Absence of M2 Retardation in $^{35}\text{Cl}$: Evidence for Stronger Isospin-Mixing Effects in A=35 Mirror Nuclei

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Abstract. The lifetime of the 3163 keV, $7/2^-$ isomeric state in $^{35}\text{Cl}$ that decays by a stretched M2 transition to the $3/2^+$ ground state, has been re-measured using the Doppler Shift Attenuation Method, by gating on the 1185 keV transition which directly feeds this state. This eliminates the uncertainties in the measurement arising from the direct feedings from the continuum. A mean life of $0.6^{+0.5}_{-0.2}$ ps has been obtained from the present work.
This is considerably smaller than the adopted value 45.3(6) ps. Implication of this major reduction in the lifetime has been pointed out.

**Keywords.** $A=40$, gamma spectroscopy, lifetime

**PACS Nos** 21.10.Tg,27.30.+t

1. **Introduction**

Low-lying isomeric states that decay by stretched M2 transitions have been observed in nuclei near the doubly closed $^{40}$Ca. During late sixties to early eighties several measurements of lifetimes of these isomeric states have been performed by populating them in fusion evaporation reactions with heavy ions or by using protons. Electronic timing techniques and different Doppler shift methods were used for the measurements. These M2 transitions are usually explained using the shell model. Their interpretation is connected with the de-excitation of a single nucleon from the $1f_{7/2}$ to the $1d_{3/2}$ orbit. The single-nucleon transfer reactions have revealed large $1f_{7/2}$ single particle components (spectroscopic factor $S\approx 0.54$ on the average) in the wavefunction of the lowest $7/2^-$ state or their analogues. The information on the lowest $3/2^+$ state in odd K, Ca, Sc, etc. indicated sizable $d_{3/2}$ single hole component. But in spite of the dominant particle hole character of these levels, a systematic hindrance of the M2 transitions by a factor of 5-200 with respect to $1f_{7/2} \rightarrow 1d_{3/2}$ single particle estimates has been observed. Several attempts have been made to account for this anomalous retardation effect. For the relatively heavier nuclei with $A=39, 41$ and the Sc isotopes, isospin effects and/or admixtures of core excited states can explain this retardation. Nuclei, which are three or more particles away from the core, need strong coupling and prolate deformation to account for the observed retardation.

Here we concentrate on the re-measurement of the lifetime of $7/2^-$ isomeric state in the $^{35}$Cl nucleus [1] using the Doppler Shift Attenuation Method (DSAM). A mean life of $0.6^{+0.5}_{-0.2}$ ps has been obtained from the present work. This is considerably smaller than the adopted value 45.3(6) ps. This present value indicates the absence of M2 retardation in this nucleus. The new result has far reaching implications which will be discussed.

2. **Experimental Details**

The present work is based on the results from two experiments done with the array of eight Clover detectors (INGA setup) at TIFR, Mumbai (Expt. 1) and NSC, New Delhi (Expt. 2). A 50 $\mu$g/cm$^2$ $^{12}$C target, backed by $\approx 10.5$ mg/cm$^2$ gold was bombarded by 70 and 88 MeV $^{28}$Si beam in the two experiments, respectively. The velocities of the recoils were 5-6% of velocity of light ($c$). The main interest was to study the higher spin states in the nuclei $^{38}$Ar, $^{35}$Cl and $^{37}$Ar and other weaker channels like $^{35}$Ar, $^{38}$K where heavy ion data are scanty. DSAM was used to measure the lifetimes of several nuclear states. In Expt. 1 the detectors were at
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30°, 60°, 65°, 90°, 105°, 120°, 145° w.r.t the beam, while in Expt. 2, they were at 81° and 134° with respect to the beam direction.

Use of "inverse" reactions in DSA measurements has some distinct advantages. These include large recoil velocities and small percentage spread in velocity [3]. For the $^{12}C(^{28}Si, \alpha p)^{35}Cl$ reaction populating the 3163 keV level at 88 MeV energy of the $^{28}Si$ beam, the recoil velocity $\beta \simeq 5.8\%$, the maximum spread in $\beta$ is $\pm 7\%$, while the maximum half angle of the cone of recoiling $^{35}Cl$ nuclei is $\simeq 13^o$, compared to the value 2.5%, ±17%, and 31°, respectively, for the corresponding "forward" reaction at the same centre of mass energy. Due to the larger velocity, the fractional energy loss of the recoils in the target material will be comparatively smaller, thereby reducing the uncertainty due to finite target thickness. Besides, there is more freedom in choosing the backing material. Also for higher recoil velocity, the main contribution to the stopping is the electronic stopping process, which is well understood.

However, due to the larger recoil velocity, the lineshape extends over a large number of channels (e.g., for 3163 keV gamma ray, with $\beta_{max} = 0.0575$ and $\theta = 134^o$, the endpoint corresponds to a shift of 126 keV). The background under this shape can be sizable, even when it does not show any noticeable structure. Very often there are structures (contribution from other genuine or spurious peaks) which interfere with the lineshape even in the gated spectrum.

3. Data Analysis and Results

In the present work we have made a preliminary estimate of the lifetime of the $7/2^-$ isomeric state in $^{35}Cl$ nucleus using the centroid shift analysis of the DSAM data. A strong 3163 keV M2 transition connects this state to the $3/2^+$ ground state. The lifetime of the 3163 keV state has been estimated by gating on the 1185 keV transition which directly feeds the state of interest [1]. This eliminates the uncertainties in the measurement arising from the direct feedings from the continuum.

3.1 Energy loss of recoil

The energy loss of the $^{35}Cl$ nuclei through $^{12}C$ target was very small for both energies (70 and 88 MeV) and hence was neglected. The energy loss of $^{35}Cl$ in gold has been simulated using the code SRIM-2003 [4]. The energy loss of the recoils is parametrised by using the relation [5],

$$-M\frac{dv_z}{dt} = K_n(v_z/v_o)^{-1} + K_e(v_z/v_o) - K_3(v_z/v_o)^3 \quad (1)$$

where $M$ is the mass of the moving ion, $v_o = c/137$. $z$ direction is along the path of the recoil. The values of the parameters $K_n = 0.1$, $K_e = 1.1$ and $K_3 = 0.006$ have been obtained by fitting the simulated data by the above relation. These parameters were used in calculating the theoretical values of the attenuation coefficient $F(\tau)$ [5], (to be discussed in the next section) as a function of mean lifetime ($\tau$) of the level emitting that particular gamma ray.
3.2 Determination of experimental $F(\tau)$

We shall assume that the recoils are all emitted along the $z$ axis and they are monoenergetic. The average energy $E_\gamma$ of the gamma radiation emitted from an ensemble of nuclei produced at $t=0$ with initial velocity $\beta(0) (= v(0)/c)$ and moving thereafter with velocity $\beta(t)$ can be expressed for $\beta(t) \ll 1$ as [5],

$$E_\gamma = E_{\gamma o}[1 + F(\tau)\beta(0)\cos\theta]$$  \hspace{1cm} (2)

$E_{\gamma o}$ is the $\gamma$-energy emitted by the recoil at rest. $F(\tau)$ is the attenuation coefficient which lies between 0 and 1. The lifetime of the level emitting that particular gamma ray can be determined if $F(\tau)$ differs measurably from 1 and 0. It can be obtained from the observed energy shift with the detector angle of the gamma, using the relation

$$F(\tau) = \frac{\Delta E_\gamma}{E_{\gamma o}\beta(0)(\cos\theta_1 - \cos\theta_2)}$$  \hspace{1cm} (3)

The $F(\tau)$ value thereby obtained has been corrected for the effective lifetime of the 4348 keV level which decays by the 1185 keV $\gamma$ ray to the level of interest, since this transition has been used as the gating transition. The centroids were determined after consideration of suitable background using the analysis program INGASORT [6]. The experimental results are summarised in Table 1.

| Energy (MeV) | $\beta_{max}$ | $\theta_1$ | $\theta_2$ | $E_\gamma$ | $\Delta E$ | $F(\tau)$ | Corrected $\tau$ |
|-------------|---------------|------------|------------|-----------|-----------|-----------|-----------------|
| 88          | 0.0575        | 81°        | 134°       | 3163      | 14        | 0.99      | 0.5             |
| 70          | 0.0513        | 90°        | 105°       | 3163      | 3         | 0.07      | 0.6             |
|             |               | 90°        | 120°       | 3163      | 7         | 0.09      |                 |

3.3 Limitation in previous measurements and estimation of error in present measurement

The large lifetime of 45.3 ps reported [2] previously may possibly be attributed to one or more of the following limitations:

- Use of evaporated targets with layered structures or backing materials whose stopping powers were poorly known.
- Population of the level of interest in forward reactions producing low recoil velocities (in most of the cases $\beta \leq 1\%$).
- Measurements in singles mode are difficult in $A \approx 40$ due to interference from overlapping gamma rays.
The single detector resolution and efficiency at high energies were poor. The present measurements were done using an array which consisted of eight clover detectors. These detectors have good resolution and efficiency at high energies. Although the present measurement also had some serious limitations, like inadequate backing thickness for Expt. 2 (resulting in an escape of \( \approx 5\% \) of recoils) and the difficulty in setting a clean gate on the 1185 keV lineshape, the associated uncertainties have been estimated and included in the errors in the lifetime result. Our energy calibration was 1 keV/channel, and therefore an error of \( \pm 1 \) channel in the determination of the centroid introduced large errors in \( F(\tau) \) especially for comparatively lower energies. As the gamma energies associated with this mass region are usually of high energies (\( > 1 \) MeV, even up to 5-6 MeV), we were bound to compress the spectrum.

A lineshape analysis of the data is in progress which is expected to yield a more accurate result. However, the present work establishes that the lifetime of the 3163 keV state in \(^{35}\text{Cl}\) is considerably less than the value reported in the literature.

4. Theoretical analysis and implications

The adopted value \([2]\) of the mean lifetime of 3163 keV level in \(^{35}\text{Cl}\) (7/2\(^{-}\)) is 45.3 (6) ps. The experimental reduced transition probabilities of the M2 transitions has been calculated using the relation given in Ref. [7]. Taking branching ratio of the 3163 keV transition to be 90\%, mixing ratio \(\delta (E3/M2) = -0.16 \) [2], and the gamma energy as 3163 keV, the calculated \(B(M2)_{old-exp}\) value comes out to be 4.72 \(\mu^2\text{fm}^2\). It is 18 times retarded compared to the single particle estimate of \(B(M2)\) (using relation mentioned in Ref. [8]) for a stretched M2 transition. The present measured value of the lifetime of 3163 keV level of \(0.6^{+0.5}_{-0.2}\) ps leads to \(B(M2)_{new-exp} \approx 200 \mu^2\text{fm}^2\), which is nearly 2.5 times the single particle estimate.

It has been discussed in Ref. [9] that isospin symmetry breaking effects can be studied in pairs of mirror nuclei, in which the number of protons and neutrons are interchanged. They lead to shifts between the excitation energies of a mirror pair, the so called mirror energy differences (MED). However, it has long been expected and recently been shown that a small part of the nucleon-nucleon interaction adds to the Coulomb force in violating the isospin symmetry [9]. Ekman et al. made a comparison of \(^{35}\text{Ar}\) (\(T_z = -1/2\)) with the \(T_z = 1/2\) mirror nucleus \(^{35}\text{Cl}\). It reveals two remarkable features: (i) A very large MED value for the 13/2\(^{-}\) states, and (ii) a dramatic difference in decay patterns of the 7/2\(^{-}\) states. The explanation for the dramatic difference in decay patterns of the 7/2\(^{-}\) states in the \(A = 35\) mirror pair has been explained to be due to a cancellation of the E1 matrix elements due to isospin mixing. Using the adopted mean lifetime \(\tau = 45.3(6)\) ps of the 7/2\(^{-}\) state and \(B(E1;7/2^{-} \rightarrow 5/2^{+}) = 2 \times 10^{-8}\) W.u. in \(^{35}\text{Cl}\), and assuming identical \(B(M2)\)'s in both members of the mirror system, it follows that \(B(E1;7/2^{-} \rightarrow 5/2^{+}) = 3 \times 10^{-5}\)
W.u for $^{35}$Ar. This means that the contributions diagonal and non-diagonal in isospin, $T$ are equal in magnitude and about $1.5 \times 10^{-5}$ W.u [9]. For present value of $B(M2)_{exp} \simeq 200 \mu^2 fm^2$, $\tau$ comes out to be $\simeq 0.15$ ps for $^{35}$Ar and $B(E1;7/2^- \rightarrow 5/2^+) \simeq 6 \times 10^{-7}$ W.u for $^{35}$Cl and $B(E1;7/2^- \rightarrow 5/2^+) \simeq 1.5 \times 10^{-3}$ W.u for $^{35}$Ar. The present results indicate the need for a stronger isospin mixing. In fact, a more detailed experimental and theoretical investigation is needed to resolve this important issue.

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