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Polarisation of electric field quench radiation from He^+(2S) ions

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Abstract. The polarisation fraction of 304 Å photons produced by an 0.1–1 kV cm^{-1} electric field (Stark) quenching of metastable He^+(2S) ions has been measured. A gold reflecting polariser was used to determine the degree of polarisation. An analytical equation was derived for the mirror polarimeter and computer fitted to the experimental data to obtain the relevant intensities. For the range of field considered the averaged P value obtained from the experiment was -0.258 ± 0.004, slightly higher than the -0.267 value from a calculation by Sellin *et al.*

1. Introduction

Polarisation of radiation emitted in collision experiments provides information on the atomic interactions. A definite polarisation fraction is generated when transitions from different unequally populated magnetic quantum sublevels of excited states occur. As polarisation gives rise to spatial anisotropy in the emitted radiation, when evaluating emission cross sections it is necessary to know the polarisation fraction in order to correct the detected number of photons at a definite solid angle. Moreover, by measuring polarisation fractions it is possible to obtain Lamb shifts values for hydrogenic ions (Van Wijngaarden *et al* 1974).

During the past decade several papers have been published on polarisation of quench-induced Lyman-α radiation. Ott *et al* (1970) measured the polarisation of Lyman-α emitted from H(2S) atoms quenched in a low electric field. Spiess *et al* (1972) experimentally determined the polarisation fraction of Lyman-α radiation to be in agreement with theoretical values for weak fields (Casalese and Gerjouy 1969) while Pradel *et al* (1974) reported measurements for electric fields between 30 and 500 V cm^{-1}.

The objective of the present work was to measure the field effect on the polarisation of radiation emitted from an He^+(2S) beam when passing through a 0.1–1 kV cm^{-1} quenching electric field. In the experiment, the ion velocity and the time spent in the electric field indicate an adiabatic process (Wooten and Macek 1972).

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2. Working equations

The electric field quenching effect on a beam of metastable $He^+(2S)$ ions results in the emission of 304 Å photons. This wavelength is large compared with the ion dimension, therefore the emitter can be treated as an electric dipole. Consider the emission of photons with propagation vector $\boldsymbol{k}$ along the observation direction and components ε_Z along the electric field and ε_Y along the beam path, respectively (figure 1). The photons are reflected by a metallic mirror with a reflection angle θ. The mirror can be rotated through an angle ϕ about the X axis and is characterised by a reference system $\varepsilon_\parallel$ and $\varepsilon_\perp$, parallel and perpendicular to the plane of incidence; then, the previous system is related to the rotable mirror by:

$$\begin{aligned}\varepsilon_\parallel &= \varepsilon_Y \cos\phi + \varepsilon_Z \sin\phi \\ \varepsilon_\perp &= -\varepsilon_Y \sin\phi + \varepsilon_Z \cos\phi.\end{aligned} \tag{1}$$

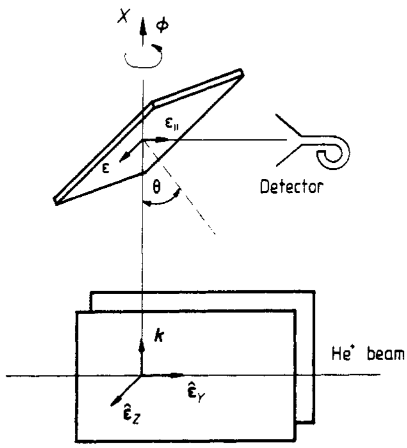

Figure 1. Mirror analyser geometry.

If $\boldsymbol{r}$ is the radius vector and A, B represent the initial and final electron states, the transition probability per unit time will be

$$W_\parallel = C|\boldsymbol{r}_{AB} \cdot \varepsilon_\parallel|^2 \qquad W_\perp = C|\boldsymbol{r}_{AB} \cdot \varepsilon_\perp|^2 \tag{2}$$

with $\boldsymbol{r}_{AB} \equiv \langle A|r|B\rangle = (X_0, Y_0, Z_0)$ and $C \propto \omega_{AB}$, the transition frequency.

Thus the reflected intensity at any angle is given by

$$I = R_\parallel W_\parallel + R_\perp W_\perp.$$

Then

$$\begin{aligned}I(\phi) \propto {} & (R_\parallel |Y_0|^2 + R_\perp |Z_0|^2)\cos^2\phi + (R_\parallel |Z_0|^2 + R_\perp |Y_0|^2)\sin^2\phi \\ & + (R_\parallel - R_\perp)(Y_0 Z_0^* + Z_0 Y_0^*)\sin\phi\cos\phi\end{aligned} \tag{3}$$

where $R_\parallel$ and $R_\perp$ are the metal parallel and perpendicular reflectivities (figure 2), at the mirror angle.

Due to the Stark effect selection rules, the interference term vanishes (see e.g. Ott *et al* 1970). In this case the $I(\phi)$ with ϕ, represented in polar coordinates, should

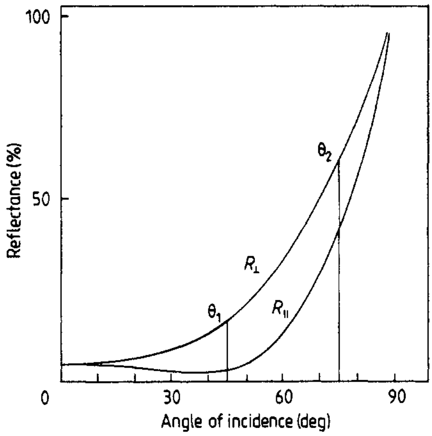

Figure 2. The calculated reflectance of the parallel and perpendicular components of radiation (304 Å) incident on the gold mirror. Measurements angles θ_1 and θ_2 are indicated. $n = 0.799$, $k = 0.317$.

show its symmetry axis as coincident with the beam direction–electric field coordinate system, otherwise it would indicate the effect was not a pure electrical one in the quenching region.

Equation (3) was used to fit the experimental data. At $\phi = 0°$ equation (3) becomes:

$$I(0°) \propto R_{\|}|Y_0|^2 + R_{\perp}|Z_0|^2 \propto N_0. \tag{4}$$

At $\phi = 90°$

$$I(90°) \propto R_{\|}|Z_0|^2 + R_{\perp}|Y_0|^2 \propto N_{90}. \tag{5}$$

N_0 and N_{90} are the counting rates with the normal to the mirror at 0 and 90° to the beam direction. If $I_{\|}$ and $I_{\perp}$ are the intensities observed at 90° to the beam axis with electric vectors parallel and perpendicular to the plane of incidence, the polarisation fraction is defined as

$$P = \frac{I_{\|} - I_{\perp}}{I_{\|} + I_{\perp}} = \frac{|Y_0|^2 - |Z_0|^2}{|Y_0|^2 + |Z_0|^2}.$$

Then, from the measurements, P can be calculated as

$$P = \left(\frac{N_0 - N_{90}}{N_0 + N_{90}}\right)\left(\frac{R_{\perp} + R_{\|}}{R_{\perp} - R_{\|}}\right). \tag{6}$$

3. Apparatus

The experimental apparatus is shown diagrammatically in figure 3. Helium ions were produced in an RF source, accelerated to an energy in the range 100–180 keV and mass analysed to sort out the He^+ beam. The ions passed through a 10.3 cm long, differentially pumped gas target cell which had entrance and exit channels of 1.2 and 2.3 mm in diameter respectively. Dry air at approximately 3×10^{-3} Torr was admitted into the cell through a needle valve. The chamber pressure was monitored

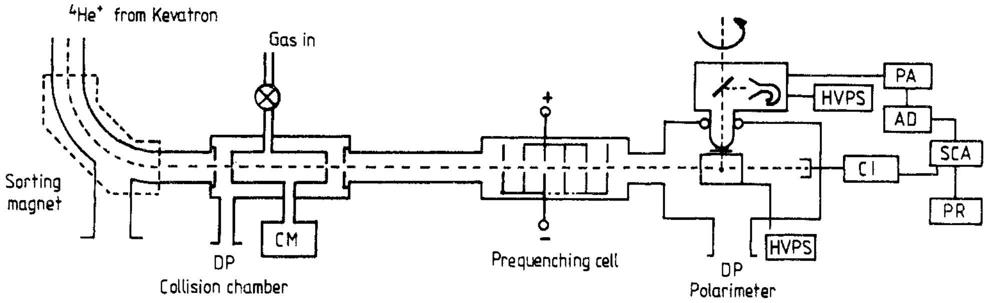

Figure 3. Schematic diagram of the apparatus. DP, liquid-nitrogen-trapped diffusion pumps; CM, capacitance manometer; HVPS, high-voltage power supplies; PA, preamplifier; AD, amplifier–discriminator; SCA, scaler; CI, current integrator; PR, printer.

with a MKS Baratron capacitance manometer. After traversing the cell, the beam passed through a DC prequenching region consisting of a set of 15 alternatively polarised copper rings. The quench field was generated by a pair of polished aluminium plates (5 cm by 9 cm) separated by 1 cm, mounted on polycarbonate isolators and located parallel to the beam path. The condenser assembly was covered with gold black to reduce photon reflections.

The 304 Å photons emitted in the 2p–1s de-excitation were viewed at 90° to the beam path and inbetween the plates by the polarimeter assembly. By plotting the electric field of the actual condenser using the electrolytic tray method a zone of homogeneous electric field was chosen as the observation region. This was located at a distance equal to three times the plate separation from the beam entrance edge. Two 2 mm apertures collimated the photon flux and a 1000 Å thick aluminium foil filtered the radiation.

A metallic surface was used as polarimeter. A 150 Å thick gold film evaporated on a good quality microscope slide was mounted on a rotatable assembly and incident angles of 45 and 75° were used. Reflected photons were detected at the mirror angle by a collimated Bendix model 4028 funnelled channeltron operating in the counting mode. Its entrance funnel was negatively biased so as to reject stray electrons.

The system was tested for asymmetries by two methods; (*a*) by checking the alignment of collimators and mirror with a He–Ne laser beam and (*b*) by leaking dry air into the quenching chamber and grounding both condenser plates. Collisions of the helium beam with air gave rise to unpolarised multi-wavelength radiation recorded by the detector assembly. If there is no misalignment, a constant counting rate—within the counting statistics—as a function of rotation angle should be obtained.

Downstream from the condenser was a biased Faraday cup which monitored the total ion flux. The magnetic field measured in the interaction zone was about 0.3 G.

4. Data system

A straightforward configuation was used. Pulses from the channeltron multiplier were fed to a preamplifier, amplifier–discriminator and finally counted in a printing scaler. A current integrator connected to the Faraday cup triggered the scaler gate signal. In this way the scaler active time was determined by a preset amount of collected charge avoiding beam fluctuation effects.

The quenching plates were checked for parallelism and separation. Within an error of $\pm 8\times10^{-4}$ cm, the plates were found to be parallel with a 1.082 cm gap. The field was produced by a pair of high-voltage Fluke power supplies. The error in the applied voltage was 0.1%. The energy of the He^{+} ions was calibrated with an electrostatic analyser to within a ± 0.5 keV uncertainty.

The beam current integrator accuracy was better than 2% while the angular position readings had a $\pm 0.5°$ error.

5. Experimental method

By rotating the polarimeter about the X axis and recording the channeltron signal each 15°, an almost elliptical pattern is generated (figure 4). The distance from the origin to each point represents the normalised counting rate while the angle ϕ corresponds to the polarimeter angle measured from the beam direction. This pattern shows a mixture of the reflected $I_{\perp}$ and $I_{\parallel}$ components.

The prequenching 'on', quenching 'on' condition was used to register the background counting rate. The effect of prequenching voltage as a function of counting rate is shown in figure 5. An applied voltage of 3 kV reduces the signal to less than 1% at 190 keV ion energy. This was the prequench voltage used throughout the experiment. Measurements were made at two ion energies: 100 and 180 keV. The quenching condenser high voltage was varied from 100 to 1000 V.

The gold mirror reflectivities (figure 2) were computed from the optical constant values (Hagemann *et al* 1974, 1975) for 304 Å radiation using the generalised Fresnel equations for reflectance (Samson 1967).

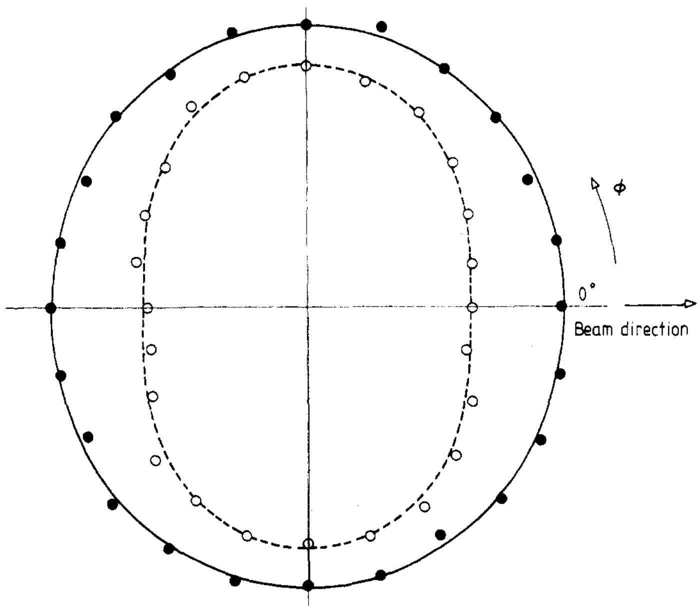

Figure 4. Typical polar representation of data: counting rate (arbitrary units) plotted against polarimeter angle ϕ. ●, 75° and ○, 45° incidence angles. Corresponding computer-fitted functions: ——, 75°; – – –, 45°.

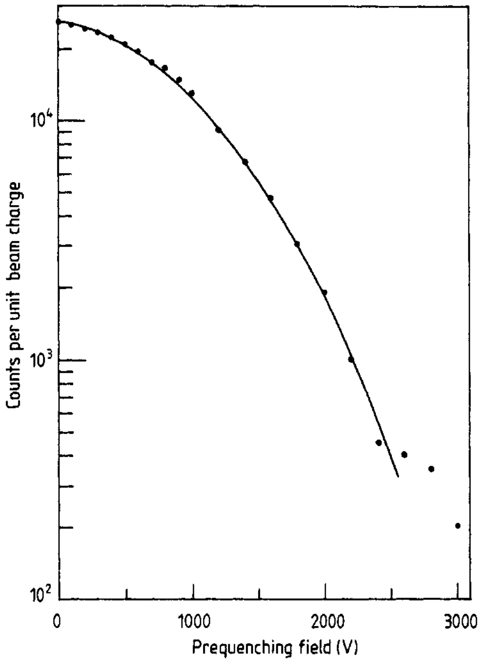

Figure 5. Effect of the prequenching field on the counting rate. A 190 keV partially excited (2S) beam was used.

6. Results and conclusions

The values of polarisation fractions against applied voltage are listed in table 1. To compute each value, a linear least square analysis was used to fit equation (3) to the experimental data. Thus, the fitted coefficients N_{0f} and N_{90f} are found. The polarisation fraction is now given by:

$$P=\left(\frac{N_{0f}-N_{90f}}{N_{0f}+N_{90f}}\right)\left(\frac{R_\perp+R_\parallel}{R_\perp-R_\parallel}\right) \tag{7}$$

with better statistics than in equation (6).

Measurements have been performed at two different incidence angles. Typical signal-to-background (including detector noise) counting rates were 15:1 at 75° and 8:1 at 45°. The 100 V (45°) value showed a 4:1 ratio. Figure 2 shows that at 75° (θ_2) the reflectivities are high, resulting in higher photon counting rates, better signal-to-noise figures and consequently improved counting statistics. On the other hand the 45° (θ_1) measurement offers lower sensitivity to incidence angle variations at the expense of lower counting rates (reflectivities). Uncertainties in the values of the optical constants n and k are somewhat difficult to assess, however we believe they are less than 1% for the values of Hagemann *et al.*

The alignment test (§ 3(*b*)) gives a constant counting rate, to within 2%, when the mirror is rotated from 10 to 345°. In the region between those values a 3% 'dip' is registered using the 75° mirror angle. For the 45° incidence position no asymmetry is detectable. The same behaviour is observed when the background signal is measured. Therefore the data points measured with the 75° incidence angle are corrected

Table 1. Values of the polarisation fraction as a function of the quench high voltage for different values of the mirror incidence angle and ion energy.

Quench high voltage (V)	Polarisation fraction			
	75°, 100 keV	75°, 180 keV	45°, 100 keV	45°, 180 keV
100	−0.287 (64)	−0.257 (62)	−0.207 (12)	−0.246 (13)
300	−0.278 (61)	−0.255 (64)	−0.249 (12)	−0.273 (11)
400	−0.259 (59)	−0.228 (66)	−0.250 (16)	−0.269 (21)
500	−0.284 (63)	−0.262 (60)	−0.258 (12)	−0.256 (14)
600	−0.285 (65)	−0.253 (62)	−0.274 (15)	−0.265 (13)
620	−0.253 (60)	−0.261 (64)	−0.257 (14)	−0.258 (12)
800	−0.255 (62)	−0.292 (65)	−0.263 (19)	−0.271 (14)
1000	−0.220 (65)	−0.274 (63)	−0.288 (13)	−0.237 (15)

accordingly before the fitting process. The fitting program was required to compute a band at both sides of the fitted function containing 85% of the data points. The resulting total bandwidth is then considered as the N_{0f} and N_{90f} error, typically about ±2%. The final step was to calculate the polarisation P according to equation (7). The total error was less than 23% at 75° and 8% at 45° (table 1). The larger error obtained with the 75° incidence angle is due to the statistical treatment of the $N_{0f}-N_{90f}$ numerator in equation (7), the difference of two large similar numbers. Two possible sources of systematic error are suspected but are difficult to investigate: (*a*) the detection of multiply scattered radiation from the collimator edges and polarimeter walls; (*b*) gold surface effects as observed by Platzöder and Steinmann (1968) that could vary the reflectance values. Our data do not account for these effects. Within the quoted errors, neither an ion velocity nor a field strength dependence were found for the respective measured ranges. The results show good agreement with the theoretical predictions in the respect of being independent of field strength in the present range, however when averaging all the values from table 1 a polarisation fraction of -0.258 ± 0.004 is obtained while Sellin *et al* (1970) calculated the polarisation to be −0.267, which is only just outside the uncertainty of the measurements (see figure 6). Assuming that the above systematic errors are negligible, the present

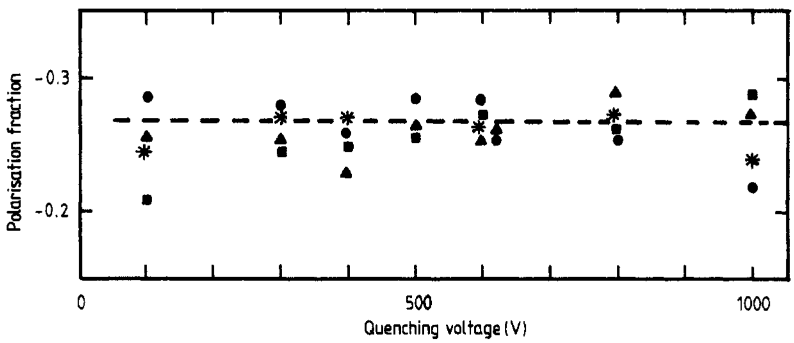

Figure 6. Quenching field variation of the polarisation fraction. ●, 75° mirror incidence angle and 100 keV ion energy; ▲, 75° and 180 keV; ■, 45° and 100 keV; ★, 45° and 180 keV; – – –, theoretical value of Sellin *et al.*

measurements seem to confirm the theoretically expected value of the polarisation fraction.

This result affects the measurements of total emission cross sections using the quenching technique on $He^+(2S)$ ions at 90° to the beam. A correction of approximately +9% should be applied for 100–1000 V cm^{-1} quenching fields.

We have also shown that a combination of a gold mirror polarimeter and computer-fitted data to the radiation distribution equation result in an adequate tool for ultraviolet and extreme ultraviolet polarisation measurements.

Acknowledgments

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