<u>Some</u> Foundations for Classification of Spectra of Highly Ionized Atoms and their impact on Collision Physics.

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ABSTRACT

This presentation divides the 'Foundation of Classification of Spectra of Highly Ionized Atoms': into three main areas. The first is the pre-1960's contribution which is reviewed by Edlén (1964) in 'Handbüch der Physik'[(2)] and excellently documented by C. E. Moore[(3)] Nat. Bur. Stand. (1949, 1952, 1958). Appropriate to this meeting is the revisiting of the second and third foundations which are contributions from laboratory experiments and space research respectively: both covering the years from 1960 to 1990[(4-8)]. Aspects of this research, especially in iron, are briefly related to ongoing projects here at Cambridge[(13-15)] as well as the transfer of information from atomic structure to collision physics[(10-16)].

1 INTRODUCTION.

Just as the light of early research of atomic structure was fading the winds of fusion and space research rekindled its renaissance and the foundations spectra of highly ionised atoms were built. My previous reviews[(4-6)] comprehensively record research of this period. Rather than repeat this, let us take a voyage with friends and colleagues at Culham and Rutherford Laboratories[(9)] and regenerate the excitement and enthusiasm also shared with international teams.

The story begins with a shock because when the first rocket borne spectrographs retrieved spectra in solar far ultraviolet spectra between 1960 and 1962, most of the spectral lines could not be accounted for in spite of previous pioneering research in line classification. Meanwhile the music of the spheres captivated some of us working on ZETA at Harwell when we made the first line classifications in spectra of a fusion plasma in 1961. On moving to Culham in 1963 I had the good fortune to work under the leadership of Alan Gabriel and there was a Ferrari in his laboratory----- well metaphorically speaking for his grazing incidence spectrograph was like a Ferrari: a superb example of engineering and the perfect vehicle for touring round the spectra of highly ionised atoms.

2 SOLAR MYSTERY SOLVED.

Our journey started in 1963 when Prof. T. K. Allen pointed out, during a visit to Culham Laboratory, that the strongest lines on our ZETA spectrum looked remarkably similar to mysterious solar XUV lines obtained in USA during rocket flights between 1960 and 1962. Using solar wavelengths communicated and compiled by T. K. Allen & Carol Jordan, we confirmed the solar and ZETA lines were identical. We had the pleasure of welcoming Carol to our team. To tackle the problem we designed a low inductance vacuum spark light source coaxial with a 100 KV capacitor and swinging cascade switch. By variation of inserted material, the electrode configuration and applied voltage: successful separation of lines from different ionisation stages was achieved between potassium and iron. Derived energy levels were plotted down to and beyond calcium where existing line classifications were known and 4s and 3d configuration interactions were graphically illustrated. The identity of the solar lines was thereby established. Solving this riddle was just the start of the iron adventure. Next a rotating shutter invented by Alan Gabriel was fitted to the two meter grazing incidence spectrograph allowing spectra of the source to be recorded as a function of time. This provided the key to discrimination of ion stages so that identifications in the Fe X and Fe XI sequences were extended and the leading lines of the Fe XII and Fe XIII sequences classified.

3 THE FIRST PROLIFIC LIGHT SOURCE: THE THETA PINCH.

This time resolution technique really took centre stage when applied to plasmas generated in a theta pinch specially designed to minimise injected impurities. Less than 1% of iron, cobalt, nickel, or manganese carbonyl or chromyl chloride, was added to the hydrogen gas in the theta pinch. The time resolved spectra recorded resulted in excellent differentiation of ionisation stages enabling the most detailed study of the 3p-3d and 3s-3p arrays of Fe IX to Fe XV and isoelectronic Cr, Mn, Co and Ni. To this day these theta-pinch spectra are probably the most revealing laboratory observations of these ions and have been recently used here at Cambridge by Helen Mason and Giulio Del Zanna el al. for their iron project [13-15] which combines atomic structure with collision studies.

4 THE SECOND PROLIFIC LIGHT SOURCE: LASER PRODUCED PLASMA.

Laser produced plasmas joined the theta pinch to become the two most prolific laboratory light sources of this era. The birth of spectroscopy of highly ionized atoms using laser produced plasmas occurred in 1966 at Culham Laboratory. Three properties, which were to make laser produced plasma spectra an invaluable tool in this field, were immediately demonstrated. Firstly they were almost free from impurity lines, secondly restricted ionization stages were favoured hence enabling their separation and thirdly the high density led to the population of many high energy levels not occupied in lower density plasmas. Next a homemade 4 GW neodymium laser extended knowledge of iron lines between 170 and 320 Å and of their isoelectronic sequences. This was facilitated by space resolution techniques.

5 GROUND CONFIGURATION SPECTRA δn =2-2 and δn =3-3.

We now consider δn =2-2 and δn =3-3 transitions near the ground level which contain doubly excited levels and were being studied by Edlén in forbidden line investigations. Laser produced plasmas consolidated the foundations on which energy levels are built by filling in the majority of gaps in spectra of these ground configurations. This exploited the fact that in laser produced plasmas, due to their high density, transitions from doubly excited levels are prominent. Identifications were accomplished by firing lasers, with powers up to 4 GW, at targets of elements in the period between potassium and iron; and also at other solids. The theta pinch added data for other elements. This provided Edlén with data for his study of forbidden lines. These laser studies were aided by others from NRL and the Lebedev Institute. They also amended identifications of lines emitted from solar flares near 100 Å recorded by OSO V. This is but one example of the teamwork entailed in these investigations for complementary to international ground based efforts a higher profile project, involving one of two on-board instruments on SKYLAB, found 80 forbidden lines: some corresponding to 28 found earlier with a slit-less Wadsworth rocket borne spectrograph during an eclipse. Thus data established through laboratory research were extended by major space projects; and it all came down to earth again when TOKAMAKS supplied precise magnetic dipole measurements. Edlén provided the final *'coup de maître'* documenting derived ground term energy levels: so foundations were established.

6 δn=2-3 TRANSITION STUDIES & SPECTRA OF SOLAR FLARES.

The solar flare spectrum below 17 Å recorded by OSO III by Neupert et al in triggered our investigations of δn=2-3 transitions.

World War I introduced the poison gases chlorine and phosgene and we added small percentages of them separately to the hydrogen gas filling our theta pinch and similarly added hydrogen sulphide and argon. This experiment provided valuable data on δn=2-3 transitions from the analysis of the spectra of phosphorus, sulphur, chlorine and argon emitted from the group's theta pinch. Then long extrapolations between potassium and iron were filled in with laser produced spectra both generated by our 4 GW laser and from lasers elsewhere: notably at NRL Washington and the Lebedev Institute. Improved laser produced spectra of Fe XVIII to Fe XXIV, plus vanadium and nickel, were recorded with a beryl-crystal spectrograph at the Rutherford Laboratory, Central Laser Facility: using a 100 GW laser. Outstanding records of corresponding flare spectra came from Solar Maximum Mission beryl-crystal-spectra and the USAF P78-1 RAP-crystal-spectra.

These three records facilitated the identification of the leading lines of Fe XVIII to Fe XXIV for δn =2-3 and 2-4 transitions. Helen joined teams to interpret solar flare line intensities.

The aforementioned international space missions and many others contributed a bonanza of atomic structure data to which more were added by new light sources: such as the 'Beam Foil' reviewed by Martinson[18]

7.LEVEL MIXING PROBLEMS HIGHLIGHTED.

For our next ventures we required the Cowan and Zeeman computer codes which Gordon Bromage installed when he joined our team in the mid 1970's.

A lesson learnt during the aforementioned classification of the Fe IX to Fe XIII solar lines was that early *ab initio* theoretical calculations did not predict either their wavelengths or oscillator strengths well enough to permit line identification. Even when the leading terms of the strongest lines were identified our pet lines were mongrels of uncertain mixed identity and one must know their composition to obtain accurate atomic data. If sufficient observational data became available then the composition of terms can be estimated[16] using familiar programs, like the Zeeman codes, which scale Slater parameters with least-squares optimisation routines on the basis of minimizing the discrepancies between measured and computed energy levels. The optimised parameters can then be input for the Cowan program to calculate the final energy levels, wavelengths and oscillator strengths. These procedures were applied to spectra of most highly ionized ions of iron and many isoelectronic ions. The resulting wavelengths and oscillator strengths were published in Atomic and Nuclear Data Tables[19] in the late 1980's and provided a useful approximation and improved oscillator strengths. Larger error bars can be expected for weaker strengths and those corresponding to closely interacting levels. Attention was then turned to the effects term mixing can have on collision strengths. For this we needed Helen Mason's help.

8 IMPROVEMENT OF COLLISION STRENGHTS.

Based on the aforementioned optimisation techniques a new computational method [10-12] was developed to calculate collision strengths for complex ions: where *ab initio* computations break down or result in reducible errors. The procedure involved input of the semi-empirical adjusted Slater parameters into collision codes so that they determine improved eigenvectors. The technique was demonstrated for Fe XIII [11] and Fe IX[12] and their collision strengths were tabulated providing the opportunity for the more accurate interpretation of corresponding solar line intensities. These methods could not in 1989 be applied to Fe X to Fe XII and many other complex ions due to the available computer speeds at that time: which restricted the number of configurations included in the computations, especially for complex ions.

Recently the baton has been picked up by Helen Mason and Giulio Del Zanna and their colleagues. They calculate new collisional and radiative data applying empirical adjustments, which take into account observed wavelengths, to their calculations (13-15). Increased computing capacity gives them the advantage of being able to include large numbers of configurations. Their special applied computational method is summarised and cross referenced in their first Fe X paper (13). Although their method is original: it is aimed at the same goals as the Fe IX and Fe XIII papers just mentioned. Objectives are therefore advanced to include Fe X, Fe XI, Fe XII and many other iron ions studied in their 'iron project'. To accomplish this they have revisited 'renaissance' atomic structure data (4-8), supplementing with recent data, critically using those they accept: hence providing the basis for the determination of mixing and composition of terms or checking the validity of their adopted model. Their improved targets and collision strengths therefore unlock information available in solar and other spectral lines.

For earlier researchers in the atomic structure field it is a pleasure to see this 'handshake' with current projects in the collision domain. We wish those at Cambridge and associated groups engaged in the 'iron project' success so that the data stored in CHIANTI maintains it reputation as the finest wine!

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