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The Triple Coincidence Detection of the Helium 3^1D State Decay*

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Abstract

The first triple coincidence detection of the scattered energy loss electron and the sequential cascading photons, $667{\cdot}8$ nm $3^1\mathrm{D} \to 2^1\mathrm{P}$ and $58{\cdot}4$ nm $2^1\mathrm{P} \to 1^1\mathrm{S}$, from the electron impact excitation of the 3^1D state of helium is reported. An experimental method for identification and determination of the triple coincidences and initial results is reported. The measurement is the final experimental step in determining all the information to define completely the excited 3D state.

1. Introduction

This paper reports the first observation of the triple coincidence detection of the scattered energy loss electron and the two sequential cascading photons from the decay of the 3^1D state of helium, following electron impact excitation. This measurement is a step towards making the necessary and sufficient measurements from which a complete quantum description of an excited D state can be made. A previous paper (Wang and Williams 1993) derived the quantum mechanical expressions for the measured coincident intensities in terms of the state multipoles $T(2)_{\mathrm{KQ}}$ for the complete description. Equivalent descriptions can be given in terms of the density matrix or the excitation amplitudes and relative phases from which a simple physical picture of the size, shape, height and angular momentum of the electron charge cloud of the excited state can be deduced.

Progress towards this goal has occurred through previous measurements of coincident pairs of the three emitted particles after the excitation process for various geometries. For example, at incident electron energies below 40 eV, angular correlations in the scattering plane of the scattered electron and the cascade $58{\cdot}4$ nm $2^1\mathrm{P} \to 1^1\mathrm{S}$ photon were used to determine the anisotropy parameters λ, $|\chi|$, $|\mu|$ and η (van Linden van Den Heuvell *et al.* 1983). The only other angular correlation measurement was performed by Perera and Burns (1990) by observing the $667{\cdot}8$ nm $3^1\mathrm{D} \to 2^1\mathrm{P}$ photons. Further coincidence measurements of the scattered energy loss electron and the $667{\cdot}8$ nm $3^1\mathrm{D} \to 2^1\mathrm{P}$ photon, using polarisation correlations in the direction perpendicular to the scattering plane, obtained the Stokes parameters P_i $(i = 1\text{–}3)$ and hence the γ,

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P_ℓ and $L_\perp$ parameters (Beijers *et al.* 1987; Batelaan *et al.* 1988; Donnelly and Crowe 1988). More complete measurements of the 3^1D state, which included the in-the-scattering plane polarisation correlations determination of the Stokes parameter P_4 and hence the electron charge cloud height parameter ρ_{00}, were performed by Batelaan *et al.* (1991), Mikosza *et al.* (1994*a*) and Donnelly *et al.* (1994). Finally, coincidences between the sequential cascading photons, with polarisation analysis of the first photon (Mikosza *et al.* 1993; Mikosza *et al.* 1995), enabled the first determination of the rank 4 state multipole for He(3^1D), and the total (integrated over scattered electron angle) magnetic sublevel cross sections for each $m = 0$, 1 and 2. The paper by Wang and Williams (1993) indicates how triple coincident measurements can determine the sign of the $m = 2$ amplitude and so complete the description of the 3^1D state. The present work describes an experimental method for identification and determination of triple coincidences and reports initial results.

2. Apparatus

The experimental method involves electron impact excitation of ground state helium atoms to the 3^1D excited state, and the detection of the scattered energy loss electrons in coincidence with the two sequential cascading photons through the intermediate 2^1P state. The apparatus has been discussed in detail elsewhere (Mikosza *et al.* 1994*b*) and only a brief description is given here.

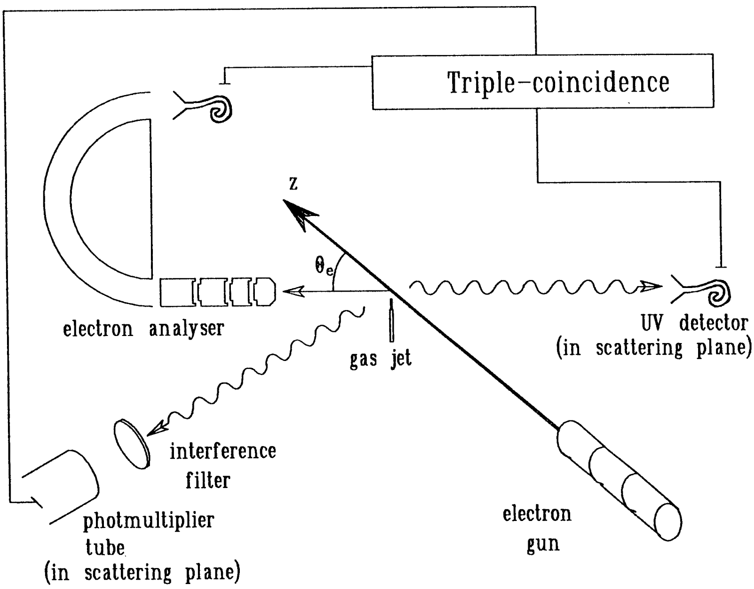

Fig. 1. Schematic diagram showing the experimental configuration of the electron analyser and the visible and UV detectors used in triple coincidence measurements. The scattering plane is defined by the plane containing the incident and scattered electron beams.

The electron scattering components are located inside a vacuum chamber with a base pressure of about 5×10^{-8} Torr. Fig. 1 indicates that the scattering plane is defined by the plane containing the incident electron beam and the scattered electron beam. The electron beam was focused to less than $0\cdot4$ mm diameter at the interaction region with the helium gas provided by a low 1·0 Torr driving pressure through a single capillary of 0·3 mm diameter and 5 mm length. The electron beam current of 600 nA was stable with beam intensity variations restricted to less than 1% throughout the long duration of the experiment.

The detector for the $3^1D \rightarrow 2^1P$ 667·8 nm photons was an EMI 9883 photomultiplier tube cooled to $-20°C$ operating in the pulse counting mode. The photomultiplier was preceded by wavelength filter and the detector was located in the scattering plane and inside the vacuum system. The UV detector for the $2^1P \rightarrow 1^1S$ 58·4 nm photons was a Mullard B418BL channel electron multiplier, located inside the vacuum system and could be rotated around the scattering centre.

The angles subtended by the detectors were $2{\cdot}3\times10^{-3}$ sr for the electron analyser, 0·3 sr for the visible (667·8 nm) radiation and 0·03 sr for the UV detector, while typical count rates were 6, 0·8 and 10 kHz respectively. The relatively large solid angle for the photomultiplier tube was designed to compensate the relatively low detection efficiency of the visible (667·8 nm) radiation by the small 1 cm square photocathode of the EMI 9863QB photomultiplier tube. The energy resolution of the electron analyser of about 0·75 eV did not allow discrimination against other $n = 3$ energy levels and hence the count rate was high in comparison with that of the visible photon detector at most scattering angles. Similarly, the typical count rate from the UV photon detector was also high as it did not discriminate between the 58·4 and 53·7 nm photons from the 2^1P and 3^1P states respectively.

The time resolutions for the visible, UV and electron detectors were 6, 8 and 10 ns respectively. The gas target driving pressure was 0·3 Torr and the estimated electron beam pathlength through the gas was 1 mm.

3. Data Acquisition and Display System

The output signals from the three detectors were amplified and shaped into fast NIM logic pulses which were counted and fed into two time-to-amplitude converters (TACs). The signals from the scattered electron e^-, the visible photon γ_1 and the cascade UV photon γ_2 were used to start and stop two TACs resulting in three types of output. The first type are the triple coincidence counts $N_{\rm real}$ with the scattered electron and the two photons originating from the same helium atom (e^-, γ_1, γ_2). The second type originates from the three possible ways in which two of the three signals are correlated, (e^-, γ_1), (e^-, γ_2) and (γ_1, γ_2), with the third signal γ_2, γ_1 and e^-, respectively, accidental. These three doubly-correlated contributions to the overall counts represent the accidental coincidences in triple coincidence measurements. The third type of output is the totally accidental contribution with all three, e^-, γ_1 and γ_2 uncorrelated.

These types of output signals, and their low coincidence count rates, required the development and optimisation of a computer controlled interactive real-time data acquisition, analysis and display system. The system is capable of uniquely identifying the triply-correlated, the doubly-correlated pairs and the totally accidental counts from the three detectors. The unique identification of each count type is achieved by: (i) the use of two TACs which are started simultaneously by one of the three detectors and are stopped separately by the other two, (ii) a 3-D histogram array presentation with two axes representing the simultaneous start (the origin) and stop (x, y point) of each TAC after a suitable delay, and (iii) the display (at the x, y point) and integration (z axis) of the output from the two TACs, only if both TACs have been stopped within a specified time which is determined by the length of the x and y axes of the histogram. The last requirement, readily provided by computer software, ensures that all three signals (e^-, γ_1, and γ_2) are represented on the 3-D histogram. The third dimension of the histogram, showing the number of counts at each (x, y) point, also enables quantisation of regions which include triple coincidence, accidental coincidences and totally random counts.

The interactive real-time acquisition and display system developed for triple coincidences uses a 33 MHz 486 IBM PC with 8 Mb of RAM. Monitoring and controlling the system is a program written in Turbo-Pascal and a I/O (PC-36A) card utilising an Intel 8255A programmable peripheral interface to provide 24 I/O lines.

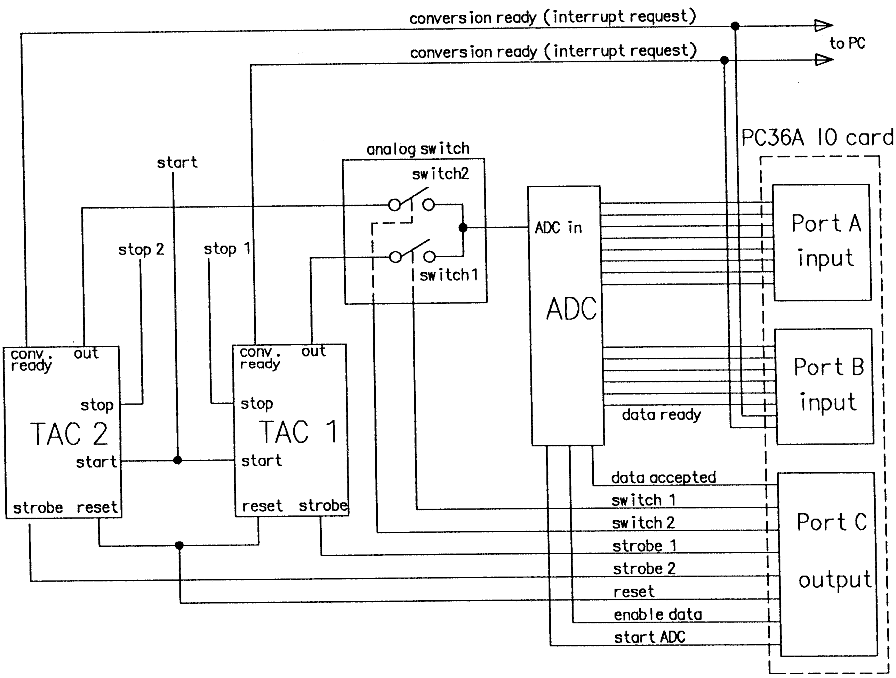

Fig. 2. Circuit diagram showing the arrangement of the programmable peripheral interface card (PC-36A utilising Intel 8255A), two TACs, ADCs and computer used for triple coincident, accidentally coincident and random data acquisition.

Fig. 2 shows the interface arrangement of the PC 36A card to the TACs and ADC. TAC1 and TAC2 which generate the 3-D histogram array in the computer's memory, and on screen display in real-time, have a common start. From the circuit diagram it can be seen that conversion ready signals from each of the two TACs are used to instigate the interrupts. Should TAC1 cause the interrupt, TAC2 is monitored for a valid stop within a specified time and if this is the case, the two time intervals between the start and stop on the two TACs will position a count on a 3-D array, used for triple coincidence measurements. If

TAC2 did not receive a stop pulse the information from TAC1 is displayed only on one of three 2-D displays (not shown), used for measurements of the three correlated pairs (e^-, γ_1), (e^-, γ_2) and (γ_1, γ_2) separately. Following an interrupt, the code for the PC-36A is activated enabling the interface to control information transfer from TACs to the ADC by switching on the appropriate routing switches, strobing the TACs and resetting TAC1 and TAC2 simultaneously.

The number of true triple coincidences is determined by measuring the number of counts included in a rectangular region in the 3-D display of correlated data. The advantage of software control of data is that the conditions under which the collection and display of coincidence data is carried out may be easily altered without addition of AND gates and similar hardware. For example, the TAC1 2-D display array can be altered to display counts only if there was a stop in TAC2, thereby selecting a subgroup of coincidence counts, corresponding to the accidental coincidences on the 3-D histogram display.

4. Results

Initial triple coincidence experiments on the excited 3^1D state of helium were attempted using the scattered electron to start simultaneously the two TACs generating the 3-D histogram array, and the two cascading photons γ_1 and γ_2, as separate stops. In this configuration the experimental planar symmetry is preserved for each TAC output, and the collected data are sufficient to determine all rank four state multipoles. The triple coincidence count rate was low because of the very small cross section and the nature of triple coincidence statistics. Our method of obtaining low statistical errors in triple coincidence measurements (see later) is to choose the channel with the highest resolution as the common start for the two TACs, and hence for 3^1D excitation, the filtered (501·6 nm) visible decay radiation is more suitable than the scattered electron or the UV cascade photon. Both the electron analyser, which registers counts from all $n = 3$ levels and the UV photon detector, registering the 58·4 nm from 2^1P and 53·7 nm from 3^1P, have relatively high count rates. Some enhancement of the 3^1D excitation with respect to the 3^1P could be obtained by increasing the scattering angle and decreasing the impact energy of the electrons to below 30 eV.

Fig. 3 shows the data obtained with the interactive computer controlled acquisition system after 44 hours of continuous accumulation of data. The accidental coincidence ridges which are clearly visible are identified as follows:

(i) Ridge 1 (*perpendicular* to the x-axis) represents the (γ_1, γ_2) correlations, i.e. with TAC 1 started by photon γ_1 and stopped by photon γ_2 with the electron e^- random.

(ii) Ridge 2 (*perpendicular* to the y-axis) represents the (γ_1, e^-) correlations, i.e. with TAC 2, started simultaneously with TAC1, by γ_1 and stopped by e^-, with the γ_2 random.

(iii) Ridge 3 (*diagonal*) represents the (γ_2, e^-) correlations with the γ_1 random, i.e. with TAC1 and TAC2 stopped by γ_2 and e^- respectively.

The width of each ridge corresponds to the approximate nanosecond lifetimes for each accidental coincidence signal. The average counts in the totally uncorrelated background representing the presence of all three detections of e^-, γ_1 and γ_2 was determined by calculating the counts in rectangular regions in between the ridges. The total counts at the intersection of the three ridges, which include possible real triple coincidences (N_{real}) were determined by choosing a region which included the widths of all three accidental coincidence lifetimes. The number of real triple coincidences in the data shown in Fig. 3 was 122±39, corresponding to approximately 3 counts per hour of data accumulation.

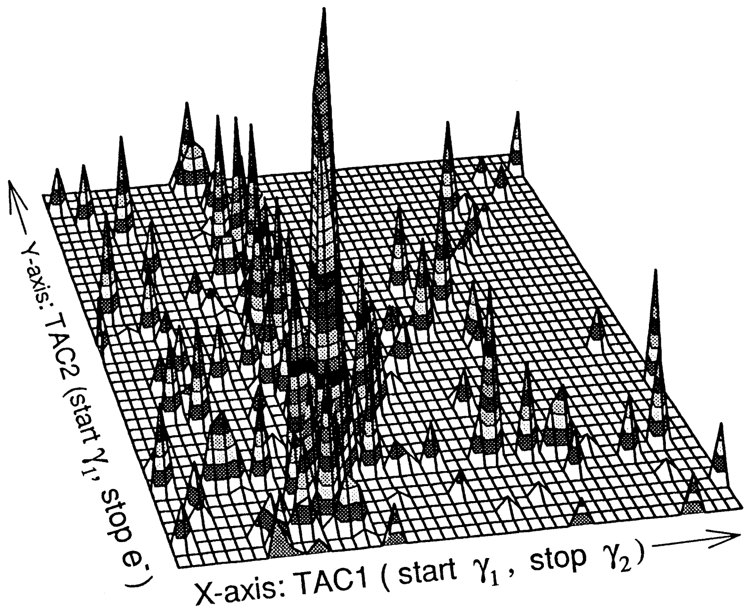

Fig. 3. A 3-dimensional perspective view of the time spectrum of triple coincidences of the electron and the two cascade photons (e^-, γ_1, γ_2) from the electron impact excited He(3^1D) state. At the intersection of the three ridges are the real triple coincidences, with the ridges representing the three pairs of accidental coincidences. For clarity of the ridges a uniform background floor at the level of subtracted background has been inserted.

The square of the fractional statistical error ($\sigma_{\text{real}}/N_{\text{real}}$) was determined

$$\left(\frac{\sigma_{\text{real}}}{N_{\text{real}}}\right)^2 = \frac{1}{T}\left[\frac{1}{IR_{\text{real}}} + \frac{1}{R_{\text{real}}^2}\sum_{a=1}^{3} R_a\, r_a(1+r_a) + \frac{I}{R_{\text{real}}^2}\left(\sum_{a=1}^{3} R_a\, r_a(1+r_a) + 2R_{\text{acc}}\, r_{\text{acc}}(r_{\text{acc}}-1)\right)\right],$$

where I is the rate of production of the excited state, T the period of data accumulation, the r are the ratios of the real counts region, on the 3-D display, to the regions chosen for the accidental and totally accidental coincidences, and the R are the probabilities of detection of the reals, the three pairs of accidental and the totally accidental coincidences.

The form of this expression is identical to that of Dupré *et al.* (1991), obtained for (e, 3e) experiments. They have also shown that a plot of $(\sigma_{\rm real}/N_{\rm real})^2$ against the intensity I for a given integration time has a distinctive minimum. The position of the minimum indicates that in triple coincidence measurements a low count rate is preferred for a low fractional statistical error in $N_{\rm real}$. The experimental methods used here to ensure low count rates, including the starting of both TAC1 and TAC2 by the lowest intensity signal (visible photon γ_1), without appreciable reduction in the possibility of detection in $N_{\rm real}$, will be further explored in future work.

A determination of one correlation sinusoid by accumulating coincidence counts at eight angular positions of the UV photon detector, for example, with the same statistical error would require approximately 16 days of data accumulation.

The present work has clearly shown that the triple coincidence detection of the scattered energy loss electron with the two sequential cascading photons from the 3^1D state is feasible. Further work is justified to improve the experiment and to develop the theory of the measurement to enable the extraction of all possible combinations of the scattering amplitudes and phases from the data.

Acknowledgments

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