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Fine structure of the $3\,^3P$ state of ^{4}He

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Several recent measurements of the fine-structure intervals in the $3\,^3P$ state of ^{4}He are compared, and the best values are recommended: the $3\,^3P_0$-$3\,^3P_2$ interval is 8772.552(40) MHz (as given by Kramer and Pipkin), and the $3\,^3P_1$-$3\,^3P_2$ interval is 658.67(9) MHz (which is a weighted average of results by Kramer and Pipkin, by Tam, and by Wieder and Lamb). Also examined are the presently available experimental data on lifetime and depolarization cross section of the $3\,^3P$ state, and the current theoretical understanding of the fine structure of this state.

The spectroscopy of the lowest several triplet P states of the helium atom have been studied by numerous authors, with improved accuracies in recent years.[1-11] The ^3P states are of fundamental importance because they represent simple two-electron atomic states (with nearly pure spin = 1 wave functions) that are amenable to detailed theoretical computations[12-15]; indeed the highly accurate experimental measurements in the $2\,^3P$ state[8] have stimulated very sophisticated theoretical calculations[14,15] for the two-electron atom. The $3\,^3P$ state has another significance in spectroscopy: recent beam-foil spectroscopy measurements[16,17] have revealed that time scale calibrations can be done most conveniently by using the $3\,^3P_1-3\,^3P_2$ interval as a reference standard, and this procedure results in great improvements in accuracies of the beam-foil measurements.[16] In this note, I would like to comment on the present experimental and theoretical status of our knowledge of the $3\,^3P$ state of ^{4}He, and recommend the current best experimental values for the fine-structure intervals.

Conventional optical spectroscopy of He (even done in cryogenic temperatures[11]) was limited in accuracy by the large Doppler width of the light atom. Wieder and Lamb[10] made the first accurate Doppler-free spectroscopy of the $3\,^3P$ state by a microwave-optical technique (see Fig. 1). Afterwards, various other Doppler-free techniques have been applied to measure the $3\,^3P_0-3\,^3P_2$ ($\equiv 3\nu_{02}$) or the $3\,^3P_1-3\,^3P_2$ ($\equiv 3\nu_{12}$) intervals. These measurements include electron-bombardment level-crossing spectroscopy,[18] ion-bombardment level-crossing spectroscopy,[9] and beam-foil quantum-beat spectroscopy.[5,6] Recently, more precise remeasurements of these intervals have been reported: Tam[2] used a stepwise-excitation level-crossing technique which he developed earlier[19] to measure the $3\nu_{12}$ interval, Lhuillier *et al.*[3] employed a neutral-beam impact level-crossing mehtod to determine the $3\nu_{02}$ interval, and Kramer and Pipkin[1] used a technique similar to Tam's[2] to measure the $3\nu_{02}$ and $3\nu_{12}$ interval. Figure 1 shows the results of these studies.

The large interval, $3\nu_{02}$, has been measured very consistently, as seen from Fig. 1. We can confidently take Kramer and Pipkin's[1] value as the current recommended value:

$$3\nu_{02} = 8772.55 \pm 0.04 \text{ MHz}. \tag{1}$$

As for the small interval $3\nu_{12}$ (which is the important reference number for beam-foil spectroscopy calibrations),[16,17] the three values reported by Wieder and Lamb,[10] Tam,[2] and Kramer and Pipkin[1] are competitive in accuracies. Note that the Kramer and Pipkin accuracy for the large interval $3\nu_{02}$ is much better than that for the small interval $3\nu_{12}$, because they only measured the two high-field level crossings near 2.3 and 3.7 kG, whose positions are not sensitive to the small interval. On the other hand, Tam[2] measured the two medium-field level crossings near 160 G, whose positions are very sensitive to the small interval. It seems reasonable to apply the usual statistical formulas for weighted mean and weighted standard errors to obtain the best value for $3\nu_{12}$. Thus the current recommended value is

$$3\nu_{12} = 658.67 \pm 0.09 \text{ MHz}, \tag{2}$$

as indicated in Fig. 1.

The current status of theoretical understanding of the $3\,^3P$ intervals is interesting. The best theoretical calculation performed so far for these intervals seems to be that of Schiff *et al.*[12,13] who employed extensive Hylleraas functions to compute the energy levels and also applied correction terms due to singlet-triplet mixing to obtain the fine-structure intervals. Their results for the $3\,^3P$ state are shown in Fig. 1. Their accuracies are estimated[12] to be better than ± 0.3 MHz. The striking fact is that their $3\nu_{02}$ result is in excellent agreement with Eq. (1), but their $3\nu_{12}$ result is in comparatively worse agreement with Eq. (2). This is possibly due to an incorrect calculated shift of

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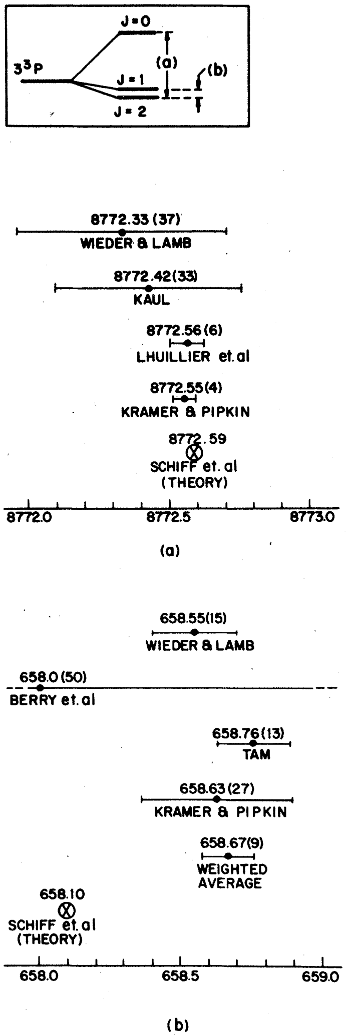

FIG. 1. Comparison of values for the $3\,^3P$ fine-structure intervals (in MHz) reported by various authors. (a) gives the overall interval ($3\,^3P_0$–$3\,^3P_2$), which is independent of singlet-triplet mixing, while (b) gives the small interval ($3\,^3P_1$–$3\,^3P_2$), which is sensitive to singlet-triplet mixing. References for the cited authors are Wieder and Lamb, 1957 (Ref. 10), Kaul, 1967 (Ref. 9), Lhuillier *et al.*, 1976 (Ref. 3), Kramer and Pipkin, 1978 (Ref. 1), Schiff *et al.*, 1965 and 1973 (Refs. 12 and 13), Berry *et al.*, 1972 (Ref. 5), and Tam, 1976 (Ref. 2). Note that Kaul actually reported the $^3P_0$–$^3P_1$ interval, and the value for Kaul indicated in this figure is the sum of his reported value and 658.67 MHz.

TABLE I. Data for the collisional depolarization cross section σ (measured for various Zeeman crossings by different authors, as described in the text) and radiative lifetime τ of the $3\,^3P$ state of ^{4}He.

Authors	σ (10^{-14} cm^2)	τ (nsec)
Experiment		
Kramer and Pipkin[a]	6.3(7)	97.6(45)
Tam[b]	2.5(3)	90(15)
Buchhaupt[c]	2.0(5)	98(4)
Schöck[d]	1.8(4)	89(10)
Bukow *et al.*[e]	···	89(5)
Theory		
Wiese *et al.*[f]	···	94.7(9)

[a] Reference 1.
[b] Reference 2.
[c] Reference 20.
[d] Reference 21.
[e] Reference 22.
[f] Reference 23.

the $3\,^3P_1$ level due to single-triplet mixing. For example, Schiff *et al.*[13] only considered the mixing with the $3\,^1P_1$ level, but not with other $n\,^1P_1$ levels, which may contribute[14] very significantly (by ~30%) to the net shift of the $3\,^3P_1$ level. Note that the $3\nu_{02}$ is not affected by the singlet-triplet mixing.[2] Thus the fact that the answer of Schiff *et al.*[12] is highly accurate for $3\nu_{02}$ but not for $3\nu_{12}$ implies that the current theoretical inadequacy is possibly in the amount of singlet-triplet mixing.

The experimental measurements by level-crossing spectroscopy also produce the collisional depolarization cross section by measuring the pressure broadening of the level-crossing signal and natural lifetime by extrapolating the linewidth to zero pressure. Thus Kramer and Pipkin[1] obtained the collisional cross section σ for coherence destruction of the high-field crossing at 2277 G, and they also obtained the radiative lifetime τ, as tabulated in Table I. Their values are compared with other values in Table I. While the various values for τ agree, the value of σ reported by Kramer and Pipkin is much larger than the values of σ reported by other authors. I must point out that a possible cause of differences is that Kramer and Pipkin measured the high-field crossing at 2277.119 G, Tam[2] measured the medium-field crossings at 161.78 G and 166.32 G, and Buchhaupt[20] and Schöck[21] both measured the zero-field crossings. However, this does not seem to be a very likely explanation, since depolarization cross sections for various level crossings of a given fine-structure multiplet are typically nearly equal,[19] and they do not disagree by a factor of 2 or more. Thus, the discrepancy in the reported values for σ remains to be explained.

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