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HYPERFINE INTERACTION STUDIES WITH HEAVY ION BEAMS: APPLICATIONS IN NUCLEAR PHYSICS

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ABSTRACT

Heavy ion reactions using pulsed beam had a great influence on the study of hyperfine interactions. Until recently the radioactivity or light-ion reactions have been used for such studies. Heavy-ion reactions however offer considerable advant~~e~~age for systematic investigation of hyperfine interactions. In this review we shall describe the basic technique of time differential perturbed angular distribution (TDPAD) and recent applications to some problems i~~s~~n nuclear physics such as the measurements of nuclear magnetic and electric quadrupole moments of high spin isomers.

INTRODUCTION

The observation of spin precession of short-lived excited nuclear states by the time differential perturbed angular correlation (TDPAC) of cascade γ-rays in radioactive decay is well known for quite some time. This method has a natural extension to the isomeric states populated in nuclear reaction. Most of the eartier work was carried out using pulsed beams of light projectiles such as p, d and α during sixties and using small machines such as van de graffs of modest energy. A major break through took place during seventies with the introduction of heavy-ion reactions. This had a great impact on this technique interms of its wide applications both in the area of nuclear physics as well as solid state physics. Heavy-ion reactions have introduced a high degree of flexibility in its application to physical problems.

The TDPAD Technique

There are some basic requirements that must be fulfilled for all time differential perturbed angular distribution experiments a) An ensemble of isomeric nuclei must be excited by a pulsed beam in a burst time $\tau_p << \tau, T_I$, where τ is the life time of the isomeric state and T_I is the characteristic interaction time; b) the de-exciting radiation (γ-rays in most cases) should be emitted anisotropically and c) the anisotropy should be preserved for a considerable portion of the interaction time T_I.

In the commonly used spin rotation method the repetition period of the beam T_p, is chosen such that $T_p >> \tau$. The nuclei excited in the beam burst τ_p have all had sufficient time to completely decay before an other ensemble of nuclei are excited in the next burst. This sequence is illustrated in Fig 1. If now the de-exciting γ-radiation is observed at a certain fixed angle θ relative to the beam direction, one observes the normal exponential decay of the isomeric state with life time τ provided there is no perturbing interaction present. In the presence of perturbing interaction (between isomer nuclear moment and extranuclear multipole field) however the exponential decay is modulated by the precession of nuclear moment. The modulated angular distribution can now be expressed as [1)]

$$W(\theta,t) = \Sigma B_k A_k G_k(t) P_k(\cos\theta)$$

where $B_k A_k$ is a measure of radiation anisotropy and $G_k(t)$ contains the complete temporal description of the interaction. The important advantage of the pulsed-beam technique is that it is a singles counting experiment and in principle there is no upper limit on the life time of the isomeric state due to random background as in coincidence experiments. The main consideration with long lived isomers is the problem of preserving the nuclear alignment for sufficiently long time. However due to constraints on the duty cycle of the beam for $\tau >> 10\ \mu$ sec new methods for observing the spin precession have been developed. In the stroboseopic method 2) the pulse repetition period T_p is chosen such that $T_p << \tau$ so that the decays from several bursts overlap. The period of spin precession is then adjusted so that the precession phases from successive bursts beat and one observes a resonance. The phase matching can be done with fixed field and fine tuning the repetion period, as in the case of quadrupole interaction. In the case of pure magnetic interaction this can also be done by varying the external field. Fig. 2 shows an example of stroboscopic precession.

The Magnetic Interaction

The interaction of nuclear magnetic moment with magnetic field results in a Larmor precession of the magnetic moment of the isomeric state. The frequency of the the Larmor precession is given by

$$\omega_L = - \mu_N g H/\hbar$$

where H is the magnetic field, μ_N the nuclear magneton and g is the nuclear g-factor. Either the field or the g-factor is the parameter of interest. The observed precession pattern is determined by the geometry of the experiment.

a) Random field orientation:

This applies to hyperfine field studies in ferromagnetic hosts with no external polarizing field. The observed modulation is given by (in the simplest case) by

$$G_2(t) = 0.2 + 0.4 \{ \cos(\omega_L t) + \cos(2\omega_L t) \}$$

Measurement of time resolved γ-ray intensity at two angles usually 0^{o} and 90^{o} is sufficient to determine this function and hence the value of the Larmor frequency. Sign of the precession is however not determined by this method.

b) Magnetic field normal to the beam detector plane:

This is the most commonly used geometry. The γ-ray intensity at one angle (45^{o}) with field directions up and down is used to obtain the ratio R(t) which in the simplest case is given by

$$R(t) = 0.75 A_2 \sin(2\omega_L t)$$

notice that in this geometry the important sign information can be obtained.

c) Magnetic field in the reaction plane and at 45^{o} to the beam axis:

This geometry 3) is very useful for measuring large hyperfine fields when one approaches the situation where $T_2\omega_L \simeq \tau_p$. With detectors at 0^{o} and 90^{o} one obtains the ratio

$$R(t) = 0.75 A_2 \cos \omega_L t$$

As can be seen almost all the amplitude goes into the single Larmor frequency in contrast to the previous geometries. The sign information is however not available. A recent appli -

cation of this geometry in a heavy-ion TDPAD experiments provides a good example as shown in Fig.3.

The Quadrupole Interaction

Unlike the magnetic case the quadrupole interaction(QI) is some what more complicated for several rasons, a) the m^2 degeneracy is involved, b) the level splitting is non uniform so there is more than one precession frequency, c) the level splitting as well as the frequency spectrum is spin dependent of the isomeric state, d) the symmetry properties of the electric field gradient (EFG) offect the frequency spectrum. For axially symmetric EFG, the quadrupole interaction frequencies are multiples of the basic frequency ω_Q given by $\omega_o = 3\omega_Q$ (for integer I) and $\omega_o = 6\,\omega_Q$ (for half-integer I) where

$$\omega_Q = e^2 q\ Q\ /\ 4I\ (2I - 1)\ \hbar$$

As in the magnetic case one can use different geometries determined by the setting of the symmetry axis of the EFG relative to the beam and detectors.

a) Random Orientation of EFG

In a polycrystalline sample the orientation of the symmetry axis is randomized and the modulation function is given by $^{1)}$

$$G_k(t) = \sum_n S_{n_k} \text{Cos } (n\omega_o)\ t$$

where the value of the index n is determined by I. For smaller values of I the madulation pattern is relatively simple however for larger values of I the frequency spectrum becomes complex.

b) Single crystals: The single crystals give the best modulation patterns. The relative orientation of the symmetry axis of the EFG strongly influences the composition of the QI frequency spectrum 4). For high spin isomers observed in heavy-ion reactions this effect is of special significance. For high spin values the basic frequency is small ($\omega_o \simeq \frac{1}{I^2}$) and the frequency components become very large so that the modulation pattern is increasingly featureless. The sharp feature of the modulation pattern occurs at long times when most of the nuclei have already decayed. A method to overcome this problem was first discovered at Rutgers 5). The symmetry axis (c-axis) of the crystal is set at 45° to the beam axis and detectors placed at 0° and 90°. Under this geometry certain frequency components of the QI are enhanced producing strong oscillations in the early part of the modulation cycle enabling precise measurements even for fairly large spin value. Figure 4 compares the modulation patterns for polycrystal, c-axis normal to the reaction plane and C-45 geometry. It can be seen that the C-45 geometry gives the best modulation pattern. The application of this geometry has been quite important in many QI studies of high spin isomers. Since the basic TDPAD experiment involves only the alignment of the isomeric state it can not yield the sign of the QI. This is equivalent to saying that the QI has a m^2 degeneracy. However under certain circunstances for example in a tilted foil experiment 6) it becomes possible to determine the sign of QI.

Advantages of Heavy Ion Reactions in TDPAD Studies

The dynamics aswell as the kinematies of the heavy-ion reaction offer advantages in the TDPAD studies. In a fusion evaporation reaction the final nucleus is formed at high excitation energy and with high angular momentum. De-excitation takes place predominantly through γ-ray emission along the yrast line 7) and a large number of isomers can be populated. These isomers are usually of simple nuclear structure and precision measurements of their moments are of great interest to nuclear structure physics. Heavy-ion reactions are also very effective in producing neutron deficient nuclei and nuclei for off the stability line. The widespread extent of isomers in a large number of elements is of particular value for applications to problems other than nuclear physics.

The most important advantage derived from the heavy-ion reaction is the large liner momentum given to the isomeric nucleus. Usually several MeV's are available for the isomer which can easily recoit out of the reaction targets (even in ≈ mg/cm^2 targets). It can then be easily implanted into a separate backing material. That is equivalent to effectively decoupling the nuclear reaction criteria from those of the solid state problems. The TDPAD technique following heavy-ion reactions thus compares with the methods such as the Mössbauer effect where the physical separation of source and absorber has been important in its wide applicability.

The sensitivity of the TDPAD experiment depends on the degree of alignment of the isomeric state after nuclear reaction. In the heavy-ion reactions a high angular momentum is transfered to the isomeric nucleus which leaves it in a highly aligned state producing large anisotropies in the de-excitation γ-rays. This is a fairly dependable feature of these reactions.

Among the disadvantages of TDPAD technique following heavy-ion reactions is the radiation damage and its associated problems. The effect relevant to most experiments is that it causes a partial loss of alignment of the isomeric state. This reduces the average amplitude of the modulations and thus the sensitivity of the method. While radiation damage is a central part of the process, wide experience in applying this technique has shown that it has not diminished the utility of the method.

Applications to Nuclear Physics

a) Nuclear g-factors:

The measurement of g-factors is the simplest application of the TDPAD technique and can be acomplished with high precision. The current interest in g-factors centres on the test of shell model with precision moments and systematic behaviour for a series of states of specific structure. The heavy-ion reactions are quite efficient in exciting an extended number of isomers of specific structure specially in the neutron deficient region. The advantage of recoil implantation has also enabled the measurement of small solid state effects such as knight shifts which must be known accurately for any precision moment determination. The possibility of using ferromagnetic hyperfine fields for measuring small g-factor is also important. A major interest in current nuclear structure physics is understanding the high-spin phenomena. High-spin isomer being the natural domain of heavy-ion reaction these studies have also benifitted significantly through g-factor measurements.

The deviation of g-factors of the nuclei with a single particle outside closed shells from Schmidt values is usually explained in terms of mesonic effects and core polarization 7). Provided these effects are of renormalized character the additivity of moments is expected to hold with the addition of a few particles. Violation of additivity should mean that either the few particle state has no unique configuration or the core structure changes with the addition of extra particles. This has been widely tested for the addition of two particles.

An excellent example of such a study is provided by the $(h_{9/2})^n$ configuration in a series of isomers with N = 126 closed shell[8)]. g-factors of such states in ^{210}Po (8^+) ^{211}At ($21/2^-$), ^{212}Rn (8^+), ^{213}Fr ($21/2^-$), ^{214}Ra (8^+) and recently ^{215}Ac ($21/2^-$) [9)] have been measured very precisely. The g-factors indicate small but significant break down of additivity showing the core polarization-blocking effect. This is however not the case of ^{209}Bi where large core polarization corrections are needed to explain the well-known g-factor anomaly. g-factor systematics of 8^+ and $17/2^-$ isomers in the N = 50 closed shell nuclei have been extended to more neutron deficint isomers recently, using heavy ion reactions[10,11)].

How nuclei respond to increasingly high angular momentum is the central theme of the study of the high-spin phenomena. Basically high-spin states can be formed either by the alignment of only a few particles in high I orbitals, or by partial alignment of many orbitals. Alignment of few particles in high angular momentum orbital produces isomers of very high spin called "Yrast traps" in spherical or weakly deformed nuclei. Measurement of the g-factors of these states is important for determining their structure.

g-factors of six isomers in ^{212}Rn, with 4 protons outside the doubly closed ^{208}Pb core have been measured, with spins ranging from 8^+ to 30^+ [12)]. Results show abrupt decrease of g-factor above I = 20, after which it remains nearly constant. The sudden change is also seen in the E versus I(I+1) plot, indicating the rotation like behaviour after I > 20. As a second example g-factors of several isomers in ^{147}Gd (near N = 82 closed shell) have been reported [13)]. The result for the highest spin isomer I = 49/2 shows that the alignment here comes from approximately equal number of neutrons and protons.

b) Static Quadrupole Moments:

The measurement of static quadrupole moments of the isomeric state presents a major problem not present in the case of magnetic moments. A sufficiently strong external EFG is not available. One must use EFG's present in solids. Presently EFG's even in a simple noncubic solid can not be calculated in a reliable way. Thus the EFG used must be calibrated experimentally. The independent choice of backing material provided by the heavy-ion recoil implantation has been of great value to calibrate host material for application to model independent Q-moment measurements. In the last few years , heavy-ion method and application of C-45 geometry of single crystals has enabled the measurement of several new Q-moments of high-spin isomers.

The polarization of the nuclear core by valence nucleons is usually taken into account by assigning an effective charge e^{eff} to the valence particle. The questions of interest are i) the relative e^{eff} of proton and neutron, ii) dependence of e^{eff} on the number of valence nucleons and iii) angular momentum dependence of e^{eff}. Recently the Rutgur's grup 14) has measured static Q-moments in $^{88,90}Zr$ and $^{90,92,94}Mo$ for $I = 8^+$ isomers $(\pi,\nu g_{9/2})^{\pm 2}$ and for the $21/2^+$ isomer in ^{91}Zr $(\pi g_{9/2}^2) \otimes (\nu d_{5/2})$. The EFG in metallic Zr metal was calibrated by the Q-moment of the I = 5/2 ground state 15) of ^{91}Zr and NQR data for this isotope in Zr metal. Some of the results are shown in Figs. 5 and 6. The results show that the polarization charges for neutrons in the $g_{9/2}$ orbital is much larger than that of proton indicating its ability to induce core excitations via strong neutron proton interaction, which is ultimately responsible for the strong deformations which occur as more neutrons are added.

An excellent example of the usefulness of this technique is provided by the work of chalk River group 16) on the Q--moment measurement of isomers in Gd isotopes. An important problem faced in these experiments is that of paramagnetic relaxation. In rare earths the unfilled 4f spins produce a large fluctuating field at the nucleus which effectively washes out the alignment in several n sec in heavy rare earths. The half-full shell f^7 in Gd makes it the most attractive case in this respect and has been important in these experiments. The Gd isomers were recoiled out of a ^{124}Sn target in (^{28}Si,xn) reactions and implanted into a Gd single crystals. Measurements were performed in a C-45 geometry at 332K, above the curi point of Gd. The calibration of EFG in Gd was available from Mössbauer measurements.

The Q-moment of the I = 49/2 isomer in ^{147}Gd was found to be very large $|Q| = 3.24(18)$b, giving extreemly large effective neutron charges. This result and other measurements of Q-values of high-spin Gd isomers indicated that the deformation of these yrast states comes from the alignment of several nucleon of high j. Such measurements have been extended to N = 126 region by the Berlin group who have reported Q-moment measurements in Pb, P_o and At isotopes 17).

CONCLUSIONS

The examples presented here are only a sampling of the problems that have been studied with the TDPAD technique following heavy ion reaction. An extensive application of this technique has been made in the study of solid state physics for example the physics of the isolated impurity in metallic systems and the study of magnetic hyperfine fields at dilute impurities in metallic hosts.

In a colaborative program with the Institute of Physics at the University of São Paulo we are planning hyperfine interaction studies with heavy ion beams from the 8 MeV Tandem Van-de-Graff. Application to nuclear physics as well as to the solid state physics problems are the goals of our research program.

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$$T_p \gg \tau \gg \tau_p$$

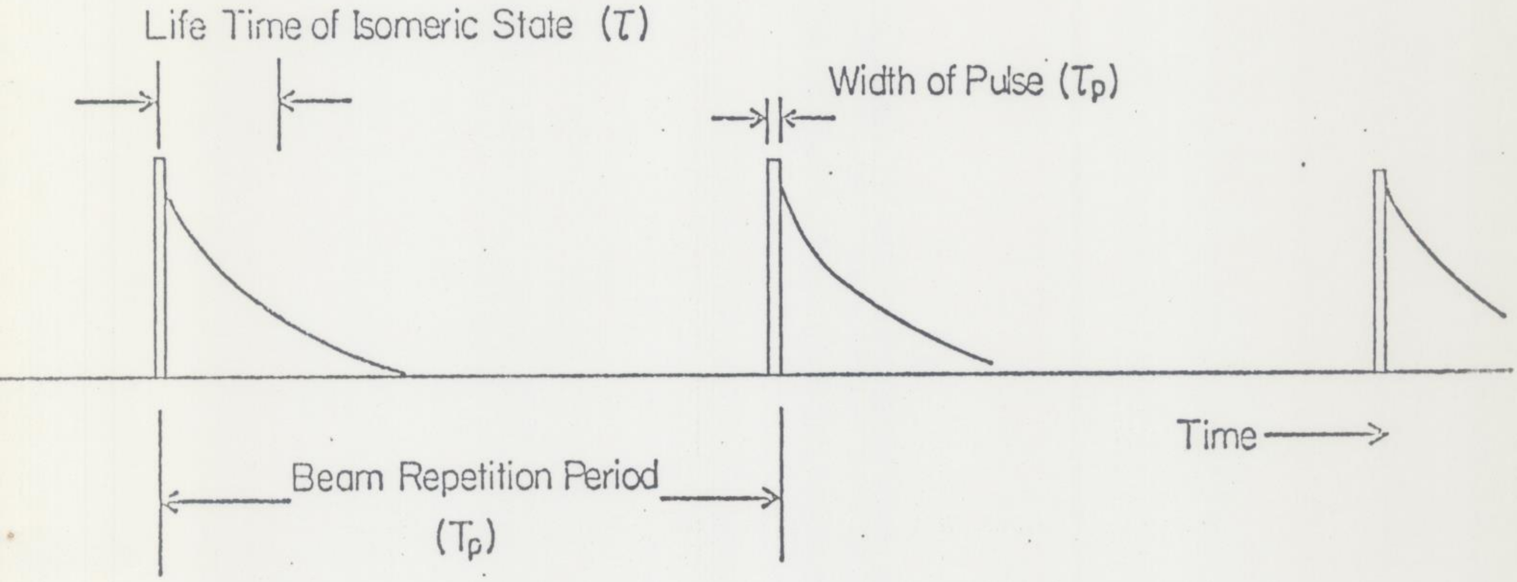
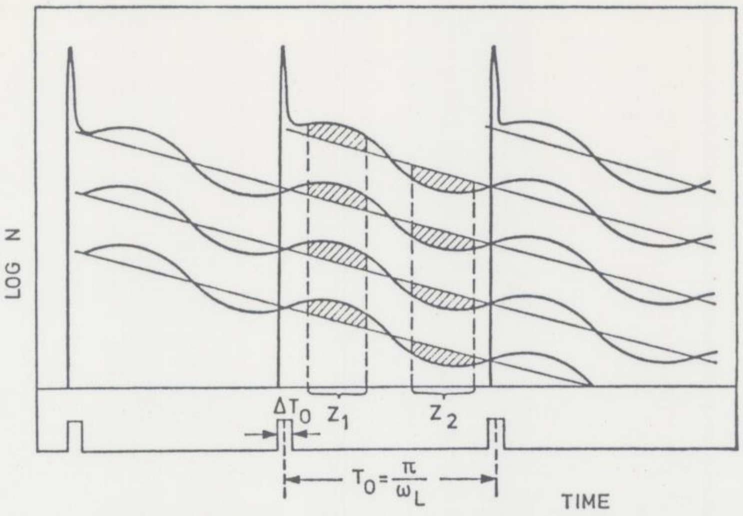
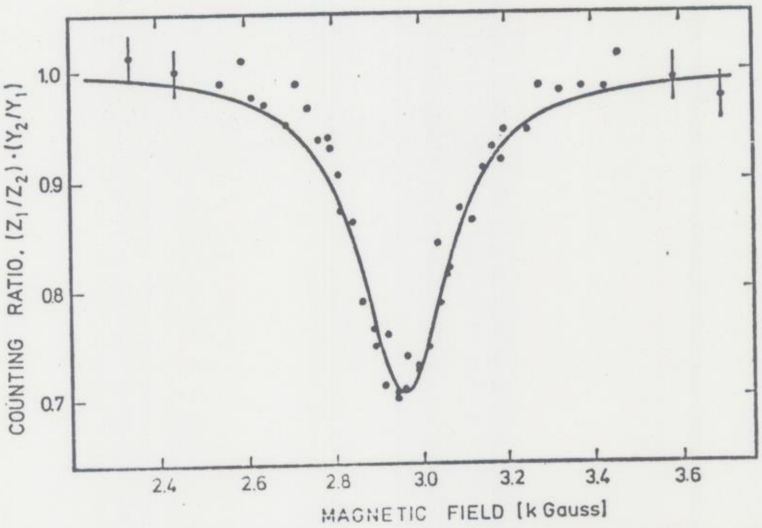


Fig 1

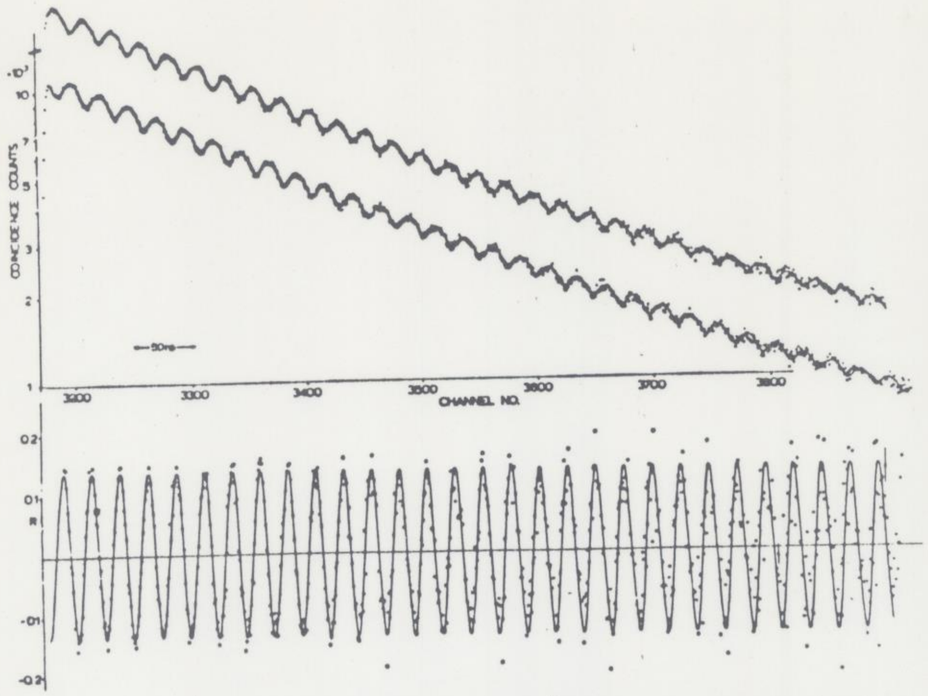


Schematic illustration of the principle of the stroboscopic method. This figure is taken from CHRISTIANSEN *et al.* [1970].



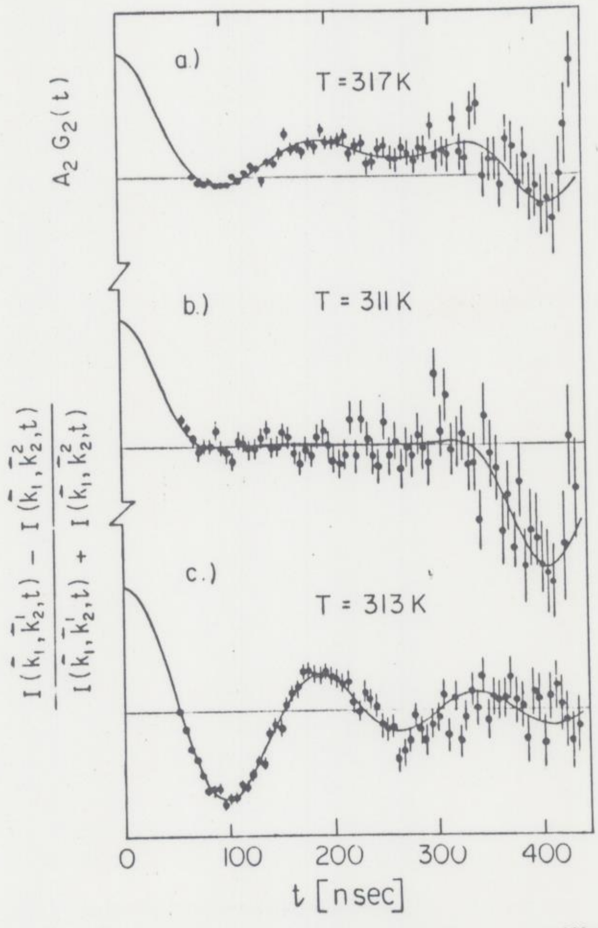
Observation of the stroboscopic resonance for the 398 keV state of ^{169}Ga. This figure is taken from CHRISTIANSEN *et al.* [1970].

Fig. 2



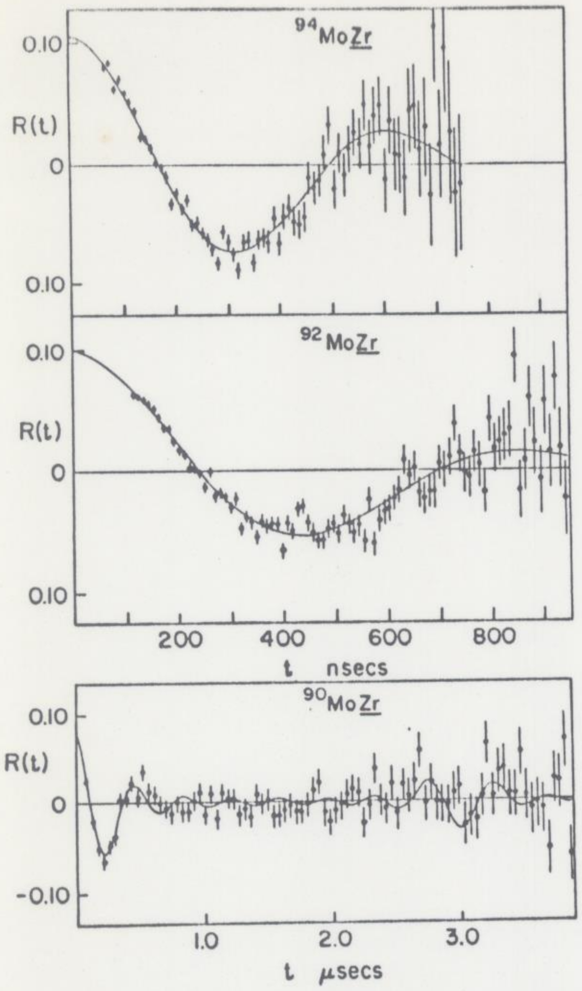
Precession of the 247 keV level of ^{111}Cd in the hyperfine field of iron, polarized by an external field in the 45 geometry. The lower curve is the function $R(t)$ with the ω_L modulation

Fig 3

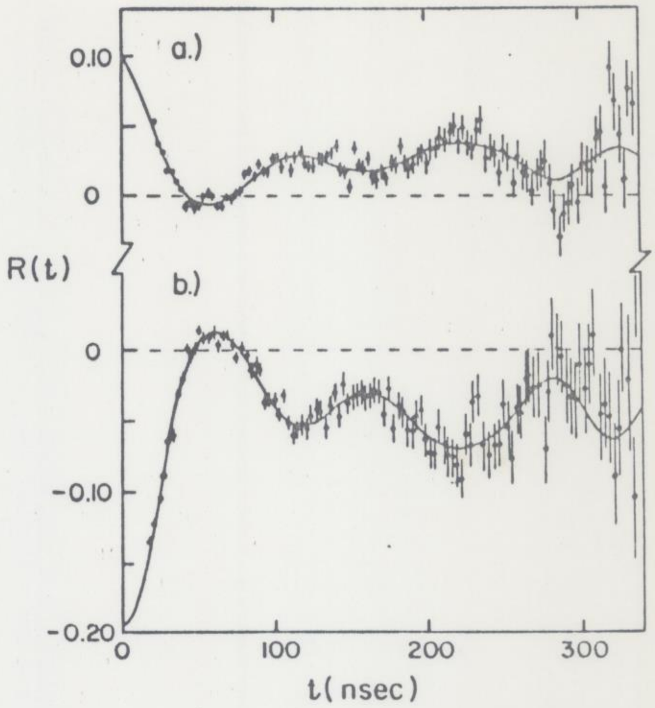


Quadrupole precession of 11/2$^-$ isomer of ^{113}Sn in metallic Sn in various crystal geometries: (a) polycrystal; (b) single crystal with c-axis normal to the reaction plane; (c) single crystal with c-axis 135 to the beam and in the reaction plane

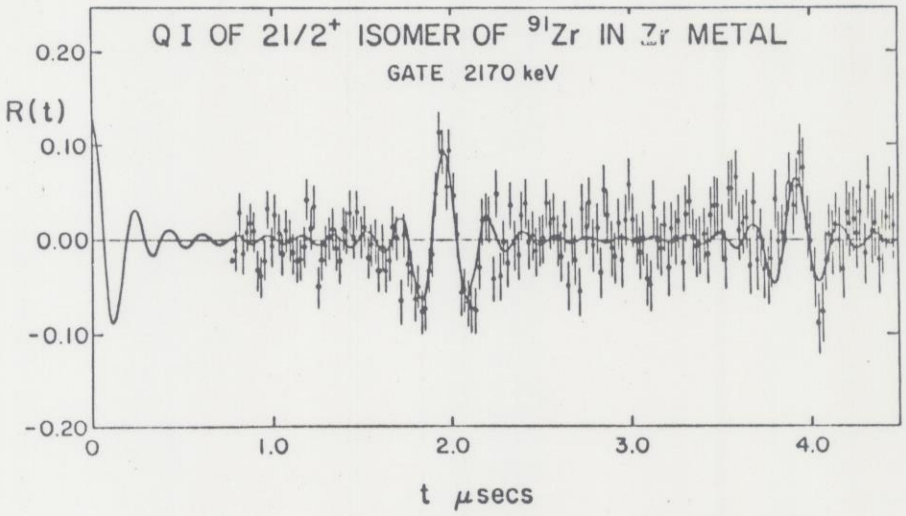
Fig 4



Quadrupole precession of the 8^+ isomers of ^{90}Mo, ^{92}Mo and ^{94}Mo in a single crystal of Zr in the *c*-45 geometry

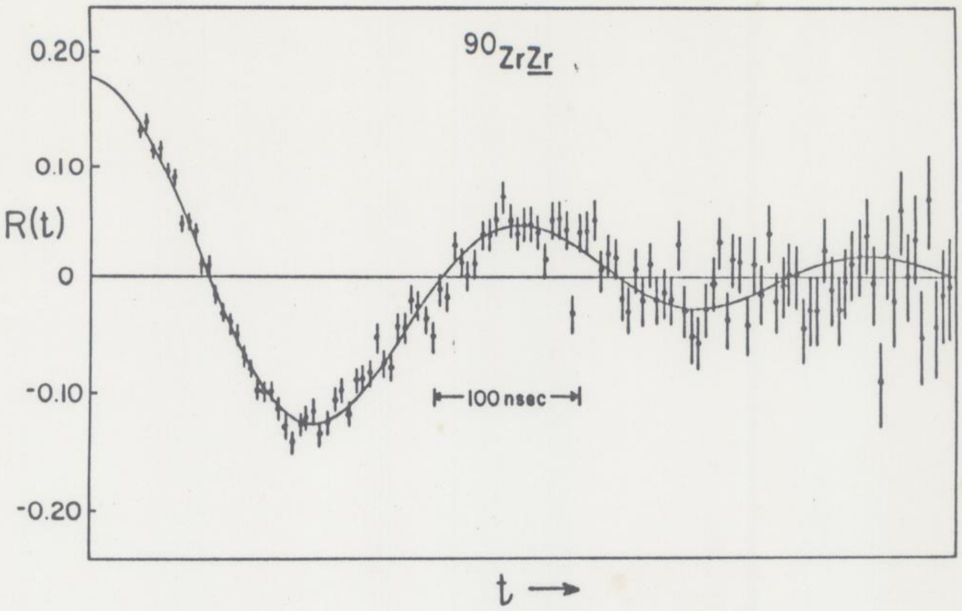


Quadrupole precession of the 7^- isomer of ^{68}Ga in polycrystalline Ga metal ($\eta = 0.179$) at 77 K, observed by the 125 keV ($A_2 > 0$) (upper curve), and by the 201 keV ($A_2 < 0$) (lower curve) γ-rays

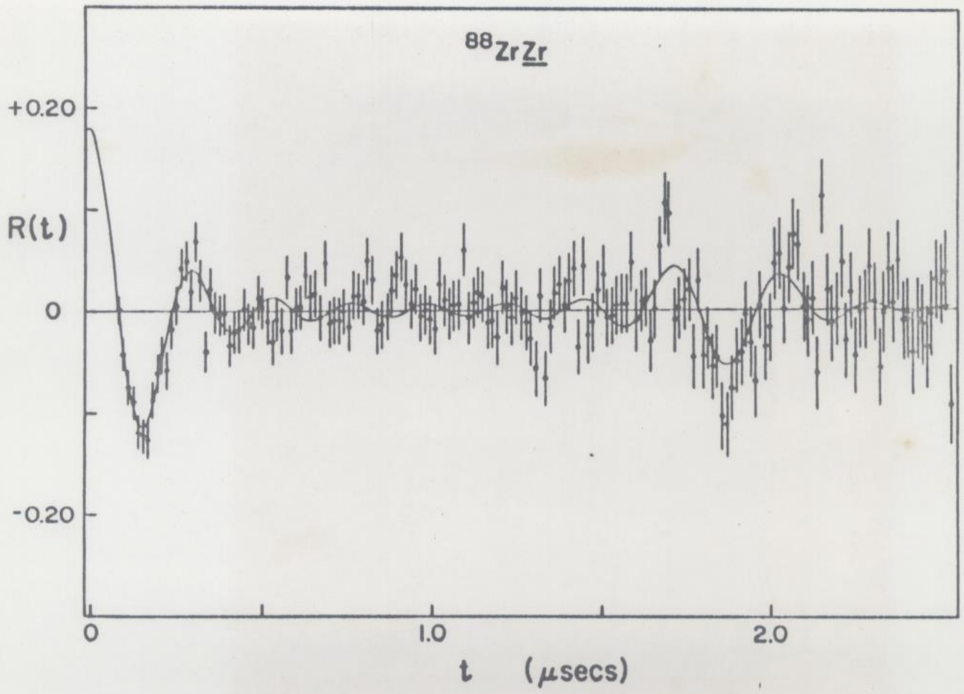


Quadrupole precession of the $21/2^+$ isomer of ^{91}Zr in a Zr single crystal in the *c*-45 geometry

Fig 5



Quadrupole precession of the 8^+ isomer of ^{90}Zr in a single crystal of Zr in *c*-45 geometry



Quadrupole precession of the 8^+ isomer of ^{88}Zr in a single crystal of Zr in *c*-45 geometry

Fig 6