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Parity of the band head at 3710 keV in ^{99}Rh using clover detector as Compton polarimeter

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Abstract. Clover detector has been used as a Compton polarimeter to measure the linear polarization of γ-rays produced in heavy ion fusion reaction. The polarization sensitivity of the clover detector has been measured over γ-ray energies ranging from 386 to 1368 keV. The E1 multipolarity of the 1117 keV transition in ^{99}Rh has been established using this polarimeter. This has resulted in the assignment of negative parity to the band head at 3710 keV in ^{99}Rh.

Keywords. Linear polarization; clover detector; multipolarity; polarization sensitivity; Compton process.

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1. Introduction

Measurement of linear polarization i.e., the direction of electric vector with respect to the beam-detector plane distinguishes the electric and magnetic characters of the γ-rays with same multipole order – an information which cannot be obtained from angular distribution measurements [1]. The angular distribution from an electric and magnetic multipole of same order are identical. On the other hand, the linear polarization measurements not only enables one to distinguish between electric and magnetic nature of the radiation but also allow a precise determination of the multipole mixing ratio δ. Thus, the measurement of linear polarization, in addition to the angular distribution measurements, determines both the spins and parities of nuclear states. Linear polarization is normally measured with the help of a Compton polarimeter. The differential cross section for Compton scattering is relatively high and is polarization sensitive over a wide range of photon energy (few hundred keV to $\sim$4 MeV). The comparison of different types of Compton polarimeters to determine the optimum choice of detector type and geometry of arrangement has been the object of several investigations [2–4]. In this report, we will discuss the polarization sensitivity of a segmented high purity Ge detector, the so called 'clover' detector, obtained from Eurisys Mesures, France, acting as a Compton polarimeter and its application to find the parity of the band based on 3710 keV energy level in ^{99}Rh.

Nuclei in the vicinity of the neutron $N = 50$ shell closure have been reported to exhibit single particle nature for $N \leq 52$ [5]. On the other hand, Gizon *et al* [6] have reported 'rotational-like' sequences for nuclei with $N \geq 56$. Hence, the level sequences of the transitional nuclei with $52 \leq N \leq 56$ would exhibit an interesting inter-play between the single particle and collective degrees of freedom. Wyss [7] has also predicted the existence of negative parity deformed band with neutron configurations involving $\nu h_{11/2}$ orbital in ^{98}Ru having $N = 54$. Levels in ^{99}Rh with $Z = 45$ and $N = 54$ were reported by Ravi Kumar *et al* [8]. It showed a sequence of E2 transitions based on the $J = (9/2)^+$ and another sequence with relatively strong $\Delta J = 1$ transitions built on 3710 keV level. The parity of this level could not be assigned in their work.

If one were to expect the contribution from $\nu(h_{11/2})$ orbital as predicted by Wyss and co-workers, we would expect the sequence to have negative parity. Hence we were motivated to perform polarization measurements to obtain the parity of the 3710 keV state and the mixing ratio of 1117 keV transition de-exciting this state in search for a high spin negative parity configuration in ^{99}Rh having $Z = 45$ and $N = 54$.

A brief discussion of the polarization measurements with clover detector is provided below.

2. Theory

The angular distribution of linearly polarized γ-rays emitted from an axially oriented ensemble of nuclei is given by [9,10]

$$W(\theta, \phi) = \frac{\mathrm{d}\Omega}{8\pi} \sum_{\lambda=\mathrm{even}} B_\lambda U_\lambda [A_\lambda P_\lambda(\cos\theta) + 2A_{\lambda,2} P_\lambda^{(2)}(\cos\theta)\cos 2\phi], \quad (1)$$

where ϕ is the angle of the electric vector $\vec{E}$ of the primary photon with respect to the reaction plane (see figure 1), B_λ are orientation tensors describing the degree of orientation of the parent nucleus and U_λ are de-orientation coefficients. The coefficients A_λ and $A_{\lambda,2}$ can be obtained from [9,10].

The degree of polarization of γ-rays is defined as

$$P(\theta) = \frac{W(\theta, \phi = 0) - W(\theta, \phi = \pi/2)}{W(\theta, \phi = 0) + W(\theta, \phi = \pi/2)} \quad (2)$$

and the normalization is such that $-1 \leq P(\theta) \leq +1$. $P(\theta) = \pm 1$ for completely polarized γ-rays and $P(\theta) = 0$ for totally unpolarized γ-rays. In experiment, the value of θ was chosen to be $\pi/2$ because the magnitude of $P(\theta)$ is maximum here. Define $2B_\lambda U_\lambda A_{\lambda,2} = (\pm)_{L'} a_\lambda^{(2)}$ and $B_\lambda U_\lambda A_\lambda = a_\lambda$ where $(\pm)_{L'} = 1$ if $(2)^{L'}$-pole radiation is electric and it is -1 if $(2)^{L'}$-pole radiation is magnetic. The polarization at 90° is given by

$$P_{\mathrm{cal}}(90^\circ) = \pm \frac{3a_2 H_2 - 7.5 a_4 H_4}{2 - a_2 + 0.75 a_4}, \quad (3)$$

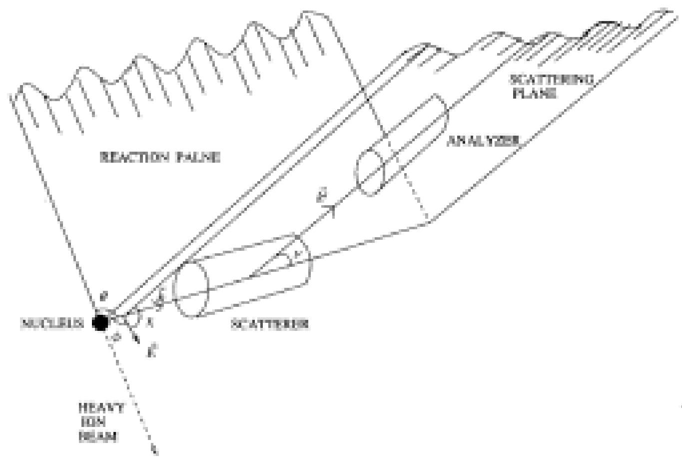

Figure 1. Schematic diagram for the emission and scattering of the initial polarized photons from aligned nuclei.

where a_2 and a_4 are angular distribution coefficients, the $+(-)$ sign applies for a transition without(with) parity change. The H_2 and H_4 functions depend on initial and final spins and on dipole–quadrapole mixing ratio δ. For pure M1 or E1 transitions $(\delta = 0) H_2 = 1$ and $H_4 = -1/6$. For mixed dipole–quadrapole transitions,

$$H_2(L=1, L'=2) = \frac{F_2(11) - 0.667\delta F_2(12) + \delta^2 F_2(22)}{F_2(11) + 2\delta F_2(12) + \delta^2 F_2(22)}, \tag{4}$$

where the $F_2(L=1, L'=2)$ coefficients have been obtained from [11]. $H_4 = -1/6$, for mixed dipole–quadrapole transition also.

The linear polarization of the γ-rays discussed above can be quite effectively detected through Compton scattering. The differential scattering cross-section of the Compton process is given by the Klein–Nishina formula [12]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{r_0^2}{2}\left(\frac{E}{E'}\right)^2 \left[\frac{E}{E'} + \frac{E'}{E} - 2\sin^2\nu\cos^2\chi\right] \tag{5}$$

where E is the incident photon energy, E' the scattered photon energy, r_0 the classical electron radius, ν the photon scattering angle and χ is the angle made by the electric vector $\vec{E}$ with respect to the scattering plane. The last equation shows a preferential emission of scattered photons perpendicular to the polarization plane which can be used to measure the linear polarization. Thus, a Compton polarimeter consists of a scatterer to produce a scattered photon of energy E' and an analyzer to detect this scattered photon. The experimental asymmetry is defined as

$$\Delta = \frac{N_\perp - N_{||}}{N_\perp + N_{||}}, \tag{6}$$

where $N_\perp$ and $N_{||}$ are the intensities of scattered photons perpendicular and parallel to the reaction plane, respectively. The measured asymmetry Δ is related to the degree of polarization by the relation

$$P(\theta) = \frac{\Delta}{Q}, \tag{7}$$

where

$$Q = \frac{\mathrm{d}\sigma(\nu = 90^\circ, \chi = 90^\circ) - \mathrm{d}\sigma(\nu = 90^\circ, \chi = 0^\circ)}{\mathrm{d}\sigma(\nu = 90^\circ, \chi = 90^\circ) + \mathrm{d}\sigma(\nu = 90^\circ, \chi = 0^\circ)}$$

is the polarization sensitivity of the polarimeter. Q is dependent on the value of the incident γ-ray energy and on the geometry of the polarimeter. It is obtained for a point scatterer and point analyzer at 90° i.e., $\nu = 90^\circ$ from Klein–Nishina formula (see eq. (7)) and the kinematics of a photon scattering from an electron i.e.,

$$Q_0(E_\gamma) = \frac{\alpha + 1}{\alpha^2 + \alpha + 1}, \tag{8}$$

where $\alpha = E_\gamma/m_e c^2$, E_γ being the incident photon energy and $m_e c^2$ is the electron rest mass energy. It should be noted here that Q_0 is independent of γ-ray multipolarity. Furthermore, the polarization sensitivity is reduced due to finite size of scatterer and analyzer. It is given by

$$Q(E_\gamma) = (CE_\gamma + D)Q_0(E_\gamma). \tag{9}$$

The value of Q can vary from 0 to 1.

3. Measurements and results

In the present work, a clover detector consisting of four closely packed n-type HPGe crystals [13] has been used as a polarimeter. The detector is placed at 90° with respect to the beam direction. The 'OR' of the timing signals from all the four crystals was used to generate a master which gates the energy spectra from the four crystals. The data were collected for each event. This list mode data is analysed to identify events in which a γ-ray incident on one of the four crystals 'A' undergoes Compton scattering parallel or perpendicular to the reaction plane. Thus, a scattering event from A→B and C→D (figure 2) or vice versa constitutes $N_{||}$ and can be identified if the sum of the energies in A and B or C and D are equal to the incident γ-ray energy. Similarly, the events B→C and A→D or vice versa are denoted by $N_\perp$. The two fold coincidence spectra AB, BC, CD and DA were generated by adding the energies of two fold events. Δ is defined for each γ-ray peak in these spectra as

$$\Delta = \frac{a(E_\gamma)(N_\perp^{\mathrm{AD}} + N_\perp^{\mathrm{BC}}) - (N_{||}^{\mathrm{AB}} + N_{||}^{\mathrm{CD}})}{a(E_\gamma)(N_\perp^{\mathrm{AD}} + N_\perp^{\mathrm{BC}}) + (N_{||}^{\mathrm{AB}} + N_{||}^{\mathrm{CD}})}, \tag{10}$$

where $a(E_\gamma)$ is the normalization factor obtained for unpolarized γ-rays by using a ^{152}Eu source placed at the target position while keeping the detector geometry unchanged and is given by

$$a(E_\gamma) = \frac{N_{||}^{\mathrm{AB}} + N_{||}^{\mathrm{CD}}}{N_\perp^{\mathrm{AD}} + N_\perp^{\mathrm{BC}}}. \tag{11}$$

The value of $a(E_\gamma)$ remains almost 1.00(03) in the energy range of 122 to 1408 keV.

The experimental values of the asymmetry parameter (Δ) were obtained for several known γ-transitions in ^{76,78}Kr and ^{80,81,82}Sr produced by bombarding 115 MeV ^{27}Al beam on an enriched ^{58}Ni target and γ-rays in ^{99}Rh and ^{101}Pd were studied through 110 MeV ^{31}P beam on ^{74}Ge target. The calculated polarizations for these transitions were obtained from the measured angular distributions using eq. (3). Experimental asymmetry of 1368 keV γ-transition in ^{24}Mg was studied from β-active ^{24}Na source. The angular correlation coefficients of the 4^+–2^+–0^+ cascade of 2756–1368 keV γ-rays were used to calculate the polarization. The measured values of $Q(= \Delta/P_{\text{cal}})$ at different γ-ray energies are plotted in figure 3. The data points were fitted with the function given in eq. (9). The fit gave a value of $D = 0.446(6)$ and $C = -0.000099(7)$ keV^{-1}. It should be noted that the finite size decreases the polarization sensitivity of the detectors.

The linear polarization measurement were performed for the 1117 keV transition to determine the parity of 3710 keV state in ^{99}Rh. The angular distribution of 1117 keV transition was measured with CS-HPGe detectors kept at 15°, 45°, 75° and 90° with respect to the beam direction. This gave a value of the angular distribution coefficients $a_2 = -0.16(1)$ and $a_4 = 0.01(1)$. The values of a_2 and a_4 suggest that 1117 keV transition is a pure dipole transition with spin change of $\Delta I = 1$ in agreement with the DCO ratios reported in [8]. The measured values of the asymmetry parameters for the 260.4 keV $(7/2^+ \to 5/2^+)$ transition in ^{101}Pd, the 493.0 keV $(19/2^+ \to 17/2^+)$ and 1117 keV $(23/2 \to 21/2^+)$ transitions in ^{99}Rh are listed in table 1. The Δ values for the 260.4 keV and 493.0 keV are negative in agreement with the M1 nature of these transitions. On the other hand, the Δ value for 1117 keV transition is positive $\Delta = +0.05(3)$ suggesting that this is an E1 transition. This gives an experimental value of polarization $P_{\text{exp}} \equiv \Delta/Q = 0.37(21)$.

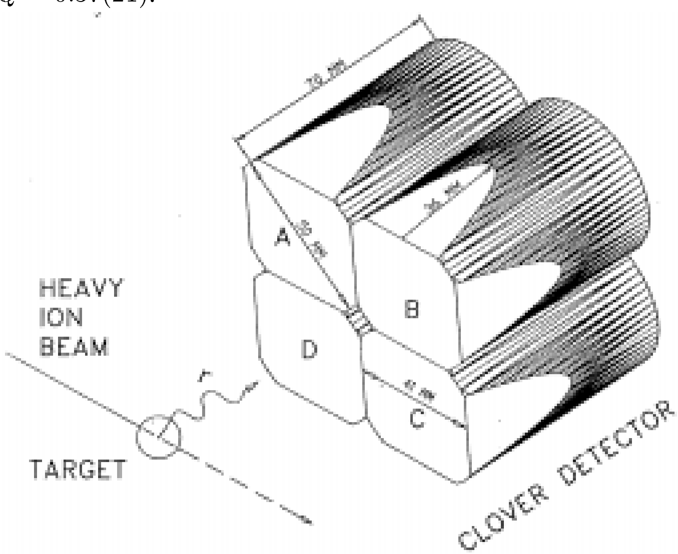

Figure 2. Schematic diagram of a clover detector consisting of four coaxial HPGe crystals. The letters A, B, C and D are used to label the different segments of the clover as used in the text.

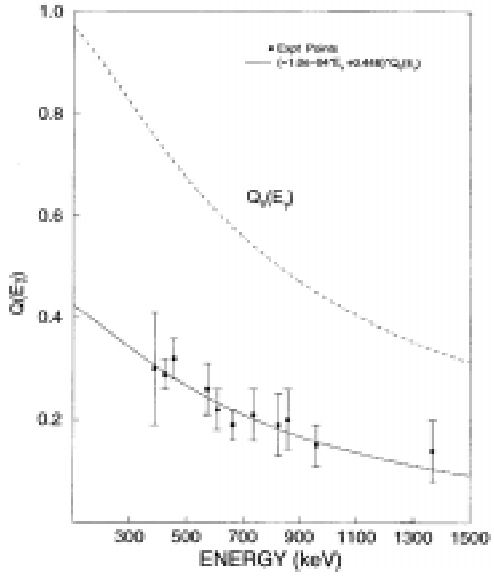

Figure 3. Polarization sensitivity of the clover detector measured as a function of gamma ray energy. The dotted line is the sensitivity for the point scatter and analyser. Solid curve is obtained by fitting experimental data to eq. (9) with $D = 0.446$ and $C = -0.0001$ keV^{-1}.

Table 1. Asymmetry parameter Δ for $\Delta I = 1$ transitions in ^{101}Pd and ^{99}Rh.

Nucleus	E_γ (keV)	$(J_i \rightarrow J_f)$	$\Lambda(\pi)$	Δ
^{101}Pd	260.4	$7/2^+ \rightarrow 5/2^+$	M1	−0.053(42)
^{99}Rh	493.0	$19/2^+ \rightarrow 17/2^+$	M1	−0.078(39)
^{99}Rh	1117	$23/2^- \rightarrow 21/2^+$	E1	+0.05(3)

The calculated value of polarization $P_{\rm cal}(90°)$ is plotted as a function arctan (δ) by assuming E1+M2 or M1+E2 multipolarities. This is shown along with the experimental value of the polarization $P_{\rm exp}$ in figure 4. The experimental value has an intercept with the calculated curve for large value of δ if 1117 keV transition has M1+E2 multipolarity. Large value of δ is, however, ruled out by the angular distribution measurement. The experimental value and calculated curve have another intercept provided the 1117 keV transition has nearly pure E1 multipolarity with mixing ratio $\delta = 0.015(55)$.

4. Discussion

The present polarization measurements along with the angular distribution measurements have led to an assignment of E1+M2 multipolarity with $\delta = 0.015(55)$ for the 1117 keV

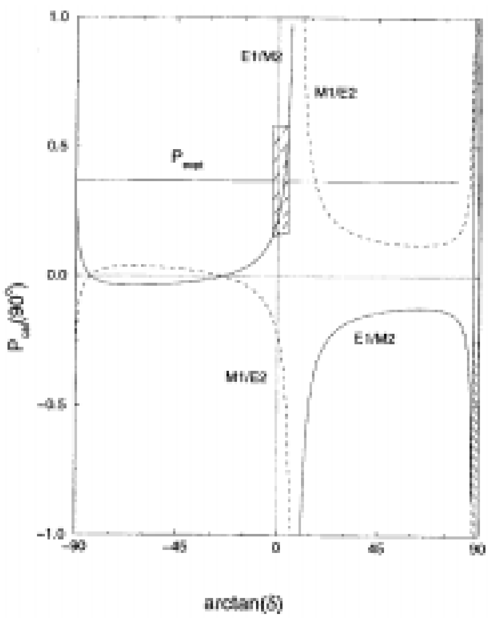

Figure 4. Calculated polarization $P_{\rm cal}(90^\circ)$ for the 1117 keV $(23/2 \rightarrow 21/2^+)$ in ^{99}Rh plotted as a function of arctan δ assuming E1+M2 and M1+E2 multipolarities. The experimentally measured polarization is shown by the shaded region. The intercept with E1+M2 curve gives $\delta = 0.015(55)$ in agreement with a small a_4 value in the angular distribution measurement.

transition in ^{99}Rh. Since the 2593 keV level in ^{99}Rh has a positive parity, the present measurements fix a negative parity for the band head at 3710 keV in ^{99}Rh. This is in contrast to the positive parity for this state suggested in [8] from systematics. The negative parity for 3710 keV state suggests that it is formed due to the coupling of $p_{1/2}$ and $g_{9/2}$ protons with $d_{5/2}$ and $s_{1/2}$ neutrons. The excitation of the neutrons in $h_{11/2}$ orbital is also possible.

The involvement of $p_{1/2}$ proton is supported by the observation of strong M1 transitions with $\Delta I = 1$ [8] in the band built over the 3710 keV $(23/2^-)$ state. But the excitation of neutrons to $h_{11/2}$ orbital can lead to an increased deformation in the band built on the 3710 keV state. This should be studied through a measurement of lifetimes of the levels above the $23/2^-$ state.

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