PHYSICAL REVIEW VOLUME 136, NUMBER 3A 2 NOVEMBER 1964

Optical Pumping in He^3†

R. C. GREENHOW*
Clarendon Laboratory, Oxford, England

(Received 8 June 1964)

Nuclear polarization of He^3 has been performed using optical pumping techniques. The polarization is produced in the triplet metastable levels and transferred to the ground-state atoms by metastability exchange processes. The cross section for this process has been measured by two different methods, giving the results $\sigma=(6.1\pm1)\times10^{-16}$ cm² and $\sigma=(7.9\pm2)\times10^{-16}$ cm². One of the methods involved a spectroscopic determination of the density of metastable atoms in a weak discharge in He^3, which was found to vary between 12.5 and 3.5×10^{10}/cc. It was shown that one hyperfine component only $(F=\frac{1}{2}\rightarrow\frac{3}{2})$ of the $2\,{}^3S_1-2\,{}^3P_0$ line of He^3 is excited by light from a He^4 lamp. For this reason a previously quoted relation between the degree of polarization and the optical pumping signal needs to be modified.

A RECENT paper by Colegrove, Walters, and Schearer[1] describes a He^3 optical pumping experiment in which polarization produced in the $2\,{}^3S_1$ metastable levels of He^3 by optical pumping is transferred to the ${}^1S_0$ ground level by a process of metastability exchange. We have performed similar experiments but in view of the completeness of the work of Colegrove *et al.*, only additional points of interest will be reported here.

The cross section for metastability exchange between ground-state and metastable atoms was determined from observations of the transverse relaxation of ground-state atoms, together with a determination of the density of metastable atoms. The result of applying a strong rotating field H_1, with frequency equal to the ground-state Larmor frequency γH_0, is to cause nutation of the macroscopic ground-state magnetization, with the frequency γH_1. For all normal field strengths H_1, the period $1/\gamma H_1$ is much greater than the time taken for the metastable atoms to exchange metastability with the ground-state atoms. This means that the nutation can be detected optically by monitoring the absorption in the metastable levels. The nutational transient so observed decays with time constant θ where

$$2/\theta=1/T_r+1/T_2.$$

T_r is the relaxation time of the longitudinal magnetization of atoms in the ground state in the absence of the rotating field, and T_2 is the transverse relaxation time under the conditions of the experiment. T_r can be measured independently (see Ref. 1), and is found to be long (>100 sec) compared with $T_2(\sim0.1$ sec). The transverse relaxation is almost entirely due to metastability exchange processes, if metastable atoms are present. We therefore obtain as a good approximation the relation

$$2/\theta\approx1/T_2=\sigma vn\,,$$

where σ is the cross section for metastability exchange, v is the mean relative velocity of the He atoms at the temperature of the cell, and n is the density of metastable atoms. T_2 was determined for a number of values of n, from photographs of the pumping transient obtained for different discharge conditions.

The quantity n was measured using a scanning Fabry-Perot interferometer[2] to determine the absorption

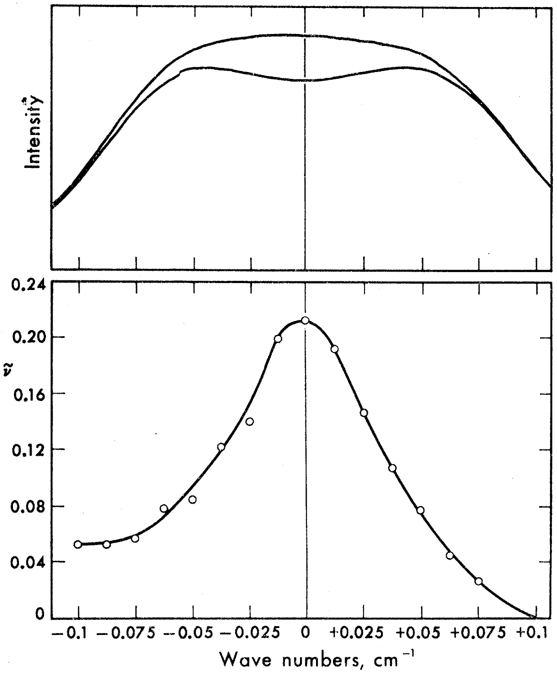

FIG. 1. Spectral profile of the $2\,{}^3S_1-2\,{}^3P_{1,2}$ fine-structure components from He^4 lamp, as seen through He^3 absorption cell. In the upper half of the figure the upper trace shows the profile with the discharge off in the absorption cell, for the lower trace the discharge was on. The lower half of the figure shows the absorption coefficient calculated from the above traces. The instrumental width was estimated to be 0.03 cm⁻¹. When "folded" with a Doppler width of 0.065 cm⁻¹ as expected for He^3 at 290°K, we obtain a width of 0.085 cm⁻¹ which is very close to that actually observed (0.08 cm⁻¹). The absorption peak is due to the $F=\frac{1}{2}\rightarrow\frac{3}{2}$ hyperfine component of the $2\,{}^3S_1-2\,{}^3P_0$ line of He^3. The tail on the left is the beginning of the peak due to the $F=\frac{1}{2}\rightarrow\frac{1}{2}$ hyperfine component.

---

† This work was supported by the Rutherford Institute (Harwell, England).

* Present address: Physics Department, University of California, Berkeley, California.

[1] F. D. Colegrove, L. D. Schearer, and G. K. Walters, Phys. Rev. **132**, 2561 (1963).

[2] H. G. Kuhn and H. J. Lucas-Tooth, J. Sci. Instr. **35**, 413 (1953).

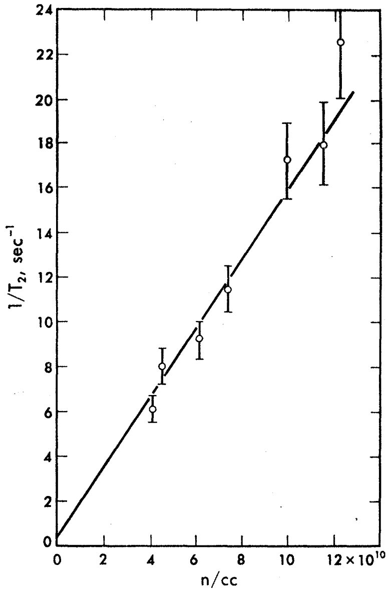

FIG. 2. Plot of $1/T_2$ as a function of metastable density "n."

profile of the metastable He^3 atoms, under the discharge conditions used in the experiment. The density is related to the absorption coefficient k_ν by the relation

$$\int_0^\infty k_\nu d\nu = \frac{\pi e^2}{mc^2} nf,$$

where f is the oscillator strength of the transition.

Ideally a white light source would be used for absorption experiments, but intensity considerations led us to try a He^3 lamp, in the hope that the emission lines from the hot lamp would be sufficiently Doppler broadened to allow a good absorption profile to be obtained. In practice, accurate values of the absorption coefficient could be obtained in the center of the line only by this method, the lamp having insufficient intensity in the wings of the lines, where absorption was weak, to allow accurate measurements. The difficulty was overcome by using a He^4 lamp as the source, as in the optical pumping experiments. The unresolved He^4 component $D_3(2\,^3S_1-2\,^3P_{1,2})$ was sufficiently broad to overlap completely the $F=\frac{1}{2}\rightarrow\frac{3}{2}$ hyperfine component of the $He^3(2\,^3S_1-2\,^3P_0)$ line. A sample trace of the absorption profile is given in Fig. 1 together with the calculated absorption coefficient. The width of this profile is in agreement with that predicted from considerations of Doppler and instrumental widths.

The value of f was taken to be 0.58,[3] and the metastable density was found to vary between 12.5 and 3.5×10^{10}/cc, according to discharge intensity, in a cell filled to 1-mm Hg pressure. The absolute accuracy of these figures is probably not better than 25%, owing mainly to the ill-defined absorption length in a spherical cell, and the fact that the discharge was somewhat inhomogeneous. A cylindrical cell was tried, but the discharge became even more inhomogeneous, so that little advantage was gained. Relative measurements of the density for different discharge conditions were evidently better than this, as a plot of $1/T_2$ against metastable density shows reasonable linearity (Fig. 2). As a result of these measurements we found $\sigma=(7.9\pm2)\times10^{-16}$ cm².

A second determination of σ was made using the method described in Ref. 1, which relies on a measurement of the linewidth of the metastable-atom resonances. If the characteristic time between exchange collisions of metastable atoms with ground-state atoms is τ_2 then

$$1/\tau_2=\sigma vN,$$

where N is the density of ground-state atoms. This method is subject to an uncertainty in N, which is determined by the pressure in the cell. This is a rather doubtful quantity for a sealed-off absorption cell. By this method we obtained the following result:

$$\sigma=(6.1\pm1)10^{-6}\text{ cm}^2.$$

This may be compared with the result of Colegrove *et al.*:

$$\sigma=(4.2\pm0.5)10^{-16}\text{ cm}^2.$$

The experiments on the absorption of He^4 light by He^3 atoms were useful in that they verified part of the work of Fred *et al.*[4] on the isotope shift and hyperfine struc-

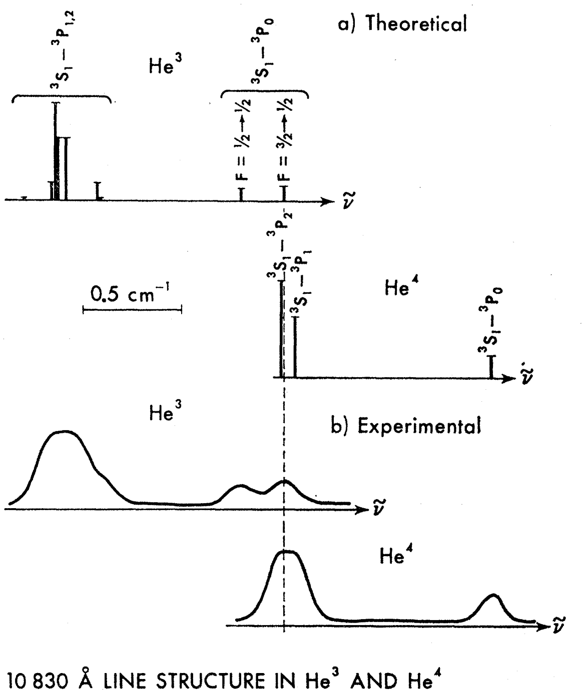

FIG. 3. The theoretical predictions of Fred *et al.* for the $2\,^3S_1-2\,^3P_{0,1,2}$ 10 830 Å transitions of He^3 and He^4, compared with our lamp profiles. In each case the relative positions of He^3 and He^4 are drawn correctly.

---

[3] C. W. Allen, *Astrophysical Quantities* (Athlone Press, 1963).

[4] M. Fred, F. S. Tomkins, J. K. Brody, and M. Hammermesh, Phys. Rev. 82, 406 (1951).

ture of He^3. They also brought to light a slight discrepancy, concerning Fig. 1 of their paper, which is also reproduced in Ref. 1. The figure is incorrectly drawn, so that the He^3 and He^4 profiles overlap more than they should. The reason is that different scales are used in the two parts of the figure. Figure 3 shows the theoretical predictions of Fred *et al.*, correctly drawn, and below are shown the profiles of our He^3 and He^4 lamps also in their correct relative positions. The importance of this is in relating the optical pumping signal observed in the experiments to the polarization of the sample. Colgrove *et al.* assumed that both hyperfine components of the He^3 $2\,^3S_1-2\,^3P_0$ line were equally absorbent to He^4 light, and obtained the relation:

$$\frac{\Delta I}{I}=\frac{P(11-2P-P^2)}{(6+2P^2)}\simeq\frac{11P}{6},\quad \text{if } P \text{ is small.}$$

In view of the above, this should be amended to

$$\frac{\Delta I}{I}=\frac{P(15-10P+3P^2)}{(6+2P^2)}\simeq\frac{5P}{2},\quad \text{if } P \text{ is small.}$$

ACKNOWLEDGMENTS

I would like to express my appreciation of the advice and encouragement given to me throughout this work by Dr. G. W. Series. I also wish to thank Dr. H. G. Kuhn for permission to use the scanning Fabry-Perot interferometer. I am particularly indebted to Dr. M. J. Vaughan, without whose cooperation the density measurements could not have been made. I wish also to acknowledge the collaboration of Dr. K. R. Lea in the construction of the apparatus, and R. B. Partridge who made a number of the measurements.

PHYSICAL REVIEW VOLUME 136, NUMBER 3A 2 NOVEMBER 1964

K-Ionization Cross Sections for Relativistic Electrons

J. W. Motz and R. C. Placious
National Bureau of Standards, Washington, D. C.

(Received 8 June 1964)

Experimental values of the *K*-shell ionization cross section are determined from scintillation spectrometer measurements of the *K* x rays emitted when thin targets of tin and gold are bombarded by 50-, 100-, 200-, and 500-keV electrons. For these energies and atomic numbers, the experimental results show differences from the cross sections given by Burhop's nonrelativisitic calculations and by Perlman's relativistic calculations, but show good agreement with the predictions of Arthurs and Moiseiwitsch, who employed relativistic free-particle wave functions for the projectile electron and nonrelativistic wave functions for the atomic electron.

1. INTRODUCTION

THEOERTICAL studies of atomic *K*-shell ionization by electrons may be divided into two main groups. First are the nonrelativistic calculations by Bethe,[1] Massey and Mohr,[2] Soden,[3] Massey and Burhop,[4] Wetzel,[5] and Burhop,[6] and second are the relativistic calculations by Arthurs and Moiseiwitsch[7] and Perlman.[8] In most cases, these calculations are not in a simple analytical form and must be evaluated numerically. Burhop[6] has evaluated the *K*-ionization cross sections for the higher atomic numbers, 28 (nickel), 47 (silver), and 80 (mercury), and among the nonrelativistic calculations listed above, his results are most pertinent to the present investigation. Arthurs and Moiseiwitsch have calculated values for a parameter S from which the *K*-ionization cross section σ can be obtained for electron kinetic energies T_1 extending

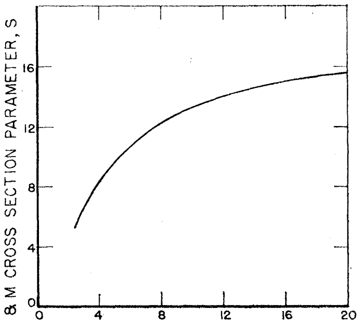

FIG. 1. Dependence of the parameter S on the ratio of the initial electron kinetic energy T_1 to the *K*-shell binding energy I_K. The parameter S is obtained from the calculations of Arthurs and Moiseiwitsch (Ref. 7) and is related to the *K*-ionization cross section by Eq. (1).

---

[1] H. Bethe, Ann. Phys. **5**, 325 (1930).

[2] H. S. W. Massey and C. B. O. Mohr, Proc. Roy. Soc. (London) **A140**, 613 (1933).

[3] D. Graf Soden, Ann. Physik **19**, 409 (1934).

[4] H. S. W. Massey and E. H. S. Burhop, Phys. Rev. **48**, 468 (1935).

[5] W. Wetzel, Phys. Rev. **44**, 25 (1933).

[6] E. H. S. Burhop, Proc. Cambridge Phil. Soc. **36**, 43 (1940).

[7] A. M. Arthurs and B. L. Moiseiwitsch, Proc. Roy. Soc. (London) **A247**, 550 (1958).

[8] H. S. Perlman, Proc. Phys. Soc. (London) **76**, 623 (1960).