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Recent advances in the problem of a complete experiment for Auger decay

N.M. Kabachnik [a,b]

[a] *Institute of Nuclear Physics, Moscow State University, Moscow 119992, Russia*
[b] *Fritz-Haber-Institut der MPG, 14195 Berlin, Germany*

Abstract

Possible ways of realization of a so-called complete experiment for atomic Auger decay, i.e. experimental determination of the Auger amplitudes, are discussed. Recently found relations between parameters characterizing the angular distributions and the spin polarization of Auger electrons have led to a revision of our understanding which measurement can constitute a complete experiment. Now it is clear that in general, information on both particles in the final state, electron and residual ion, is necessary. Examples of recent almost complete experiments are discussed.

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1. Introduction: a concept of a complete experiment for Auger process

A set of measurements is called a “complete” or “perfect” experiment if from the results of the measurements it is possible to obtain the most complete quantum mechanical information about the studied process, namely the transition amplitudes and their relative phases. These experimentally determined amplitudes can serve as an ultimate test for the theoretical calculations. Due to their fundamental importance the complete experiments are widely discussed in photo- and scattering processes [1]. It is clear that the experiment is “complete” only within the framework of the theory used [2]. A more detailed theoretical description may need more parameters (more amplitudes) and therefore requires more measurements before the experiment is complete.

A concept of a complete experiment for the Auger processes in atoms was first formulated in [3] within the framework of the conventional two-step model of creation and decay of a core-ionized or core-excited resonant state. An Auger decay itself is considered as a quantum transition from a well-defined initial ionic state, characterized by its energy, angular momentum (J_i), and parity (π_i), to a certain final state of the residual ion (J_f, π_f) and the Auger electron in the continuum. The initial ionic state is prepared in the first step of the Auger process: ionization or excitation of an atom by photon or particle impact. It is convenient to expand the Auger electron wave function in partial waves. Then the Auger decay may be described in terms of a limited number of complex matrix elements (Auger amplitudes) $M_{lj} \equiv \langle J_f\pi_f, lj\|\mathcal{O}\|J_i\pi_i\rangle$, where l and j are the orbital and total angular momenta of the Auger electron and $\mathcal{O}$ is the transition operator. The number of Auger amplitudes is limited by the angular momentum and parity selection rules. In the general case the total number of the amplitudes is $2J_i + 1$ [3]. For example, for the transition $M_4N_{2,3}N_{2,3}(J_f = 2)$ there are four different electron continuum channels: $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ and correspondingly four complex Auger amplitudes. The moduli of the amplitudes and relative phase shifts form a set of the $4J_i + 1$ real parameters to be determined experimentally for a complete characterization of the Auger decay. In many cases the number of possible decay channels is less than maximum. If $J_f < J_i$ then the number of amplitudes reduces to $2J_f + 1$, thus only $4J_f + 1$ parameters need to be determined experimentally. Another possibility to diminish the number of required parameters is to use some additional approximation for the description of the Auger decay. For example, application of the LSJ approximation for the ionic states and the non-relativistic approximation for the Auger electron considerably diminishes the number of necessary amplitudes.

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In practice, the absolute measurements of the Auger electron yield are very rare. In the experiments discussed below only relative cross sections, relative partial widths, etc. are determined. Therefore, relative Auger amplitudes and phases are obtained from the experiment which is then dubbed "almost complete" experiment. Obviously, the above consideration is valid not only for the Auger decay but also for the resonant Auger process and for the autoionization of any strong resonance which can be described within the two-step model. In recent years several attempts have been made to perform the complete experiment for Auger or resonant Auger (autoionization) processes in atoms using various technique [4–14]. Some of them will be discussed below in more detail.

2. Measurable parameters of the Auger decay

2.1. Anisotropy and spin polarization of Auger electrons

In the following we discuss what parameters can be measured in experiments with the Auger decay, in principle. First, consider the experiments in which only Auger electrons are detected. The first observable quantity is, naturally, the intensity of the Auger line which is proportional to the sum of all matrix elements squared: $I_0 \approx \sum_{lj} |M_{lj}|^2$. This gives the first equation connecting the observable quantity and the unknown amplitudes. More detailed information about the chosen Auger transition can be obtained from angular distribution and spin-polarization measurements. In fact, in many cases the excited initial Auger state is not isotropic in a sense that the magnetic substates related to some physically selected axis are not statistically populated. The anisotropy of the initial state may be characterized by the orientation (k = odd) and alignment (k = even) statistical tensors $\mathcal{A}_{kq}$ which in the simplest case reduce to the statistical tensors of the first and second rank, respectively [15]. The angular distribution of the Auger electrons emitted from an aligned state can be presented as [16]:

$$I_{J_\mathrm{f}}(\vartheta) = \frac{I_0}{4\pi}\left[1 + \sum_{k=2,\mathrm{even}}^{k_\mathrm{max}} \alpha_k \mathcal{A}_{k0}(J_\mathrm{i}) P_k(\cos\vartheta)\right] \quad (1)$$

where I_0 is the total yield of the transition, $P_k(x)$ are the Legendre polynomials, $\mathcal{A}_{k0}(J_\mathrm{i})$ are statistical tensors of even rank describing the alignment of the initial state and α_k are intrinsic anisotropy parameters, characteristic for a particular Auger transition. (The z-axis of a laboratory system is chosen along the alignment axis and ϑ is the angle of electron emission.) The summation in (1)is over even values of k, and $k_\mathrm{max} \le 2J_\mathrm{i}$. In photoinduced Auger emission $k = 2$ only. The alignment parameters $\mathcal{A}_{k0}(J_\mathrm{i})$ can be measured in independent experiments. Sometimes they are exactly known (for example, in photoexcitation of resonances from the $J = 0$ ground state). In any case, we can consider Eq. (1) as an equation relating the experimentally observed angular distribution and the intrinsic anisotropy parameters α_k which are expressed in terms of Auger amplitudes as

$$\alpha_k = \sum_{lj,l'j'} a_{lj,l'j'} \,\mathrm{Re}(M_{lj} M^*_{l'j'}) \quad (2)$$

where $a_{lj,l'j'}$ are the known combinations of the Clebsch–Gordan coefficients [16].

The Auger electrons can be spin polarized [17,18]. Measurements of the spin polarization of Auger (autoionization) electrons are difficult but quite feasible as demonstrated by recent experiments [4–6,19–23]. The three components of the spin-polarization vector can also be expressed in terms of orientation and alignment tensors and the corresponding intrinsic parameters [24]. It is convenient to present the spin-polarization components in the frame S' with the z'-axis along the direction of Auger electron emission [25–28]. The spin component along the direction of electron motion (longitudinal component, $P_{z'}$) may be presented as

$$P_{z'} = \frac{\sum_{k=\mathrm{odd}} \delta_k \mathcal{A}_{k0}(J_\mathrm{i}) P_k(\cos\vartheta)}{1 + \sum_{k=2,\mathrm{even}} \alpha_k \mathcal{A}_{k0}(J_\mathrm{i}) P_k(\cos\vartheta)}. \quad (3)$$

Here δ_k are the intrinsic parameters which determine the angular distribution of the longitudinal spin component. Note that the sum in the numerator contains terms with only odd k values while the sum in the denominator contains only even k terms. The transverse spin component in the reaction plane ($P_{x'}$) is

$$P_{x'} = \frac{\sum_{k=\mathrm{odd}} \xi_k \mathcal{A}_{k0}(J_\mathrm{i}) P^1_k(\cos\vartheta)}{1 + \sum_{k=2,\mathrm{even}} \alpha_k \mathcal{A}_{k0}(J_\mathrm{i}) P_k(\cos\vartheta)} \quad (4)$$

while another transverse component, perpendicular to the reaction plane, is

$$P_{y'} = \frac{\sum_{k=2,\mathrm{even}} \bar{\xi}_k \mathcal{A}_{k0}(J_\mathrm{i}) P^1_k(\cos\vartheta)}{1 + \sum_{k=2,\mathrm{even}} \alpha_k \mathcal{A}_{k0}(J_\mathrm{i}) P_k(\cos\vartheta)}. \quad (5)$$

In Eqs. (4) and (5) the functions $P^1_k(x)$ are the associated Legendre polynomials, the coefficients ξ_k (k odd) and $\bar{\xi}_k$ (k even) are the intrinsic parameters which determine the transverse spin components in the reaction plane and perpendicular to it, respectively. Note that the values $\mathcal{A}_{k0}(J_\mathrm{i})$ in Eqs. (3)–(5) are still determined in the laboratory frame and angle ϑ is measured from the laboratory z-axis. Since we consider the orientation and alignment tensors of the initial state $\mathcal{A}_{k0}(J_\mathrm{i})$ as known values, the measurements of the spin polarization of Auger electrons provide the intrinsic parameters δ_k, ξ_k (k odd) and $\bar{\xi}_k$ (k even) which may be expressed in terms of the Auger amplitudes by the relations of the general form similar to Eq. (2):

$$\tau^{(i)}_k = \sum_{lj,l'j'} c^{(i)}_{lj,l'j'} M_{lj} M^*_{l'j'} \quad (6)$$

where $\tau^{(i)}_k$, $i = 1-3$, represents all three intrinsic parameters. Simple explicit expressions for the coefficients $c^{(i)}_{lj,l'j'}$

may be found in [25,28]. The total number of intrinsic parameters which can be in principle obtained from the measurements of the angular dependence of the intensity and spin polarization of Auger electrons is $4J_i + 1$ [3] which is accidentally, equal to the total number of real parameters characterizing the amplitudes. Thus if the intrinsic parameters had to be independent, the complete experiment would be possible by only measuring the parameters of the Auger electrons. However, as was found recently, the intrinsic parameters are not all independent. There are relations connecting them, which reduce the number of equations for determining Auger amplitudes [5,6,28–31]. These equations will be discussed later, but the consequence of their existence is that measurements of the parameters of Auger electrons only is not sufficient for a complete experiment.

2.2. Polarization parameters of the residual ion

Another possibility to get information about the Auger amplitudes is to measure the polarization parameters of the residual ions. In the Auger decay, some part of the initial orientation and alignment is transferred to the residual ion [32]. If the ion is formed in the excited state its anisotropy can be revealed by studying the angular distribution and polarization of the subsequent fluorescence or the second step Auger electrons. In particular, the alignment transfer can be studied by measuring the angular distribution of the second-step Auger electrons (see, for example, [33,34] and references therein) or by measuring the angular distribution or linear polarization of fluorescence (see [35–37] and references therein). The orientation of the residual ion is measured by studying the circular polarization of fluorescence [14,38,39] excited by circularly polarized primary photon beam. In principle, information about the orientation transfer can be obtained also from spin-resolved measurements of the second-step Auger electrons. Such experiments are much more difficult, although feasible as demonstrated by Kuntze et al. [19,20] for the case of Ba(5p) resonant photoionization.

Both alignment and orientation transfer are described by the relation [32,15]:

$$\mathcal{A}_{k0}(J_f) = \mathcal{A}_{k0}(J_i)\left(\sum_{lj}|M_{lj}|^2\right)^{-1} \times \left(\sum_{lj}\hat{J}_i\hat{J}_f(-1)^{j+J_i+J_f}\begin{Bmatrix} JJ_i & J_f & j \\ J_f & J_i & k\end{Bmatrix}|M_{lj}|^2\right). \qquad (7)$$

where $k = 2, \dots$, even for alignment and $k = 1, \dots$, odd for orientation. Obviously both the alignment and the orientation transfer are determined by the Auger matrix elements squared. There is no interference between Auger channels and therefore the phase differences do not enter Eq. (7).

2.3. Coincidence measurements of angular correlations

Finally, we consider the angle resolved coincidence measurements in which the Auger (autoionization) electron is detected together with the subsequent fluorescence or another Auger electron. First angle resoled experiments on autoionization electron-fluorescence coincidences have been done by West and collaborators [10–13]. The experiments were done in Ca and Sr with the polarization analysis of the following fluorescence. The feasibility of the angular correlation study for two successively emitted Auger electrons measured in coincidence has been demonstrated for the resonant Auger–normal Auger correlations in noble-gas atoms [7,40–44].

For both types of experiment the angular correlation between the emitted Auger (autoionization) electron and the following radiation (fluorescence or the second step Auger electron) can be presented in the general form [32,45]:

$$W(\vec{n}_1, \vec{n}_2) = c \sum_{k_1 k_2 k_0} G_{k_1 k_2 k_0}\, \rho_{k_0 q_0}(J_i)\, [Y_{k_1}(\vec{n}_1) \times Y_{k_2}(\vec{n}_2)]_{k_0 q_0} \qquad (8)$$

where unit vectors $\vec{n}_1$ and $\vec{n}_2$ show the directions of the Auger emission and the following radiation, $[Y_{k_1}(\vec{n}_1) \times Y_{k_2}(\vec{n}_2)]_{k_0 q_0}$ are the bipolar spherical harmonics, $\rho_{k_0 q_0}(J_i)$ is the statistical tensor describing the initial Auger state, and $G_{k_1 k_2 k_0}$ are generalized anisotropy coefficients which are determined by the Auger decay amplitudes. The range of indexes is $k_0 \le 2J_i$, k_1 and k_2 are both even and satisfy the triangle rule. This shows that the number of coefficients which in principle can be extracted from the experiment may be much larger than the number of unknown amplitudes. Therefore, there exists redundance which is almost necessary in such complicated experiments.

3. Relations between intrinsic parameters

In previous section we have demonstrated that experiments involving Auger decay can provide many measurable parameters which contain information about the Auger amplitudes. The question, however, arises if all these parameters are independent or not. It is clear that only independent parameters are important for realization of the complete experiment. For the case of the non-coincidence measurements of Auger electrons this question was first discussed by Schmidtke et al. [5,6]. It was found experimentally and then proved mathematically that angular anisotropy and spin-polarization parameters are not independent. Moreover, first relations between intrinsic parameters have been found for some particular transitions. Below we discuss this problem in considering as an example the Auger decay of a $J_i = 3/2$ state [28].

Consider first the case when the angular momentum of the final ionic state $J_f > J_i$. As it follows from the above discussion the Auger electron emission in this case is determined by the $2J_\mathrm{i}+1=4$ complex amplitudes (seven real parameters). On the other hand, the angular distribution is characterized by one intrinsic parameter α_2 while the spin-polarization is characterized by five intrinsic parameters δ_1, δ_3, ξ_1, $\bar{\xi}_2$ and ξ_3. One can consider the intensity and all these six intrinsic parameters as functions of the seven unknown values (amplitudes and phases) and solve the problem of their independence by considering the Jacobi matrix of the system of equations. In this way we have proved that the equations are not independent and that there should be two (!) equations connecting the intrinsic parameters. The equations have been found [28] to be:

$$\sqrt{5}(1-\alpha_2)+(\delta_1-3\delta_3)-4(-1)^{l+J_\mathrm{f}}(\xi_1-3\xi_3)=0, \quad (9)$$

$$2[1-\alpha_2-\sqrt{5}(-1)^{l+J_\mathrm{f}}\xi_1]^2+2(2\xi_2)^2-[\sqrt{5}(1-\alpha_2) - (\delta_1-3\delta_3)]\times\left[\delta_1-2(-1)^{l+J_\mathrm{f}}\xi_1+\frac{3}{\sqrt{5}}\right]=0. \quad (10)$$

It is interesting to note that one relation is linear, another one is quadratic and of the same type as found earlier for photoionization [46] and for other Auger processes [5,6]. These relations are independent since relation (9) contains both δ_3 and ξ_3 while relation (10) contains ξ_2 and δ_3 but not ξ_3. (We suppose that all the intrinsic parameters are non-zero.) The equations are exact and should be valid for a set of amplitudes calculated in any theoretical model. We remind, however, that they are based on the two-step approach and therefore valid only within the validity of the model. The existence of these equations shows that even if one measured intensity and all six intrinsic parameters only five of them are independent and therefore it is not possible to solve unambiguously the inverse problem and to obtain seven amplitude ratios and phases.

It is interesting to consider the case $J_\mathrm{f}=1$ where the number of Auger matrix elements is only three (five real parameters). Although the number of measurable quantities (intensity + intrinsic parameters) is still seven, inspection of the Jacobi matrix shows that in this case there are three equations connecting the intrinsic parameters. One equation connects parameters with $k\le 2$. It was the first relation of this kind found in connection with the experiments by Schmidtke et al. [5,6]:

$$[\alpha_2-\sqrt{5}(\delta_1+(-1)^l\xi_1)]^2+(2\xi_2)^2 - (1+\alpha_2)[5-\sqrt{5}(\delta_1-(-1)^l 2\xi_1)]=0 \quad (11)$$

The second equation relates the anisotropy and the longitudinal spin-polarization parameters [30]:

$$\sqrt{5}(1+\alpha_2)-(3\delta_1+\delta_3)=0 \quad (12)$$

Finally, the third equation relates also the anisotropy and spin-polarization parameters but contains the higher order ξ_3 parameter:

$$\sqrt{5}(1+2\alpha_2)-[5\delta_1+2(\xi_1-3\xi_3)]=0 \quad (13)$$

The relations (11)–(13) are all independent. Their existence limits the number of independent measurable quantities to only four which again is insufficient for the complete determination of all amplitudes in spite of their reduced number.

The above equations are valid for $J_\mathrm{i}=3/2$. Similar equations have been found for the cases of Auger decay from $J_\mathrm{i}=1/2$ and for the resonance Auger decay from $J_\mathrm{i}=1$ [29] as well as for some other cases [6,30]. Although it is almost obvious that such equations should exist for any initial state, the general form of them is still not yet found. It is also not clear what is the physical reason of their existence. Since the equations are valid for any matrix elements, they are independent of the dynamics of the decay and therefore should reflect the most general symmetry properties and angular momentum conservation law. In one case of Eq. (12) and similar equations for other J_i, it has been found that they follow from the conservation of the angular momentum projections in the decay [30]. I believe that other equations exist due to conservation of angular momentum and parity, however, this should be proved. In almost all considered cases the number of independent intrinsic parameters characterizing the emitted Auger electron is less than necessary for a complete experiment. Thus in general, the complete experiment cannot be realized by measuring only parameters of the Auger electrons. Information about the residual ion is necessary. The only exception from this rule is a transition from $J_\mathrm{i}=1$ to $J_\mathrm{f}=1/2$ states, where information about two possible amplitudes (three parameters) can be obtained from the intensity and two independent α_2 and ξ_2 parameters.

4. Examples of the complete experiments

During the last years several attempts to realize a complete experiment for Auger or autoionization process have been made. Autoionization from photoexcited resonances in Ca and Sr has been studied by measuring in coincidence the angular correlation between the emitted electron and subsequent fluorescence with polarization analysis of the latter [10–13]. Fit of the experimental data by the parametrized theoretical expressions obtained in [47] yields the generalized anisotropy parameters. Combining them with the measured anisotropy parameters for the angular distributions of the autoionization electrons the authors determined the autoionization amplitudes and phases.

Interesting idea was suggested by Grum-Grzhimailo et al. [8,9]. They studied the decay of the $Na^+(2s2p^64p\ ^3P)$ autoionizing resonance produced by electron impact from laser excited sodium atoms. The LSJ coupling approximation was used in order to diminish the number of unknown amplitudes. By measuring the ratios of the electron yield for two resolved fine-structure components of the final ion and the angular distributions of the autoionization electrons they determined the absolute ratio of decay amplitudes and the relative phase.

A spin polarization study for some of the lines of resonant and normal Auger $N_{4,5}O_{2,3}O_{2,3}$ spectrum excited by photons have been combined with the angular anisotropy data to obtain the ratios of Auger amplitudes and relative phases in [4,5]. Similar investigation have been made for Kr $M_{4,5}N_1N_{2,3}$ transitions [6]. As discussed above, in general, these measurements do not constitute a complete experiment. However, for the particular case $J_f = 1/2$ only two partial waves contribute to the decay, therefore only one ratio and one phase difference should be determined, what was made in [4]. A more difficult situation was encountered in [5]. The studied transition $N_4O_{2,3}O_{2,3}\,{}^3P_1$ is described by three amplitudes corresponding to three partial waves $s_{1/2}$, $d_{3/2}$ and $d_{5/2}$. Thus two ratios of absolute values of amplitudes $\eta_1 = |M_{1/2}|/|M_{5/2}|$ and $\eta_2 = |M_{3/2}|/|M_{5/2}|$ and two phase differences $\delta_1 = \Delta_{1/2} - \Delta_{5/2}$ and $\delta_2 = \Delta_{3/2} - \Delta_{5/2}$ should be determined. In experiment, the transition was induced by circularly polarized light and two spin-polarization parameters (equivalent to δ_1 and ξ_1) and the angular anisotropy parameter α_2 have been measured [5]. The third component of the spin-polarization vector, perpendicular to the reaction plane, does not give new information due to the existence of the relation (11). It is clear that one cannot obtain two ratios and two phase differences from three measured values. However, we can consider one of the unknown values, for example, the relativistic phase difference δ_2, as a parameter and draw the parametric curves for the other three quantities using the measured values of the spin-polarization and anisotropy parameters. This is shown in Fig. 1. The solid curves represent the values of η_1, η_2 and δ_1 as functions of δ_2 which are consistent with the measurements. Now we note that according to theoretical calculations the relativistic phase difference δ_2 is usually small, close to zero. Inspection of Fig. 1 shows that in the region of $\delta_2 \approx 0$ all curves are rather flat, therefore, the ratios are not very sensitive to the exact value of δ_2. Assuming $\delta_2 = 0$ (i.e. changing the model!) one gets the values η_1, η_2 and δ_1 i.e. realizes an almost complete experiment [5].

Very recently a combination of measurements of circular polarization of fluorescence and parameters of the Auger electrons was used to obtain the amplitudes for the resonant Auger decay of the Xe $4d^{-1}_{5/2}6p$ core-excited state [14]. The resonance was excited by circularly polarized synchrotron radiation. A decay to the Xe^+ $5p^46p$ $J = 1/2$ states with the following fluorescence transition to the $5p^46s$, 5d states has been studied. The residual ion states with $J = 1/2$ have been selected what diminished the number of unknown parameters to only one amplitude ratio ($R = |M_{1/2}|/|M_{3/2}|$) and one phase difference ($\Delta = \delta_{1/2} - \delta_{3/2}$). A measurement of the circular polarization of fluorescence yields the orien-

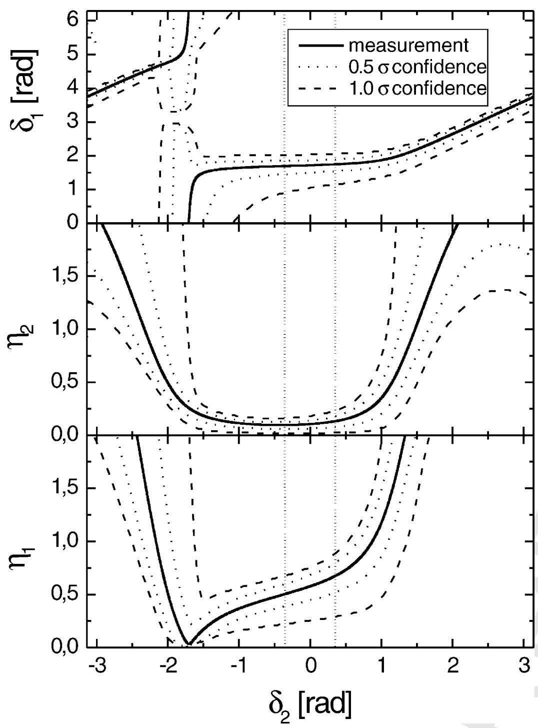

Fig. 1. Solution space of the amplitude ratios and phase shift differences for the Xe $N_4O_{2,3}O_{2,3}$ $^3P_1$ Auger decay transition. The solid curve represents the solution which correspond to the measured values of the intrinsic parameters [5]. The dotted/dashed curves mark the area which may be occupied if the measured intrinsic parameters are varied within the range of $1/2\sigma/1\sigma$, respectively. The figure is taken from [5].

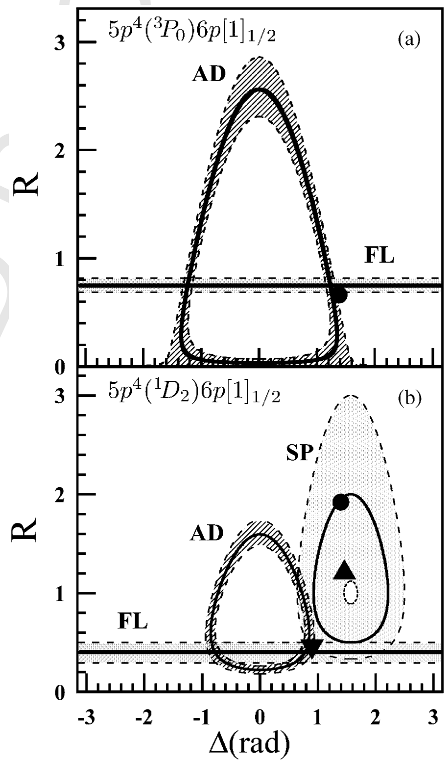

Fig. 2. (a) Parametric plot $R(\Delta)$ for the electron angular distribution (AD) data together with the value of R determined from the fluorescence polarization (FL) for final state $5p^4(^3P_0)6p[1]_{1/2}$ [14]. (b) The equivalent data for final state $5p^4(^1D_2)6p[1]_{1/2}$ along with the plot for the spin-polarization (SP) data [4]. The shaded areas show the error bars. Theoretical results from [48] (●); [35] (triangle down) and [4] (triangle up). The figure is taken from [14].

tation of the residual ion after the resonant Auger decay and determines the ratio of the absolute values of two amplitudes. The authors then used the anisotropy parameter of the angular distribution of resonant Auger electrons in order to obtain the cosine function of the phase difference. The intersection of the two parametric plots $R(\Delta)$ gives the absolute value of the phase difference (see Fig. 1(a)) . In one case additional information about the sign of the phase difference was obtained using the data on the spin-polarization of the Auger electrons [4] (see Fig. 2(b)). This almost complete experiment was realized without any additional approximation [14].

As the last example, I have chosen a coincidence study of a cascade of Auger transitions in resonant photoexcitation of Ar $2p^{-1}4s$ [7,42] by linearly polarized light. Resonant Auger decay to the states of Ar^+ $3s^{-1}3p^{-1}4s$ ^2P has been studied. The latters can further decay with the emission of the second-step Auger electrons to the states Ar^{2+} $3p^4$ ^3P_J. Both resonant and the second-step Auger electrons were detected in the plane perpendicular to the photon beam. The angular correlation function in this case can be written using a general approach developed in [45,32]. In the particular geometry of this experiment (see inset in Fig. 3) the second-step Auger electron was detected at the angle $\theta = 270^\circ$ with respect to the photon polarization vector. Then the angular distribution of the resonant Auger electrons can be presented as

$$I(\theta) = A_0 + A_2 \cos 2\theta + A_4 \cos 4\theta \qquad (14)$$

Fitting this expression to the experimental points (see Fig. 3(b)) yields two parameters A_2/A_0 and A_4/A_0 which depend on matrix elements of Auger decay. Another two parameters were obtained from the independent measurements of the angular anisotropy of the first (β_1) and the second (β_2) Auger emissions. These four experimental values are not sufficient to determine three relativistic amplitudes ($s_{1/2}$, $d_{3/2}$ and $d_{5/2}$-waves) describing the resonant Auger decay. However, if LSJ approximation is used for the ionic states and the non-relativistic approximation for the Auger electrons, then only two, s- and d-amplitudes describe the resonant Auger decay, thus only one ratio and one phase difference are necessary to determine. In this case, the experimental information obtained is even redundant [7]. This is an advantage since the experiment is rather complicated and the error bars are large. Analysis of the experimental data yields the amplitudes and cosine function of the phase difference [7].

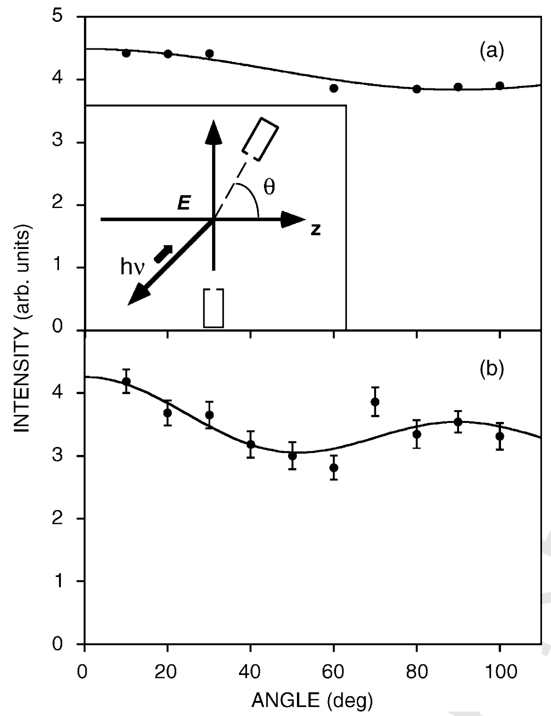

Fig. 3. Angular distributions for the resonant Auger electrons ejected in the first-step decay of the Ar $2p_{3/2} \rightarrow 4s$ excitation; (a) without detecting the second-step Auger electrons and (b) detecting in coincidence the second-step Auger electrons in the direction of $\theta = 270^\circ$. The solid curves show the result of the fit to the theoretical expressions. In the inset of (a) the kinematics of the experiment is shown. The figure is taken from [7].

5. Conclusions

In conclusion, a complete experiment for Auger decay is not only in principle possible but also quite feasible with modern experimental facilities. Several successful attempts of almost complete experiments for normal and resonant Auger processes have been published.

In general, it is not possible to realize a complete experiment by studying the parameters of Auger electrons only, information about the polarization state of the residual ion is necessary. The only exception from this rule are the transitions to the $J_f = 1/2$ final ionic states.

Intrinsic parameters describing the angular distribution and spin polarization of the Auger electron are interrelated. For many particular cases of practical interest all relations between intrinsic parameters are found. However, in the general case the relations are still unknown. Additional theoretical efforts are also necessary in order to understand the physical reason for the existence of those relations.

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References

[1] U. Becker, A. Crowe (Eds.), Complete Scattering Experiments, Kluwer Academic Publishers/Plenum Press, New York, 2001.

[2] J. Kessler, Comments Atom. Mol. Phys. 10 (1981) 47.
[3] N.M. Kabachnik, I.P. Sazhina, J. Phys. B 23 (1990) L353.
[4] U. Hergenhahn, G. Snell, M. Drescher, B. Schmidtke, N. Müller, U. Heinzmann, M. Wiedenhöft, U. Becker, Phys. Rev. Lett. 82 (1999) 5020.
[5] B. Schmidtke, T. Khalil, M. Drescher, N. Müller, N.M. Kabachnik, U. Heinzmann, J. Phys. B 33 (2000) 5225.
[6] B. Schmidtke, T. Khalil, M. Drescher, N. Müller, N.M. Kabachnik, U. Heinzmann, J. Phys. B 34 (2001) 4293.
[7] K. Ueda, Y. Shimizu, H. Chiba, Y. Sato, M. Kitajima, H. Tanaka, N.M. Kabachnik, Phys. Rev. Lett. 83 (1999) 5463.
[8] A.N. Grum-Grzhimailo, A. Dorn, W. Mehlhorn, Comments Atom. Mol. Physics Comments Mod. Phys. 1D (1999) 29.
[9] A.N. Grum-Grzhimailo, A. Dorn, W. Mehlhorn, in: U. Becker, A. Crowe (Eds.), Complete Scattering Experiments, Kluwer Academic Publishers/Plenum Press, New York, 2001, p. 111.
[10] H.-J. Beyer, J.B. West, K.J. Ross, K. Ueda, N.M. Kabachnik, H. Hamdy, H. Kleinpoppen, J. Phys. B 28 (1995) L47.
[11] H.-J. Beyer, J.B. West, K.J. Ross, K. Ueda, N.M. Kabachnik, H. Hamdy, H. Kleinpoppen, J. Electron Spectrosc. Relat. Phenom. 79 (1996) 339.
[12] J.B. West, K.J. Ross, K. Ueda, H.-J. Beyer, J. Phys. B 31 (1998) L647.
[13] K. Ueda, J.B. West, K.J. Ross, H.-J. Beyer, N.M. Kabachnik, J. Phys. B 31 (1998) 4801.
[14] P. O'Keeffe, S. Aloise, M. Meyer, A.N. Grum-Grzhimailo, Phys. Rev. Lett. 90 (2003) 023002.
[15] V.V. Balashov, A.N. Grum-Grzhimailo, N.M. Kabachnik, Polarization and Correlation Phenomena in Atomic Collisions: A Practical Theory Course, Kluwer Academic Publishers/Plenum Press, New York, Chapter 1, 2000.
[16] N.M. Kabachnik, I.P. Sazhina, J. Phys. B 17 (1984) 1335.
[17] H. Klar, J. Phys. B 13 (1980) 4741.
[18] N.M. Kabachnik, J. Phys. B 14 (1981) L337.
[19] R. Kuntze, M. Salzmann, N. Böwering, U. Heinzmann, Phys. Rev. Lett. 70 (1993) 3716.
[20] R. Kuntze, M. Salzmann, N. Böwering, U. Heinzmann, V.K. Ivanov, N.M. Kabachnik, Phys. Rev. A 50 (1994) 489.
[21] G. Snell, M. Drescher, N. Müller, U. Heinzmann, U. Hergenhahn, J. Viefhaus, F. Heiser, U. Becker, N.B. Brookes, Phys. Rev. Lett. 76 (1996) 3923.
[22] G. Snell, M. Drescher, N. Müller, U. Heinzmann, U. Hergenhahn, U. Becker, J. Phys. B 32 (1999) 2361.
[23] G. Snell, B. Langer, A.T. Young, N. Berrah, Phys. Rev. A 66 (2002) 022701.
[24] N.M. Kabachnik, O.V. Lee, J. Phys. B 22 (1989) 2705.
[25] B. Lohmann, Habilitation thesis, Westfälisher Wilhelms-Universität Münster, 1998.
[26] U. Kleiman, B. Lohmann, K. Blum, J. Phys. B 32 (1999) 309.
[27] B. Lohmann, J. Phys. B 32 (1999) L643.
[28] N.M. Kabachnik, I.P. Sazhina, J. Phys. B 35 (2002) 3591.
[29] N.M. Kabachnik, I.P. Sazhina, J. Phys. B 34 (2001) L559.
[30] N.M. Kabachnik, A.N. Grum-Grzhimailo, J. Phys. B 34 (2001) L63.
[31] N.M. Kabachnik, in: D.H. Madison, M. Schulz (Eds.), Correlation, Polarization and Ionization in Atomic Systems, AIP Conference Proceeding, vol. 604, 2002, p. 223.
[32] N.M. Kabachnik, I.P. Sazhina, K. Ueda, J. Phys. B 32 (1999) 1769.
[33] H. Yoshida, K. Ueda, N.M. Kabachnik, Y. Shimizu, Y. Senba, Y. Tamenori, H. Ohashi, I. Koyano, I.H. Suzuki, R. Hentges, J. Viefhaus, U. Becker, J. Phys. B 33 (2000) 4343.
[34] M. Kitajima, M. Okamoto, Y. Shimizu, H. Chiba, S. Fritzsche, N.M. Kabachnik, I.P. Sazhina, F. Koike, T. Hayaishi, H. Tanaka, Y. Sato, K. Ueda, J. Phys. B 34 (2001) 3829.
[35] B.M. Lagutin, I.D. Petrov, Ph.V. Demekhin, V.L. Sukhorukov, F. Vollweiler, H. Liebel, A. Ehresmann, S. Lauer, H. Schmoranzer, O. Wilhelmi, B. Zimmermann, K.-H. Schartner, J. Phys. B 33 (2000) 1337.
[36] B. Zimmermann, O. Wilhelmi, K.-H. Schartner, F. Vollweiler, H. Liebel, A. Ehresmann, S. Lauer, H. Schmoranzer, B.M. Lagutin, I.D. Petrov, V.L. Sukhorukov, J. Phys. B 33 (2000) 2467.
[37] M. Meyer, A. Marquette, A.N. Grum-Grzhimailo, U. Kleiman, B. Lohmann, Phys. Rev. A 64 (2001) 022703.
[38] R.H. Schill, D. Hasselkamp, S. Krammer, S. Mickat, B. Zimmermann, K.-H. Schartner, A. Ehresmann, H. Schmoranzer, M. Schlüter, Yu.A. Schutov, B.M. Lagutin, V.L. Sukhorukov, J. Phys. B 36 (2003) L57.
[39] B.M. Lagutin, I.D. Petrov, V.L. Sukhorukov, S. Kammer, S. Mickat, R. Schill, K.-H. Schartner, A. Ehresmann, Yu.A. Shutov, H. Schmoranzer, Phys. Rev. Lett. 90 (2003) 073001.
[40] R. Wehlitz, L.S. Pibida, J.C. Levin, I.A. Sellin, Phys. Rev. A 59 (1999) 421.
[41] U. Becker, J. Viefhaus, in: D.M. Campbell, H. Kleinpoppen (Eds.), Selected Topics on Electron Physics, Plenum Press, New York, 1996, p. 333.
[42] K. Ueda, Y. Shimizu, H. Chiba, M. Kitajima, H. Tanaka, S. Fritzsche, N.M. Kabachnik, J. Phys. B 34 (2001) 107.
[43] K. Ueda, Y. Shimizu, H. Chiba, M. Kitajima, M. Okamoto, M. Hoshino, H. Tanaka, T. Hayaishi, S. Fritzsche, I.P. Sazhina, N.M. Kabachnik, J. Phys. B 36 (2003) 319.
[44] G. Turri, G. Battera, L. Avaldi, R. Camilloni, M. Coreno, A. Ruocco, R. Colle, S. Simonucci, G. Stefani, J. Electr. Spectrosc. Relat. Phenom. 114-116 (1999) 199.
[45] N.M. Kabachnik, in: R.L. Johnson, H. Schmidt-Böking, B.F. Sontag (Eds.), X-Ray and Inner-Shell Processes, AIP Conference Proceedings, 389, 1997, p. 689.
[46] B. Schmidtke, M. Drescher, N.A. Cherepkov, U. Heinzmann, J. Phys. B 33 (2000) 2451.
[47] N.M. Kabachnik, K. Ueda, J. Phys. B 28 (1995) 5013.
[48] B. Lohmann, U. Kleiman, in J. Berakdar, J. Kirschner (Eds.), Many-Particle Spectroscopy of Atoms, Molecules, Clusters and Surfaces, Kluwer Academic Publishers/Plenum Press, New York, 2001, p. 173.