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A plunger set-up for measuring picosecond nuclear half-lives

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Abstract. A plunger set-up has been designed and constructed to measure picosecond nuclear half-lives using recoil distance method (RDM). The system has been used to measure the half-lives of nuclear states in ^{35}Cl, ^{37,38}Ar and ^{40}K. The shortest half-life measured with the system is $T_{1/2} = 0{\cdot}36(14)$ ps for the 4366 keV (8^+) state and the longest half-life is $T_{1/2} = 1{\cdot}10(7)$ ns for the 2543 keV (7^+) state in ^{40}K.

Keywords. Picosecond half-lives; nuclear excited states; plunger set-up; flat and uniform target and stopper foils; capacitance measurement.

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1. Introduction

The study of the electromagnetic properties of nuclear states has been extremely popular for many years in probing the structure of nucleus. In recent years, the electromagnetic transition probabilities have proved to be extremely sensitive tools to study the changes in nuclear structure with increasing spin and excitation energy in medium heavy nuclei (Twin *et al* 1985; Nolan 1986). The reduced transition probability is experimentally determined from the knowledge of the multipolarity of the γ-transition between the initial and final nuclear states and the half-life of the initial state. Theoretically, it involves the reduced matrix element of the electromagnetic operator between the wave functions of the initial and final states of the nucleus. The wave functions and therefore, the reduced transition probabilities are quite sensitive to the details of the nuclear structure. There are a large number of high spin states with half-lives ranging between 1 ps and a few nanosecond in light and medium heavy nuclei. It is possible to populate these high spin states using heavy ion beams from the TIFR-Pelletron and this provides the necessary motivation to develop techniques to measure half-lives of excited states in this region. In the present communication, we report the design and construction of a plunger set-up which has enabled us to measure half-lives of excited states ranging between 0·5 ps and 1 ns in ^{35}Cl, ^{37,38}Ar and ^{40}K.

2. Experimental details

The recoil distance apparatus was first described by Alexander and Allen (1965) and later a variation of this method using Ge(Li) detectors was provided by Alexander and Bell (1970). In this method, the nuclear excited state of interest is produced by bombarding a thin, flat and uniform target with a heavy ion beam. The highly excited reaction products are recoiled out of the target into vacuum until they are stopped in a thick, flat and uniform foil placed at a distance 'D' from the target foil. The γ-rays deexciting the nucleus are detected in a HPGe detector placed at 0° with respect to the beam direction. The γ-ray energy is Doppler shifted if it is emitted when the nucleus is in motion but unshifted energy is obtained if emitted after the recoiling ion comes to rest in the stopper foil. Thus, each γ-transition gives rise to two peaks in the HPGe detector: the narrow and unshifted peak corresponds to γ-rays emitted from nuclei at rest and the broad and Doppler-shifted peak corresponds to γ-rays emitted from nuclei moving with an average velocity $\bar{v}$ in vaccum. The average velocity ($\beta = \bar{v}/c$) of the recoiling ions is determined from the separation between the centroids of the shifted and unshifted γ-peaks through the second order Doppler shift equation

$$E_{sh}(\theta) = E_\gamma(1 + \beta\overline{\cos\theta} + \beta^2\overline{\cos^2\theta} - 1/2\beta^2)$$

E_γ and $E_{sh}(\theta)$ are the unshifted and Doppler-shifted γ-ray energies, respectively and θ is the angle of the HPGe detector with respect to the beam direction. The terms $\overline{\cos\theta}$ and $\overline{\cos^2\theta}$ are evaluated over the solid angle of the HPGe detector. In the present experiment, the detector was placed at a distance $L \sim 16$ cm from the target which corresponds to $\overline{\cos\theta} \sim 0{\cdot}995$.

The average travel time of the ions between the target and the stopper is obtained through an accurate measurement of the distance D between them. The mean life of the nuclear state is derived from the intensities of the shifted and stopped γ-peaks measured as functions of the separation D between the target and stopper foils i.e.

$$R(D) = \frac{I_0}{I_0 + I_s} = K_1\left(\exp\left(-\frac{D}{\bar{v}\tau}\right)\right) + K_2. \tag{1}$$

I_0 and I_s denote the intensities of the stopped and shifted peaks, respectively, τ is the mean life of the excited nuclear state. K_1 and K_2 are constants to be determined experimentally. The measured intensity of the stopped peak I_s is multiplied by a factor $(1 + \beta)$ to correct for the smaller detection efficiency of the shifted peak (higher energy) compared to the stopped peak. This assumes $1/E_\gamma$ dependence of the detector efficiency. The motion of the recoiling nucleus also makes the effective solid angle for the shifted peak larger compared to the stopped peak. This effect is taken into account by multiplying I_s with a factor $(1 - \beta)/(1 + \beta)$. The combined effect of the detector efficiency and Lorentz correction gives

$$R(D) = I_0/(I_0 + (1 - \beta)I_s). \tag{2}$$

The energy straggling of the incident beam in the Ta backing, the kinematics of the nuclear reaction and the energy straggling of the recoiling ions in the target can give rise to a recoil velocity distribution of considerable width. The effect of this recoil velocity distribution on $R(D)$ has been considered by Jones *et al* (1969).

It is apparent from the discussion above that it is desirable to have higher recoil velocity in order to measure shorter nuclear life times because a faster moving ion takes a shorter time to travel a given target to stopper distance. The lower limit on the measureable lifetime from a plunger system, however, depends on the minimum

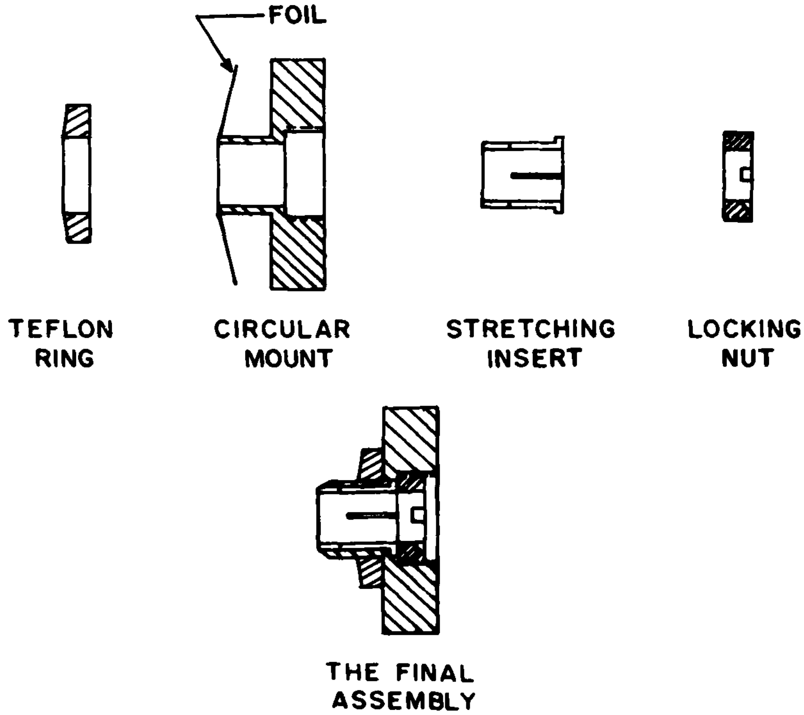

Figure 1. The components and assembly of the target holder used for stretching of tantalum foils.

distance of approach between target and stopper, which further depends on the following two factors:

1) The flatness and uniformity of target and stopper foils.
2) The parallelism between the surfaces of the target and stopper foils.

The flatness and uniformity of the target and stopper foils is achieved through the double stretching technique first developed by Gallant (1970). A schematic procedure for stretching the foils is shown in figure 1. We have also used another method for stretching thin Ta foils used as backing for the target. This method is similar in concept but slightly different in details. A schematic diagram showing the details for obtaining a stretched target from this technique is presented in figure 2. A photograph of the stretched target and the stopper foils used in the present experiment is also shown in figure 3.

The target and the stopper assemblies prepared with the technique discussed above are fixed in two teflon holders which are screwed to two vertical stainless steel plates mounted inside a vacuum chamber (see figure 4). While the target foil plane was held fixed, the stopper foil plane could be oriented by adjusting the spring loaded screws used for mounting the teflon housing. Thus, the parallelism betweeh the target and stopper foils is achieved by suitably adjusting the three screws holding the stopper teflon housing.

In the present system, the stainless steel plate holding the target assembly is kept in a fixed position by screwing it to a fixed bottom plate, whereas the stainless steel

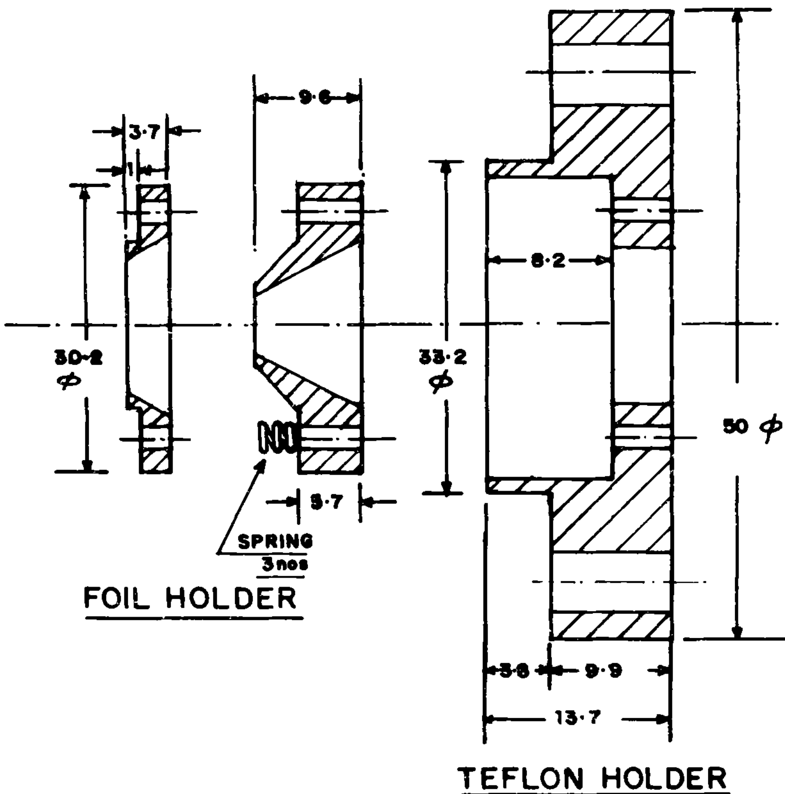

Figure 2. The target holder used for stretching thin (1 to 2 mg/cm^2 thickness) tantalum foils. The dimensions indicated are in mm.

plate holding the stopper assembly is screwed to a second plate which moves over the bottom plate with the help of a micrometer screw operated from outside the vaccum chamber. The ball bearings between the two plates make the motion smooth and a spring between them minimizes the backlash. The parallelism and the distance between the target and the stopper foils are monitored with the help of capacitance measurement technique described by Alexander and Bell (1970). The schematic diagram of this method is shown in figure 5. In this method, the inverse of capacitance (C_T^{-1}) between target and stopper foils is plotted as a function of the micrometer reading. A typical plot of C_T^{-1} vs micrometer reading in mm (d) for the present system is shown in figure 6. It shows a linear behaviour from large separation $\sim 100\,\mu$m to small distances where it suddenly deviates from linearity because the target and stopper foils touch each other at some point due to non-uniformity, slight deviation from parallelism or the presence of some fine dust particles. The extrapolation of this curve to zero value of C_T^{-1} gives the position of zero distance between the foils. Therefore, the distance of minimum approach between the foils is obtained from the zero distance position and the point of deviation from linearity in the C_T^{-1} vs d curve. Figure 6 shows that a minimum distance of $8 \pm 1\,\mu$m could be obtained for the present system. In all our experiments, the distance was always monitored with the capacitance measurements.

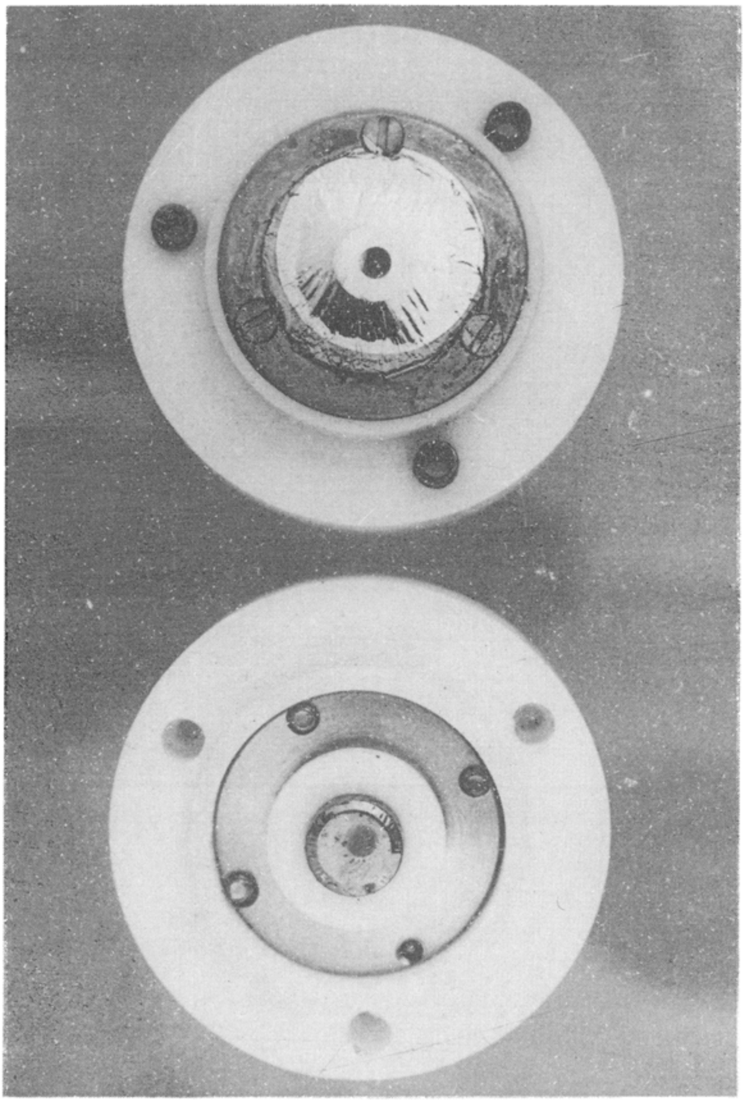

Figure 3. The photograph of the stretched target and stopper foils used in the present experiment.

3. Measurements and results

The plunger set-up discussed in §2 was used to measure the half-lives of excited states in nuclei with $A \sim 40$. The nuclear states of interest were populated through the reaction ^{27}Al (^{16}O; $xn, yp, z\alpha$) using 60 MeV ^{16}O beam obtained from the 14 UD-Pelletron at TIFR. Since the target was prepared by evaporating $\sim 350\,\mu$g/cm^2 thick Al on a 1·8 mg/cm^2 thick stretched Ta foil, the ^{16}O beam lost nearly 3·5 MeV energy before being incident on the Al target. The stopper, as mentioned earlier, was a 6 mg/cm^2 thick stretched Ta foil and was sufficient to stop the recoiling ions produced

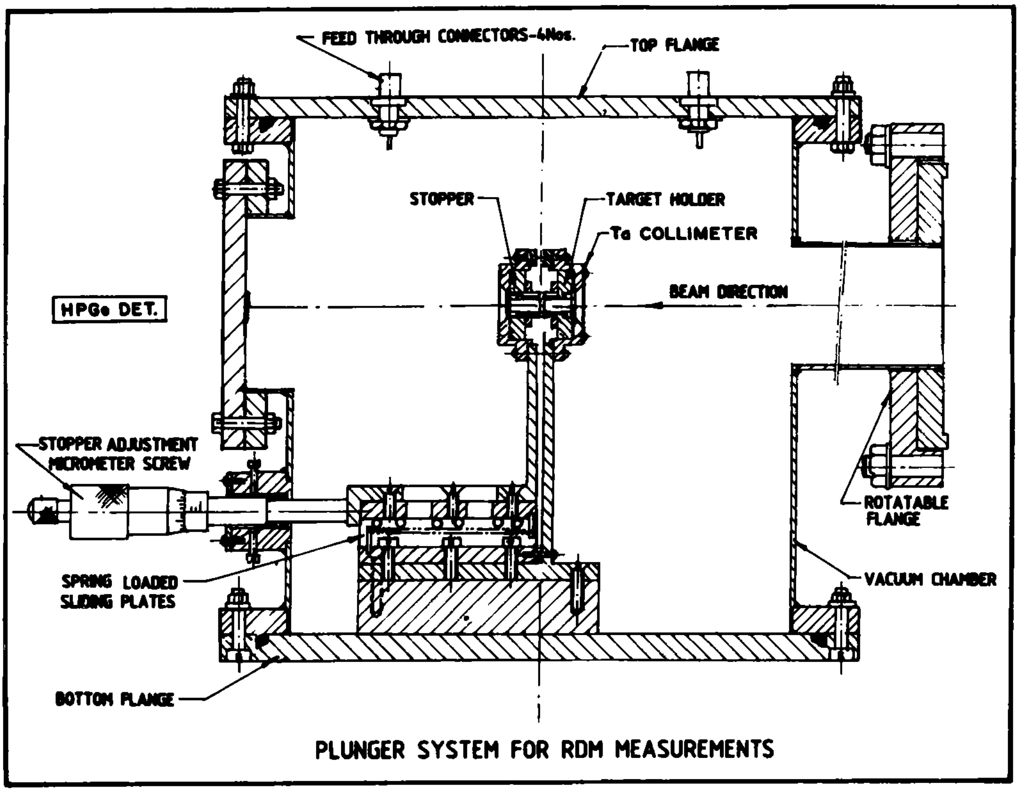

Figure 4. Schematic diagram of the plunger assembly inside the vacuum chamber.

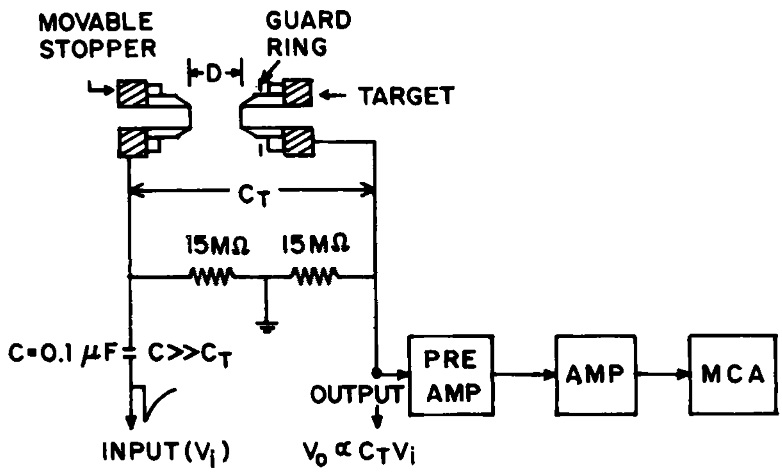

Figure 5. Schematic diagram for the arrangement used for monitoring the target to stopper distance through the capacitance measurement technique.

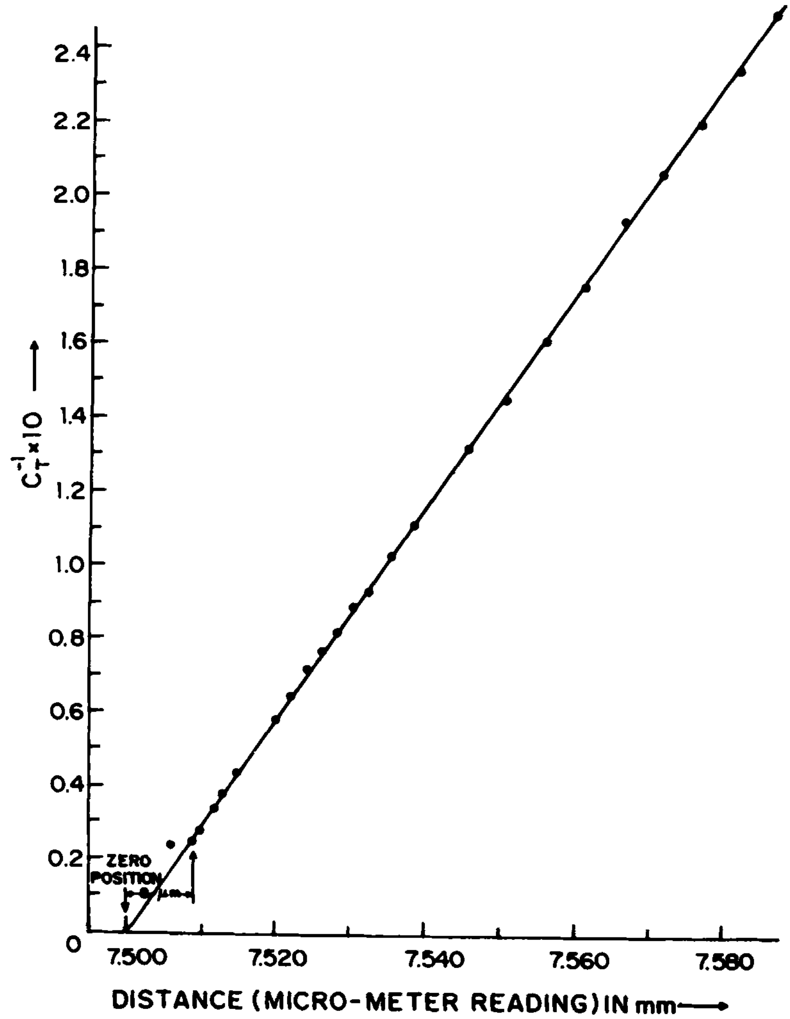

Figure 6. The inverse of capacitance (C_T^{-1}) between the target and stopper foils measured as a function of the micrometer position (d).

in the reaction. The γ-rays were detected in a HPGe detector with 23% intrinsic efficiency and placed at 0° with respect to the beam direction. The half-lives measured in the present experiment are discussed below.

3.1 *Half-lives of excited states in* ^{37}Ar

The half-lives of the 6473 keV ($15/2^+$) and 6150 keV ($13/2^+$) states in ^{37}Ar have been measured through the plunger technique in the present experiment. The 6473 keV ($15/2^+$) state in ^{37}Ar deexcites through the emission of 323 keV γ-ray. Figure 7 shows a typical partial γ-ray spectrum in the HPGe detector at 0°. It shows a γ-ray peak at 323 keV for a target to stopper distance $D = 10\,\mu$m (bottom). The top part of the figure shows the same spectrum taken for a target to stopper distance $D = 3160\,\mu$m. It is seen that the peak at 323 keV disappears completely for large target to stopper

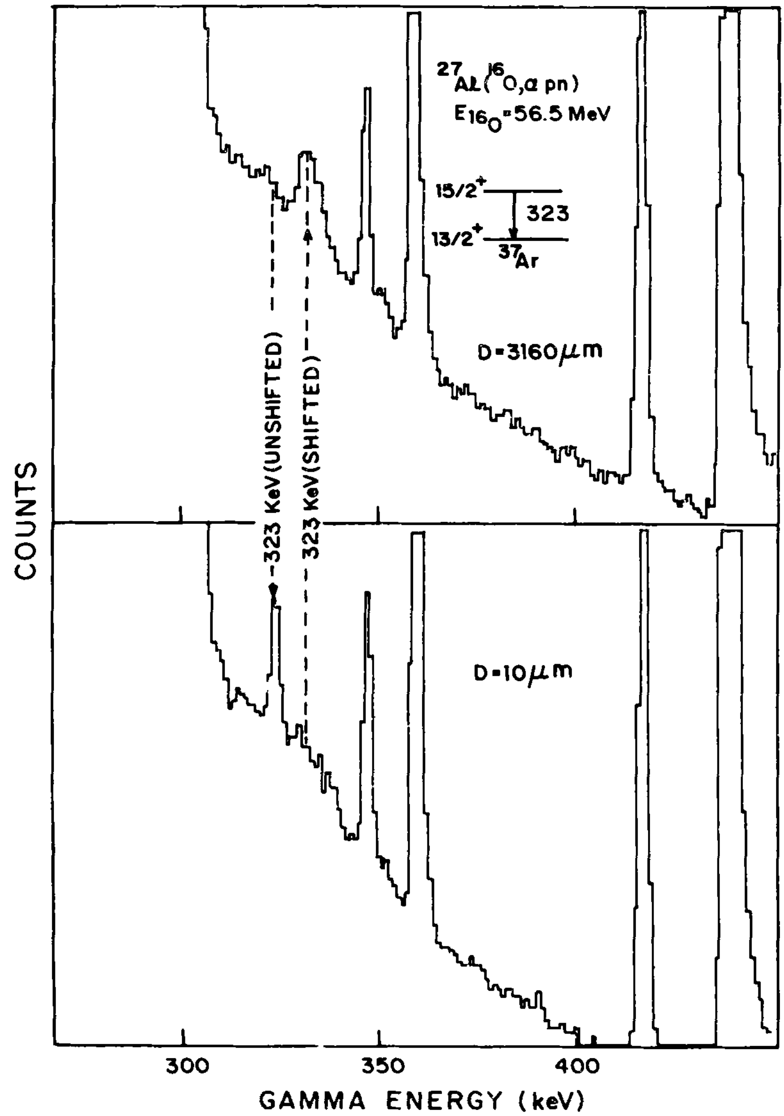

Figure 7. A partial γ-ray spectrum showing 323 keV γ-ray deexciting 6474 keV ($15/2^+$) state in ^{37}Ar produced in ^{27}Al (^{16}O,αpn) reaction at E ^{16}O $\sim$ 56·5 MeV. The spectrum at the bottom was obtained for a target to stopper distance $D = 10\,\mu$m showing unshifted 323 keV γ-ray. The spectrum at top is for $D = 3160\,\mu$m showing the fully shifted 323 keV γ-ray.

separation. Instead, a broad Doppler-shifted peak appears at an energy of 333 keV. An average recoil velocity $\beta = 0{\cdot}0291(3)$ was obtained from the observed separation between the centroids (obtained by peak-fitting program) of the shifted and unshifted γ-ray peaks. Figure 8 shows a plot of $I_0/(I_0 + (1-\beta)I_s)$ vs the target to stopper distance in microns for the 323 keV γ-ray. As mentioned in §2, the shifted peak intensity I_s has been multiplied by the factor $(1-\beta)$ to account for the energy dependence of the detector efficiency and also for the effective solid angle for nuclei in motion. The shifted peak is broader relative to the stopped peak indicating a

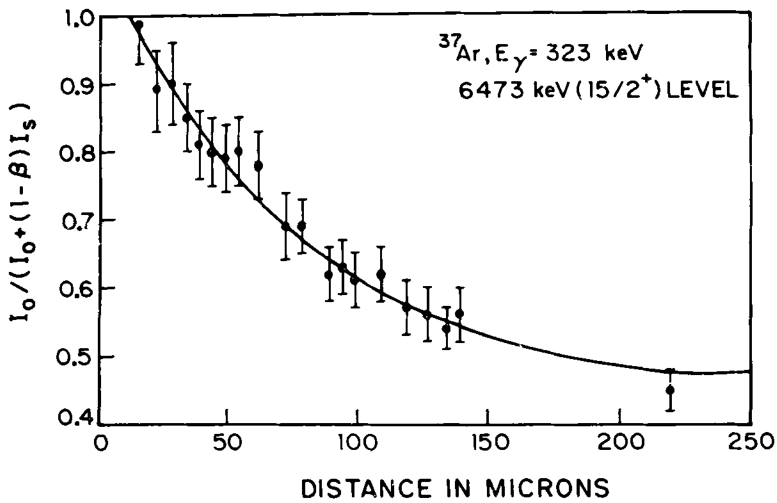

Figure 8. The plot of $I_0/(I_0+(1-\beta)I_s)$ vs D for the 323 keV γ-ray deexciting 6473 keV level in ^{37}Ar.

distribution in velocity. The effect of this distribution was estimated by using the procedure suggested by Jones *et al* (1969). This assumes a velocity distribution consisting of components of equal intensities with $\bar{v}_{min} = (1-\Delta)\bar{v}$ and $\bar{v}_{max} = (1+\Delta)\bar{v}$. The value of Δ is estimated to be $\sim 0{\cdot}15$ from the shifted peaks in the present experiment. This gives rise to a correction $\leqslant 1$ per cent in the calculated values of $R(D)$ for $D/\bar{v}\tau$ ranging between 0 and 1·5. The least square fit to the experimental data gave a half-life $T_{1/2} = 6{\cdot}1(6)$ ps for the 6473 keV (15/2$^+$) state in ^{37}Ar. This half-life was found to be insensitive to the variation in the position of zero-distance by $\pm 1\ \mu$m.

The lifetime of the lower excited state at 6150 keV was least square fitted using the three level formula with the two top levels having lifetimes τ_1 and τ_2 respectively. This gave a value of $T_{1/2} = 2{\cdot}1(10)$ ps for the 6150 keV (13/2$^+$) level in good agreement with the value reported by Warburton *et al.*

3.2 *Half-lives of excited states in ^{38}Ar*

The half-life of the 7609 keV (8$^+$) state in ^{38}Ar was measured by the plunger technique as $T_{1/2} = 2{\cdot}6(4)$ ps in agreement with the values 4·3 (22) ps reported by Kolata *et al* (1976). The half-lives of the 4585 keV (5$^-$) level and 4480 keV (4$^-$) levels were also measured by observing the Doppler shift of the 670 keV γ-ray deexciting the 4480 keV level. The measured Doppler shift gave a value of $\beta = 0{\cdot}0356(4)$ for the average recoil velocity of the ^{38}Ar ions. Figure 9 shows the plot of $I_0/(I_0+(1-\beta)I_s)$ vs the target to stopper distance for the 670 keV γ-ray. The data clearly shows two slopes. The least square fit to the data gave the long-lived component $T_{1/2} = 136(4)$ ps for the half-life of the 4585 keV (5$^-$) level and the short-lived component gave $T_{1/2} = 0{\cdot}93(20)$ ps for the half-life of the 4480 keV level. These are in good agreement with the values reported by Kolata *et al* (1976) and Van Driel *et al* (1974).

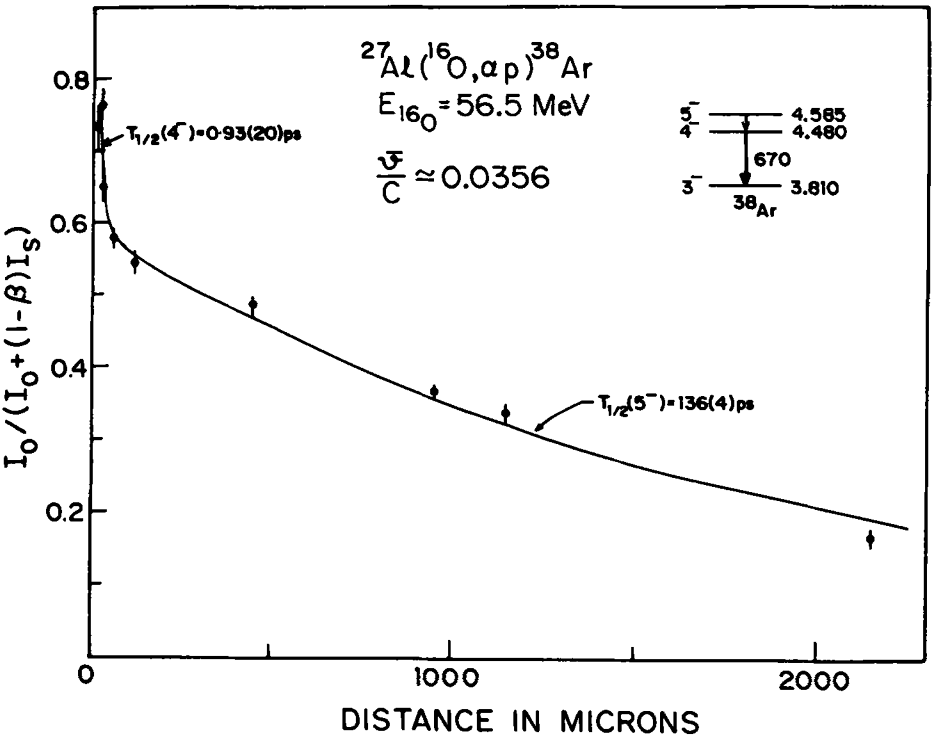

Figure 9. The plot of $I_0/(I_0+(1-\beta)I_s)$ vs D for the 670 keV γ-ray deexciting the 4480 keV level in ^{38}Ar. The measurement gave a value of $T_{1/2}=136(4)$ ps for the 4585 keV level and $T_{1/2}=0{\cdot}93(20)$ ps for the 4480 keV level in ^{38}Ar.

3.3 *The half-lives of excited states in* ^{40}K

The observed Doppler shift for the 892 keV γ-ray deexciting the 892 keV (5^-) state gave a value of the recoil velocity $\beta = 0{\cdot}0292(3)$ for the ^{40}K nucleus. The least square fit to the plunger data for the 892 keV γ-ray gave a value of $T_{1/2}=2{\cdot}3(10)$ ps for the 892 keV (5^-) level and $T_{1/2}=1{\cdot}10(7)$ ns for the 2543 keV (7^+) level in ^{40}K. The half-life of the 4366 keV (8^+) in ^{40}K has also been measured in the present experiment. The value of $T_{1/2}=0{\cdot}36(14)$ ps is consistent with the upper limit of 1·0 ps suggested by Eggenhuisen *et al* (1977). This value can, however, have an additional error because the lifetime of the 4366 keV level is comparable to the stopping time of ^{40}K ions in the Ta stopper.

3.4 *Half-lives in* ^{35}Cl

The Doppler shift measurements gave a value of $\beta = 0{\cdot}0294(3)$ for the average recoil velocity of the ^{35}Cl ions. A value of $T_{1/2}=31{\cdot}4(4)$ ps has been obtained for the half-life of the 3162 keV ($7/2^-$) state and $T_{1/2}=6{\cdot}1(11)$ ps for the half-life of the 8844 keV ($17/2^+$) state in ^{35}Cl. These are in good agreement with the values reported by Warburton *et al* (1976).

4. Conclusions

A plunger system has been fabricated and fully tested for in-beam measurements of half-lives of nuclear excited states populated in reactions using heavy ion beams from the 14 UD Pelletron at TIFR. This plunger system can be used to measure half-lives as short as 0·3 ps and up to a few nanoseconds. The life-time of the 4·366 MeV (8^+) state has been measured for the first time and the half-lives of several other excited states in ^{35}Cl, ^{37,38}Ar and ^{40}K have been obtained in the present work. The technique of obtaining flat and uniform target surfaces along with the procedure to obtain parallelism between the target and stopper have been well established.

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