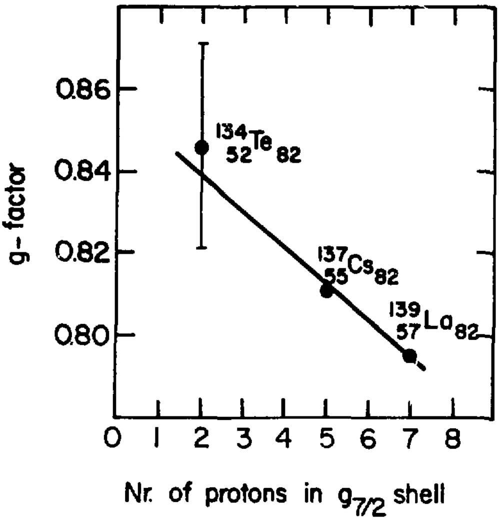


Fig. 7. Experimental g-factors of $g_{7/2}$ protons states as a function of the number of protons in the $g_{7/2}$ shell. The value of $^{134}Te$ is result of this experiment, values of $^{137}Cb$ and $^{139}La$ results were taken from reference (13).

number of protons in the $g_{7/2}$ shell is expected when polarization of the core by these protons occurs[18]. Measurements of g-factors in $^{209}$Bi and $^{210}$Po by Yamazaki et al.[14] demonstrated the lack of a blocking effect in the lead region. Yamazaki et al.[14] have measured the g-factor of the $8^+$ isomeric state ($T_{1/2}$ = 110 nsec) in $^{210}$Po which is analogous to the $6^+$ state in $^{134}$Te, both having two protons coupled to the maximum angular momentum outside a double magic core. However, only half of the deviation from the Schmidt value of the measured g-factor of the $8^+$ state in $^{210}$Po could be explained by the core polarization as calculated by Arima and Horie[12]. As was seen above, in our case 20-40% of the difference $g_{exp}-g_{s.p.}$ remains unexplained. It was suggested[14] that $g_\ell$ is not equal to 1, and thus can be responsible for the deviation. Our experimental result is not in contradiction with such an approach.

b. <u>g-factors of other isomeric states.</u>

The decay schemes of the first three isotopes listed in Tables I, II are not known. Therefore interpretation of the g-factors in terms of specific nuclear configurations must await further spectroscopic data. It should, however, be noted that the photon yields of these transitions constitute over 25% of the independent yield of each of the isotopes. When corrected for internal conversion, the total yields of the states in question are even higher, thus showing that these are most probably very low-lying states. These states are therefore expected to appear also in β-decay.

Two of the cases, $^{107}Mo$ and $^{109}Ru$, are neutron-rich nuclei with odd neutron numbers. The fact that negative g-factors were found indicates that neutron configurations are involved.

Conclusion

In conclusion, we have shown that the inherent alignment of the fission fragments can be used for g-factor measurements of specific states in neutron-rich nuclei. The advantage of this method is that a large variety of neutron-rich nuclei are produced simultaneously using a radioactive source. So far, we have used only one value of the external magnetic field in a time-differential measurement. Further measurements, with different values of external magnetic fields, and possibly the use of internal magnetic fields of various hosts may provide g-factors of other interesting states populated in fission fragments.

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