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Time-resolved atomic spectroscopy with fast-ion beams, heavy-ion storage rings and ion traps

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Abstract.
The understanding of the light received from astrophysical sources requires knowledge of atomic structure and dynamics, or of excitation cross sections and conditions, wavelengths and transition probabilities, f-values, branching ratios and level lifetimes. Fast ion beams (by beam-foil spectroscopy) and ion traps, as well as their cross-breed, the heavy-ion storage ring, can contribute to the field of X-ray astronomy. Fast-ion beam spectroscopy has a long track record in all spectral ranges, including XUV and X-ray, with a plethora of data supporting astrophysics. In contrast, most of the time-resolved work with the ion trap techniques has been done in the UV and VUV/EUV above 100 Å, but it can be extended into the region of interest.

1. Introduction

X-ray spectroscopy at wavelengths of below 100 Å and in an astrophysical context is the topic of this conference. My field of interest for about a quarter century now has been the study of ions with a time resolution that permits the investigation of atomic properties, that is level lifetimes, branching ratios, multiplet mixing and the like. Most of my (and everybody else's) work in this field was not in the aforementioned wavelength band. However, at least some of it was, and that work demonstrates what can be done. Moreover, there is a lot of interesting work that has been done in other wavelength ranges and that paved the way for future work in the desired region. Some of the work was done in the near-ultraviolet, some in the vacuum-UV (VUV), most in the extreme-UV (EUV), and also some in the very range to be discussed at this meeting. My presentation is structured by the techniques and devices used, and it lists the particular properties and advantages. With such a catalog, it should become possible to identify the most suitable technique and the probably best-versed laboratory for soliciting specific information when it will be needed to interpret the data from future soft-X-ray astronomical work. As I am presenting my views, I found it easiest (for me) in several cases to offer entries for the search into the vast further literature on the subject (in particular beam-foil spectroscopy, a field that has been covered in a sequence of topical conferences) via my own work, although, of course, that represents only a fraction of all the work done. An "executive-style" summary of lifetime measurements and capabilities is presented in Table 1.

2. Beam-foil spectroscopy

Beam-foil spectroscopy, the study of light emitted by fast ion beams after being sent through a thin foil of solid material (Figure 1), has been invented in the early 1960s. One of the very first papers in the field claimed the "Laboratory excitation of the emission spectrum of a Nova", stressing the fact that the optical spectrum of an energetic nitrogen ion beam looked very different from that of ordinary (thermal, dense) light sources and that it contained lines that also appeared in astrophysical data, but that had not been seen in other terrestrial light sources (Bashkin and Meinel 1964). This feature is just one of many interesting ones of the beam-foil technique (Träbert 1997).

Table 1. Examples of lifetime studies

Beam-Foil work at Bochum, Lund, Oxford, Argonne, RIKEN (and many other places):
Allowed transition rates in Li-, Be-, B-, Ne-, and Na-like ions
Intercombination transition rates in He-, Mg-, Al-, and Si-like ions (Träbert et al. 1988)
High-J level identification and lifetimes in Si-, P-, and S-like ions (Träbert 1999)
Lifetimes 1 ps to 30 ns, typical precision 5 - 10%

Heavy-ion storage ring at Heidelberg:
Intercombination transition rate in C^{2+} to $\pm 0.14\%$ (Doerfert et al. 1997)
Systems investigated:
B^{+} (Träbert et al. 1999b), C^{2+} (Doerfert et al. 1997), C^{+}, N^{2+} (Träbert et al. 1999c),
N^{+} (Träbert et al. 1998), O^{2+} (Träbert et al. 2000a), Al^{+} (Träbert et al. 1999b)
Lifetimes 0.3 ms to 100 ms

M1/E2 transition rates to $\pm 0.2\%$ to $\pm 5\%$
Systems investigated:
F^{+} (Calamai et al 2000), O^{2+}, F^{3+} (Träbert et al. 2000a), Si^{6+}, Si^{8+} (Träbert et al. 1998a),
S^{9+} (Träbert et al. 2000a), Sc^{12+} (Träbert et al. 1999), Ti^{13+}, Ti^{17+} (Träbert et al. 2000b),
B^{3+}, C^{4+}, N^{5+} (Schmidt et al. 1994)
Lifetimes 0.5 ms to 500 ms

Livermore EBIT:
M1 transition rates
in B- and F-like ions of Ar (UV) to $\pm 2\%$ (Träbert et al. 2000c)
Lifetimes up to 15 ms
M1 transition rates in He-like ions (soft-X-ray) to $\leq 1\%$:
N^{5+} (Neill et al 2000), O^{6+} (Crespo López-Urrutia et al. 1998), F^{7+} (Neill et al. 2000), and
Ne^{8+} (Träbert et al. 1999a)
Lifetimes 30 μs to 4 ms

The beam-foil excitation process largely takes place in a dense medium. It is violent, non-thermal and non-selective, and it reaches high-lying levels in ordinary atomic level systems as well as core-excited states. In stark contrast, de-excitation of the ions, after leaving the bulk of the foil, takes place in good vacuum without further collisions, and the light source is optically thin. Magnetic and electrical fields guide the ion beams to the experimental site; consequently the beams are isotopically pure, and it can be ascertained that a specific spectral line in a beam-foil spectrum belongs to a specific element. The charge state distribution of the ions after the foil is a function of the ion beam energy; the beam energy can be varied in order to identify the ion charge state that gives rise to a given spectral line. With a suitable accelerator, any charge state of any element is accessible. For data to compare with the solar chromosphere (singly charged ions), a few hundred keV of ion energy are ample (see the ion-beam laser work at Edmonton (Pinnington et al. 1992, 1993) and at various other places that helped to check on solar abundances). For ions and charge states typical of the solar corona, accelerators are needed that provide ion beams of up to about 30 MeV, while for the reproduction of some solar flare data, an ion energy of order 100 MeV is necessary.

Fast-ion beam spectroscopy works in all spectral ranges; there are X-ray spectra, EUV, UV, visible and infrared studies, as well as laser-assisted investigations in the near-UV to the IR, and some long-wavelength laser resonance experiments exploit X-ray detection schemes. From neutral atoms to hydrogen-like Fe, all ions of primary astrophysical interest have already been studied (though far from exhaustively). For the wavelength range of present interest, that is on the short side of 100 Å, grazing-incidence spectrometers with concave gratings (R=2.2 m or 1.5 m, angle of incidence 86^o to 88^o) and channeltron detectors have been successfully employed down to about 10 Å(Möller et al. 1998). Multichannel detection nowadays is feasible, but it has not yet been used on many "astrophysical" ions in the present range of interest. For beam-foil spectroscopy in the true X-ray range, R=5" curved-crystal

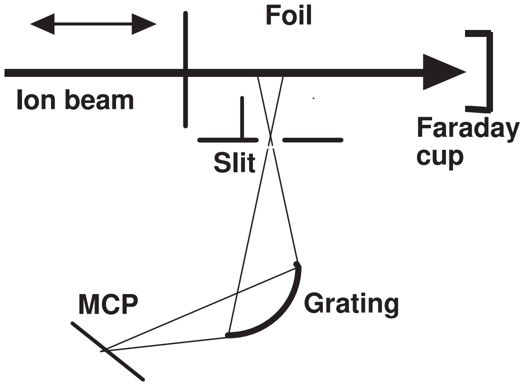

Figure 1. Schematics of beam-foil spectroscopy, with a grating spectrometer that is equipped with a microchannelplate (MCP) multiplex detector. The foil can be moved with respect to the viewing region of the detection system, and thus time-resolved spectra of different delay time after excitation, or decay curves for lifetime measurements, can be recorded.

spectrometers proved their value in survey spectra down to about 2 Å(Träbert et al. 1979; Armour et al. 1980). The results compared well with X-ray spectra from early sounding rockets and satellite missions.

Interestingly, there are satellite lines on the short-wavelength side of the resonance lines in He-like ions that have been seen by beam-foil spectroscopy some 20 years ago (Träbert et al. 1979; Armour et al. 1980). Meanwhile such lines from multiply-excited few-electron atoms are being subsumized in the fashionable field of "hollow atoms" that links fields seemingly as far apart as ion-surface interactions and plasma pinches. The resolving power of the experiments that observed fast-ion beams with curved-crystal spectrometers, equipped with commercial crystals (RAP, EDT and the like) and with proportional counter detectors, was sufficient at the time. However, significant improvements in spectral resolution, at the cost of accelerator time, would clearly be feasible, as is the use of multichannel detectors. Some of the satellite line structure can be reduced by using a dilute gas target instead of a foil target. An extended gas target, however, takes away most of the geometry-related intrinsic time resolution, but it can be beneficial for high spectral resolution work on the diagram lines. Earlier attempts at precision spectroscopy on H-like and He-like Ar ions in a gas target ran aground with the problem of modeling the satellite line intensity distribution for $n>2$.

A very interesting and unique feature of the beam-foil light source is the already mentioned intrinsic time resolution. Close to the foil, the spectrum is full of lines and dominated by the decays of very many short-lived levels. Observing the ion beam farther away (centimeters) from the foil corresponds to an observation at times of nanoseconds after excitation. Short-lived levels (picosecond-range), like the resonance levels in ordinary ions or levels in core-excited ions, are depleted by then, and the emphasis in the spectra shifts to long-lived levels (nanosecond range). Typical levels of such lifetimes in multiply charged ions are the upper levels of intercombination transitions, or levels that otherwise only weakly couple to lower-lying levels. An upper limit of the level lifetimes in such observations is given by geometry: With ever longer lifetimes, the decay lengths (ion velocity times lifetime) grow beyond the size of practical vacuum chambers and laboratories, and the signal per unit length of ion beam observed drops below the noise level of the detector. In any case, such studies need powerful ion sources that are not available at or compatible with every type of ion accelerator.

The "delayed" spectra (Träbert et al. 1988) resemble solar coronal spectra in several ways. It has thus been possible to identify a number of intercombination transitions (Mg-, Al-, Si-, S-like ions of Ti to Cu) (Träbert et al. 1987, 1988) as well as the decays of some low-lying high-J levels (J=3 in Si-, J=7/2 in P-, J=5/2 in Cl-like ions (Träbert et al. 1993, 1996; Jupén et al. 1993; Träbert 1996, 1998), first in the delayed beam-foil spectra of iron group elements, and then, often with the benefit of better wavelength numbers, also in solar spectra that existed much earlier. In the latter spectra, many of the lines had either not yet been identified at all, or, because of the incompleteness of information in the atomic data bases, they had been assumed to originate from other ions. Obviously, these delayed spectra are a valuable ingredient in the analysis of the n=3 shell structure that draws on complementary data from laser-produced plasmas, tokamaks, the sun, and foil-excited ion beams. (On the not quite funny side, I am not going to cite a 1999 Ap.J. paper that claims that the ground state intercombination transitions in Al-like Fe XIV are not yet known, giving as evidence for this claim a NIST bibliography of 1988 (10 years old at the time!). That bibliography, indeed, did not yet cite the aforementioned 1987 publication (Träbert et al. 1987) of those very lines and their re-identification in spectra of the solar corona. However, other colleagues spotted that paper within a few years, and nowadays it is easily found using the ASD abstract service. I am afraid that in many cases a "has not been measured" ought to read as "has possibly been measured, but has not on its own account reached the eyes of a given person yet".)

Last, but not least, by observing the light of a given wavelength as a function of distance from the foil (time after excitation), it is possible to derive level lifetimes and transition probabilities. In practice, the longest lifetimes measured reasonably well by beam-foil spectroscopy are of order 30 ns (special cases reach up to a few hundred nanoseconds). The measurement of short lifetimes with this technique is also limited by geometry, the width and shape of the field of view of the detection system at the position of the ion beam, the displacement of the foil along the ion beam (a matter of μm precision) and the foil properties (Engström 1993; Engström and Bengtsson 1991). Although lifetimes of less than 1 ps have been reported, routine work starts from a few picoseconds up. In this usual working range, a precision of typically 5 to 10% is generally being reached. In a few cases, correlating the decay curve of a given level with transitions feeding it, even smaller lifetime uncertainties have been demonstrated.

For unbranched decays, the inverse of the upper level lifetime is the transition probability. In case of branched decays, transition probabilities of individual lines can be derived from the combination of a lifetime measurement with a determination of branching fractions (which may be based on the wavelength dependence of the relative detection efficiency). This has been demonstrated by a fast-beam experiment in the EUV (Träbert et al. 1983). An extension of this technique to the wavelength range below 100 Å is difficult because of the often poor and irregular performance of grazing-incidence optics.

The light observed from a fast ion beam is Doppler shifted and broadened. While for normal-incidence spectrometers "refocusing" techniques are known that can reduce the Doppler width of spectral lines in fast-beam observations, the same refocusing techniques affect the dispersion and make lines from stationary calibration light sources appear broadened. Furthermore, the geometry of grazing-incidence spectrometers is not compatible with these known schemes. Hence in most cases, EUV/XUV wavelength data from solar spectra will be available with a higher accuracy than those from fast ion beams. However, with appropriate precautions (often reducing the solid angle of observation) and employing a high-groove density diffraction grating, precise wavelengths can be obtained with fast ion beams, too (Mannervik et al. 1989). Line widths (FWHM) as small as 0.1 Å have been reached for beam-foil spectra below 200 Å, as has been demonstrated at Bochum, for example, for the H_β line of O VIII (Müller et al. 1982) and for the 3d-4f array in Ne-like Ti XIII (Jupén et al. 1996). This particular spectrum, by the way, is very similar in appearance to what has been observed at a tokamak plasma.

Much of this work has been done at the superbly suited Bochum accelerator facility where, alas, atomic physics is presently being phased out. Comparable spectroscopic facilities with grazing-incidence spectrometers (with a more limited accelerator performance for the ions of X-ray - astrophysical interest) are available, for example, at Université Laval (Québec, Canada; Lapierre and Knystautas 1999), Lund University (Sweden; Engström 1993), Argonne National Laboratory, Notre Dame (IN), and RIKEN (Japan; Hutton et al. 1997).

3. Ion traps

Ion traps aim at keeping ions contained in a small volume, for extended observation times. They come in many flavors or operating principles (Ghosh 1995), using electrostatic (Kingdon), magnetic (Penning) or radiofrequency electromagnetic field (Paul) confinement, or derivatives thereof, like the heavy-ion storage ring and the electron-beam ion trap (EBIT). One of the decisive factors in doing reliable lifetime measurements in such traps is the background pressure that limits the storage time because of collisional losses, including scattering and charge exchange reactions. For a long time, low-charge state ions have been produced from gas inside the trap (under high vacuum conditions, but nevertheless expecting the more signal from the more gas). This ambient gas then remains in the trap volume while the decay curve measurement takes place. Evidently, with less gas in the trap, less perturbation and fewer charge exchange collisions would occur. Pressure variation and decay-rate extrapolation towards zero pressure are regularly done, but they often remain unsatisfactory. It would obviously be much cleaner to produce the ions in one place, select the right species and transfer only that sample to a storage trap that runs under clean ultrahigh vacuum conditions.

One such approach at separating ion production and ion storage has been the combination of an electron cyclotron resonance ion source (ECRIS) with a Kingdon trap (electrostatic ion trap, at Texas A&M (Church 1993; Yang 1994), Reno (Moehs et al. 1991; Moehs and Church 1988, 1999a, 1999b), and Caltech (Smith et al. 1999). When the ion trap potentials are switched on, a fraction of the keV-ion beam that has been passing through the trap volume may be captured. The optical emission of this sample of trapped ions is then monitored, and the optical decay curve corrected for the ion losses from the trap. A number of cases in Ar, Mn and Fe, including some of astrophysical interest, has been treated this way, and the more recent lifetime results bear error bars of 1% to 15%. The authors, however, state that the comparison with theory remains largely inconclusive (although the very fact of these measurements marks a considerable step forward).

In a case (Ar^{14+}) where extensive theoretical calculations corroborate earlier calculations rather than the Kingdon trap lifetime measurements, a renewed discussion by the experimental authors (Church et al. 1999) has not brought to light any likely cause of the present disagreement which various parties would like to blame on the experimental side. Meanwhile an EBIT experiment done at Livermore (Träbert et al. 2000d) supports the theoretical claims rather than the Kingdon trap results. In another Kingdon trap experiment, on C^+ (Smith et al. 1999), the results initially came close to earlier radiofrequency ion trap data rather than to the concurrent, much more precise results from a heavy-ion storage ring experiment (Träbert et al. 1999c), but have shifted closer to the latter since. In this case, three exponential components have to be fitted to a spectrally unresolved decay curve that represents the superposition of lines from three closely-spaced levels ($^4P_{1/2,3/2,5/2}$), and good statistics are of utmost importance. Some extra caution seems warranted with data that required many weeks of collection at a Kingdon trap and then still remained poorer in statistics by about an order of magnitude in comparison to the data from a two-day experiment at the storage ring! Elaborate statistical tests cannot overcome poor data statistics in first place.

4. Heavy-ion storage rings

Another approach to separating ion storage from ion production is the heavy-ion storage ring (Müller and Wolf 1997), as available at Heidelberg, Stockholm, Aarhus, Darmstadt - none in the USA (Figure 2). In such a storage ring, the vacuum beam pipe and magnetic guidance system of an accelerator system are being turned into a ring into which an ion beam is injected and then left circulating. Ion production (in an ion source that is feeding an ion accelerator), charge-state selection (by the magnets in the ion beam transport system) and storage (in the storage ring) are spatially separated from each other (by 10 to 100 m) and can be optimized individually. Detection can exploit the change of ion trajectory after a change of ion charge state, for example by dielectronic recombination with electrons in a superimposed cold electron beam (Schmidt et al. 1994), or can proceed by straightforward optical observation (Doerfert et al. 1997). Ion storage times for MeV-ion beams are much longer (many seconds, in some cases minutes) than with the aforementioned Kingdon trap, and they can be measured directly and more reliably as well.

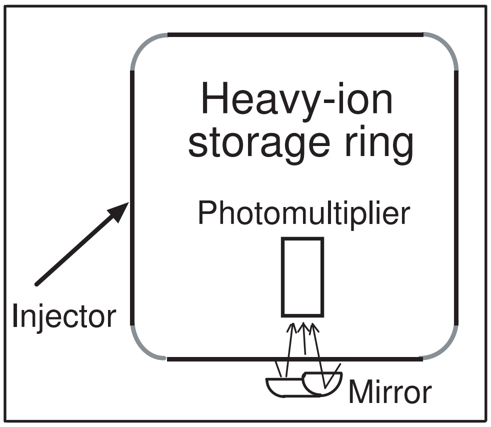

Figure 2. Schematics of atomic lifetime measurements at a heavy-ion storage ring. A single-charge state, single-isotope ion beam is injected into the storage ring and stacked for about 30 turns. Then injection ends, and the optical emission from the coasting ion beam is monitored for up to a few seconds.

At present, this type of heavy-ion storage ring experiment seems to be the technique of lowest systematic error, and it is also capable of high statistical precision in the lifetime range 0.5 to 500 ms. This lifetime range covers both, ground-state intercombination transitions in several light ions (Doerfert et al. 1997; Träbert et al. 1998, 1999b, 1999c) and forbidden transitions in quite a number of ions of astrophysical interest (Eidelsberg et al. 1981; Lynch et al. 1991; Träbert et al. 1998, 2000a, 2000b; Calamai etal 2000). The experimental lifetime results obtained so far on intercombination and on M1/E2 transitions lie within the range of scatter of the theoretical predictions, but carry much smaller uncertainties, often with a precision of 1% and better. Such a precision is testing theory in some cases, but not in all. For example, the $2s^2\ ^1S_0$ - $2s2p\ ^1P^o_1$ resonance transition in Be-like ions can be calculated by elaborate algorithms to a precision of better than 0.1%, which for nanosecond-lifetimes (and shorter) cannot be reached by experiment yet. The same calculations yield the intercombination transition rate with a precision of no better than about 1%, but the heavy-ion storage ring measurements can do much better than that for the millisecond lifetimes involved here (Jönsson et al. 1998). For "forbidden" transition rates, that is for M1 and E2 transitions, the calculations for a long time have been claimed to be "easy" and reliable even in the absence of tests. However, the usual theoretical uncertainty estimates were in the 10 to 20% range. Now storage ring measurements yield lifetime results that are more precise by an order of magnitude and confirm only some, but not all of the calculations. Apparently, conceptual simplicity does not necessarily translate into calculational reliability. However, the blame for scattered predictions does not rest on theory alone, as some earlier RF ion trap measurements later turned out to be rather misleading. As stated by Alan Hibbert (Belfast) years ago, "the incidental agreement of experimental and theoretical data is no proof that either of them is correct". A certain competition of experimenters and theoretician seems to be beneficial for both.

Most of the systems studied so far at the TSR storage ring at MPI Heidelberg have transitions that lie in the near ultraviolet, which is a selection governed by the constraints of the initial detector arrangement. Detectors for the VUV and EUV are being contemplated, but would have to be mounted inside the storage ring vacuum vessel. Encouragement of the local scientists by the astrophysical data users might help these technical developments to proceed faster.

5. EBIT

A particularly versatile ion trap is the electron-beam ion trap (EBIT) (see also Peter Beiersdorfer's contribution to this conference), which confines ions - like a Penning trap - mostly by a combination of a strong magnetic field with electrically charged drift tubes. The essential addition to the basic Penning trap is a high-density electron beam that runs along the axis of the trap and produces ions of any charge state from the ambient gas (under true UHV conditions) or from an injected low-charge ion cloud. This electron beam also compensates the space charge of the ion cloud, thus keeping the ions in place for further ionizing collisions. The stepwise ionization is only limited by the electron beam energy in comparison to the increasing ionization potentials of the ions that are successively produced. Again, any charge state of any element is accessible. As the ions have rather low kinetic energies, high-resolution spectroscopy is feasible. For lifetime measurements, the electron beam is suddenly switched off (thus removing the dominant collision partners while the ions remain trapped in the Penning trap), and the light intensity of a given line is followed as a function of time.

Lifetime measurements in the X-ray range (using the Livermore EBIT) have reached a precision of better than 0.5% (Crespo López-Urrutia et al. 1998; Träbert, et al. 1999a), and in the visible of better than 2% (Träbert et al. 2000c; 2000d). The systematic errors seem to be under better control in these experiments than in the competing ECRIS/Kingdon trap experiments discussed above. How do we know that? Well, the Kingdon trap lifetime results on M1 transitions in various Ar ions (in the near-UV/visible range) as well as some of the early EBIT lifetime data (at NIST and LLNL) fell short of theoretical predictions by about 10 to 15%. This might have been interpreted either as toothing problems of new experimental techniques or as a possible problem with theory. Meanwhile, however, there are heavy-ion storage ring results on similar atomic systems, and they are not in disagreement with theory. Also, improved data collection techniques at the Livermore EBIT have resulted in lifetime data (Träbert et al. 2000c, 2000d) that turned out to be close to theory and to carry little intrinsic uncertainty. The combination of these experimental findings gives mutual assertion and increased confidence in the capability of EBIT.

6. Conclusion

The major experimental techniques for time-resolved measurements of possible interest in the context of the expanding field of X-ray astrophysics can contribute very different data and supporting information. The elemental purity and, to a lesser extent, the control over charge-states of the fast-ion beam techniques are major assets as they help with the identification of unknown lines. Beam-foil spectroscopy is most easily employed, but does not reach some of the very-long lived levels that can be exploited for the study of low-density astronomical objects. Here ion traps of various designs come into play. A more extensive review of the recent achievements with lifetime measurements using such ion traps of all sizes is being presented elsewhere (Träbert 2000).

For the vast majority of all atomic levels, there will never be enough time and money to do appropriate experimental studies, and therefore theory is needed for the mass production of transition rate data for modeling and similar efforts. Theory may be better than foreseeable experiments could do on many of the electric-dipole (E1) allowed transitions, but that is no general guarantee of reliability, and it does not automatically extend to intercombination or E1-forbidden transitions either. Clearly, theory is not being corroborated by measurement in all cases. Theory appears to be reliable (at the few-percent level of uncertainty) for simple cases like the M1 transition in the ground state of B-like ions, and perhaps only slightly less so for the similar case of F-like ions. With more electrons in the open valence shell, the typical scatter of the theoretical predictions of M1/E2 transition rates in lowly-charged ions of second- and third-row elements rises to about 20% (and sometimes a factor of two or three). 10 to 20% is also the uncertainty estimate given with some such calculations. Here the new experimental data discussed above yield an improvement by an order of magnitude that helps shift the astrophysical error budget away from atomic parameters.

Developments are under way to extend the time-resolved EBIT measurements to the XUV spectral range of present interest. If enough encouragement from prospective users can be mustered, similar extensions of the working ranges of present heavy-ion storage ring experiments seem likely. These developments would bear on EUV coronal transitions, some of which have predicted lifetimes that exceed the practical limit (30 ns) of the beam-foil technique, but might be observable in the low-density environments of storage rings or EBIT. Thus they would not only help with the identification of X-ray features in the spectra obtained by the new or coming space crafts dedicated for X-ray work, but also with the analysis of forbidden transitions in the VUV detection ranges of the SUMER instrument on the SOHO space craft, and on the FUSE mission.

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