Magnetic-field-dependent angular distributions and linear polarizations of emissions from the $2p^53s\,^3P_2^o$ state in Ne-like ions

Jiguang Li,[1,*] Tomas Brage,[1] Per Jönsson,[2] and Yang Yang[3,4]

[1]*Department of Physics, Lund University, 22100 Lund, Sweden*

[2]*Materials Science and Applied Mathematics, Malmö University, 21120 Malmö, Sweden*

[3]*Key Laboratory of Applied Ion Beam Physics, Minister of Education, Shanghai 200433, China*

[4]*Shanghai EBIT Laboratory, Institute of Modern Physics, Fudan University, Shanghai 200433, China*

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We have investigated the effect of an external magnetic field on the angular distribution and the linear polarization of the $2s^22p^53s\,^3P_2^o \rightarrow 2s^22p^6\,^1S_0$ emission line in Ne-like ions. Since an electric dipole decay channel is opened by the magnetic field and competes with the inherent magnetic quadrupole transition, these properties strongly depend on the magnetic field strength, B. As an example, we discuss in some detail this transition in neonlike magnesium. This is of special interest, since the B-dependent angular distributions and linear polarization degrees are potentially unique diagnostic tools for the magnetic field in different plasmas.

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Magnetic-field-induced transitions (MITs) arise from mixing between atomic state wave functions (ASFs) with different total angular momenta J due to an external magnetic field [1,2]. They have attracted increased attention lately, since they are potential diagnostic tools to determine the strength of the magnetic field in plasmas [3]. Recently, we investigated in detail the influences of MITs on the lifetimes of the $^3P_2^o$ and $^3P_0^o$ metastable states of Ne-like ions [4]. It is worth noting that in this case there are two decay channels from the $^3P_2^o$ level to the ground state—the magnetic quadrupole ($M2$) and magnetic-field induced electric dipole ($E1$) transitions. It is clear that in the presence of a magnetic field this can give rise to the interference between the two decay modes. This interference effect, although sensitive to the transition amplitudes involved and thus the strength of the magnetic field, does not affect the lifetimes of the $^3P_2^o$ level, as we show later. We need to investigate the spatial distribution of the radiation to observe the effect of this interference and in this paper we therefore study the angular distributions and the linear polarizations of the decay from this level and their dependence on the magnetic field strength.

In general, the spontaneous differential rate from an initial state Ψ_i to a final state Ψ_f is given in the atomic unit by

$$\frac{dA_{if}}{d\Omega} = \frac{\alpha}{2\pi}\omega_{if}|T_{if}|^2, \tag{1}$$

where α is the fine-structure constant and ω_{if} is the frequency of the emitted photon. According to the multipole expansion of the vector potential describing the radiation field, the differential transition amplitude T_{if} is written as [5]

$$T_{if} = 4\pi \sum_{jm\lambda} i^{j-\lambda}\big[\boldsymbol{Y}_{jm}^{(\lambda)*}(\vec{k})\cdot\hat{\epsilon}\big]\big[T_{jm}^{(\lambda)}\big]_{if}. \tag{2}$$

Here, $\boldsymbol{Y}_{jm}^{(\lambda)}(\vec{k})$ is the vector spherical harmonics [6], where $\vec{k}$ represents the direction of the photon's propagation. The vector $\hat{\epsilon}$ describes the photon's polarization. $T_{jm}^{(\lambda)} = \sum_{q=1}^{N} t_{jm}^{(\lambda)}(\mathbf{r}_q)$ are the multipole-transition operators for an N-electron atomic system with $\lambda = 0$ for the magnetic and $\lambda = 1$ for the electric multipoles [5]. The subscripts j and m represent the total angular momentum and its z component, respectively, of the photon. It should be emphasized that all information about the photon's propagation direction and its polarization is contained in the expansion coefficients $[\boldsymbol{Y}_{jm}^{(\lambda)*}(\vec{k})\cdot\hat{\epsilon}]$ in Eq. (2).

In the presence of an external magnetic field, it is convenient to choose the magnetic-field direction as the quantization axis. As a result, atomic state functions with the same parity and the magnetic quantum number M but different total angular momenta J are mixed, according to

$$|\Psi(M)\rangle = \sum_{\Gamma J} d_{\Gamma J}|\Phi(\Gamma J M)\rangle \tag{3}$$

with $\{d_{\Gamma J}\}$ labeled mixing coefficients. In the first-order perturbation approximation, they can be expressed as

$$d_{\Gamma J}(M) = \frac{\langle\Phi(\Gamma J M)|H_m|\Phi(\Gamma_0 J_0 M_0)\rangle}{E(\Phi(\Gamma_0 J_0)) - E(\Phi(\Gamma J))}, \tag{4}$$

where the subscript 0 denotes the atomic state concerned at $B = 0$. The interaction Hamiltonian between the external magnetic field and an N-electron atom is written by [7]

$$H_m = (\mathbf{N}^{(1)} + \Delta\mathbf{N}^{(1)})\cdot\mathbf{B} \tag{5}$$

with

$$\mathbf{N}^{(1)} = \sum_q -i\frac{\sqrt{2}}{2\alpha}r_q(\boldsymbol{\alpha}_q\mathbf{C}^{(1)}(q))^{(1)}, \tag{6}$$

$$\Delta\mathbf{N}^{(1)} = \sum_q \frac{g_s-2}{2}\beta_q\Sigma_q. \tag{7}$$

Here, the last term is the so-called Schwinger QED correction. $\boldsymbol{\alpha}$ and β constitute the Dirac matrices, $\Sigma = \begin{pmatrix}\sigma & 0\\ 0 & \sigma\end{pmatrix}$ is the relativistic spin matrix, and the electron g factor, with the

*Present address: Data Center for High Energy Density Physics, Institute of Applied Physics and Computational Mathematics, P. O. Box 8009, Beijing 100088, China; Li_Jiguang@iapcm.ac.cn

QED correction, is $g_s = 2.000232$. As can be seen from Eq. (3), new decay channels may be opened by the external magnetic field due to the mix of atomic state wave functions with different total angular momenta J. These lines are called magnetic-field-induced transitions (MIT) [4].

For the case of Ne-like ions under consideration, we approximately express the initial (i) and final (f) atomic state involved as [4]

$$\begin{aligned} \left|\Psi\left(2p^5 3s\,^3P_2^o M\right)\right\rangle_i &= d_0\left|\Phi\left(2p^5 3s\,^3P_2^o M\right)\right\rangle \\ &\quad + d_1\left|\Phi\left(2p^5 3s\,^3P_1^o M\right)\right\rangle \\ &\quad + d_2\left|\Phi\left(2p^5 3s\,^1P_1^o M\right)\right\rangle \end{aligned} \tag{8}$$

and

$$|\Psi(2p^6\,^1S_0\,M)\rangle_f = |\Phi(2p^6\,^1S_0\,M)\rangle. \tag{9}$$

As can be seen from the equations above, the external magnetic field gives rise to the mixing between the $2p^5 3s\,^3P_2^o$ state and the $2p^5 3s\,^3P_1^o$ and $2p^5 3s\,^1P_1^o$ states. However, it is worth nothing that the mix arises only for the levels with magnetic quantum number $M = 0, \pm 1$. As a result, there are two decay channels, the magnetic-field-induced $E1$ transition and the $M2$ transition, for $M = 0, \pm 1$ magnetic sublevels. Moreover, these two decay channels will potentially interfere. The other two sublevels of $2p^5 3s\,^3P_2^o$ will only decay via the $M2$ transition. By summing over the photon's polarization, the differential transition rates from different magnetic sublevels of the $2p^5 3s\,^3P_2^o$ state to the ground state are given by

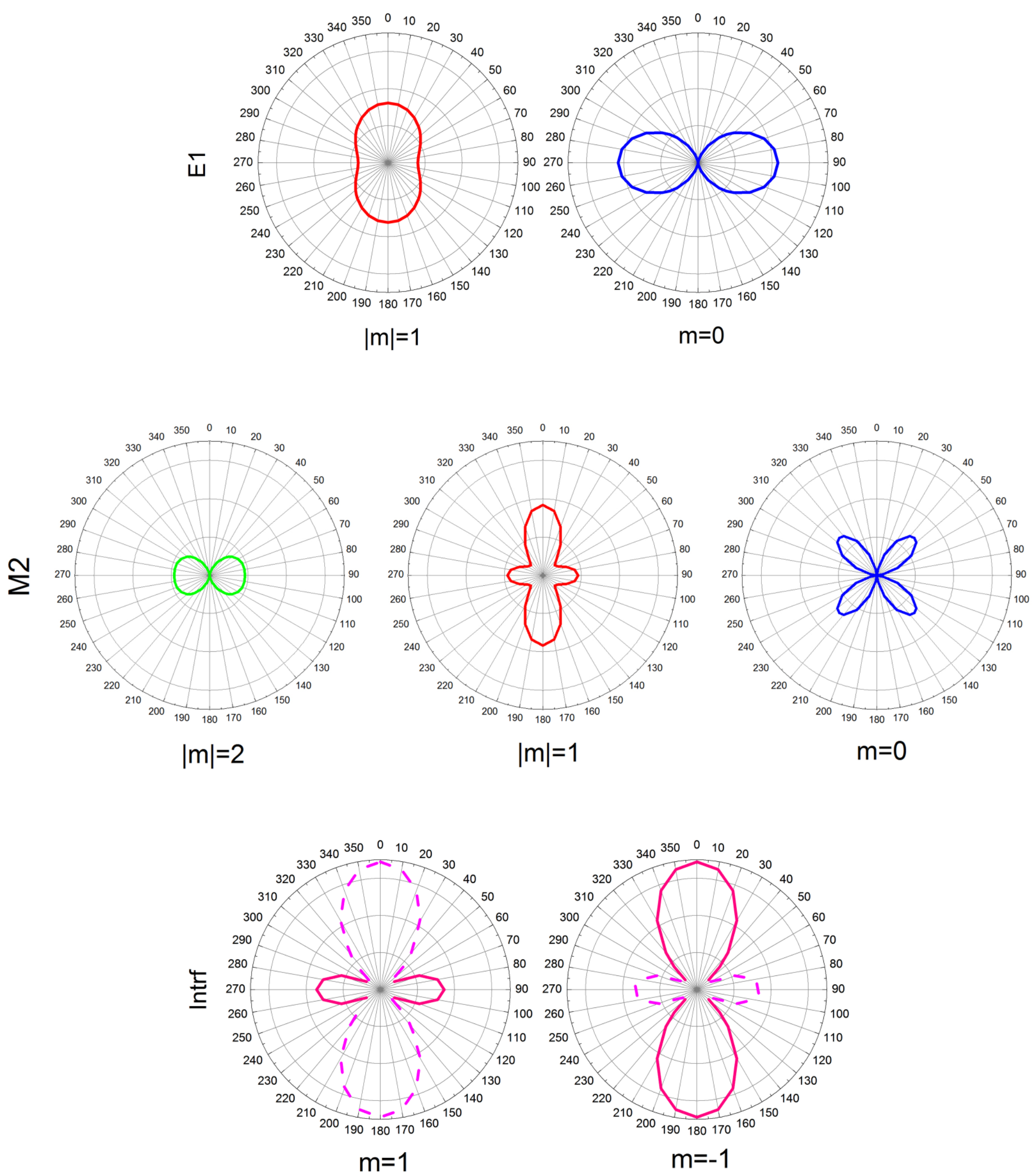

FIG. 1. (Color online) Contributions to the angular distributions of rates, without distinguishing the photon's polarization, for the magnetic-field-induced $E1$ transition, $M2$ transition, and the contribution from the interference (labeled with Intrf) between these two transitions in Ne-like Mg at $B = 1$ T. 0° stands for the direction of the external magnetic field. The m values are magnetic quantum numbers of the photon produced by the corresponding transition. The values of the radii is 7 in the atomic unit. The dashed lines represent negative value.

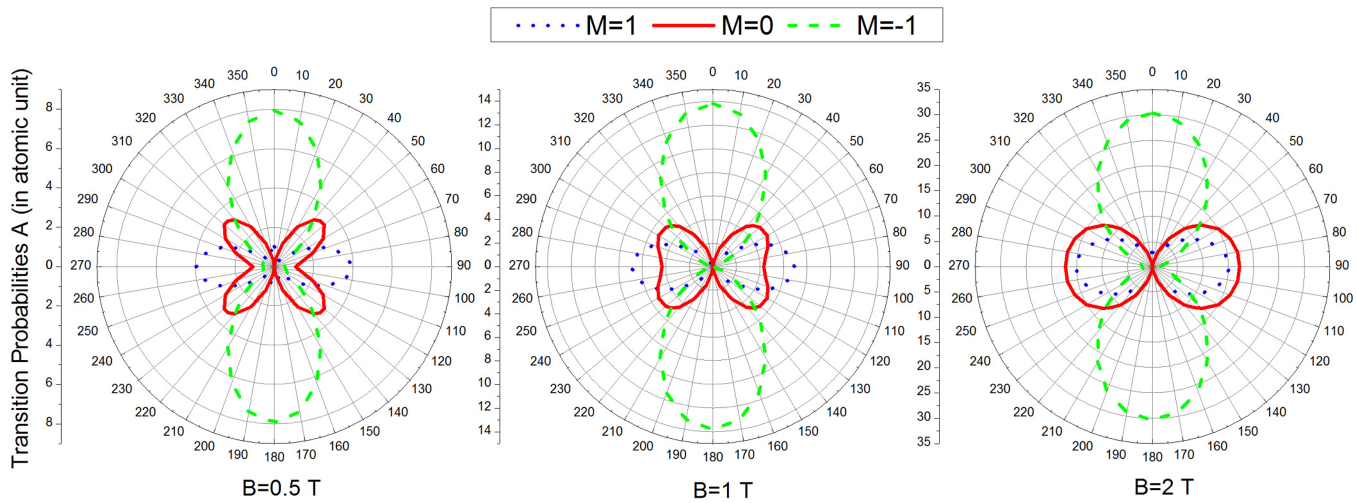

FIG. 2. (Color online) The angular distributions of the total differential transition probabilities, under the circumstance of $B = 0.5, 1$, and 2 T, for the transitions from $M = 0, 1$, and -1 magnetic sublevels in $2p^5 3s\ {}^3P_2$ state to the $2p^6\ {}^1S_0$ ground state in Ne-like Mg. 0° stands for the direction of the external magnetic field. The transition rates are in atomic units and magnified by a factor of 10^{17}.

$$\frac{dA_{if}}{d\Omega} = \frac{\alpha}{2\pi}\omega_{if} \begin{cases} \left|\boldsymbol{Y}^{(0)}_{2m}(\vec{k})\right|^2 \left|\left[T^{(0)}_{2m}\right]_{if}\right|^2 & \text{for } m = \pm 2 \\ \left|\boldsymbol{Y}^{(0)}_{2m}(\vec{k})\right|^2 \left|\left[T^{(0)}_{2m}\right]_{if}\right|^2 + \left|\boldsymbol{Y}^{(1)}_{1m}(\vec{k})\right|^2 \left|\left[T^{(1)}_{1m}\right]_{if}\right|^2 - 2\left[\boldsymbol{Y}^{(0)*}_{2m}(\vec{k}) \cdot \boldsymbol{Y}^{(1)}_{1m}(\vec{k})\right]\left[T^{(0)}_{2m}\right]^*_{if}\left[T^{(1)}_{1m}\right]_{if} & \text{for } m = \pm 1 \\ \left|\boldsymbol{Y}^{(0)}_{2m}(\vec{k})\right|^2 \left|\left[T^{(0)}_{2m}\right]_{if}\right|^2 + \left|\boldsymbol{Y}^{(1)}_{1m}(\vec{k})\right|^2 \left|\left[T^{(1)}_{1m}\right]_{if}\right|^2 & \text{for } m = 0. \end{cases} \quad (10)$$

Note that the interference effect between the MIT and $M2$ decay channels does not affect the lifetimes of the ${}^3P_2$ level, as the total transition rates is given by the incoherent sum of the individual multipole transition rates due to the orthonormality of the vector spherical harmonics when differential transition rates are integrated over $d\Omega$, the spatial direction. Also, this interference effect only appears in the transitions from $M = \pm 1$ sublevels, when the photon's polarization is neglected. The B dependence of the angular distributions of A_{if} results from the fact that the MIT transition rate is proportional to B^2 [4].

As an example, we show the angular distributions of the rates in Fig. 1 for the transitions in Ne-like Mg in a magnetic field of strength $B = 1$ T. The transition amplitudes T_{if} were taken from Ref. [4,8]. The rates in atomic unit were scaled by a factor of 10^{17}. Since the same scaling was used in all figures, they give the relative magnitude for different terms in Eq. (10). We found that the contributions from the interference term are larger than those from the MIT and $M2$ terms and therefore very pronounced. In addition, the angular distributions of the interference term, unlike the MIT and $M2$ transitions, are dependent on the magnetic quantum number rather than its absolute value. For the present case, the interference term from the $M = 1$ sublevel is positive along the direction of the external magnetic field but negative in the perpendicular direction. The case of $M = -1$ has the opposite sign.

The angular distributions of the combined transition rates are depicted in Fig. 2 for the $M = 0, \pm 1$ sublevels in $2p^5 3s\ {}^3P^o_2$. Since the MIT transition and the interference term are proportional to B^2 and B, respectively, the angular distributions of these rates show a pronounced dependence on the magnetic field. To illustrate this, we also presented in Fig. 2 the angular distributions related to field strengths of $B = 0.5, 1$, and 2 T. It is clear that the angular distributions of the emissions from $M = 1$ and $M = -1$ are very different due to the different signs of the interference effect in these two transitions. It is also worth noting that the pattern of the angular distribution for the photon with $M = 0$ is strongly dependent

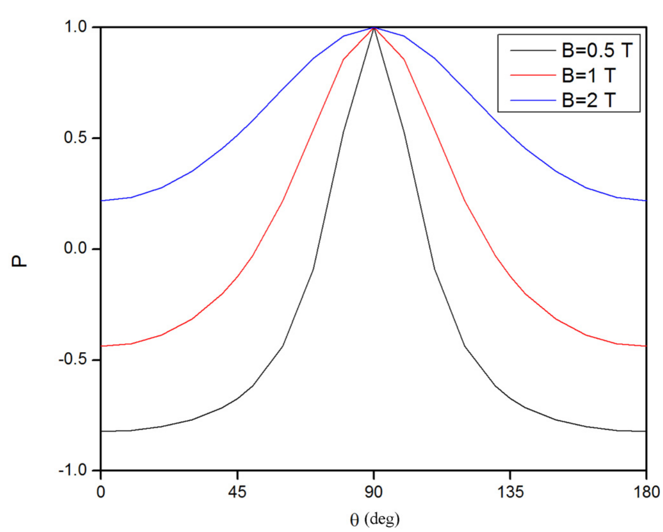

FIG. 3. (Color online) The linear polarization degrees of the emission with $M = 0$ from the $2s^2 2p^5 3s^3 P^o_2$ in the Ne-like Mg ion in a magnetic field of strengths of $B = 0.5, 1$, and 2 T.

on the strength of the external magnetic field. This results from the competition between the MIT and $M2$ transitions and the fact that the MIT rate is proportional to the square of the magnetic-field strength.

In addition to the anisotropic angular distributions, the linear polarization of the radiation field is also affected by the external magnetic field. In atomic physics, the linear polarization is specified by its degree [9]

$$P(\theta) = \frac{I_{\parallel}(\theta) - I_{\perp}(\theta)}{I_{\parallel}(\theta) + I_{\perp}(\theta)}. \tag{11}$$

Here, θ denotes the angle of the photon's propagation direction ($\vec{k}$) relative to the external magnetic field. $I_{\parallel}$ and $I_{\perp}$ refer to the intensities of light linearly polarized in the parallel and perpendicular direction, respectively, in the plane that is orthogonal to the photon's propagation direction. For simplicity, but no loss of generality, we calculated the linear polarization degree for the emission with $M = 0$. According to Eq. (3), the linear polarization degree can be expressed in the form

$$P(\theta) = \frac{\Delta - 5\cos^2\theta}{\Delta + 5\cos^2\theta}, \tag{12}$$

where Δ represents the ratio of rates between the MIT and $M2$ transitions, and thereby introduces the dependence on the magnetic field, which we illustrated in Fig. 3 for the Ne-like Mg case, for different field strengths.

In summary, we have studied the effect of an external magnetic field on the angular distributions and the linear polarizations of emissions from magnetic sublevels of the $2s^22p^53s\ ^3P_2^o$ state to the ground state in Ne-like ions. It was shown that these two physical quantities strongly depend on the magnetic-field strength and that the effects can be seen for other Ne-like ions at the beginning or even in the middle of isoeletronic sequence, for realistic magnetic-field strengths. In these ions the MIT transition rate will then be comparable to the $M2$ rate. This makes the magnetic-field-dependent angular distributions and linear polarizations a unique tool for diagnostics of magnetic fields in different plasmas.

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