

Polarization of line radiation emitted from He-like and H-like ions following electron impact

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The polarization fraction P of the radiation emitted in the transitions 2^1P-1^1S of He-like ions and $2p-1s$ of H-like ones is studied theoretically. The calculation is made with the use of a distorted-wave method. The resulting P is found to be almost independent of nuclear charge, when expressed as a function of electron energy in threshold units and compared along an isoelectronic sequence. The degree of polarization approaches a threshold value very different from that of neutral atoms, due to the long-range Coulomb interaction.

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I. INTRODUCTION

The polarization of radiation emitted from atoms following electron impact provides detailed knowledge about their excited states [1]. If any cascade contribution can be ignored, the polarization fraction reflects the excitation mechanism. It gives information on the cross section for the excitation of each magnetic sublevel. Thus the measurement of the polarization is supplement to the conventional measurement of cross sections summed over the sublevels.

When the electrons have an anisotropic or beamlike velocity distribution, particular sublevels are preferentially populated. This affects sensitively the polarization fraction of the radiation emitted.

Measurement of polarization, therefore, can be used as diagnostic tools for determining departure of the electron distribution from isotropy. Furthermore, the knowledge of polarization is necessary when one deduces an excitation cross section from measurement of emission following the excitation process [2].

The polarization of radiation emitted from neutral atoms has been studied extensively (see, for example, a recent review by Heddle and Gallagher [2]). The polarization of radiation from atomic ions, however, has been not so thoroughly investigated, though several theoretical papers have been published on the subject [3,4] or partly mentioned that [5-7]. The present paper reports a systematic study of polarization in electron-ion collisions. Considered are the emissions from the transition 2^1P-1^1S of He-like ions and the $2p-1s$ multiplet of H-like ones. The variation of the polarization fraction along the isoelectronic sequence is investigated theoretically. It is found that the polarization fraction for the above radiations is insensitive to the nuclear charge and can be well represented by a universal function of collision energy in threshold units. For the $2p-1s$ transition of H-like ions, a similar universal function was obtained by Haug [3]. It is shown, however, that an error is involved in his result.

As for the He-like ions, Inal and Dubau [4] calculated the polarization fraction for Fe XXV, and, very recently, Henderson *et al.* [8] measured the polarization fraction

for Sc XX. The present result can be compared to these two sets of data.

II. THEORY

Here we consider the light emitted in the transitions 2^1P-1^1S of He-like ions and $2p-1s$ of H-like ones. The upper state of each transition is assumed to be excited only through the electron collision with the ion in its ground state and deexcited only by the radiative transition. Thus the polarization fraction of the emission can be determined by the relevant cross section σ_m for the excitation of magnetic sublevel m of the excited state [1]. In the present paper, the LS coupling scheme is adopted and neither the relativistic effect nor the effect of nuclear spin is taken into account.

The cross section σ_m is calculated here with the distorted-wave method developed by Itikawa and Sakimoto [9]. The method [called the distorted wave with electron exchange approximation (DWXA)] uses as a distortion potential the spherical average of the electrostatic potential formed by the target ion in its initial state. This distortion potential is adopted for the calculation of the distorted waves both in the initial and in the final channels. Electron exchange is taken into account, but only for the interacting two electrons. No unitarization is made. More details of the method are given in a previous paper [10], where the scattering amplitudes for the excitation of magnetic sublevels are calculated to obtain the alignment and orientation parameters for the transitions considered here. The state of the He-like ion is represented by a configuration-interaction (CI)-type wave function produced by the computer code CIV3 [11], as in the previous work [9,10].

As is described in the previous papers [10,12], the cross section multiplied by Z^4 (Z being the nuclear charge) does not much change along an isoelectronic sequence when compared at a given value of the collision energy in threshold units, $X (=E/\Delta E)$, ΔE being the excitation energy. The polarization fraction P is given by a ratio of cross sections [see Eqs. (2) and (3) in the next section]. If P is expressed as a function of X and compared along an isoelectronic sequence, it is expected to be almost in-

dependent of nuclear charge, at least for highly charged ions. This is shown in the following sections.

III. He-LIKE IONS

The polarization fraction, measured at right angles to the electron beam, is defined by

$$P = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}}, \quad (1)$$

where I_{\parallel} (I_{\perp}) is the intensity of photons with electric vectors parallel (perpendicular) to the beam direction. For the radiation from the transition 2^1P-1^1S of He-like ions, we have [1]

$$P(2^1P) = \frac{\sigma_0(2^1P) - \sigma_1(2^1P)}{\sigma_0(2^1P) + \sigma_1(2^1P)}. \quad (2)$$

Here $\sigma_m(2^1P)$ ($m=0$ or 1) is the excitation cross section of the magnetic sublevel m of the 2^1P state.

In Table I, we compare the $P(2^1P)$ for Li II ($Z=3$), O VII ($Z=8$), and the limit $Z \rightarrow \infty$. (The procedure to obtain the limiting value is described in a previous paper [12].) The comparison is made at the same value of X (i.e., the electron energy in threshold units). The resulting P 's are almost independent of Z . As representative data, we show in Fig. 1 the $P(2^1P)$ obtained in the limit $Z \rightarrow \infty$. In the same figure, we plot also the polarization fraction calculated for Fe XXV by Inal and Dubau [4]. They obtained their values with the use of a distorted-wave method similar to ours. An overall agreement between the two curves in Fig. 1 is fairly good. This confirms our finding that the polarization fraction is almost independent of nuclear charge, when compared along an isoelectronic sequence as a function of X .

The small difference between the present calculation and the calculation by Inal and Dubau may be ascribed to the relativistic effect, which is not considered in our calculation but is taken into account by Inal and Dubau. In particular, the $P(2^1P)$ of Inal and Dubau has a small dip at threshold, but ours does not. Actually the spin-orbit coupling between the 2^1P_1 and 2^3P_1 states has the largest effect on the 2^1P_1 state at $X=1$, because the (non-relativistic) cross section for the excitation of 2^3P_1 state has a maximum there [4].

In Fig. 1 also shown are the experimental values of P for Sc XX obtained recently by Henderson *et al.* [8]. Our result for $Z = \infty$ almost reproduces the measured data, if the experimental error is taken considered. Dubau calculated $P(2^1P)$ also for Sc XX (quoted in the experimental paper [8]). His value ($P=0.60$ at $X=1.02$), however,

TABLE I. Polarization fraction (in percent) of the 2^1P-1^1S line of the He-like ions, calculated with the DWXA method. The energy (X) of the incident electron is expressed in threshold units.

X	Li II	O VII	$Z = \infty$
2	54.3	53.8	53.4
4	35.9	35.5	35.3
5	29.5	28.8	28.7

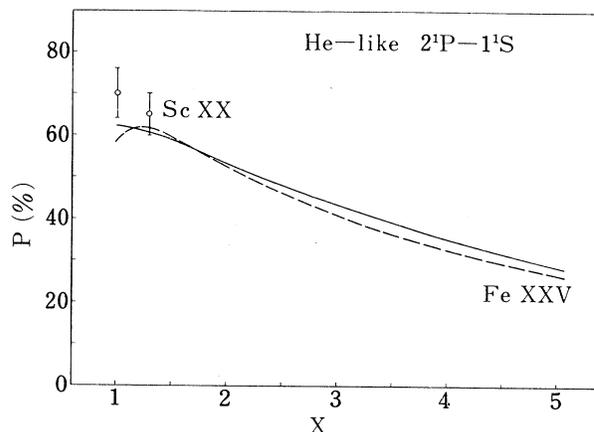


FIG. 1. Polarization fraction (in percent) of the 2^1P-1^1S line of the He-like ions, detected at the perpendicular to the incident electron beam. The collision energy is expressed in threshold units (i.e., $X=E/\Delta E$). The solid line shows the present calculation for $Z = \infty$, Z being the nuclear charge. The dashed line is the value for Fe XXV calculated by Inal and Dubau [4]. Circles are the experimental data for Sc XX obtained by Henderson *et al.* [8].

does not show so much good agreement with experiment as ours.

The emission line from the 2^1P-1^1S transition in neutral He is predicted to be 100% linearly polarized at threshold [1]. As is seen in Fig. 1, the same line for the He-like ions is only about 62% polarized at $X=1$. In the case of He, only the s wave has a contribution at threshold, so that only states with $m=0$ can be excited there [resulting in $P=1$ from Eq. (2)]. For electron-ion collisions, the long-range Coulomb interaction makes many partial waves contribute to the cross section even at threshold. This causes a remarkable difference in polarization fractions of ions and neutrals near threshold.

IV. H-LIKE IONS

The polarization fraction of the $2p-1s$ multiplet lines of H-like ions is given by [1]

$$P(2p) = \frac{3[\sigma_0(2p) - \sigma_1(2p)]}{7\sigma_0(2p) + 11\sigma_1(2p)}, \quad (3)$$

where $\sigma_m(2p)$ ($m=0$ or 1) is the cross section for the excitation of the sublevel m of the $2p$ state. Since we do not consider any spin-dependent phenomena, a spin-averaged cross section is used for σ_m as in the previous paper [10].

TABLE II. Polarization fraction (in percent) of the $2p-1s$ multiplet of the H-like ions, calculated with the DWXA method. The energy (X) of the incident electron is expressed in threshold units.

X	He II	C VI	$Z = \infty$
2	22.6	21.3	20.8
4	12.8	12.9	12.9
5	10.1	10.3	10.4

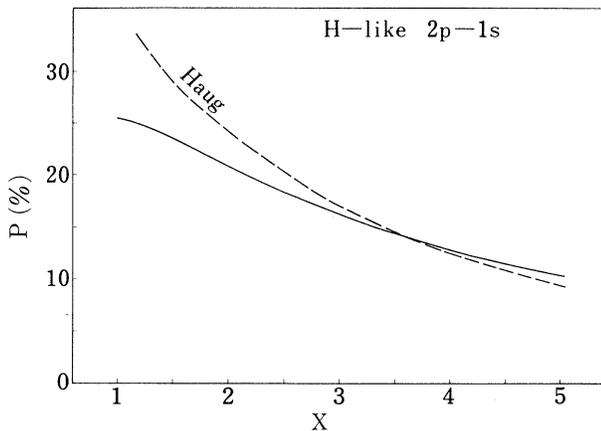


FIG. 2. Polarization fraction (in percent) of the $2p-1s$ multiplet of the H-like ions, as a function of collision energy (X) in threshold units. The solid line represents the present calculation for $Z = \infty$. The dashed line is the calculation by Haug [3], which approaches the limiting value of $\frac{3}{7}$ with energy going to threshold ($X = 1$).

Table II shows the result of the present calculation for He II ($Z=2$), C VI ($Z=6$), and the limit $Z \rightarrow \infty$. Again the $P(2p)$ is not much different for different ion species, when compared at the same X . As in the case of He-like ions, we plot, in Fig. 2, the $P(2p)$ obtained in the limit $Z \rightarrow \infty$. Haug [3] reported a very similar calculation: $P(2p)$ for the H-like ion with $Z \rightarrow \infty$. His values are compared with ours in Fig. 2. There is a large discrepancy at $X < 3.0$. Haug's calculation implicitly assumes that $P(2p)$ should reach $\frac{3}{7}$ as X goes to unity. This limit is expected from the behavior of $P(2p)$ for neutral H (i.e., no contribution of σ_1 at threshold). As is mentioned in the previous section, however, this limit does not hold for ions. Thus the result of Haug is in error, at least at small X .

V. CONCLUDING REMARKS

In the present paper, we have studied theoretically the polarization fraction of the emission following electron-impact excitation of atomic ions. The transitions considered are the 2^1P-1^1S of He-like ions and the $2p-1s$ of H-like ones. It has been found that the polarization fraction P calculated is almost independent of nuclear charge when expressed as a function of X (i.e., the electron energy in threshold units) and compared along an isoelectronic sequence. In Figs. 1 and 2, we plot P obtained in the limit $Z \rightarrow \infty$ and let them serve as a representative value for the respective isoelectronic sequences.

The present calculation is based on the distorted wave with electron exchange approximation (DWXA). To the knowledge of the present authors, there are no other calculations of P reported for He-like or H-like ions than

those mentioned in the previous sections. It is difficult, therefore, to estimate the accuracy of the present calculation. Judged from the cross sections obtained in the previous study [9], the DWXA method can be expected to work well except in the threshold region for low charged ions. For H-like ions, no comparison has been made between the results of the DWXA and any more elaborate calculation. At $X=2.0$, for example, our cross section, summed over magnetic sublevels and multiplied by Z^4 , for the $1s-2p$ excitation of C VI ($1.43\pi a_0^2$, a_0 being the Bohr radius) agrees very well with that ($1.42\pi a_0^2$) by a close-coupling calculation [13], and the present result ($1.34\pi a_0^2$) for the same cross section of He II is in fair agreement with the result ($1.27\pi a_0^2$) of the most recent calculation with the R -matrix method [14]. Based on their comparison between a distorted-wave method and a close-coupling calculation for H-like ions, Hayes and Seaton [15] reached the same conclusion as we stated above for the validity of the distorted-wave method.

It should be noted that the DWXA includes no resonance effects. For the dipole-allowed transition such as considered here, resonances do not have any significant contribution to the total cross section, except again in the region near threshold for low charged ions. Although there has been no detailed study of the effect of resonance on the polarization fraction, we may expect the same conclusion on the polarization as on the total cross section. As a result of this and the above considerations, the universal function P shown in Figs. 1 and 2 may not be applicable in the region $X < 2$ for low charged ions like Li II or He II.

Further restrictions in using the present result are as follows. First, no relativistic effect is taken into account in the present study. The effect increases, in principle, with increasing Z . The difference between the present values and those of Inal and Dubau shown in Fig. 1 probably represents the relativistic effect in the 2^1P-1^1S transition at $Z=26$. The difference is about 10%. This is reasonable because the relativistic effect on the oscillator strength of the same transition for Fe XXV is also about 10% [16]. The second reservation in use of the present result is that the effect of nuclear spin is not considered here. This effect becomes evident when the hyperfine splitting exceeds the natural linewidth of the relevant transition. As the ionic charge increases, this effect becomes less significant for the dipole-allowed transitions, because their transition probability increases with the charge.

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- [1] I. C. Percival and M. J. Seaton, *Philos. Trans. R. Soc. London, Ser. A* **251**, 113 (1958).
- [2] D. W. O. Heddle and J. W. Gallagher, *Rev. Mod. Phys.* **61**, 221 (1989).
- [3] E. Haug, *Sol. Phys.* **71**, 77 (1981).
- [4] M. K. Inal and J. Dubau, *J. Phys. B* **20**, 4221 (1987).
- [5] F. A. Parpia, D. W. Norcross, and F. J. da Paixao, *Phys. Rev. A* **34**, 4777 (1986).
- [6] J. Mitroy and D. W. Norcross, *Phys. Rev. A* **37**, 3755 (1988).
- [7] J. Mitroy, D. C. Griffin, D. W. Norcross, and M. S. Pindzola, *Phys. Rev. A* **38**, 3339 (1988).
- [8] J. R. Henderson, P. Beiersdorfer, C. L. Bennett, S. Chantrenne, D. A. Knapp, R. E. Marrs, M. B. Schneider, K. L. Wong, G. A. Doschek, J. F. Seely, C. M. Brown, R. E. LaVilla, J. Dubau, and M. A. Levine, *Phys. Rev. Lett.* **65**, 705 (1990).
- [9] Y. Itikawa and K. Sakimoto, *Phys. Rev. A* **31**, 1319 (1985).
- [10] R. Srivastava, Y. Itikawa, and K. Sakimoto, *Phys. Rev. A* **43**, 4736 (1991).
- [11] A. Hibbert, *Comput. Phys. Commun.* **9**, 141 (1975).
- [12] Y. Itikawa and K. Sakimoto, *Phys. Rev. A* **38**, 664 (1988).
- [13] N. Abu-Salbi and J. Callaway, *Phys. Rev. A* **24**, 2372 (1981).
- [14] K. M. Aggarwal, K. A. Berrington, A. E. Kingston, and A. Pathak, *J. Phys. B* **24**, 1757 (1991).
- [15] M. A. Hayes and M. J. Seaton, *J. Phys. B* **10**, L573 (1977).
- [16] J. A. Fernley, K. T. Taylor, and M. J. Seaton, *J. Phys. B* **20**, 6457 (1987).