particular, one still does not know how the three- and four-point vertices in the quantum-hydrodynamic approach depend on the illusive condensate fraction n_0, if at all.[13]

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PHYSICAL REVIEW A VOLUME 6, NUMBER 1 JULY 1972

Classifications in the Spectra of Autoionization Electrons from Lithiumlike Oxygen and Fluorine

H. G. Berry
Laboratoire de Physique de l'Atmosphère (Associé au Centre National de la Recherche Scientifique), Université Lyon 1, 69, Villeurbanne, France
(Received 29 November 1971)

We suggest some classifications for the spectra observed by Sellin *et al.* [Phys. Rev. Letters 27, 1108 (1971)] of autoionization electrons from highly ionized oxygen and fluorine atoms, and comment on some of their suggestions. They appear to have observed the lowest nonautoionizing doubly excited doublet term in the Li I sequence, $1s2p^2\ ^2P$. High-angular-momentum states may be responsible for their observed resonances of higher energy.

INTRODUCTION

In a beam-foil study at high energies (2.5–30 MeV), Sellin *et al.*[1] have investigated the energy spectrum of electrons ejected from highly ionized oxygen and fluorine after excitation by the foil. They suggest that some, but not all of these electrons arise from doubly excited quartet levels isoelectronic to Li I which are metastable against Coulomb autoionization. The autoionization probability then comes from spin-orbit and spin-spin interactions and is competitive with radiative decays to lower quartet levels. The lowest quartet level decays solely by autoionization, and has a much slower lifetime.[2]

It is well known that the beam-foil collision provides strong excitation of multiply excited levels.[3] In Li I, systems of doubly excited doublet and quartet levels lie more than 50 eV above the first ionization potential of 5 eV, and they are, consequently, difficult to excite in a hollow cathode discharge.[4] Some of these quartet levels have been observed through their radiative decay after beam-foil excitation, mainly in lithium, but also in higher members of the isoelectronic sequence, Be II, B III, and C IV.[5] Transitions in higher members of the isoelectronic sequence have observed in plasma discharges[6] and in the solar corona,[7] where the levels have excitation energies in excess of 500 eV.

EXPERIMENTAL RESULTS

Although the experimental evidence is not conclusive, the quartet energy levels Li I appear to be in good accord with the calculations of Holøien and Geltman[8] and Weiss[9] for the lowest $^4S^e$, $^4p^e$, and ^4D levels. The energies of the $^4P^0$ terms are less certain, and recent observations in Li I[10] suggest that better agreement is obtained with the calculations of Weiss,[9] indicating less mixing of the $2pns\ ^4P^0$, and the $2snp\ ^4P^0$ terms ($n = 2$–5) than proposed by Holøien and Geltman.[8] The quantum defects for the $^4S^e$, $^4P^0$, and $^4P^e$ terms are generally large and range between 0.2 and 1.0.

TABLE I. Electron energies (in eV) assuming zero quantum defects.

Terms	$2s3l$	$2s4l$	$2s5l$	$2p3l$	$2p4l$	$2p5l$
O VI calc.	506.3	530.1	541.1	513.9	537.7	548.7
observed	507	531	540	512	540	550
F VII calc.	649.9	682.1	697.0	658.4	690.7	705.6
observed	650	681	697	656	690	705

Observations of the $2snd\,^4D$ and $2pnd\,^4D$ terms ($n=3$–5) in Li I[10] from radiative decays show them to have quantum defects of less than 0.1, and in general, much closer to 0.0.

INTERPRETATIONS

The quartet energy levels to O VI and F VII have been extrapolated assuming the quantum defects remain zero (to within the precision of the experiment,[1] this is a good assumption). Then, good agreement is found between these energies and the electron energies observed by Sellin *et al.*[1] as shown in Table I. The maxima observed in Ref. 1 are evidently mixtures of many levels, but the transitions from the ^4D terms are the strongest in the Li I spectra and may be the most important also in these electron spectra. It is clear that terms of small quantum defect are responsible for the autoionization spectra, whereas the ^4S and ^4P terms have large quantum defects. A reasonable conclusion appears to be that terms of high angular momentum are responsible for the observed resonances: that is, ^4D and ^4F states for $n=3$, and for $n=4$ and higher the ^4F and ^4G states, all of which can be expected to have very small quantum defects. The relative magnitudes of autoionization and decay radiative decay rates are unknown, and other terms such as $2pnp$, ^4S, ^4D ($n>2$) may also be important in these electron spectra, but have not been observed from radiative decays, nor have their energies been calculated.

The peak labeled *A* in Fig. 1 of Ref. 1 can be assigned to the lowest nonautoionizing doubly excited doublet term in the Li I sequence, $1s2p^2\,^2P$. This term is able to decay radiatively as observed in plasma discharges[6] and the solar corona[7] and hence is not strong in the electron spectrum. There are no other nonautoionizing terms near this energy in the Li I isoelectronic sequence. The $1s2p^2\,^2S$, ^2D levels are expected to autoionize too rapidly to be observed in Ref. 1. They may possibly contribute to the peak labeled *B* in Ref. 1, whose origin was suggested to arise from metastable berylliumlike ions.

The observation of the $1s2p^2\,^4P$ term in the autoionization spectrum explains the minimum value in the "effective oscillator strength" for the $1s2s\,^4P$-$1s2p^2\,^4P$ transition, observed between Be II and B III.[5] As suggested in Ref. 5 for the higher members of the sequence, the observed lifetime is being shortened by the opening of the autoionization channel, whereas the calculations of Cowan[5] take only the radiative decay into account. It would be of interest to confirm this trend in O VI and F VII. Furthermore, since the autoionization probability is strongly dependent on the total angular momentum J (the radiative lifetime is independent of J), the higher sequence members should present complex decay curves. However, up to C IV, the decays were essentially single exponential.

The lifetime noted in Ref. 1 of 1.00 ± 0.04 nsec may belong to the $2p3p\,^4P$ or the $2p3s\,^4P$ terms. The other terms suspected of producing blending, $2s4s\,^4S$ and $2p3d\,^4D$, have similar (10.4 and 2.3 nsec, respectively) already in Li I (5.10) and should be orders of magnitude faster in O VI and F VII. (N. b. it is not noted in Ref. 1 whether the measured lifetime is in O VI or F VII). The lifetime of the first terms are not known because of uncertainties in the energies of the $^4P^0$ terms, but Weiss[9] has calculated their radiative transition probabilities in Li I to be very low. This lifetime value may thus be in accord with the calculations of Weiss.

CONCLUSIONS

We agree with the suggestions of Sellin *et al.*[1] that their autoionization electron spectra arise mostly from doubly excited quartet system of the Li I sequence and have suggested that high-angular-momentum states ($L=2+$) are responsible for the higher-energy resonances.

Their observation[1] of the $1s2p^2\,^4P$ term indicates that its autoionization probability is increasing faster than the radiative transition probability to $1s2s2p\,^4P^0$ for higher members of the isoelectronic sequence. This is also indicated in earlier f-value measurements.[5] This is in contrast to the doubly excited systems of two electrons (He I-like) where radiative decays rapidly become competitive with autoionization rates for higher members of the isoelectronic sequence.[11]

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Consequences of Anisotropic Sound Velocities in hcp Solid He^4 †

R. H. Crepeau and D. M. Lee

Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850

(Received 7 January 1972)

The elastic constants for hcp solid He^4 recently published by Crepeau, Heybey, Lee, and Strauss are used for calculating the wave surfaces associated with elastic waves, according to the recent method of Wanner. The deviation of the energy path or ray from the wave normal is calculated and is correlated with experimental sound-velocity data previously obtained by the authors.

Wanner[1] has recently analyzed some of the early sound-velocity data on bcc solid He^3 and He^4 in which the crystal orientation was unknown and has shown that the observations can be used to estimate the elastic constants for these solids. Part of his arguments were based on the fact that the observed sound velocities in some of the earlier data were restricted to a few rather widely separated values, rather than a smoothly varying continuum. This behavior was shown to result from the nature of sound propagation in highly anisotropic media rather than from preferred crystal orientation as supposed by some of the earlier investigators.[2] Using an analysis similar to that used by Wanner,[1] we consider the recent sound-velocity results obtained for hcp solid He^4 in oriented crystals by Crepeau *et al.*[3] It is shown that the data are entirely consistent with this type of analysis.

When discussing sound velocities in anisotropic solids, the three surfaces generally referred to are the velocity, inverse, and wave surfaces.[4,5] From the point of view of an experimentalist measuring sound velocities in a crystal, the velocity surface is the one most directly useful.

Figure 1 shows a typical experimental setup for measuring sound velocities. Sound transducers are affixed to either side of the experimental crystal, and with one transducer as a source of sound waves in the crystal and the other as a receiver, the time for a sound pulse to traverse the crys-

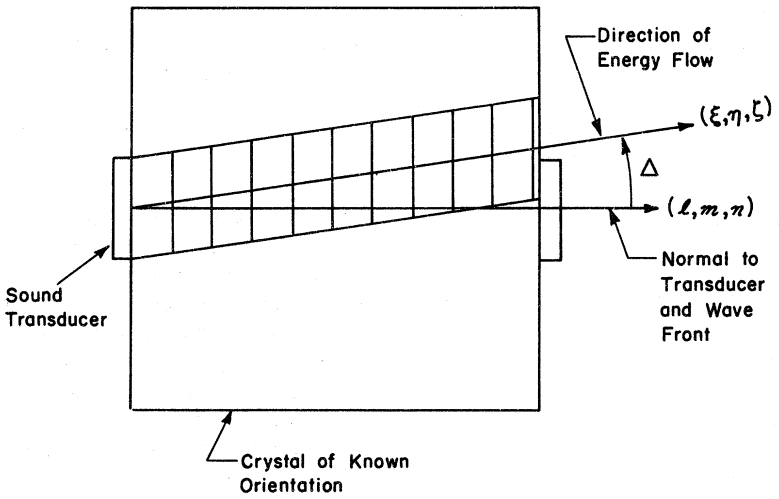

FIG. 1. General experimental design for measuring sound velocities.