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MEASUREMENTS OF He I LIFETIMES AND FINE STRUCTURE BY A TWO-SPECTROMETER METHOD

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ABSTRACT:

We have developed a two-spectrometer procedure which gives an accurate time scale in beam-foil experiments. The foil-excited beam is simultaneously viewed by two optical spectrometers. In He I studies one of these spectrometers observes the 3889 Å line ($1s2s\ ^3S - 1s3p\ ^3P$) where the accurately known $^3P_2 - ^3P_1$ separation of 658.55 MHz serves as the calibration frequency. The other spectrometer can be set to any He line. By this technique we have studied the lifetimes of the $1s3p\ ^1P$ levels and the fine structure for $1s4p\ ^3P$ and $1snd\ ^3D$ (n = 3-6).

1. INTRODUCTION

The well-known merits of the beam-foil source (e.g. coherent, anisotropic excitation, good time resolution, production of doubly-excited states, etc.) have motivated efforts to eliminate or reduce several of its disadvantages, such as cascading in lifetime measurements. Both here and in quantum beat studies by BFS the beam spreading and velocity straggling seriously limit the accuracy. The beam-laser technique, introduced at the previous BFS conference [1] and greatly extended since then avoids these problems but does not provide an overall substitute for the beam-foil source excitation properties.

We have developed a procedure which largely avoids errors due to velocity uncertainty and straggling. The foil-excited beam is simultaneously viewed by two optical spectrometers one of which is used for normalization purposes while the other records exponential decay curves or quantum beat patterns. This two-spectrometer method

is particularly well suited to systems in which the properties of some levels are accurately known. In the He I spectrum, for instance, the accurately known fine structure of the 1s3p ^3P term, which in beam foil excitation manifests itself in quantum beats for the 1s2s ^3S - 1s3p ^3P (3889 Å) decay curve [2] provides an accurate time scale for the foil-excited beam. In lifetime work this method does not avoid cascading effects, but examples can be found where, despite the unselective excitation, cascading is of minor importance, e.g. in the case of the 1s np ^1P in He I.

The two-spectrometer method is also well suited for relative measurements of lifetimes. Simultaneous recordings of two decay curves under identical conditions permit accurate measurements of lifetime differences. When the lifetime of one level in the spectrum is accurately known, e.g. from laser or pulsed electron excitation, Hanle effect, etc., lifetimes of several other levels can be put on a firmer scale. In this context it should also be possible to study the J-dependence on lifetimes within LS multiplets. In particular, the two spectrometer method permits studies of fine- and hyperfine structure separations relative to a well established energy difference. The present paper reports such results for the 1s np ^3P and 1s nd ^3D terms of He I.

2. EXPERIMENT

The measurements were performed using 100 - 300 keV He^+ ions from the Stockholm 400 kV heavy ion accelerator. The experimental arrangement is schematically shown in Fig. 1. The light from the beam is dispersed by two optical monochromators, a 35 cm Heath and a 25 cm Jarrell Ash, of which the latter is used for calibration. Photon counting is performed with Peltier cooled EMI 6256 photomultipliers. The foil motion is achieved through a precision ruling engine screw which is resetably (± 0.01 mm) driven by a stepping motor. The step size and number of steps are adjustable by an on-line programming unit. The stepping is triggered by the accumulation of a fixed number of counts from a monitor phototube which uses fiber optics to view the beam at a fixed position downstream from the foil. By means of a foil-fixed Faraday cup and a gate circuit, data accumulation is suspended if the beam current varies outside of present limits. In each position of the foil the number of counts from each of the photomultipliers and the accumulation time is routed and stored in an Intertechnique 4000 channel analyzer. After a prescribed number of foil sweeps the data are read into a paper tape buffer. Background corrections and data reduction (using standard non-linear least square and Fourier transform algorithms) are then performed in the TRASK computer.

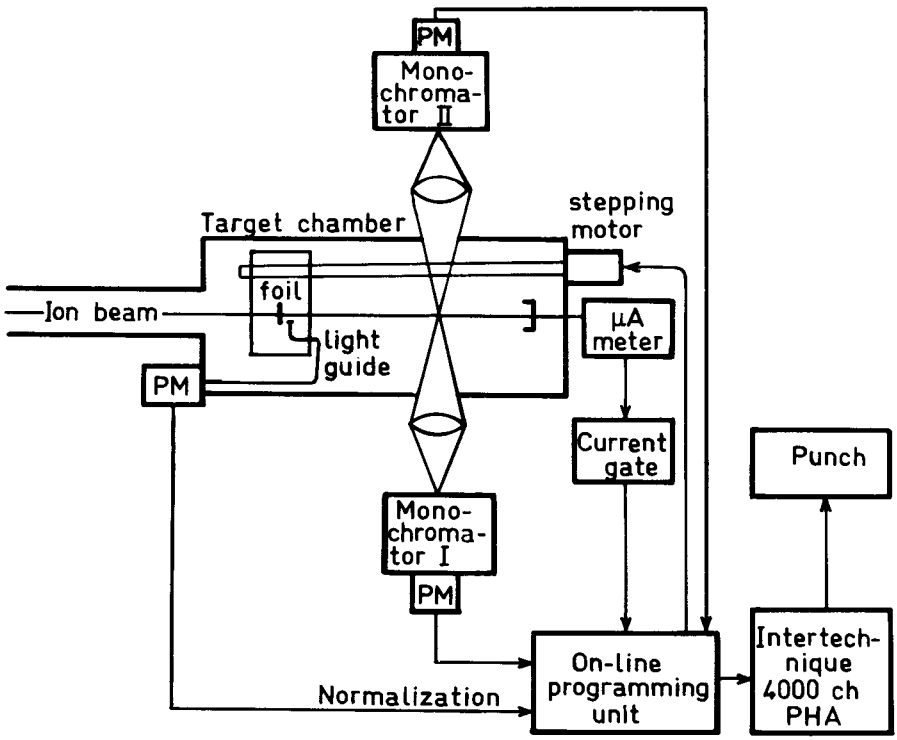

Fig. 1. Schematic diagram of the experimental arrangement.

The lifetimes were measured for the He I 1s3p ^{1}P and 1s4p ^{1}P levels. The corresponding transitions to 1s2s ^{1}S (5015 and 3964 Å, respectively) were observed by the Heath monochromator whereas the Jarrell-Ash instrument was set at 3889 Å (1s2s ^{3}S - 1s3p ^{3}P). With 180 keV He^+ beams, for example, the 658.55 MHz $^3P_1 - {}^3P_2$ quantum beats [3] have a spatial period of approximately 4.4 mm.

Because of the resonance transitions to $1s^2$ ^{1}S the 1snp ^{1}P levels have much shorter lifetimes than the 1sns ^{1}S and 1snd ^{1}D terms which populate to the ^{1}P levels. Cascading therefore plays a minor role for the 1s3p and 1s4p ^{1}P decays. In addition to curve decomposition into two exponentials we also investigated cascading by simultaneous decay measurements for the 1s3p ^{1}P and 1s4d as well as 1s5d ^{1}D levels.

Simultaneous measurements were also made of the 1s3p ^{3}P and 1s4p ^{3}P decay curves in order to establish a value for the $4p(^3P_2 - {}^3P_1)$ splitting relative to that for the 3p term. The method was also extended to the 1s3d, 1s4d, 1s5d and 1s6d ^{3}D terms. In all cases the $^3D_1 - {}^3D_2$ energy separations were measured relative to the 658.55 MHz calibration frequency.

3. RESULTS

Lifetimes

An example of the data is shown in Fig. 2, which displays the 1s3p ^{1}P decay curve. The present results for the 3p and 4p ^{1}P levels are given in Table I, together with previous theoretical and experimental values. The statistical RMS uncertainties in our data are around 1 % to which we have added estimated systematic errors, arising e.g. from decay curve decomposition into two exponentials and a fixed background. In analyzing the data advantage was taken of Davidson's study of initial populations of beam-foil excited helium [4].

Table I does not provide a complete list of previous work, for this we refer to the papers by Burger and Lurio [5] and Anderson and Weinhold [6]. We note that our new 3p ^{1}P lifetime of 1.74±0.02 ns is in excellent agreement with the Hanle-effect measured of Ref. [5] as well as with previous beam-foil [7] or "beam-Hanle" [8] experiments.

Recently an accurate 3p ^{1}P beam-foil measurement was reported by Heine et al. [9]. Despite the absence of a simultaneous velocity measured they obtained data in excellent agreement with the present work. Good accord with Ref. [9] can also be found for the 4p ^{1}P term. Here the new data are much more accurate than earlier beam-foil results [7].

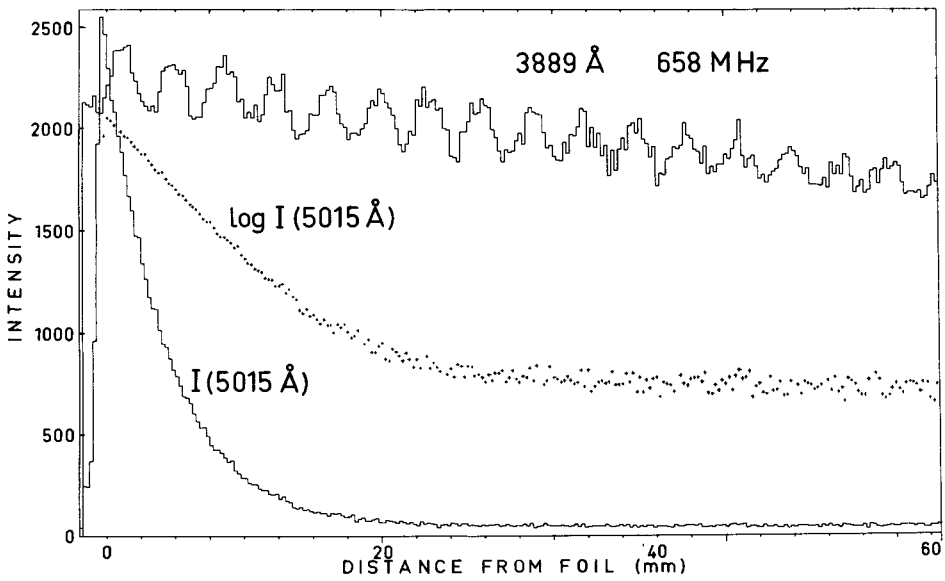

Fig. 2. Example of a decay curve, velocity-normalized by a simultaneous quantum-beat measurement.

TABLE I Lifetimes in He I

Term	Wavelength (Å)	Lifetime (ns)		
		This work	Other experiments	Theory
$3p\ ^1P$	5015	1.74 ± 0.02	1.78 ± 0.10[a]	1.73[e]
			1.8 ± 0.1[b]	1.72[f]
			1.73 ± 0.11[c]	1.72 ± 0.09[g]
			1.70 ± 0.04[d]	
$4p\ ^1P$	3964	4.02 ± 0.10	3.7 ± 0.4	3.92[e]
			4.05 ± 0.12[d]	3.95[f]
				3.9 ± 0.9[g]

[a]Ref. [7] [e]Ref. [10]
[b]Ref. [8] [f]Ref. [11]
[c]Ref. [5] [g]Ref. [6]
[d]Ref. [9]

The He I lifetimes have been the subject of several theoretical investigations, among the most accurate of which are the variational calculations of Weiss [10] and Schiff et al. [11]. Their results agree within 1 % for the ^1P levels. In recent calculations Anderson and Weinhold [6] suggest rigorous error limits for their theoretical values. For the $3p\ ^1P$ lifetime a 5 % error is estimated while the error in the case of $4p\ ^1P$ exceeds 20 %. In both cases the resonance lines are the main contributors to the errors. Unfortunately the theoretical lifetime errors for these levels are too high for an estimate of the validity of the theoretical method, agreement between this work and Ref. [6] indicates that all the significant configurations were included by Anderson and Weinhold [6].

Fine-Structure Intervals

An example of a fine-structure measurement is given in Fig. 3, which shows the decay curves for the 3889 Å (1s2s ^{3}S - 1s3p ^{3}P) and 3819 Å (1s2p ^{3}P - 1s6d ^{3}D) lines. From this measurement we obtain the $^3D_1$ - $^3D_2$ splitting for the 6d ^{3}D term. (For intensity reasons this is the most unfavourable case studied in the present work.)

Our results are summarized in Table II together with previous beam-foil [12] and level-crossing [13] data. The present value for the 4p ^{3}P term splitting is somewhat less accurate than that given by Wittmann et al. [12]. Our ^{3}D term intervals have smaller uncertainties than the early beam-foil results of Berry et al. [12], the improvement being probably due to a better velocity definition. Table II further shows that our data are in good agreement with level-crossing results of which those found by Tam [13] are particularly accurate. Indeed, for the low-lying ^{3}P and ^{3}D levels it is difficult for BFS to compete with such methods. Table II shows, however, that already for n=5 and n=6 the accuracies are comparable. It is finally well known that in the spectra of ions BFS frequently

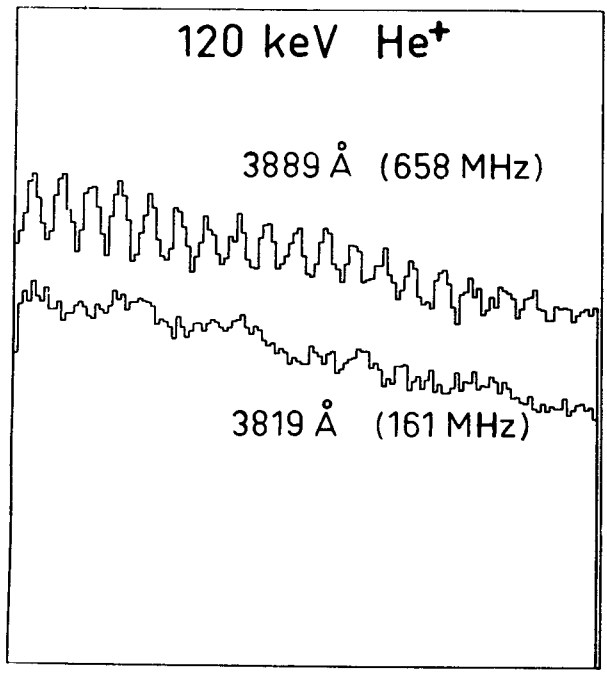

Fig. 3. Result of a measurement of the 6d ^{3}D term splitting.

TABLE II Fine Structure Intervals between J=1 and J=2 in He I

Upper term	Wavelength (Å)	Interval (MHz)	
		This work	Other experiments [a]
$4p\ ^3P$	3188	269 ± 2	269 ± 1[b] 275 ± 10[c] 269 ± 0.1[d]
$3d\ ^3D$	5875	1320 ± 30	1349 ± 25[c] 1324.7 ± 0.4[e]
$4d\ ^3D$	4471	550 ± 7	536 ± 30[c] 555.1 ± 0.3[e]
$5d\ ^3D$	4026	281 ± 4	290 ± 20[c] 282 ± 2[d]
$6d\ ^3D$	3819	161 ± 5	150 ± 20[c] 166 ± 3[d]

[a] For a complete list experimental and theoretical results cf. [12,13].

[b] Wittmann et al. [12], beam-foil.

[c] Berry et al. [12], beam-foil.

[d] Dely and Descoubes [13], level crossing.

[e] Tam [13], level crossing.

produces more accurate fine- and hyperfine structure intervals than other experimental methods.

It is worth emphasizing that our data presented in Tables I and II are of a preliminary character. Analyses are in progress which will reduce present uncertainties.

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