Lifetime and g-factor measurements of the 11^- isomer in ^{92}Tc

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The half-life ($T_{1/2}$) and g factor of the 2002 keV 11^- isomer in the odd-odd nucleus ^{92}Tc produced by the pulsed heavy-ion reaction ^{68}Zn(^{28}Si,$p3n$)^{92}Tc have been measured using time differential perturbed angular distribution method. The measured $T_{1/2}$ value is 3.15(20) ns. From the observed spin precession frequency ω_L of a ^{92}Tc recoil implanted into a ferromagnetic Ni host, we obtain the g factor to be 0.806(20). The measured value of the g factor is in good agreement with a shell model analysis carried out using $\pi(p_{1/2}g_{9/2})$ and $\nu(p_{1/2}g_{9/2})$ orbitals for the proton particles and neutron holes outside the ^{88}Sr core. [S0556-2813(96)00612-7]

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I. INTRODUCTION

Recently, high spin states in nuclei with $A=90$ have attracted a great deal of experimental and theoretical attention. Theoretical understanding of nuclear structure in this mass region using shell model calculations has achieved considerable success under the assumption of a closed $^{88}_{38}\mathrm{Sr}_{50}$ core, with protons and neutrons as particles (or holes) distributed in the $2p_{1/2}$ and $1g_{9/2}$ orbitals [1,2]. Of particular interest is the study of spectroscopy and electromagnetic moments of the $N=49$ nuclei, e.g., ^{92}Tc, where due to the interaction between protons and neutron holes occupying the same orbitals a large number of high spin states at relatively low excitations are predicted [1,2]. The spectroscopy of the odd-odd nucleus ^{92}Tc has been studied by several groups [3,4]. Fields *et al.* [3], using a (α,3$n\gamma$) reaction, established several high spin states in ^{92}Tc. More recently, using the NORDBALL facility, Arnell *et al.* [4] have made a detailed study of the ^{92}Tc nucleus. Figure 1 shows their proposed partial level scheme. In their study, in addition to a positive parity band several high spin states belonging to a negative parity band were reported. Further, from Doppler shift measurements with stacked thin targets, they inferred the presence of a 11^- isomeric state at an excitation energy of 2 MeV and estimated its half-life to be 1.9(4) ns. Here we report our results on the half-life and g factor of the 11^- isomer in ^{92}Tc using time differential perturbed γ-ray angular distribution (TDPAD) method. The experimental results are compared with theoretical calculation using the shell model.

II. EXPERIMENTAL DETAILS

High spin states in ^{92}Tc were populated by the heavy-ion reaction ^{68}Zn(^{28}Si,$p3n$)^{92}Tc with a 2-ns-wide pulsed Si beam ($E_{\mathrm{lab}}=100$ MeV, pulse separation $\sim$100 ns) provided by the 14 UD Pelletron Accelerator facility at TIFR, Mumbai. The targets for the nuclear reaction were made from isotopically enriched ^{68}Zn metal rolled to a thickness of 2.6 mg/cm^2. The γ-ray spectra were recorded by four Compton-suppressed high purity Ge (HPGE) detectors having an efficiency of 23% relative to a $3''\times3''$ NaI(Tl) detector and an energy resolution of 2.1 keV at 1332 keV. The detectors were positioned at angles $\pm45°$ and $\pm135°$ with respect to the beam direction at a distance of 12 cm from the target. The time signal from the HPGe detector was used to start the time to amplitude converter (TAC), which was stopped by the primary rf signal of the buncher. The time resolution of the HPGe-detector–pulsed-beam coincidence setup was typically 5 ns for 1.3 MeV. All the measurements were carried out at room temperature.

The experiment was performed in two steps: (i) identification and placement of isomeric state in ^{92}Tc and (ii) measurement of the half-life and g factor of the isomeric state. In the first part of the experiment, the ^{68}Zn target was backed by 50 mg/cm^2 Pb and data were collected in list mode with eight parameters comprised of energy and time signals from each detector. In the second part of the experiment the recoiling ^{92}Tc ions were stopped in 3.7-mg/cm^2-thick natural Ni. A static external magnetic field $B_{\mathrm{ext}}=3.6$ kG was applied perpendicular to the beam-detector plane to polarize the ferromagnetic Ni host. The data were collected in the form of a two-dimensional (2D) matrix (energy vs time for each detector) for both up and down directions of the external magnetic field.

III. RESULTS

A. Measurement of the half-life of the 11^- isomeric state in ^{92}Tc

Figure 2 displays typical γ-γ coincidence spectra obtained from the list mode data. The spectra were found to be consistent with the level scheme proposed by Arnell *et al.* [4]. In order to identify the existence of isomeric states in ^{92}Tc, delayed γ-ray energy spectra gated by different time intervals with respect to the pulsed beam were generated. The delayed γ spectra for the energy range of interest are shown in Fig. 3. The intensities of several γ rays were found to show variation with delay time, the most prominent ones being 932, 1004, and 1097 keV lines (not shown in the figure) arising from the decay of the isomers $21/2^+$ in ^{89}Nb and 11^- in ^{92}Mo, respectively, which are produced in the same heavy-ion reaction. In addition, the delayed spectra also

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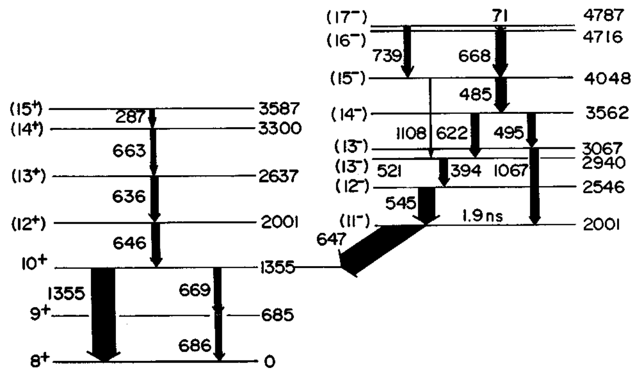

FIG. 1. Partial level scheme of ^{92}Tc.

showed variation of intensity for a number of other γ rays with energies 647, 669, 686, and 1355 keV which were identified to originate from the decay of ^{92}Tc, indicating the presence of an isomer with a short half-life $\sim$3–4 ns. Considering the near degeneracy of the transition energies in the cascade 12^+-10^+ and 11^--10^+ (see Fig. 1) the observed isomer in ^{92}Tc can be attributed either to the 12^+ or the 11^- state. Arnell *et al.* [4] have argued and assigned this isomer to the 11^- state in ^{92}Tc. For further confirmation and placement of the isomer, coincidence spectra $(\gamma,\gamma,\Delta t)$ were constructed from the list data with the first energy gate on γ rays feeding the 10^+ state and the second energy gate on the 1355 keV (10^+-8^+) ground state transition. The time spectra obtained with the first energy gate on the 636, 663 keV and 485, 495, 545 keV γ rays belonging to the positive and negative parity bands, respectively, are displayed in Figs. 4(a) and 4(b). From Fig. 4 it is clear that the time spectrum gated by the energies from the positive parity band shows only a prompt peak, whereas the spectrum gated by the γ rays from the negative parity band distinctly shows a lifetime decay, confirming the earlier assignment [4] of the isomer to the 11^- state.

For a precise measurement of the lifetime, background-corrected energy gated time spectra for various γ rays, e.g., 545, 647, and 1355 keV lines in the ^{92}Tc state, were extracted from the (E_γ,t) 2D data. To eliminate the perturbation of angular distribution due to the magnetic interaction the time spectra of each detector for both the directions of external magnetic field were added after matching at the time

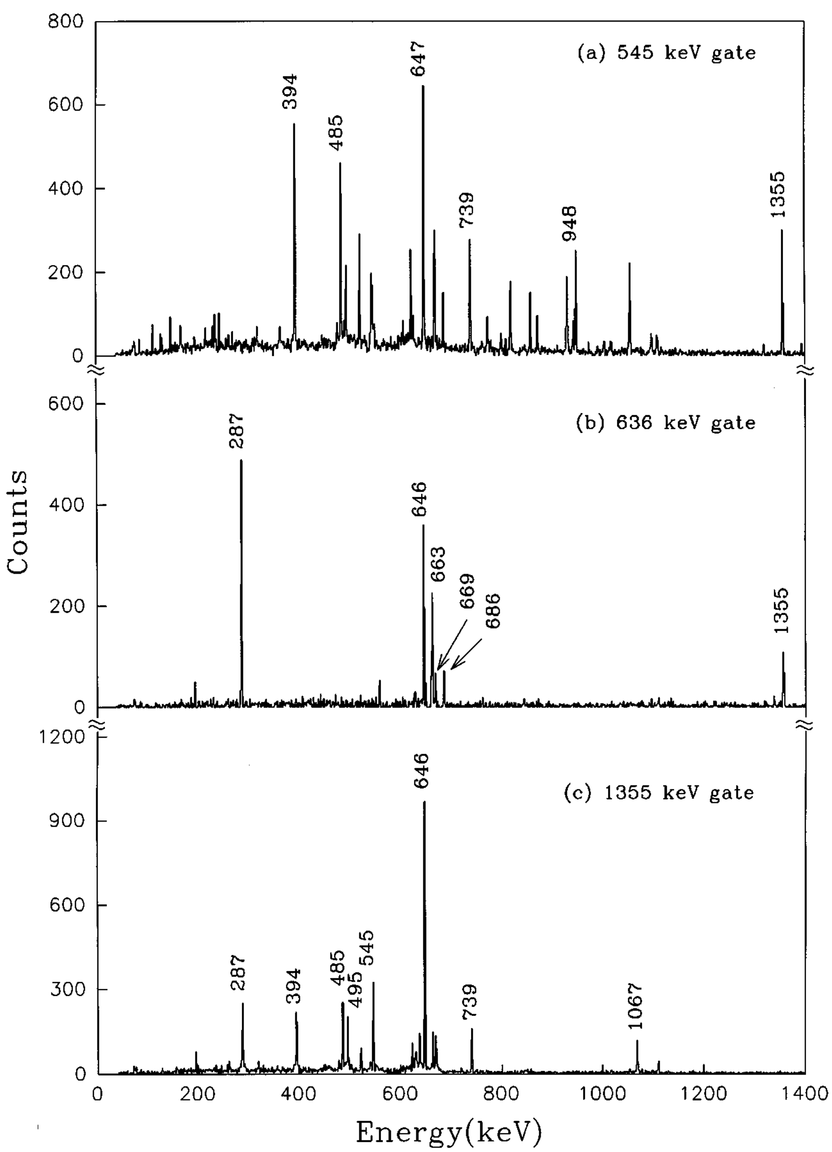

FIG. 2. γ-γ coincidence spectra of ^{92}Tc with gates on the 545, 636, and 1355 keV transitions.

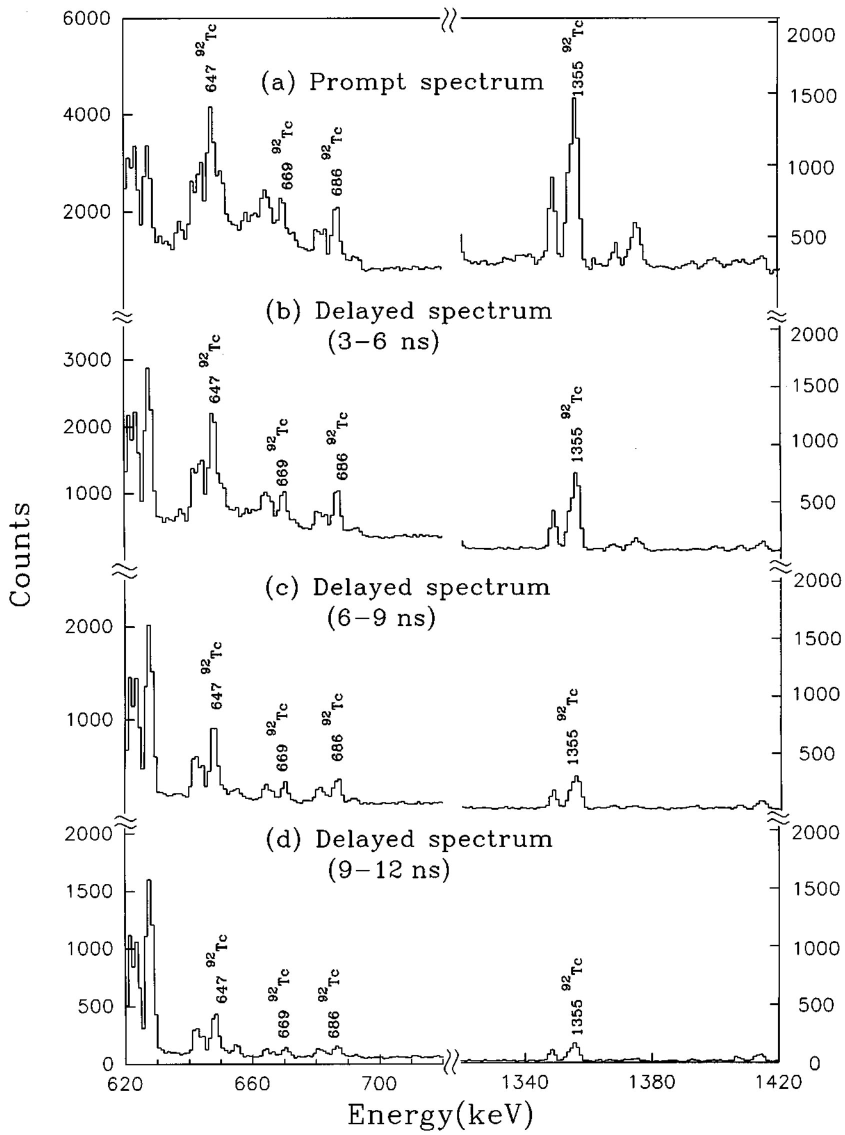

FIG. 3. Examples of prompt and delayed γ-ray spectra for different time windows showing the variation of intensities of γ ray belonging to ^{92}Tc.

$t=0$, and are shown in Fig. 5. The time spectra with energy gates on 647 and 1355 keV γ rays show an exponential decay of the intensities. The decay region was fitted to the function

$$N(t)=P_1+P_2e^{-\lambda t}, \tag{1}$$

to extract the decay constant λ and hence the half-life. The coefficients P_1 and P_2 represent the background and the counts at time $t=0$ in the time spectra $N(t)$, respectively. The extracted half-life for the 11^- state is 3.15(20) ns which is higher than the earlier estimated value of 1.9 ns [4].

B. *g*-factor measurement

When the recoils are stopped in the ferromagnetic Ni host the γ-ray angular distribution shows time-dependent modulations, characterized by the Larmor precession frequency ω_L, due to the hyperfine interaction of the nuclear magnetic moment of the isomeric state with the effective magnetic field $B_{\text{eff}}(=B_{\text{hf}}+B_{\text{ext}})$ present at the nucleus [5]. The background-corrected time spectra recorded by the detectors at angles $\pm45°$ and $\pm135°$ were first normalized for equal counting time for both directions of the magnetic field. The spectra of suitable detector combinations, after matching their prompt positions $(t=0)$, were then added to form the sum spectra $N\uparrow(\theta,t)$ and $N\downarrow(\theta,t)$ from which the ratio function $R(t)$, defined as

$$R(t)=\frac{[N\uparrow(\theta,t)-N\downarrow(\theta,t)]}{[N\uparrow(\theta,t)+N\downarrow(\theta,t)]}, \tag{2}$$

was formed. Figure 6 shows $R(t)$ spectra obtained for the

TABLE I. Summary of various parameters extracted from the least squares fitting of the spin rotation spectra $R(t)$. Column 3 contains the A_2 coefficient obtained from angular distribution data, taken from Refs. [3,4].

Energy gate keV	A_2 (TDPAD)	A_2 (angular distribution)	ω_L (Mrad/sec)	g_N
647	−0.07	−0.08	171.9(45)	0.802(20)
1355	+0.12	+0.50	169.7(45)	0.811(21)

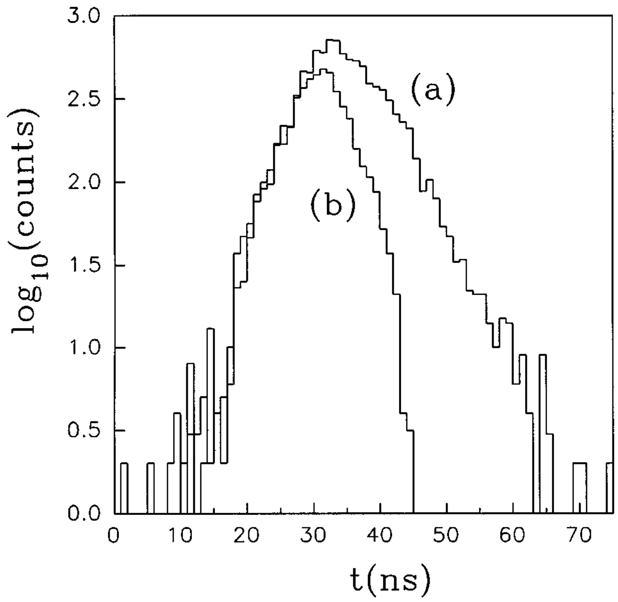

FIG. 4. Projected time spectra of the 1355 keV ground state transition in coincidence with γ rays from the (a) negative and (b) positive parity bands.

647 and 1355 keV energy gates. The spectra were fitted by the function

$$R(t)=(3/4)A_2\sin(2\omega_L t), \quad (3)$$

to extract the Larmor frequency ω_L. Here A_2 is the anisotropy of the γ-ray angular distribution. The fitted parameter values are listed in Table I. From the measured value of Larmor precession frequency the g factor of the isomeric state can be estimated using the relation $\omega_L=(g_N\mu_N B_{\text{eff}}/\hbar)$. The room temperature hyperfine field of ^{99}Tc in Ni has been measured to be $B_{\text{hf}}=-47.8(1.5)$ kOe [6] using a source prepared by melting radioactive ^{99}Mo with Ni. After correcting for the external field of 3.6 kOe used in our experiment, the effective magnetic field at the ^{92}Tc nuclear site comes out to be -44.2 kOe. With this value of B_{eff} the g factor of the 11^- state in ^{92}Tc is estimated to be $+0.806(20)$. The sign of the g factor was determined by taking into account the sense of rotation observed in the spin rotation spectra and the sign of A_2 coefficients of the relevant γ transitions [3,4].

TABLE II. The dominant components in the shell model wave function and their amplitudes for the 11^- isomeric state in ^{92}Tc.

Configuration	Amplitude
$\pi[(p_{1/2})^1_{1/2}(g_{9/2})^4_8]_{17/2}\ \ \nu(g_{9/2})^{-1}_{9/2}$	0.577
$\pi[(p_{1/2})^1_{1/2}(g_{9/2})^4_7]_{15/2}\ \ \nu(g_{9/2})^{-1}_{9/2}$	−0.492
$\pi[(p_{1/2})^1_{1/2}(g_{9/2})^4_6]_{13/2}\ \ \nu(g_{9/2})^{-1}_{9/2}$	−0.446
$\pi[(p_{1/2})^1_{1/2}(g_{9/2})^4_8]_{15/2}\ \ \nu(g_{9/2})^{-1}_{9/2}$	0.325
$\pi[(p_{1/2})^1_{1/2}(g_{9/2})^4_6]_{13/2}\ \ \nu(g_{9/2})^{-1}_{9/2}$	−0.262
$\pi[(p_{1/2})^1_{1/2}(g_{9/2})^4_{10}]_{21/2}\ \ \nu(g_{9/2})^{-1}_{9/2}$	0.179
$\pi[(p_{1/2})^1_{1/2}(g_{9/2})^4_7]_{13/2}\ \ \nu(g_{9/2})^{-1}_{9/2}$	0.093
$\pi[(p_{1/2})^1_{1/2}(g_{9/2})^4_{10}]_{19/2}\ \ \nu(g_{9/2})^{-1}_{9/2}$	0.052

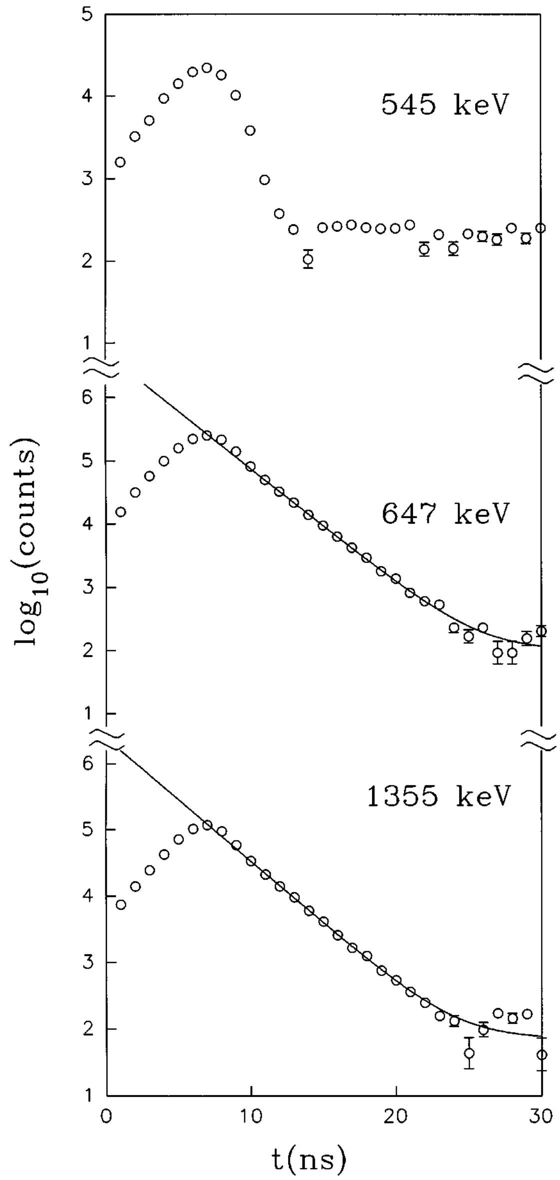

FIG. 5. Time spectra of 647 and 1355 keV energy gates in ^{92}Tc nucleus showing the half-life of the 11^- isomer. Top panel shows the spectrum for the 545 keV transition feeding the 11^- state.

IV. DISCUSSION

Before discussing the g factor of ^{92}Tc, it is worthwhile to compare the experimental result with the g values of similar high spin states in neighboring nuclei with $N=49$, e.g., ^{90}Nb and ^{94}Rh. The lifetime and the g factor of the 11^- state in ^{94}Rh have not been measured so far [4]. However, the g factor of the 11^- state in ^{90}Nb [7] has been measured to be 0.798. The measured g factor $[g=0.806(20)]$ of the $11^-(\pi[(p_{1/2})^1(g_{9/2})^4]\nu(g_{9/2})^{-1})$ state in ^{92}Tc (present work) is very close to the value reported ($g=0.798$) for the $11^-(\pi[(p_{1/2})^1(g_{9/2})^2]\nu(g_{9/2})^{-1})$ state in ^{90}Nb. The close similarity of the g values measured for ^{92}Tc and ^{90}Nb would be consistent with a simple scalar addition of the effective proton and neutron g factors. In such an approximation the net g factor of the state would depend only on the angular momenta and not on the details of the occupation of the orbitals.

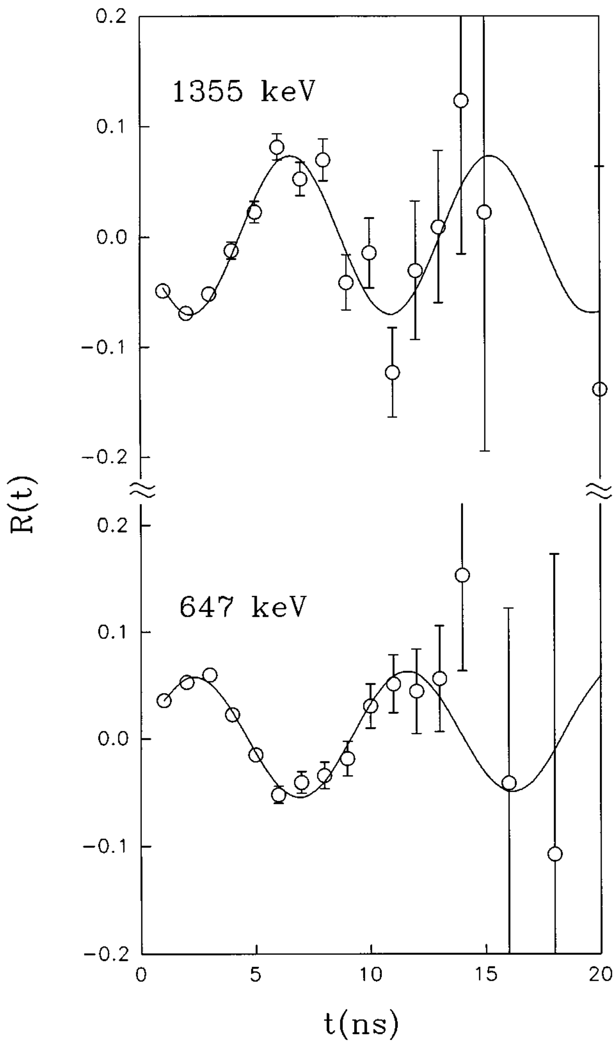

FIG. 6. Spin rotation spectra $R(t)$ for 647 and 1355 keV γ rays deexciting the 11^- isomer in the ^{92}Tc recoil implanted into a ferromagnetic Ni host.

Shell model analysis of the *g* factor

For a better estimation of the g factor for the 11^- state in ^{92}Tc we have made a shell model calculation with the valence protons and neutrons occupying the $(2p_{1/2},1g_{9/2})$ configuration space with $^{88}_{38}$Sr as the inert core. The calculations were performed in the neutron-proton product formalism with the Hamiltonian represented by

$$H=H_{pp}+H_{nn}+H_{np}, \tag{4}$$

where H_{pp}, H_{nn}, and H_{np} are the effective proton-proton, neutron-neutron, and proton-neutron interactions, respectively, and their strengths were chosen as given in Ref. [2]. The calculated shell model level scheme was found to reproduce the experimentally observed energy levels of ^{92}Tc and be consistent with the results reported in Ref. [4]. For subsequent calculation of the g factor we used the amplitudes of the dominant components of the shell model wave function for the 11^- state which are listed in Table II. It can be seen from Table II that all the dominant components belong to the $\pi[(p_{1/2})^1(g_{9/2})^4]\nu(g_{9/2})^{-1}$ configuration. The g factor of

TABLE III. Experimental g factors in the mass $A=90$ region taken from Ref. [9].

Valence configuration	Nuclide	I^π	g_N
$(\pi p_{1/2})$	^{89}Y$_{39}$	$1/2^-$	$-0.274846(10)$
$(\nu g_{9/2})$	^{87}Sr$_{49}$	$9/2^+$	$-0.2429(7)$
	^{86}Sr$_{48}$	8^+	$-0.241(3)$
$(\pi g_{9/2})$	^{90}Zr$_{50}$	8^+	1.356(7)
	^{92}Mo$_{50}$	8^+	1.413(6)
	^{94}Ru$_{50}$	8^+	1.387(5)

such a composite state involving the addition of three angular momenta can be approximated in terms of the constituent proton and neutron contributions. The g factors of the constituent states which involve the momenta j_1,j_2 with g factors g_1,g_2, respectively, are evaluated using the expression,

$$g=(1/2)(g_1+g_2)+(1/2)(g_1-g_2) \times\{[j_1(j_1+1)-j_2(j_2+1)]/J(J+1)\}. \tag{5}$$

This formula can be used in the first step to calculate the g factor of a proton configuration using the effective g factors of $p_{1/2}$ and $g_{9/2}$ levels. This is then combined with the g factor of a neutron hole in the $g_{9/2}$ state to estimate the g factor of a particular component in the wave function of the 11^- state. Finally, the g factor of the 11^- isomeric state is obtained by using the relation [8]

$$g=\sum_i g_i * (A_i)^2, \tag{6}$$

where A_i are the amplitudes of the different components of the wave function of the 11^- state (see Table II). In order to calculate the g factor of the 11^- state in ^{92}Tc, it is necessary to know the effective single-particle g-factor values of $\pi p_{1/2}$ and $\pi g_{9/2}$ protons and the $g_{9/2}$ neutron hole. Table III gives a list of the experimentally measured g factors for some nuclei in the mass-90 region [9]. The g factors of the ground states of $^{89}_{39}$Y$_{50}$ and $^{87}_{38}$Sr$_{49}$ can be used as the effective g factors of $\pi(p_{1/2})$ and $\nu(g_{9/2})$ levels. For the g factor of the $\pi(g_{9/2})$ state, we can use the value of 1.387(5) measured for the 8^+ state in $^{94}_{44}$Ru$_{50}$. With the above single-particle g-factor values and the amplitudes listed in Table II, the g factor of the 11^- state in ^{92}Tc is estimated to be $+0.771$. Alternatively, using $g(\pi(g_{9/2}))$ = 1.413(6) as measured for $^{92}_{42}$Mo$_{50}$, the g factor comes out to be $+0.785$. The estimated g factor for the 11^- state in ^{92}Tc closely agrees with the experimentally measured value of $+0.806(20)$.

In conclusion, using pulsed heavy ion beam and TDPAD method we have measured the half-life and g factor of the

11^- high spin state in the odd-odd nucleus ^{92}Tc. We observe a higher value of the half-life $T_{1/2}$=3.15(20) ns compared to the result reported earlier. The measured g factor is 0.806(20). The experimental result is in good agreement with the value estimated from shell model calculations.

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