CHAPTER III
MAGNETIC MOMENT MEASUREMENTS

Recently the techniques of measuring magnetic dipole moments of nuclear excited states with short lifetimes have developed to the extent where they can provide a significant addition to our knowledge about the magnetic properties of nuclei. Already the experimental work done has proved to be of major significance in testing the well developed theories, and one can no doubt expect that the additional results in other areas now being obtained will also play a significant role in understanding other aspects of nuclear structure and nuclear magnetism. The magnetic moment measurements are carried out with the help of the time differential ($\gamma-\gamma$) perturbed angular correlation technique (TDPAC). This technique yields directly the interaction strength independent of any knowledge of the nuclear lifetime of the excited state. This method also gives information on the environmental conditions of the source, i.e. the time dependent perturbation effects, relaxation processes, etc. The differential method has an upper limit, it can also be used if the resolving time of the coincidence arrangement is considerably smaller than the lifetime of the excited state under consideration. Since the number of oscillations obtained in the measurements with TDPAC technique
is quite large, therefore, the Larmor frequency can be determined very accurately using Fourier transformation technique. Hence the value of the magnetic moment obtained with this method will be more accurate as compared to other techniques.

The angular correlation and Mössbauer methods of determining electromagnetic moment of excited nuclear states are based on the static interaction between external field and the nuclear moments. Thus, these methods give results which are independent of any assumption concerning the origin of these moments and are, therefore, classified as model-independent or spectroscopic methods. It is possible to establish relationships between the static electromagnetic moments and dynamical properties of nuclear states with some degree of confidence. It is thus feasible to obtain reasonably reliable values of the electromagnetic moments of excited states by observing the properties of transitions between nuclear states. The results on nuclear moments obtained in this manner are obviously model dependent. The magnetic properties of deformed nuclei (in this thesis we are presenting a case of $^{187}$Re which belongs to the deformed region) are of interest both because they represent another group of nuclei whose structure is thought to be reasonably well understood, and also because there is a considerable amount of experimental data available.
The measurements on lifetimes together with the measurements on magnetic moments should be very valuable for the understanding of the structure of the particular nuclear excited level.

A. MAGNETIC MOMENT OF 206-keV STATE IN $^{187}$Re

1. Source preparation: The g factor measurement of the 206-keV level is carried out with the source in the solution form as sodium tungstate. The source is procured from the Department of Atomic Energy, Bombay (India).

2. Experimental set-up: A smaller, C-frame iron core electromagnet, capable of producing a maximum field of 7 kOe over a 1 cm gap with a 1 cm diameter of pole piece, is used. The stability of the magnetic field is 1% for a typical run of 7 days. The field of the magnet is measured either by a Hall probe (Bell model 240) or by a rotating coil gaussmeter (New Rochelle, model FM). These instruments are calibrated using proton resonance. Thus, errors in fields are due principally to inhomogeneities and drift.

There are two basic types of shielding material - medium permeability (NETIC) material for medium attenuation (which will withstand high magnetic fields) and high permeability (Co-NETIC) or high attenuation shielding material (which will saturate at lower fields). Multiple
layers of Co-netic and Netic material, separated by non-magnetic spacers, are used for shielding the photomultiplier tubes. For maximum shielding of the photomultipliers these layers of Co-netic and Netic material are extended well beyond the face of the photomultiplier tubes. The effect of the field is checked in single γ-ray spectra and prompt time spectra as well.

In the magnetic moment measurements the two detectors are kept at an angle of 135° to each other in a plane perpendicular to the external polarizing field (as shown in Fig. 21).

3. **Decay scheme and gamma rays**: In Fig. 22 the decay scheme of $^{187}$W pertinent to our studies is given$^{50}$. The $(480-72)$ keV gamma cascade is used for the magnetic moment measurement of the 72-keV state in $^{187}$Re.

4. **Magnetic moment measurement of 206-keV state**: Two 5.1 cm x 5.1 cm NaI(Tl) scintillation detectors coupled to 56 AVP photomultipliers are used for the detection of 480-72 keV cascade. The fast pulses from the photomultiplier tube in the stop channel are amplified using EG&G 1 nsec DC amplifier. The outputs of the ORTEC fast discriminators are fed into a model 437 ORTEC time-to-pulse height converter. The source of appropriate strength is put in very small bulb provided at one end of the pyrex glass capillary tube. This source is placed at the centre of the pole pieces of the
FIG. 21 ARRANGEMENT OF MAGNET AND DETECTORS
FIG. 22  DECAY SCHEME OF $^{187}\text{W} (24 \text{h}) \rightarrow ^{187}\text{Re}$. 
magnet. The experiment is carried out at 7.00 kOe and a Packard 400 channel analyzer is used to record the time spectra. The ratio,

$$R(t) = \frac{C(\Theta, t, H \downarrow) - C(\Theta, t, H \uparrow)}{C(\Theta, t, H \downarrow) + C(\Theta, t, H \uparrow)}$$

is obtained for each time channel.

Here $C(\Theta, t, H \downarrow)$ and $C(\Theta, t, H \uparrow)$ are coincidence counts in the same time channel for field down and field up respectively and $\lambda_2 = \text{relaxation constant}, \omega_L = \frac{g I \mu_B H}{\hbar}$ is the Larmor frequency of a nucleus in the magnetic field $H$. The time spectrum with field on is given in Fig. 23. Fig. 24 shows the measured expression $R$ as a function of time $t$. The sine, cosine and absolute transforms defined by

$$A(\omega) = \sum_{t} R(t) \sin (2\pi \omega_L t)$$
$$B(\omega) = \sum_{t} R(t) \cos (2\pi \omega_L t)$$
$$F(\omega) = \sqrt{A^2(\omega) + B^2(\omega)}$$

are plotted in Fig. 25.

The value of the Larmor frequency is obtained from the absolute transform $F(\omega)$ which is independent of phase. The value of the double Larmor frequency is $= 12.1 \pm 0.2$ MHz. The measured Larmor frequency is related through the relation,
FIG. 23  TIME DIFFERENTIAL PERTURBED ANGULAR CORRELATION SPECTRA OF $^{187}\text{Re}$ IN AN EXTERNAL MAGNETIC FIELD OF 7 KOe.
FIG. 24  $R(t)$ vs TIME $t$ PLOTTED FOR THE TDPAC SPECTRA OF $^{187}$Re IN AN EXTERNAL MAGNETIC FIELD OF 7 Koe.
FIG. 25  THE FOURIER TRANSFORMS OF $R(t)$ FOR $^{187}$Re IN AN EXTERNAL MAGNETIC FIELD OF 7 KOE.
\[
\omega_L = - \frac{\mu_N H_{\text{ext}}}{\hbar}
\]  

(3-3)

Where \(\mu_N\) is the nuclear magneton and \(H_{\text{ext}}\) is the externally applied magnetic field. After applying the diamagnetic correction, the final measured value for g-factor is \(= +1.12 \pm 0.03\). Since the spin of the 206-keV level is \(9/2\)\(^5\) and the value of the magnetic moment \(\mu\) of the state is \(=(+5.04 \pm 0.14)\) nm.

B. MAGNETIC MOMENT OF 68-keV STATE IN \(^{44}\)Sc

1. Source preparation: The \(^{44}\)Ti source is obtained in solution form as chloride from Nuclear Science and Engineering Corporation (NSEC), USA and is used as such for carrying out the experiment for the magnetic moment measurement.

2. Decay scheme and gamma rays: In Fig. 26 the decay scheme of \(^{44}\)Ti pertinent to our studies is given\(^{12}\). The (72-68)-keV gamma cascade is used to carry out the magnetic moment experiment of 68-keV state in \(^{44}\)Sc.

3. Magnetic moment measurement of 68-keV state: Two 5.1 cm x 5.1 cm NaI(Tl) scintillators coupled to 56 AVP photomultiplier tubes are used for the detection of (78-68)-keV cascade. The fast pulses from the photomultipliers are amplified using EG&G 1 nsec DC amplifiers. The outputs are processed through the ORTEC fast discriminators and time-to-pulse height converter. The source of proper strength is put in a very small bulb provided at one end.
FIG. 26 DECAY SCHEME OF $^{44}\text{Ti}$ (47.3y) → $^{44}\text{Sc}$.
of the pyrex glass capillary tube. This source is placed at the centre of the pole pieces of the magnet. This experiment is also carried out at 7.00 KOe, applied perpendicular to the plane of the detectors, and a Packard 400 channel analyzer is used to record the data. The application of magnetic field produces oscillations on the time spectrum with the sign of the modulation depending upon the direction of the applied field (see Fig. 27). With the field up and field down the spectra have modulations of opposite phase. The ratio,

\[
R(t) = \frac{C(\Theta, t, H^\downarrow) - C(\Theta, t, H^\uparrow)}{C(\Theta, t, H^\downarrow) + C(\Theta, t, H^\uparrow)} = \frac{3A^2 \sin 2\omega t}{4 + A^2}
\]

where \(C(\Theta, t, H^\downarrow)\) and \(C(\Theta, t, H^\uparrow)\) have the usual meaning as explained earlier since the intermediate state has a spin 1, therefore, the \(A^4\) term is zero\(^{12}\). Fig. 28 shows the plot of the measured expression \(R\) as a function of time \(t\). No attenuation of \(R\) is seen upto some \(\mu\)sec.

Using the expressions given in relation (3-2), the Fourier transforms of the data are plotted in Fig. 29. The Larmor frequency is obtained from the absolute transform \(F(\varphi)\) which is independent of phase \((\varphi)\). Thus the value of the double Larmor frequency is \(= 3.65 \pm 0.05\) MHz. Using the relation (3-3) the value of the \(g\)-factor is calculated.

After applying diamagnetic correction the value obtained
FIG. 27  TIME DIFFERENTIAL PERTURBED ANGULAR CORRELATION
SPECTRUM OF $^{44}\text{Sc}$ IN AN EXTERNAL MAGNETIC FIELD
OF 7 KOe.
FIG. 28  $R(t)$ vs TIME $t$ PLOTTED FOR THE TDPAC SPECTRA
OF $^{44}\text{Sc}$ IN AN EXTERNAL MAGNETIC FIELD OF 7 KOe.
Figure 29: The Fourier transforms of $R(t)$ for $^{44}$Sc in an external magnetic field of 7 kOe.
for the $g$-factor is $= + 0.345 \pm 0.007$. Since the spin of the 68-keV state to be $^{12}_{12}$, the magnetic moment $\mu$ of the 68-keV state is $(+ 0.345 \pm 0.007)$ nm.

C. RESULTS AND DISCUSSION

Our measured results are tabulated in Table 6 along with the other available experimental values in the literature for comparison. The 206-keV excited state in odd $A$ deformed nucleus $^{187}$Re has been identified$^{53}$ as a Nilsson state$^{54}$ with the quantum numbers $9/2^-$ ($514^+$) i.e. $[I = \frac{9}{2}^-, K = \Omega = \frac{9}{2}, N=5, N_2=1, \Lambda=4$, and $\Sigma=1$]. Using the Differential perturbed angular correlation method Koicki et al.$^{47}$, Walter et al.$^{46}$ and Nigam and Bhattacharya$^{51}$ obtained the values for $g$ are $1.046 \pm 0.03$, $1.11 \pm 0.03$ and $1.04 \pm 0.04$ respectively. Koicki et al. made their measurement at two different fields 1720 and 5020 Oe. respectively while Walter et al. and Nigam-Bhattacharya used external fields of 3150 and 3100 \pm 30 Oe. respectively. In the present measurement, however, the external magnetic field is $7000 \pm 70$ Oe. Our measured $g$-factor is in fair agreement with the previous measurements (see Table 6).

If rotational $g$-factor is taken as $g_R = \frac{2}{A} = 0.407$ and free proton spin $g$-factor $g_s = 5.585$, then using the Nilsson's formula$^{54}$ a value of $g = 1.32$ is obtained, which is considerably larger than the experimentally measured $g$ value. However, as suggested by De Boer and
Rogers\textsuperscript{55}) if the free nucleon spin g-factor is taken to be 0.6 \( g_s \), then a value of \( g = 1.08 \) is obtained and it is in fair agreement with the experimentally determined value of \( g \). The sign of the g-factor is also determined from the sign of the anisotropy and the sign of the first oscillation (when the modulated time spectrum is carefully extrapolated to zero time).

From Table 6 we observe that our measured g-factor value for 68-keV state in \( ^{44}\text{Sc} \) also agrees well with the previously reported values for \( g \). If the levels of \( ^{44}\text{Sc} \) are all derived from the same configuration for the neutrons and protons, the magnetic moments of the levels are given by:

\[
\mu = \left( \frac{1}{2} I \right) (g_1+g_2) + \left( g_1-g_2 \right) \frac{I_1 (I_1+2) - I_2 (I_2+1)}{2 (I+1)}
\]

where \( I \) is the total angular momentum, \( I_1 \) and \( I_2 \) are the angular momenta and \( g_1 \) and \( g_2 \) are the g-factors for the proton and neutron groups respectively. If the angular momenta of the proton and neutron groups in \( ^{44}\text{Sc} \) are taken 7/2\textsuperscript{56}), the g-factors for all the energy levels will be identical and will be given by \( g = \frac{1}{2} (g_1+g_2) \). Using Schmidt values for the odd neutron and odd proton, a g-factor of + 0.55 is obtained. If the configurations for a proton and a neutron groups are assumed to be \( (f_{7/2})^{1/2} \) and \( (f_{7/2})^{3/2} \) respectively, a g-factor of
+ 0.50 is obtained. These values of g-factor do not agree with the experimentally measured g-factor values for various levels in $^{44}$Sc. This clearly indicates that this simple model is not appropriate for $^{44}$Sc. The absence of any definite knowledge of the configuration of 68-keV state in $^{44}$Sc is an hindrance in interpreting the g-factor of this state.

It is interesting to note in Figs. 24 and 28 that no attenuation of the function R or of the differential angular correlation in a period of 0.7 μsec (in $^{187}$Re measurement) and 0.4 μsec (in $^{44}$Sc measurement) is detected. Nevertheless, for sources in liquid form, this attenuation must always be present (even though too small to detect during the nuclear lifetime) due to the interaction between the nuclear quadrupole moment and the fluctuating electric field gradients produced by neighbouring atoms. From Figs. 24 and 28 a limit may be set for the exponential attenuation factor or relaxation constant $\lambda \geq 4 \times 10^6$ sec$^{-1}$ and $\lambda \geq 2 \times 10^6$ sec$^{-1}$ respectively for $^{187}$Re and $^{44}$Sc.

The Fourier transform of the R(t) function is essentially the NMR line having a Lorentzian shape. In the case of $^{44}$Sc magnetic moment measurement, the observed width (FWHM) $\sim 9 \times 10^{-9}$ eV is about twice the
natural width = $4.4 \times 10^{-9}$ eV. In the $^{187}$Re magnetic moment measurement the observed width (FWHM) $= 1.5 \times 10^{-9}$ eV compared to the natural width of $= 1.25 \times 10^{-9}$ eV. The large observed width may probably be due to the quadrupole interactions etc.
Comparison of the present magnetic moment measurements with available published values

<table>
<thead>
<tr>
<th>Nucleus (keV)</th>
<th>Level</th>
<th>External field applied (K0c)</th>
<th>g-factor</th>
<th>References</th>
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<tbody>
<tr>
<td>$^{187}$Re</td>
<td>206</td>
<td>1.72</td>
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<td>47</td>
</tr>
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<td></td>
<td></td>
<td>5.02</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>3.15</td>
<td>1.11±0.03</td>
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<tr>
<td></td>
<td></td>
<td>3.10±0.03</td>
<td>1.04±0.04</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.00±0.07</td>
<td>+1.12±0.03</td>
<td>Present measurement and $\mu = +5.04\pm0.14$ nm</td>
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<td>$^{44}$Sc</td>
<td>68</td>
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<tr>
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<td></td>
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<td>+0.342±0.006</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.00±0.07</td>
<td>+0.345±0.007</td>
<td>Present measurement and $\mu = +0.345\pm0.007$ nm</td>
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</table>