Vol 10 No 11, November 2001
1009-1963/2001/10(11)/1017-04

Chinese Physics

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and IOP Publishing Ltd

DETERMINATION OF THE LIFETIME OF THE $4p^1P^0$ STATE OF CALCIUM BY ELECTRON PHOTON COINCIDENCE

M.A.K.Elfayoumi

Department of Physics, Beni-suef Faculty of Science, Cairo University, Egypt

(Received 22 February 2001; revised manuscript received 17 June 2001)

The electron–photon delayed coincidence technique has been used to measure precisely the lifetime for the $4p^1P^0$ state in calcium. The lifetime of this state was obtained by measuring the time correlation spectrum between the inelastically scattered electrons and the corresponding de-excitation photons. By using the least-squares fitting program to fit Gale's equation to the data points, a value of (4.15±0.17) ns was obtained. The result was compared to some of the earlier experimental measurements.

Keywords: electron–atom collision
PACC: 3480D, 3270C

I. INTRODUCTION

The electron–photon coincidence method was first adopted by Imhof and Read[1] and other workers[2−4] to measure the lifetimes in atoms and molecules, both neutral and ionic. A detailed review of the measurements of lifetimes in atoms, molecules and ions using coincidence techniques has been given by Imhof and Read.[5] Fairly little work has been done on earth alkaline atoms using the coincidence technique. Most of the lifetime measurements on some of the earth alkaline elements were carried out by using phase shift,[6] Hanle effect,[7,8] atomic beam,[9] zero-field level crossing[10] and beam foils[11] techniques. Recently, Rosner *et al.*[12] used the cascade-photon coincidence technique with a sputtered-atom source for measuring the lifetimes of the $4p^2P^0_{3/2}$ state of CaII, the $6p^2P^0_{3/2}$ state of BaII and the $4p^2P^0_{3/2}$ state of Al III. In the present work a precision measurement of the lifetime of the $4p^1P^0$ state of calcium was carried out by using the output data of the best peak-to-background ratio resultant in the electron–photon coincidence experiment.

II. THEORY

If the transition under study measured by the electron–photon coincidence has too short a lifetime ($\tau \leq 10^{-12}$s) then the data are a measure of the prompt coincidence resolution curve $P(t)$. This curve is a measure of the transfer function of the apparatus, which depends on the finite length of the beam pulse and the time spreads in the instrument. If the lifetime is finite, the de-excitation photon has a probability $W(t)\mathrm{d}t$ of occurring at a time t after the formation of the state. The yield of true coincidences $Y(t)$ as a function of time is then given by the convolution integral,

$$Y(t) = \int_{-\infty}^{\infty} P(t-t')W(t')\mathrm{d}t'.$$

If only a single exponential decay component is operating, then the probability distribution for the de-excitation photons is

$$W(t) = 0, \qquad t < 0;$$
$$W(t) = (1/\tau)\exp(-t/\tau), \quad t > 0,$$

where τ is the lifetime.

The analysis method used in the present work was described by Gale,[13] which assumes that the prompt spectrum can be represented by a Gaussian

$$P(t) = (h/\sqrt{\pi})\exp(-h^2t^2),$$

where $h = (1/\sigma\sqrt{2}) = \dfrac{\sqrt{\ln 2}}{W}$, σ the standard deviation of the Gaussian and W is the half-width of the Gaussian at half height.

The coincidence spectrum can be represented by the function

$$N(t) = A + B\left[1 + \mathrm{erf}\left(ht - \frac{1}{2h\tau}\right)\right]\exp\left[\left(\frac{1}{4h^2\tau^2}\right) - \frac{t}{\tau}\right],$$

where A is the background count due to the random coincidences, B is the amplitude of the decay, and erf is the normalized error function. This function is fitted by a nonlinear least-squares program to yield the lifetime value.

Ⅲ. APPARATUS

In the present experiment the electron beam intersected the atomic beam at right angles and the observation of the photon emitted in the decay of the excited state was made along the third orthogonal axis. The intersection of the electron and atomic beams defined the interaction region. The scattering plane was defined by the momenta of the incident and the observed scattered electrons. The direction of the incident electron was in the z-direction and the rotation axis of the turntable, where the 127° electron analyser was held, was in parallel to the y-direction. The scattering plane was thus defined by the z- and x-axes. An electron gun following the design outlined by Erdman and Zipf[14] was used. The electron beam current produced from the gun was non-monochromatized and covered a wide range of electron energies (5–60eV). Typical electron currents were $\sim 0.2\mu$A at low energies ($\leq$10eV) and $>1.0\mu$A at higher energies. An electron impact energy of 35.7eV was used for these measurements. The beam profile was continuously monitored by measuring the Faraday cup current as a function of the angle θ_f (the angular setting of Faraday cup with respect to the direction of the electron beam). The atomic beam (calcium beam) was produced from a stainless-steel oven consisting of two parts. The bottom part served as a reservoir for calcium metal chips and held approximately 40g of calcium metal and the top part had a canal-like aperture (nozzle) of a length of 8mm and a diameter of 0.8mm, through which the calcium atoms were effused to the interaction region. The oven was heated by two independent sets of coils made from tantalum wire of 0.25mm diameter. A special four-fold wiring was employed to compensate the magnetic field of the heating current in the interaction region. The oven was heated up to 590°C. To ensure a good thermal insulation a three separate cylindrical shields with top and bottom covers made of tantalum were used. The angular spread of the calcium beam was effused restrictively in the forward direction and was further restricted by three coaxial apertures on the top of the shields. The width of the calcium beam was 10mm at the interaction region which was 300mm away from the nozzle of the oven. A 127° electron analyser based upon the principle outlined by Marmet and Kerwin[15] was used to select the inelastically scattered electrons which had lost the energy required to excite the $4p^1P^0$ state of calcium.

The energy selected electrons were collected by a Mullard-type (B318) channel electron multiplier fixed in front of the exit slit of the 127° analyser. The electron gun, Ca oven, 127° analyser and the Faraday cup all were enclosed within a vacuum chamber where the pressure was $\sim 1.6 \times 10^{-4}$Pa. The 127° analyser and the Faraday cup were mounted on two separate turntables in such a way that both could be rotated individually from outside the vacuum chamber by means of two independent feedthroughs. The angular range of the 127° analyser was 15° $\rightarrow$120° while that of the Faraday cup was $+10° \rightarrow -10°$. A set of three mutually perpendicular Helmholtz coils was used to reduce the Earth's magnetic field to less than 20mG over the entire electron beam trajectory.

An optical system was used to detect and to measure the intensity of radiation emitted from the interaction region. The optical system mainly consisted of a quartz lens, a linear polarizer, an interference filter and a photomultiplier tube. The quartz lens of a focal length of 100mm was held at distance of 110mm from the interaction region to form a large-sized image for the interaction region on the cathode of the photomultiplier tube. To prevent systematic errors due to the detection of photons from the decay of states other than those of interest, a narrow-band optical interference filter (420FS-25) was used, which was chosen accurately for this wavelength and has a peak transmission of 54.5% centred at 422.6nm. The thin sheet polaroid (HN38) having a transmission of 33% for 422.6nm was used as a linear polarizer in front of the interference filter. Finally a photomultiplier tube (9883QB) was selected especially for low noise to detect the photons emitted at right angles to the scattering plane along the y-direction.

A. Experimental details

The electron beam current, typically 0.2μA at 35.7eV, was continuously monitored by a Faraday cup located 70mm beyond the interaction region as a function of the angle θ_f (the angular setting of Faraday cup was calculated with respect to the direction of the electron beam). The upper lid of the oven was about 25mm from the interaction region where the density of the calcium beam at the centre of the in-

teraction region was 1.39×10^{10} atoms/cm^3.The heating up of the reservoir was done slowly to avoid the abruptly increase of the pressure inside the vacuum chamber. The ultimate pressure after two hours was $\sim1.6\times10^{-4}$Pa. The electron beam (35.7eV) was used to excite the calcium atoms from the ground state $4s^1S$ to the $4p^1P^0$ state. The inelastically scattered electrons in the forward direction were energy analysed by the 127° electron analyser and those electrons which have suffered an energy loss of 2.91eV were detected by the Mullard channel electron multiplier. Subsequent decay photons corresponding to the decay $4p^1P^0 \rightarrow 4s^1S$ were collected by the quartz lens and directed through the linear polarizer and the interference filter which provide the wavelength selection to be detected by the photomultiplier tube. The signal from the 127° electron analyser and the photomultiplier tube was amplified and fed into a constant fraction discriminator (CFTD). The electron limiting pulse from the CFTD starts the ramp of a time-to-amplitude converter (TAC), and the photon timing pulse, suitably delayed, was used to stop the ramp. The amplitude of the TAC output signal was then proportional to the time difference between the stop and start pulses. A multichannel analyser (MCA) was used to record the resulting pulse height spectrum from the TAC. Figure 1 shows the time spectrum of the resultant shape of the calcium coincidence peak.

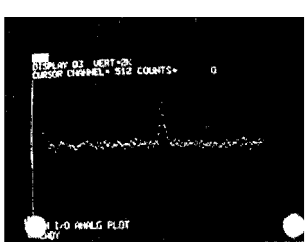


Fig.1. Coincidence time spectrum of $4p^1P^0$ state in calcium, the data collection time being 12h.

A good determination of the Ca oven temperature has been made so as to make sure that the signal count rate is linearly proportional to the calcium vapour.

A time calibration of the system was achieved by using the procedure described by Smith *et al.*[3] This procedure consists of applying random pulses to the start input of TAC and the pulses derived from a frequency generator whose frequency can be accurately measured and is set such that the time separation between the stop pulses is less than the time window of the TAC. Then it is inevitable that every start pulse will be stopped in some time which is less than or equal to the period of the stop pulses. Moreover, at times in the spectrum corresponding to delays greater than the period of the stop pulses, there can be no events recorded. The result is a spectrum consisting of a flat background with a sharp cut-off. The position of cut-off is the characteristic of the frequency of the stop pulses.

IV. RESULTS AND DISCUSSION

The delayed coincidence spectrum obtained from the decay of the $4p^1P^0$ state in calcium together with the theoretical fitted curve are shown in Fig.2.

The spectrum shows an exponential decay, the leading edge of which is rounded by the finite resolving time of the apparatus on a flat background of random coincidence. The value of the lifetime (τ=4.15±0.17ns) was obtained by using a least-squares fitting program to fit Gale's equation to the measured data points. The χ^2 per degree of freedom for the fit was 1.18.

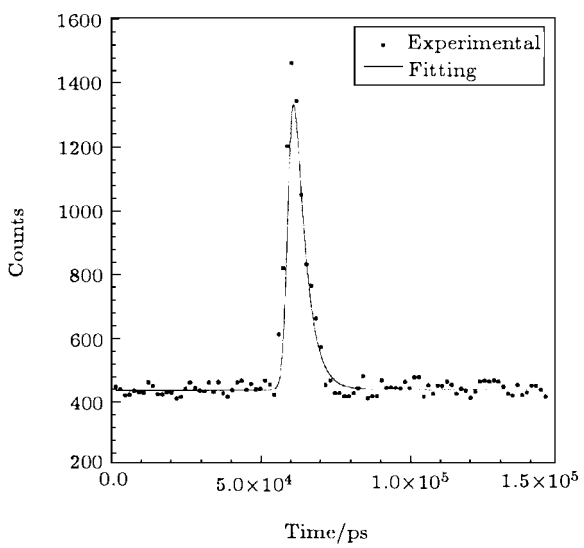


Fig.2. Delayed coincidence spectrum of the $4p^1P^0$ state in calcium. The full curve represents the least-squares fit of the data to Gale's equation.

A comparison between some of the previous experimental measurements is listed in Table 1.

Table 1 shows the lifetime values of the state $4p^1P^0$ measured by different methods. The present lifetime value is in good agreement with that of Kelly, Lurio, Hulpke and Smith, while it is significantly shorter than the 6.2ns obtained using the beam foil technique.[11] Theoretically, the lifetime of the resonance lines can be affected by: (a) cascading from the higher excited levels, and (b) resonance trapping. The

coincidence methods reported in the present work successfully avoided the above two factors by: (1) a good selection of the spectral lines by a very narrow interference filter; (2) a very low calcium pressure ~ 2.66Pa at the centre of the interaction region, maintained during the collision process.

Table 1. Some of the measured lifetimes for the $4p^1P^0$ state.

Authors	Methods	Measured lifetime/ns
Odintsov (1963)	Atomic beam	5.00±0.30
Lurio (1964)	Zero field level crossing	4.48±0.15
Hulpke *et al.* (1963)	Phase shift	4.67±0.11
Smith and Gallagher (1966)	Hanle effect	4.62±0.15
Andersen *et al.* (1970).	Beam foil	6.20±0.50
Kelly *et al.* (1980)	Hanle effect	4.49±0.07
Present value (2000)	Electron–photon coincidence	4.15±0.17

V. CONCLUSION

The present measurements have demonstrated the ability of the electron–photon coincidence technique for measuring the lifetimes of the excited state atoms in metal vapours.

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