Indrek Martinson

Experimental determinations of oscillator strengths in ions

ABSTRACT

Recent measurements of radiative lifetimes and transition probabilities in singly and multiply ionized atoms, by means of beam-foil and beam-laser spectroscopy, are reviewed. The spectra discussed include Ca II and ions of the iron-group and rare-earth elements.

INTRODUCTION

Experimental studies of lifetimes and oscillator strengths (f-values) have been discussed at the two previous meetings in this series. In Lund, six years ago, Richter (1984) reviewed results for neutral and singly ionized atoms, whereas Curtis (1984) also included data for higher charge states. Three years later, in Toledo, Ohio, Wiese (1987) summarized progress and challenges in this field of research. These three reviews, together with several other papers presented at the two previous symposia, contain much useful material of current interest.

The present article concentrates on recent accelerator-based studies of transition rates and lifetimes for ions. After a survey of experimental problems, results for systems of interest to astrophysics and the spectroscopy of fusion plasmas will be briefly surveyed.

EXPERIMENTAL ASPECTS

Most experimental methods used to determine lifetimes and f-values are normally limited to neutral and singly ionized atoms. For detailed discussions of various techniques two excellent reviews (Imhof and Read, 1977, Huber and Sandeman, 1986) can be consulted.

In the case of higher charge states only ion-beam methods, in particular beam-foil spectroscopy (Bashkin, 1976), are generally applicable. With this method the intensities $I(t)$ of the spectral lines of interest are measured as a function of the time t after excitation in the foil. From such data the lifetimes τ of the excited levels may be deduced, in the simplest case by using the relation $I(t) = I(0)\exp(-t/\tau)$, where $I(0)$ is the intensity close to the foil.

In practice many levels in a given ion can be excited. The observed decay curves are thus sums of exponentials. Unless properly accounted for, such cascading may complicate data analyses and introduce systematic errors. However an efficient technique for cascade corrections (ANDC, i.e. arbitrarily normalized decay curves), introduced by Curtis et al. (1971), has essentially eliminated this drawback. Recent experience has shown that modern beam-foil data, analyzed by means of ANDC, compare favorably with the results of elaborate theoretical studies of oscillator strengths (Martinson, 1988, Engström, 1989).

Whenever the spectra are line-rich (e.g. in the case of 3d- and 4f-elements), blending of lines complicates lifetime studies. Careful spectral studies are now necessary before decay measurements can be untertaken. It should further be realized that the available information on spectra is normally far from complete, and unexpected line blends may thus occur. Furthermore, the ion-foil excitation process strongly populates hydrogen-like states (high n and l quantum numbers) as well as doubly-excited levels, transitions from which are very weak or even absent in most other light sources (sparks, laser-produced plasmas, tokamaks, etc.).

The beam-laser method of Andrä et al. (1973), constitutes an important development of the beam-foil concept. The fast ions are now excited by monochromatic laser light (instead of by the foil) into the levels of interest. There is no distorsion of the data due to cascades or line blends. Furthermore, the velocity of the ions (and thus the time scale after excitation) is more precisely known than in the beam-foil case where corrections for energy loss and straggling in the foil must be made. At low ion energies these effects are fairly large.

The beam-laser method is unfortunately limited by the presently available lasers to transitions with wavelengths longer than 2000 Å. In spectra such as C I, N I, O I, S I and in multiply ionized atoms, the most important spectral transitions (in particular the resonance lines) lie well below this limit. In practical beam-laser work several factors must be carefully investigated, for instance stray light from the laser.

SINGLY IONIZED CALCIUM

In the important spectrum Ca II the f-value of the 4s ^2S - 4p ^2P multiplet (the famous H and K lines at 3933 and 3968 Å) has been theoretically studied by many authors, usually by means of single-configuration approximations. There have also appeared lifetime results, e.g. a beam-foil study in which ANDC corrections were included (Emmoth et al. 1975). A typical decay curve which explicitly shows the cascading situation is depicted in fig. 1.

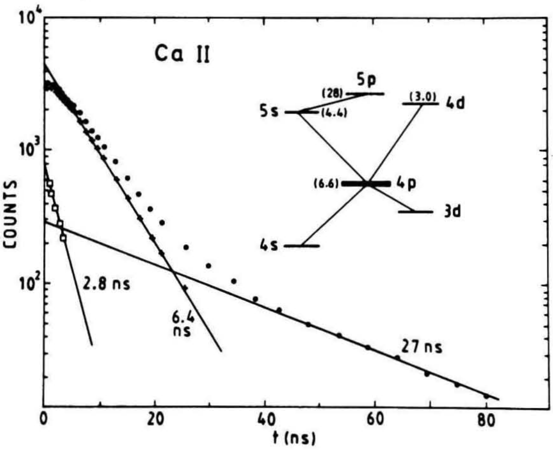

Fig. 1. Decay curve of the 4p ^2P (J = 3/2) level in Ca II (Emmoth et al., 1975), showing both the primary decay and some important cascades. The theoretical lifetimes of are also indicated.

More recently, an accurate beam-laser study has been reported (Gosselin et al., 1988), resulting in improved error limits. A very interesting method, introduced by Masterson and Stoner (1973) and later developed by Becker and Andrä (1985), has been applied to Ca^+ by Becker (1985). The method involves measurement of photon-photon coincidences on foil-excited ions. This apparently highly effective way of eliminating the influence of cascading unfortunately suffers from the fact that the coincidence rates are very low in optical measurements. In the case of Ca II, the preliminary 4p ^2P lifetime, as given in Becker's thesis (1985), is much shorter than most earlier data. Since the final result has not appeared yet, no detailed conclusions can be drawn, however. These facts prompted a new configuration interaction (CI) calculation of Ca II lifetimes (Cowan and Martinson 1988). The CI results (table 1) are in agreement with the beam-foil and beam-laser data. A new, careful beam-foil study of Ca II lifetimes is meanwhile being concluded (Haar 1989). Because of various technical developments, modern beam-foil results are normally much more accurate than the data obtained in the 1970's and earlier.

Table 1. Lifetimes (ns) in Ca II

Level	Without CI	With CI	Experiment
4p $^2P_{1/2}$	6.22	6.75	6.96 (18)[a]
$^2P_{3/2}$	6.05	6.57	6.87 (18)[a]
			6.4 (7)[b]
4d $^2D_{3/2}$	2.94	2.98	
$^2D_{5/2}$	2.99	3.03	2.9 (3)[b]
5s $^2S_{1/2}$	4.62	4.40	3.4 (4)[b]
5p $P_{1/2}$	30.7	27.7	29 (5)[b]

[a]Gosselin et al. (1988) [b]Emmoth et al. (1975)

IRON-GROUP ELEMENTS

Several of the iron-group elements are of great astrophysical significance, because of their high solar, stellar and interstellar abundances. Metals such as Ti, Cr, Fe, Ni and their alloys are used as materials for the first wall, limiters and divertors in tokamaks and other fusion devices. Astrophysical and laboratory (fusion) plasmas thus produce lines belonging to the 3d-elements in various degrees of ionization. However, the spectra and f-values for these elements are of great interest to atomic structure physics as well, presenting challenging problems but also providing insights into many-electron effects for complex atoms and ions.

In this paper some results for Ti, Fe and Ni will be mentioned. This task has been facilitated by the recent appearance of two valuable compilations of atomic transition probabilities, for Sc-Mn (Martin et al., 1988) and Fe-Ni (Fuhr et al., 1988).

Titanium

The beam-laser method has recently been extended to Ti II (Gosselin et al., 1987). A beam of Ti^+ ions was excited from the level a ^4F (J = 7/2) to z $^4D^o$ (J = 5/2) by means of laser radiation and the decay of the upper level was measured. In this way a very accurate $^4D^o$ lifetime was obtained, 4.01 ± 0.06 ns. This value is in good agreement with a previous result τ = 4.5 ± 0.6 ns (Roberts et al., 1975), based on a combination of emission and beam-foil data (Roberts et al., 1973), but the accuracy has been improved by a factor of ten. By means of the beam-foil method, decay times for transitions in Ti IV - Ti VII (400 - 800 Å) were determined some years ago (Dumont et al. 1981). Typical uncertainties were in the 10 - 20% range. Much interest has recently been focussed on the structure of highly ionized Ne-like ions, largely because of their applications in VUV and soft x-ray laser schemes (Matthews and Rosen 1988). The laser transitions occur between $2p^5 3s$ and $2p^5 3p$ levels. For Ne-like Ti XIII extensive beam-foil measurements of lifetimes of many $2p^5 3p$ and $2p^5 3d$ levels have been reported (Träbert 1986). The results nicely confirm theoretical predictions.

Iron

The spectra and f-values of Fe in various charge states have been studied by many authors, but much important information is still missing. According to Fuhr et al. (1988) there exist very few experimental data points (lifetimes, f-values) for Fe III and higher spectra. However, two beam-foil lifetime papers have appeared, one dealing with Fe II and Fe III (Dolby et al., 1979) and the other with Fe V and Fe VI (Dumont et al., 1979) which were not listed by Fuhr et al. (1988). Dolby et al. investigated three multiplets in Fe II and one in Fe III. For the latter, the a ^5D - z $^5P^o$ resonance multiplet, 1122 - 1132 Å, an experimental mean lifetime of τ = 0.88 ± 0.04 ns was found, whereas a very recent calculation predicts 1.40 ns (Fawcett, 1989). The reason for this rather substantial disagreement is not known. Beam-foil data have been reported for some other Fe III multiplets (Andersen et al., 1977), but here Fawcett (1989) notes that the experimental lifetimes are longer than the theoretical ones. This trend is indeed more common in complex spectra. On the other hand, the experimental data for Fe V and Fe VI (Dumont et al., 1979) agree well with the Thomas-Fermi calculations of Abbott (1978).

Additional experimental work, with careful monitoring of cascades and blends, should be undertaken for many Fe ions. We may also note that the spectrum of Dumont et al. (1979) shows about 20 Fe V lines between 1350 and 1450 Å, whereas there are 140 classified lines in the spark spectrum of Fe V in this region (Ekberg 1975). The two spectra are compared in fig. 2. However, since Dumont et al. (1979) concentrated on strong lines, blending was apparently not too serious.

Nowadays, beam-foil work at higher spectral resolution, by using a large UV spectrometer and a multichannel detector, should be carried out for Fe III - Fe X and perhaps additional

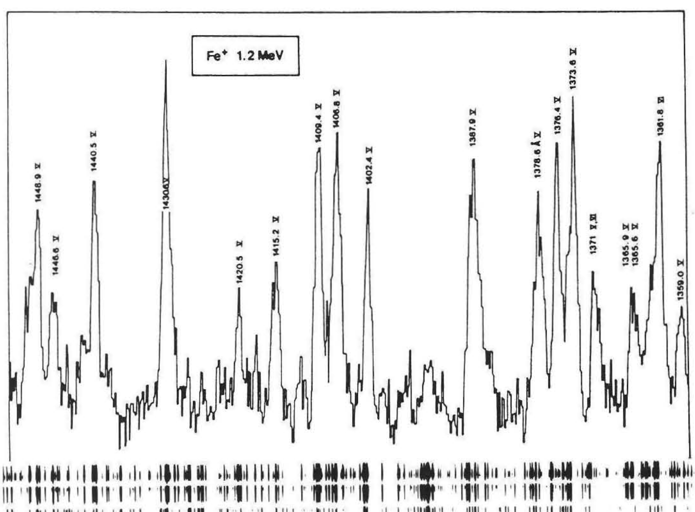

Fig. 2. Comparison of a beam-foil spectrum of Fe (Dumont et al., 1979) and three photographic recordings of spark spectra (Ekberg, 1975). Most lines belong to Fe V.

higher charge states. Studies of this kind may not appear as "trendy", but the data are badly needed by atomic theorists and astronomers.

Some experimental values are available for higher ionization stages of Fe. In these systems there are only a few valence electrons, and the spectra are easier to analyze. A very clean beam-foil spectrum of Fe in the VUV is depicted in fig. 3.

In one of the earlier beam-foil studies of highly stripped Fe, Träbert et al. (1982) measured decay times for some transitions in Fe XIII - Fe XVI. More recently, accurate beam-foil data have been obtained for the resonance lines in Fe XV and Fe XVI (Hutton et al., 1988a, 1988b). In these two papers, which also included some other ions, careful cascade corrections, using the ANDC method, were performed.

Nickel

It can be seen from Fuhr et al. (1988) that experimental data on f-values and lifetimes are rare for this element. Following some early beam-foil results, there has now appeared a paper on Ni II in which lifetimes of 12 levels were determined using the laser-induced fluorescence technique, the final uncertainties being about 6% (Lawler and Salih 1987). No experimental data seem to exist for Ni IV - Ni XIV, however.

However, a recent paper reports lifetimes for several levels belonging to the $3s3p^3$ and and $3s^2 3p3d$ configurations in Si-like Ni XV (Träbert et al., 1989). The experimental data agree with theoretical results. No rigorous corrections for cascading were possible, however, largely because the $3s3p^2 3d$ and $3p^4$ configurations, from which cascading can take place, have not been established for this ion. Biémont (1986) has calculated the decay rates and excitation energies of these levels and this data will be valuable in further spectroscopic work.

Intercombination lines

Intercombination lines are E1 transitions which violate the $\Delta S = 0$ selection rule. They are made possible by the spin-orbit interaction. Since these lines connect systems of different multiplicities, their wavelengths will be useful in placing the various term systems on an absolute scale. The importance of such lines for plasma diagnostics, for instance in determining electron densities, is well known.

Recently, intercombination lines in several highly charged iron-group elements have been experimentally studied. The results include Mg-like, Al-like and Si-like ions. In these systems there are metastable levels ($3s3p\ ^3P$, $3s3p^2\ ^4P$, $3s3p^3\ ^5S$, respectively) that decay to the various ground states by intersystem lines. These transitions are frequently very difficult to classify with certainty because the lines are fairly weak compared to other lines appearing in the same region. However, in "delayed" beam-foil spectra, recorded far downstream from the foil, these intersystem lines (which have markedly longer decay times than most other transitions in the same

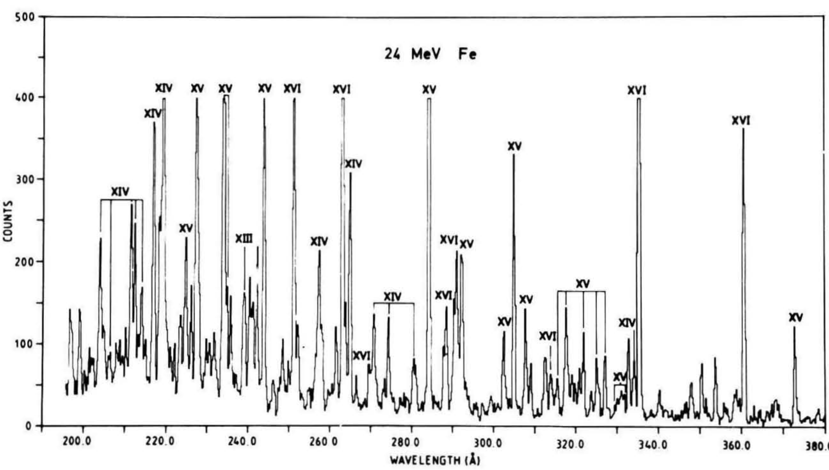

Fig. 3. A high-energy beam-foil spectrum of Fe, showing transitions in Fe XIII - Fe XVI (Hutton et al., 1988a).

wavelength range) appear as distinct peaks (Träbert et al., 1988). Following such line identifications, many experimental transition probabilities have been determined in recent years (Träbert et al., 1988, Ellis et al., 1988). The experimental results usually confirm theoretical predictions, in particular those based on relativistic treatments.

RARE EARTH IONS

In the early 1970's several solar astronomers emphasized the need for reliable gf-values for neutral and singly ionized rare earth elements. These data were necessary for establishing the solar abundances of these 4f-elements. In Aarhus and Stockholm the beam-foil method was therefore extended to such complex systems. A preliminary study of some Tm II lines (Curtis et al., 1973) showed that the gf-values given by Corliss and Bozman (1962) in their classic monograph were *too low* for this ion. Such a result was not expected at that time (because the trend was the opposite in most other cases), and the beam-foil data were initially doubted by solar astronomers (Ross and Aller 1974). However, in a more comprehensive beam-foil investigation, Andersen and Sørensen (1974) provided the necessary confirmation for Tm II, and they also showed that the differences between beam-foil data and the gf-values of Corliss and Bozman (1962) did not follow a simple general trend for the rare earths.

Nowadays beam-foil work on singly ionized rare-earth elements has been replaced by beam-laser studies which are here very much superior. Such results were already reviewed by Richter (1984). As a rather early example the work on Er II (Bentzen et al., 1982) deserves mentioning. Here the lifetimes were determined with about 10% uncertainties. It was also shown that a previous beam-foil study of Er II (Engman et al., 1976) had not resulted in correct lifetimes. Since the line spectrum of Er II is much more dense than that of Tm II, blends must have affected the beam-foil data. To paraphrase Crossley (1984) and Hibbert (1989), the beam-foil work was "over-ambitious". It is worth noting that for Er II the beam-laser data agree fairly well with the emission results (Corliss and Bozman, 1962). Recently, very accurate beam-laser lifetimes (1-3% uncertainties) were reported for Sm II (Vogel et al., 1988). Three of their decay curves are displayed in fig. 4.

For some levels previous lifetime data were available, but in these cases the new values represent marked improvements.

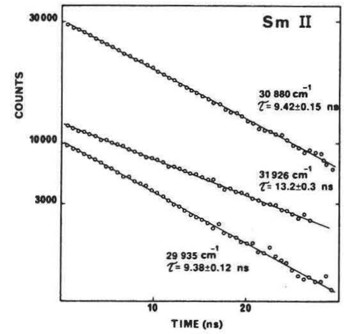

Fig. 4. Beam-laser decay data for three levels in Sm II (Vogel et al., 1988).

VERY ACCURATE DATA

At the symposium in Lund Crossley (1984) reviewed the developments in f-value calculations, thereby dividing the results into four categories, a) Very accurate calculations, b) Accurate calculations, c) Calculations for larger systems and d) Mass production. Recent theoretical studies have emphasized very accurate calculations of f-values, see e.g. Frose Fischer (1988). Among the motivations for such efforts is the existence of highly accurate (0.2%) beam-laser data, e.g. by Gaupp et al.(1984). Presently there seem to persist certain small differences between the "best" theoretical and experimental f-values in the case of Li I, Li II, Na I and K I (Froese Fischer 1988). On the other hand, an earlier beam-foil result for He I, which has a total uncertainty of 0.26% (Astner et al. 1976), agrees quite well with theory.

Very interesting results have recently appeared for the 3s - 3p resonance doublet in the Na I sequence. As noted, the value of Gaupp et al. (1984) for Na I deviates from that predicted by very "sophisticated" models wheras agreement is very good with the results of simpler theoretical approaches, such as the semiempirical Coulomb approximation. In recent beam-foil studies of Na-like Ti, Fe, Ni and Cu, Hutton et al. (1988b) also noted a small systematic shift from theoretical f-values. Quite recently this trend was established for Na-like Mg II for which Ansbacher et al.(1989) report an accurate beam-laser measurement. A new high-precision result has been meanwhile reported for Na I (Carlsson, 1989) which is in nearly perfect agreement with the lifetime of Gaupp et al. (1984). All these studies yield a consistent picture, i.e. there exists an admittedly small but persistent deviation from theoretical results based on *ab initio* methods. However, a recent semiempirical calculation in which the central field Hartree-Slater approximation is combined with core polarization (Theodosiou and Curtis (1988) agrees quite closely with these recent experimental data.

CONCLUDING REMARKS

In this brief survey we have sketched some cases where progress has been made on the experimental side in recent years. With a few exceptions only beam-foil and beam-laser methods have been considered.

A number of experimental developments are expected for the future. For example, with short-wavelength lasers transitions in mutliply ionized atoms can be resonantly excited. Laser techniques have already been applied to such ions, in connection with Lamb shift and fine-structure measurements, see e.g. Silver (1988), but here "ordinary" lasers (gas or solid-state lasers) have been employed to induce transitions between excited levels in H-like and He-like ions. A particularly interesting novel idea involves the excitation of highly stripped ions with synchrotron radiation from a dedicated storage ring for electrons, see e.g. Jones et al. (1987).

ACKNOWLEDGEMENTS

This work has been supported by the Swedish Natural Science Research Council (NFR).

REFERENCES

Abbott, D.C., 1978 - J. Phys. B **11**, 3479-3497.

Andersen, T., and G. Sørensen, 1974 - Solar Phys. **38**, 343-350.

Andersen, T., P. Petersen and E. Biémont, 1977 - J. Quant. Spectrosc. Radiat. Transfer **17**, 389-392.

Andrä, H.J., A. Gaupp and W. Wittmann, 1973 - Phys. Rev. Lett. **31**, 501-504.

Ansbacher, W., Y. Li and E.H. Pinnington, 1989 - Phys. Lett. **A 139**, 165-169.

Astner, G., L.J. Curtis, L. Liljeby, S. Mannervik and I. Martinson, 1976 - Z. Physik **A 279**, 1-6.

Bashkin, S., ed., 1976 - Beam-Foil Spectroscopy, Berlin, Springer.

Becker, B., 1985 - Thesis, University of Münster.

Becker, B., and H.J. Andrä, 1985 - Nucl. Instr. Meth. **B9**, 650-654.

Bentzen, S.M., U. Nielsen and O. Poulsen, 1982 - J. Opt. Soc. Am. **72**, 1210-1212.

Biémont, E., 1986 - private communication.

Carlsson, J., 1989 - Phys. Scr. **39**, 442-446.

Corliss, C.H., and W.R. Bozman, 1962 - NBS Monograph 53, Washington, D.C.

Cowan, R.D., and I. Martinson, 1988 - Atomic Spectroscopy, University of Lund, pp 36-37 and unpublished data.

Crossley, R., 1984 - Phys. Scr. **T8**, 117-128.

Curtis, L.J., 1984 - Phys. Scr. **T8**, 77-83.

Curtis, L.J., H.G. Berry, and J. Bromander, 1971 - Phys. Lett. **34 A**, 169-170.

Curtis, L.J., I. Martinson and R. Buchta, 1973 - Nucl. Instr. Meth. **110**, 391-394.

Dolby, J.S., R.W.P. McWhirter and C.J. Sofield 1979 - J. Phys. B **12**, 187-201.

Dumont, P.D., Y. Baudinet-Robinet, H.P. Garnir E. Biémont and N. Grevesse, 1979 - Phys. Rev. **A 20**, 1347-1351.

Dumont, P.D., H.P. Garnir, Y. Baudinet-Robinet and M. Kapenyak, 1981 - J. Opt. Soc. Am. **71**, 502-503.

Ekberg, J.O., 1975 - Phys. Scr. **12**, 42-57, and private communication.

Ellis, D.G., I. Martinson and E. Träbert, 1989 - Comm. At. Mol. Phys. **22**, 241-262.

Emmoth, B., M. Braun, J. Bromander and I. Martinson, 1975 - Phys. Scr. **12**, 75-79.

Engman, B., J.O. Stoner, Jr., I. Martinson and N.E. Cerne, 1976 - Phys. Scr. **13**, 363-364.

Engström, L., 1989 - Phys. Scr. **40**, 17-24.

Fawcett, B.C., 1989 - At. Data Nucl. Data Tables **41**, 181-255.

Froese Fischer, C., 1988 - Nucl. Instr. Meth. **B31**, 265.

Fuhr, J.R., G.A. Martin and W.L. Wiese, 1988 - J. Phys. Chem. Ref. Data **17**, Suppl. No. 4.

Gaupp, A., P. Kuske and H.J. Andrä, 1984 - Phys. Rev. **A 26**, 3351.

Gosselin, R.N., E.H. Pinnington and W. Ansbacher, W., 1987 - Phys. Lett. **A 123**, 175-178.

Gosselin, R.N., E.H. Pinnington and W. Ansbacher, W., 1988 - Nucl. Instr. Meth. **B31**, 305-310.

Haar, R.R., 1989 - Thesis, University of Toledo..

Huber, M.C.E., and R.J. Sandeman, 1986 - Rep. Prog. Phys. **49**, 397-490.

Hibbert, A., 1989 - Phys. Scr. **39**, 574-580.

Hutton, R., L. Engström and E. Träbert, 1988a - Nucl. Instr. Meth. **B 31**, 294-299.

Hutton, R., L. Engström and E. Träbert, 1988b - Phys. Rev. Lett. **60**, 2469-2472.

Imhof, R.E., and F.H. Read, 1977 - Rep. Prog. Phys. **40**, 1-104.

Jones, K.W., B.M. Johnson, M. Meron, . B. Crasemann, Y. Hahn, V.O. Kostroun, S.T. Manson and S.M. Younger, 1987 -

Comm. At. Mol. Phys. **20**, 1-18.
Lawler, J.E., and S. Salih, 1987 - Phys. Rev. **A 35**, 5046-5050.
Martin, G.A., J.R. Fuhr and W.L. Wiese, 1988 - J. Phys. Chem. Ref. Data **17**, Suppl. No. 3.
Martinson, I., 1988 - Rep. Prog. Phys. **52**, 157-225.
Masterson, K.D., and J.O. Stoner, Jr., 1973 - Nucl. Instr. Meth. **110**, 441-444.
Matthews, D.L., and M.D. Rosen, 1988 - Scientific American **259**, 60-65.
Richter, J., 1984 - Phys. Scr. **T8**, 70-76.
Roberts, J.R., T. Andersen and G. Sørensen, 1973 - Astrophys. J. **181**, 567-586.
Roberts, J.R., P.A. Voigt and A. Czernichwski, 1975 - Astrophys. J. **197**, 791-798.
Ross, J.E., and L.H. Aller, 1974 - Solar Phys. **36**, 21-23.
Silver, J.D., 1988 - Phys. Scr. **37**, 720-727.
Theodosiou, C.E., and L.J. Curtis, 1988 - Phys. Rev. **A 38**, 4435-4445.
Träbert, E., 1986 - Z. Physik **D 1**, 283-286.
Träbert, E., K.W. Jones, B.M. Johnson, D.C. Gregory and T.H. Kruse, 1982 - Phys. Lett. **87A**, 336-340.
Träbert, E., P.H. Heckmann, R. Hutton and I. Martinson, 1988 - J. Opt. Soc. Am. **B5**, 2173-2182.
Träbert, E., N. Reistad, I. Martinson and R. Hutton, 1989 - Z. Phys. D **11**, 207-211.
Vogel, O., B. Edvardsson, A. Wännström, A. Arnesen and R. Hallin, 1988 - Phys. Scr. **38**, 567-572.
Wiese, W.L., 1987 - Phys. Scr. **35**, 846-850.

AUTHOR'S ADDRESS

Department of Physics, University of Lund,
Sölvegatan 14, S-223 62 Lund, Sweden