g(2_1^+) factor measurement with radioactive beams

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The g factor studies in the short lived nuclear states provide valuable information on various structural properties observed at high spins in nuclei. The importance of transient magnetic field method in measuring the g factor of such short lived states in stable nuclei has been well recognised. The fast development of physics of unstable nuclei produced as radioactive ion beams over the last one decade has put an increased demand for g factor measurement in these short lived exotic nuclei. Their special means of production require some new methods of measuring g factor in them. In this pursuit, a new technique, the high velocity transient magnetic field (HVTF) has emerged as a promising technique and has been tested successfully in some realistic cases. There are some issues in the techniques which need to be looked at before it can be applied at wider level

1. Introduction

The nuclear g-factors due to their sensitivity to the small admixtures in wave function have the potential to probe the single particle structure of nuclei. Realising their importance in resolving various structural issues, a number of g-factor studies have been done in different nuclei over the years. A comprehensive account of all the measured g factors has been given by Raghvan **[1]** and Stone **[2]**. For measuring these g-factors a number of different techniques have been applied. Various factors like lifetime and spin of the nuclear state involved, the way the state was produced and its decay mode and also its chemical properties guided the way for the development of all these techniques.

In the past 40 years, though the g-factors have successfully resolved many structural issues, the measurements were restricted only to the stable or near stable nuclei. In the last two decade with the advent of big accelerator facilities at CERN (Switzerland), GSI (Germany), GANIL (France), TRIUMF (Canada), NSCL & Oak Ridge (USA), RIKEN (Japan), it has become possible to explore the regions of nuclear landscape much beyond the valley of stability. The new methods of production, selection and detection adopted at these intermediate and high-energy projectile fragmentation facilities [3,4] resulted in a variety of new nuclear species both on the proton and neutron-rich side of the nuclear chart. The detailed spectroscopic investigations done on these exotic nuclei have revealed a number of interesting features like existence of 'halo' structure [5], the appearance and disappearance of magic numbers in different mass regions [6-7], etc. in them. The Shell model, which otherwise has successfully resolved many structural issues in stable and near stable nuclei, substantially failed to account for these observed exotic phenomena. So g-factor measurement in exotic nuclei are essentially required to set the limits (if there are any) of shell model and also to suggest the parameters that need to be incorporated (or modified) into the model, to make it applicable for exotic nuclei also.

Compared to the stable beam measurements the g-factor measurement in exotic nuclei is very difficult and therefore somewhat challenging. The major difficulty is posed by the way these exotic nuclei are produced in the laboratories. The exotic nuclei are produced as the Radioactive Ion Beams (RIBs), which are orders of magnitude (~ 10^4 pps) weaker than the conventional stable beams (~ 10^9 pps). The low intensity directly lowers the yield of gamma rays, and hence increases the statistical uncertainty of the measurement. Additionally, the impure nature of RIBs and the background radiation arising from the beam stopping near the detection system pose another level of difficulty to such g-factor measurements via conventional methods. Therefore alternate methods of g-factor measurements with RIBs need to be developed. Recently two new methods ; the high velocity transient field (HVTF) technique and the recoil in vacuum (RIV) technique have been developed to measured the g-factor in nuclei produced as radioactive ion beams. In the present manuscript the aim is to discuss the HVTF technique and its potential to measure the g-factor of pico-sec lifetime states in exotic nuclei produced as RIBs.

2. Measurements in pico-second Lifetime States

An excited nucleus (spin I, magnetic moment μ) when placed in an external magnetic field (B), experiences a torque ($\tau = \mu \cdot B$) that causes it to rotate about the direction of the external magnetic field with Larmor frequency,

$$\omega_L = g \cdot (\mu_N / \hbar) . B$$

where, g is called the gyromagnetic ratio

Due to the nuclear rotation, the associated γ- ray angular distribution pattern also rotates with the Larmor frequency, resulting in a highly anisotropic angular distribution pattern of γ- rays in space. Almost all the g-factor measurement techniques are more or less based on measuring this anisotropy of angular distribution as a function of time.

For small time interval Δt, the angular precession $\Delta\theta$ (= ω_L. t) depends on the product of the strength of the applied magnetic field and the interaction time (mean lifetime of the nuclear state). So for pico second lifetime states the magnetic field of few kTesla strength is required to induce a detectable precession (few milliradians). Such strong fields cannot be provided by laboratory magnets, and therefore one has to relay on the internally produced (hyperfine) magnetic field for which the strength as high as 70 kTesla has been reported. There are two ways in which the nuclei experience such strong hyperfine magnetic fields :

(i) when an ion rapidly moves through a polarized ferromagnetic material (Transient Magnetic field (TF) Technique) and

(ii) when a hydrogen like ion leaves a solid medium and recoils in vacuum (or a gas at low pressure) (Recoil in Vacuum (RIV) Technique)

In the past though the TF technique has been used extensively for measuring g-factor of pico-sec lifetime states, the use of RIV technique was somewhat limited by the problems in obtaining calibrations of the hyperfine interactions for particular electronic configurations, ion velocities and the atomic number *Z* of the nucleus.

3. Transient Field Measurements

(a) With Stable Beams

The TF and is experienced by the ions moving rapidly through a polarized ferromagnetic material [8,9]. It is basically an effective magnetic hyperfine field created at the nucleus of a moving ion by its electronic cloud. Only inner-shell electrons can produce the observed transient field strength of several kilo Tesla. These fields are usually insensitive to the mean life of the nuclear states but are found to increase with the increase in ion velocity [10, 11].

A typical TF experiment involves the following three steps –

(a) production of spin aligned excited ion using a nuclear reaction

(b) The passing of produced ion polarized magnetic substance , so that it experiences the transient field and undergo a spin precession

(c) The measurement of spin precession as a perturbation of the angular correlation.

In transient field measurements using stable beams usually a multilayer target is used and the ion of interest are produced via Coulomb excitation in the conventional ($A_{beam} < A_{target}$) as shown in Fig. 1 or inverse ($A_{beam} > A_{target}$) kinematics geometry shown in Fig. 2. A detailed discussion on the TF measurement technique of g factor measurement has been discussed in a review article by N Benczer-Koller and G J Kumbartzk**i** [12].

Over the last three decades, a large number of TF measurements have been

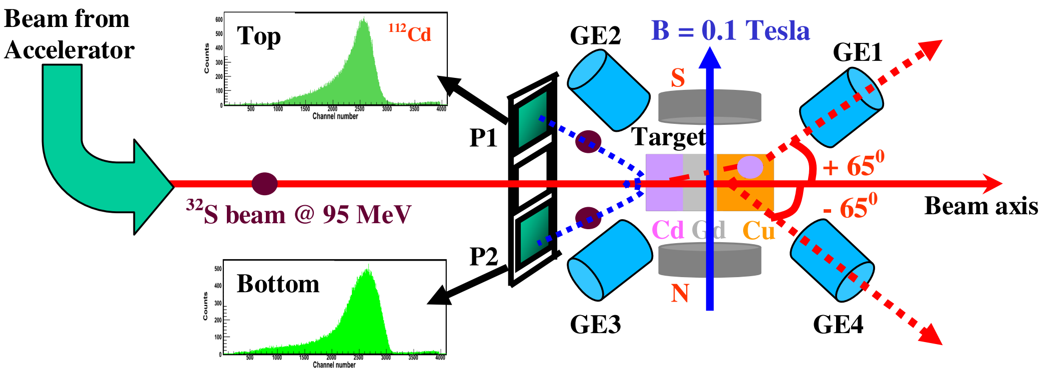

Fig. 1: Schematics of transient field measurement in the conventional kinematics

carried out and g factors of the first few excited states in stable nuclei have been measured. Though a majority of these measurements have been done with Coulomb excitation in conventional kinematics, the thrust has been shifted to inverse kinematics over the last one decade due to enormous advantage of projectile being used as a beam. In Inverse kinematics, the particles are focused in the beam direction which allows the most complete detection of all the reaction products and therefore results in high counting statistics.

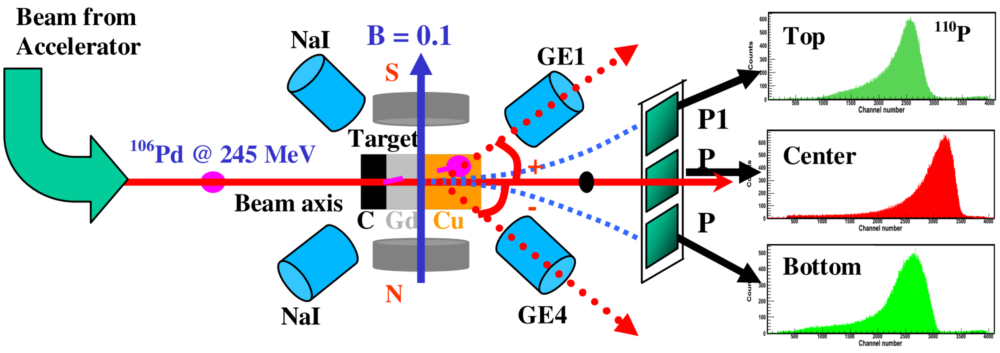

Fig. 2: Schematics of transient field measurement in the Inverse kinematics

Additionally, when heavy ion beams (compared to the target which is usually Carbon) are used as projectiles, higher recoil energies within the polarized ferromagnetic material are obtained, which results in increased transient field and improved precession effect. A comprehensive review of the magnetic moments of short-lived states measured with the transient field technique in inverse kinematics was written by Speidel, Kenn and Nowacki [13].

In Transient field measurements one of the major areas of concern is to accurately determine the strength of produced hyperfine magnetic field. In principle the HF field can be calculated from first principles (Hartree–Fock) for any electron configuration. For 1s electron, the HF field produced at the nucleus is given by :

$$B_{ns}\,(Z) = 16.7\,R(Z)\,.\;(Z/n)^3$$

where, $R(Z) \approx 1 + (Z/84)^{5/2}$

Since the 1s electrons have maximum overlap with the nucleus, the largest field occurs for H-like ions. Consequently, the TF strength is proportional to the number of ions with unpaired electrons in 1s orbits. Also, as the field direction comes from the electron spin directions in these states, the net TF strength depends on the 'polarization' of the electrons in such states. One more factor which is found to influence the strength of the TF is the velocity of moving ions. For light ions ($Z \leq 20$), the field strength is found to increase with ion velocity until reaching a maximum for ions moving with K-shell electron velocities, v_K ($= Z \cdot v_0$). For still higher velocities the TF decreases and finally approaches to zero at relativistic ion velocities [14] as shown in Fig. 3.

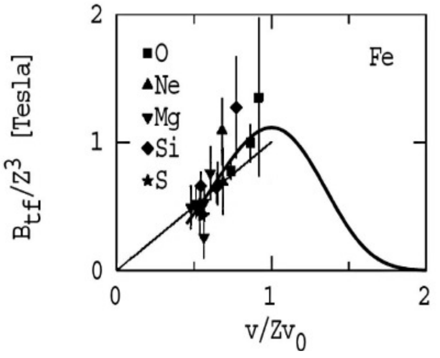

Fig. 3: TF strength of light ions in Fe (data points) and high velocity transient field parameterization (solid line).

In general the TF can be formulated as :

$B_{tf} = \sum q_{ns}(Z, v_{ion}) . p_{ns}(Z, v_{ion}, host) . B_{ns}(Z)$

where $q_{ns}(Z, v)$ represent the charge state distribution for single 1s electron configurations and $p_{ns}(Z, v)$ their degree of polarization.

The use of above formula to accurately calculate the TF produce in the realistic situations is somehow limited by the little knowledge of the charge state distribution of moving ions while passing through the ferromagnetic host. Experimentally, the charge state distributions can be obtained only for ions exiting from solids. Even if it is assumed that inside the solid a similar charge state distribution exists, it may have different velocity dependence. Also, the necessary polarization transfer from the ferromagnetic medium to the moving ions is not well understood.

Due to all these problems and many more [15,16], in TF measurements the strength of the field is either calibrated with a known g-factor or parameterized with some realistic formulism. Over the years a number of different parameterizations (Bonn group [17], Rutgers group [18], Chalk River group [19,20]) have been developed and used but none of them can claim to represent all available data at this time.

(b) With Radioactive Ion Beam

The transient magnetic field technique was originally developed to work with stable beams. However, with the growing availability of good intensity radioactive ion beams at various research facilities, several groups begin modifying the TF technique to incorporate the changes required in it due to the special means of production of exotic nuclei. The task is not easy as there are new geometrical conditions involved apart from various restrictions that come into picture while working with RIBs.

Since it is impractical to fabricate radioactive targets, especially when the nuclei are short-lived, the radioactive nuclei need to be produced as projectiles. This requirement introduces a lot of problems as the high speed radioactive projectiles when hit the stationary target produce huge amount of low energy atomic background which virtually blinds the detectors for some time. Also the unknown m-state populations and the possible feeding from higher-lying states, resulting from the production mechanism of RIB, puts an uncertainty in the interaction time for the state of interest and hence in the TF.

In order to address all these issues related to RIBs, recently a new approach, called High Velocity Transient (HVTF) technique [21] has been introduced. This technique specifically applies to the radioactive isotopes produced using in-fight fragmentation, which offers access to numerous isotopes away from stability but with velocities higher than those obtained in the stable beam transient field measurements. The HVTF technique consists of three key components:

(i) the production of a beam of radionuclides with sufficient intensity,

(ii) the intermediate energy Coulomb excitation to produce spin alignment, using a thick target designed to degrade the projectile velocity to near Zv_0

(iii) knowledge of the transient field strength, B_{TF} (Z, v) which depends on the ion and ferromagnet combination and is a function of ion velocity that is usually described by a parameterization.

In Intermediate energy Coulomb excitation [22], the beam energy is above the Coulomb barrier, so the distance of closest approach can be smaller than the sums of the nuclear radii, and therefore projectile and target can interpenetrate. In this situation, nuclear reactions can then take place, including few-nucleon removal and fragmentation reactions, which are undesirable because they result in nuclear species changes rather than inelastic scattering. So, the experiments are designed such that only particles that are come within a small angle θ_{max} (corresponding to a large enough minimum impact parameter b_{min}) are detected (Fig. 4).

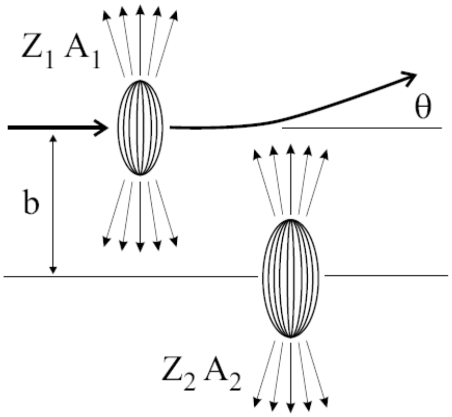

Fig. 4: Schematic view of the Intermediate energy Coulomb excitation.

The radioactive nuclei produced by fragmentation reactions often have velocities of the order of 0.3-0.5c that are much higher than their K-shell electron velocity (~ 0.3 c). At such high velocities, a major concern is whether or not there would be sufficient precession effect to make a HVTF technique feasible for radioactive beams. There is not enough experimental data available at such high velocities ($v > Zv_0$) to suggest anything conclusive in this respect, though a great number of experiments have been done at ion velocities between the L and K shell electron velocities ($0.5Zv_0 < v < Zv_0$). At present parameterization of TF is the only way to extract g factors from possible spin precessions. The parameterization given by Stuchbery et al [24] gives TF strength for fast moving H-like light ions ($6 \leq Z \leq 16$).

$$B_{tf}\,(v, Z) = A\,.\,Z^{P}.\,(v/Zv_0)^2.\,e^{-1/2(v/Zv0)4}$$

with the parameters A and P determined for Fe and Gd hosts by fitting the available data on transient field strengths. For Fe hosts (Figure 3), the value of A = 1:82 (5) T with P = 3 and for Gd hosts (Fig. 5), A = 26.7 (11) T with P = 2 was obtained.

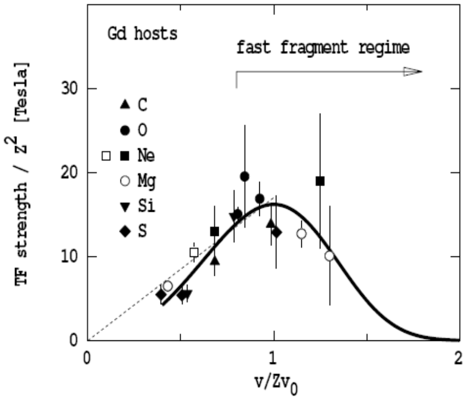

Fig. 5: Compilation of previously known TF strength of light ions in Gd (data points) and high velocity transient field parameterization (solid line)

In HVTF experiments, the designing of proper target geometry is very important. The concentration of transient field strength near Zv_0 provides a stringent constraint on the experiment design. Slowing the fast radioactive projectiles to near Coulomb barrier velocities is the most critical aspect to be addressed in the choice of the experimental parameters, i.e. primary beam energy, primary target thickness, wedge degrader thickness, and HVTF target layer thicknesses. Without a proper slowing of the projectiles, there is no transient field induced spin precession. Slowing down of ions in matter necessarily increases the energy spread of the projectiles. A compromise must therefore be made between how much slowing can be done in the fragment separator and the amount of slowing that gets left for the HVTF target itself Accomplishing this task in an optimum fashion involves several compromises to ensure a successful experiment. Some aspects of the compromises that affect the experimental sensitivity to spin precession can be quantified by figure of merit expressions involving the number of γ-ray counts and the slope of the γ-ray angular distribution at the detector position.

An additional constraint on the experiment design is the slowing down time. In the HVTF, the slowing must be done quickly because after the Coulomb excitation event, the states begin decaying. Decays that occur in the non-ferromagnetic layer accomplish nothing because there is no transient field present. However, since the cross section for Coulomb excitation goes as Z^2_{target}, it is advantageous to use a thick, high-Z Coulomb excitation layer to ensure enough excitation yield. The thickness of the Coulex layer increases the transit time of the ions prior to their arrival in the ferromagnet, so a compromise needs to be made between excitation yield and the need to ensure a large interaction time with B_{TF} prior to the decay governed by the excited-state lifetime τ. It turns out that iron has a higher stopping power than many common Coulex targets such as gold, so if iron is used, it is beneficial to place the ferromagnetic layer at a point where the ion velocity is still beyond $2Zv_0$. There is no transient field initially, but the ions are quickly slowed into the velocity range where B_{TF} is large. To determine whether a particular nuclear excited-state g factor can be measured using the HVTF method, the slowing time needs to be compared to the excited-state lifetime. The slowing time can be estimated using tabulated ranges of ions in matter, with the program SRIM [25].

There are many more microscope issues which need to be addressed before any creditable HVTF g factor measurement can be done on nuclei produced as RIBs. In the first successful use of HVTF technique, A.E. Stuchbery, et. al. [26] measured the g factors of the first excited 2^+ state in $^{38,40}S$ at Michigan State University (USA). The results of the experiment are very promising and give enough hope of using the HVTF technique for future g factor measurement with radioactive ion beams.

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