# Observation of the *KLL* Dielectronic Recombination Process in Highly Stripped Argon Ions

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A novel technique for studying the dielectronic recombination process is presented. The interaction of very highly stripped trapped ions with a tunable energy electron beam is studied using an electron-beam ion source. Dielectric recombination resonances have been observed in $Ar^{12+,13+,14+,15+}$ for single configurations (*KLL* resonances). The generality of this method which makes possible the selective study of electron-ion interactions of plasma diagnostic interest is discussed.

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The dielectronic recombination process (DR), i.e., the simultaneous capture of a free electron and excitation of an ion,

$$A^{n+}+e^{-}\rightarrow A^{(n-1)+}\text{ (doubly excited)}\rightarrow A^{(n-1)+}+h\nu,$$

has been observed in plasmas for a very long time. The resonant behavior of this process, which is the inverse Auger effect and occurs only at the energy of the corresponding autoionization electron, has been, only very recently, observed in cross beam experiments.[1-3] In such experiments, in contrast with what is observed in plasmas, one can observe the interaction of a given ion with an electron of a given energy. In all these experiments, it was then possible, for the first time, to measure the integrated absolute cross sections of DR on all the individual resonances up to the continuum, of singly,[1,2] doubly, and triply[3] ionized atoms.

We present in this Letter a novel and general technique in which, instead of studying DR in cross beam experiments, we bombarded with an electron beam a target of trapped ions in an electron-beam ion source (EBIS). This general technique is illustrated in this Letter where the resonant behavior of DR on single $n=2$ ($^2D$) term of $Ar^{14+}$ ions has been observed. This new technique can be used to study any ion prepared inside an EBIS source, and to measure the differential DR cross sections on each energy level of each of these ions.

The method consists of studying the interaction of an electron and a given ion inside an EBIS and in detecting the DR resonances by observing the emitted x rays. An EBIS source (Fig. 1) is mainly made of a very intense and very narrow electron beam in which a neutral gas is injected. The injected atoms are ionized, then trapped inside the electron beam by its charge density, and, if the vacuum is good enough to prevent electron capture via charge exchange with the residual gas impurities, the ions can reach, step by step, the ultimate charge state (bare nuclei). The experiment was carried out with the SILFEC III

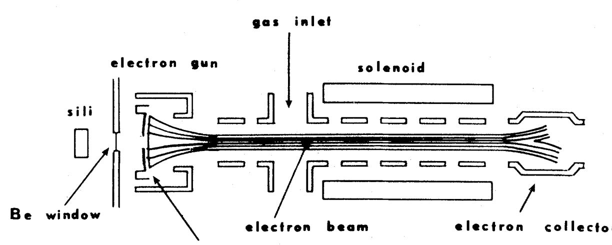


FIG. 1. Scheme of an EBIS source.

EBIS source built at the Institute for Nuclear Physics in Orsay. This source which serves as a prototype of the CRYEBIS II[4-6] source in preparation is made of a long solenoid providing a 0.5-T magnetic field, in which a ~20 mA electron beam is injected. In this very compressed beam (≤1 mm) some argon gas is injected and ionized up to the 16+ charge state. A series of cylindrical electrodes, centered on the axis of the solenoid allowed a longitudinal trapping of the ions.

The principle of the experiment is to study the interaction between the ions in the source and the ionizing electron beam by looking at the x rays emitted through a very small hole drilled into the cathode of the electron gun and closed by a beryllium foil. In this preliminary experiment the detection is simply achieved by using a SiLi detector, located outside the source. After being prepared, the ions, instead of being ejected into a particle accelerator as in the normal running, are maintained trapped for a very long time (up to 10 s) inside the source before being ejected, and the cycle is reproduced up to sufficient yield for a given energy. The electron beam energy is then tuned, step by step, until the resonance condition is reached.

For a given ion, various resonances can be observed depending on the quantum numbers of the final state of the ion and on the energy spread of the electron beam. The energy spread in an EBIS source is mainly determined by two parameters: the depth of the potential well created by the beam charge density (the energy of the electrons in the beam depends on their distance from the solenoid axis) and the voltage fluctuations in the electron gun supply. In the present experimental conditions, the potential well depth is, as it can be easily calculated, equal to 6 eV, and the overall beam resolution turns out to be equal to 10+6=16 eV. With such an energy resolution, it is possible, for instance, to separate the first resonances of the argon $(2l)(nl')$ final doubly excited configurations, and in some cases some of the level structures of these configurations. The energy spread of the beam is, however, much larger than the width of the resonance, which is equal to the natural width of the level (typically ~0.03 eV). Then it is not possible with the present experimental conditions, to scan the shape (Fano profiles) of the individual resonances.

Three different interaction processes between the electrons and the ions, producing $K$ x rays in the source, have to be considered.

(i) *Ionization.*— This process has the largest cross section at high energy and its absolute energy threshold is equal to the $K$ binding energy $B_K$.

(ii) *Excitation.*— This process is less efficient and its threshold is equal to $B_K - B_L$.

(iii) *DR.*— The calculated cross section for this process is between the two previous ones. Its resonance energy is less than that of the excitation threshold. In the case of a $KLL$ DR, it is $\cong B_K - 2B_L$ (we use for the DR process the same labels as those for the Auger effect: A $KLL$ DR corresponds, for instance, to the case of a $K$ electron excited to the $L$ shell and a free electron captured in the $L$ shell). All the $K$ x rays of the argon ions appearing at excitation energies less than $B_K - B_L$ can then be unambiguously attributed to DR reactions (Fig. 2).

In the SILFEC III source, the vacuum was of the order of $10^{-9}$ Torr and many charge states of the considered element were simultaneously present at equilibrium. For studying, for instance, only the $KLL$ DR resonances in argon ions we will be dealing only with the ions having two $K$ electrons and at least two holes in the $L$ shell (one for the capture of the free electron and another one for the excitation of a $K$ electron to the $L$ shell). The DR cross sections for all the considered ions in all the final states have been calculated as well as the resonance energies by using theoretical methods described elsewhere.[7-11] The theoretical excitation spectrum obtained by folding these values with the relative intensity of the measured equilibrium charge state distribution is presented in Fig. 3. It appears from this figure that the energy separation of all the $KLL$

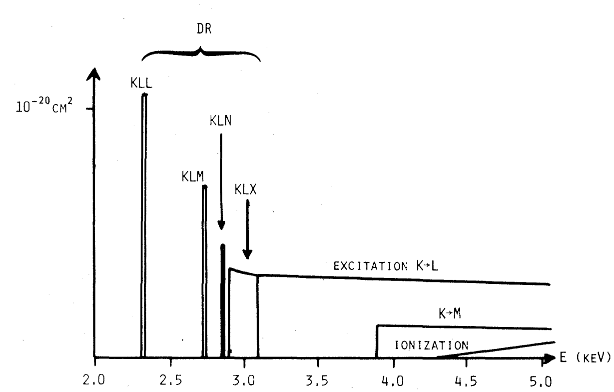


FIG. 2. Typical excitation function in the $e^- + Ar^{14+}$ reaction.

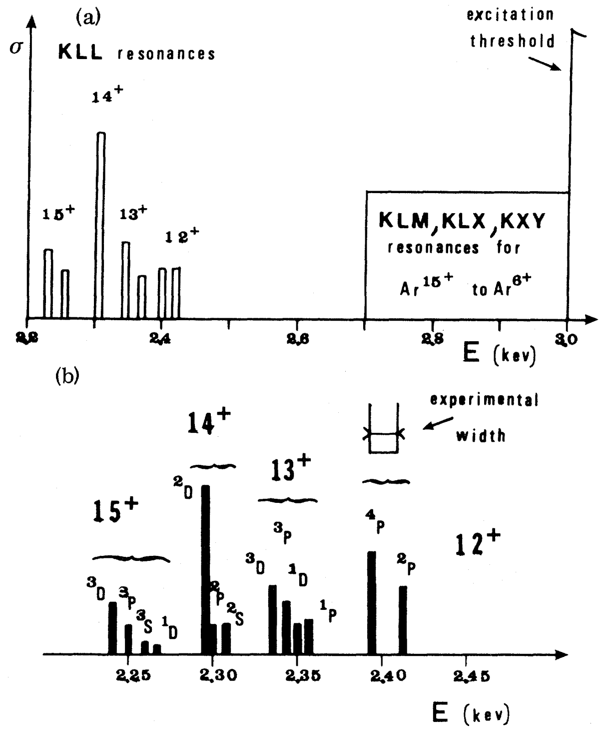


FIG. 3. (a) Schematic view of the excitation function of various charge states of argon. (b) Detailed theoretical predictions for the *KLL* DR resonances for $Ar^{15+,14+,13+}$ and $Ar^{12+}$.

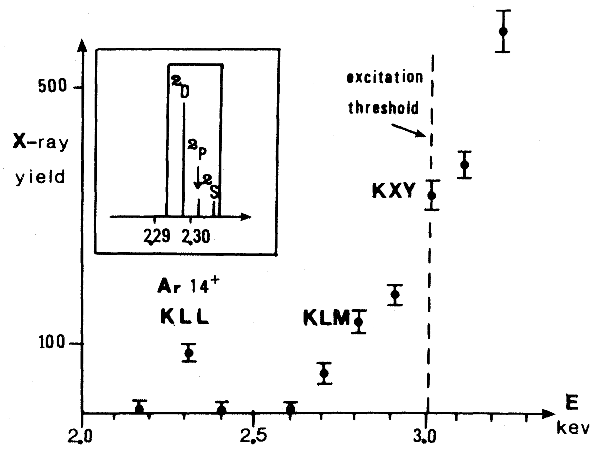


FIG. 4. Experimental x-ray yield (absolute counting rate). The horizontal error bar represents the uncertainty in the absolute energy of the electrons.

resonances for the various argon ions under consideration is larger than the energy resolution of the beam, allowing among all the present ions to select, in principle, the resonances of a given ion. In contrast, the different *KLM*, *KLX*, *LMX*,... DR resonances may not be separated, some *KLN* resonances of a given charge state being very close, for instance, to those of the *KLO* of another one.

In a first series of experiments with a narrow energy-band pass of the electron beam as compared to the energy region to scan (15 eV compared to 300 eV), we only searched for the $Ar^{14+}$ peak at 2.3 keV which exhibits the sharpest and the most pronounced resonance (85% of the total cross section is expected to appear in the $^2D$ term). The experimental results are presented in Fig. 4 where a significant resonance at the expected (2.3 keV) energy has been observed and a background compatible with zero has been found on both sides of the zone of the resonances for all the considered ions. In this spectrum one can also observe a nonmonotonic unresolved spectrum in the region where the *KLM*...*KXY* resonances are all mixed and a continuous increase of the x-ray yield above the absolute excitation threshold for the whole set of charge states present in the source. With the present uncertainty in the absolute energy measurement of the electron beam, ±15 eV, no conclusion can be formulated, in this series of experiments, about the other resonances, like the 12+ for instance. In a second series of experiments, at lower resolution, a broad structure extending over the 15+ to 12+ resonance energy range has also been observed. The absolute x-ray counting rate can, in principle, provide a value for the absolute DR cross section, if all the geometric parameters of the source, the electron beam intensity, and the number of ions stored in the source are known. The number of stored ions can easily be measured with a Faraday cup and a time-of-flight apparatus, and the electron beam intensity by a conventional device. A rough estimate of the absolute cross section for the $Ar^{14+}$ resonance is found to be of the same order of magnitude as the theoretical predictions,[7-11] i.e., $10^{-20}$ cm$^2$. However, it can be noticed that some uncertainties remain in the determination of the diameter of the confinement cylinder because the electron beam does not follow a pure Brillouin flow.

This technique, whose feasibility has been proved in this experiment, can be applied to any highly stripped ion which can be prepared in an EBIS or CRYEBIS source, i.e., for instance, up to $Ar^{17+}$, $Kr^{34+}$, ..., $U^{90+}$.[12] Most of the ions appearing in laboratory and solar plasmas could be studied in measuring their DR cross sections as well as their excitation cross sections.

Moreover, this technique is of general interest for extended spectroscopic studies, the geometrical conditions of the sources as well as the nature of the emitters (few electron ions of narrow natural width) allowing high-resolution spectroscopic analysis.

[1]J. B. A. Mitchell, C. T. Ng, J. L. Forand, D. P. Levac, R. E. Mitchell, A. Sen, D. B. Miko, and J. W. McGowan, Phys. Rev. Lett. 50, 335 (1983).

[2]D. S. Belic, G. H. Dunn, T. J. Morgan, D. W. Mueller, and C. Timmer, Phys. Rev. Lett. 50, 339 (1983).

[3]P. F. Dittner, S. Datz, P. D. Miller, C. D. Moak, P. H. Stelson, C. Bottcher, W. B. Dress, G. D. Alton, and N. Neskovic, Phys. Rev. Lett. 51, 31 (1983).

[4]E. D. Donetz, V. I. Ilyuschenko, and V. A. Alpert, in *Proceedings of the First International Conference on Ion Sources, Saclay, France, 1969* (Institute Nationale des Sciences et Techniques Nucleaires, Saclay, 1970), p. 635.

[5]J. Arianer and R. Geller, Ann. Rev. Nucl. Part. Sci. 31, 19 (1981).

[6]J. Arianer, A. Cabrespine, and C. Goldstein, Nucl. Instrum. Methods 193, 401 (1982).

[7]F. Bely-Dubau, A. H. Gabriel, and S. Volonté, Mon. Not. R. Astron. Soc. 186, 405 (1979).

[8]F. Bely-Dubau, J. Dubau, P. Faucher, and A. H. Gabriel, Mon. Not. R. Astron. Soc. 198, 239 (1982).

[9]F. Bely-Dubau and J. Dubau, in *Proceedings of the Thirteenth International Conference on the Physics of Electronic and Atomic Collisions, Berlin, 1983, Abstracts of Contributed Papers*, edited by J. Eichler (ICPEAC, Berlin, 1983), p. 215.

[10]D. J. Mc Laughlin and Yukap Hahn, Phys. Lett. 88A, 394 (1982).

[11]K. LaGattuta and Y. Hahn, Phys. Rev. A 27, 1675 (1983).

[12]J. Arianer, M. Brieut, C. Collart, C. Goldstein, J. MacFarlane, M. Malard, P. Nical, A. Serafini, and A. Steinegger, in Proceedings of the II EBIS Workshop, Saclay-Orsay, May 12–15, 1981 (unpublished), p. 240.