PROBABILITIES FOR FORBIDDEN TRANSITIONS IN ATOMS AND IONS : 1968-1989. A BIBLIOGRAPHY

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Résumé.

On donne une liste de plus de 240 références concernant les probabilités des transitions interdites dans les atomes et ions. La période couverte va de 1968 à 1989. Cette bibliographie est indexée en fonction des espèces traitées dans chacune des publications retenues.

Summary.

A list is given of over 240 references concerning probabilities for forbidden transitions in atoms and ions. The period covered goes from 1968 to 1989. This bibliography is indexed according to the species treated in each of the selected publications.

Why a bibliography on atomic forbidden transition probabilities?

It is hardly necessary to recall here the importance of forbidden lines in astrophysical or fusion studies (see, for example, Seaton, 1968, Osterbrock, 1974 & 1989, or Hinnov & Suckewer, 1980). For those lines, astrophysicists and fusion specialists need accurate atomic data, such as radiative transition probabilities. To respond to this need, atomic physicists have put a great deal of effort into computing (and sometimes measuring) the required data. There are excellent compilations (some of which are critical) and review papers on the subject of probabilities for forbidden lines in atoms and ions (see Item 1 in the index to the present bibliography). For example, members of the NIST (formerly the NBS) are engaged in a large-scale assessment of transition probabilities, including those for forbidden transitions. Recent publications (Fuhr *et al.*, 1988; Martin *et al.*, 1988) contain recommended data for a number of cases and demonstrate that, on completion of the work in progress towards an update and extension of the older (and widely used) NBS compilations (Wiese *et al.*, 1966; Wiese *et al.*, 1969), an extremely useful tool will have been made available to users and producers of such data. Mention should also be made of the general bibliographies regularly issued by the IAEA, and which include references on atomic transition probabilities.

It is the opinion of the authors of the present paper that there is however room for this more modest project of an indexed bibliography on the subject. The reasons are as follows. 1. The number of papers we have been able to find while limiting ourselves to the 1968-1989 period shows that the field has attracted a lot of physicists' attention. 2. Whereas for some of the cases treated "definitive" transition probabilities seem to be available, there are still many instances where the accuracy of the published data is in doubt. 3. With time, physicists tackle more and more of those cases which were out of reach before the advent of supercomputers. 4. Many different methods are being used to calculate transition probabilities and it is of course of primary importance to compare the various sets of data in order to check the validity of the techniques employed. 5. Similarly, the practical "recipes" used by the teams engaged in this type of work are becoming more and more refined and it is all the more indispensable to assess their limitations in particular through detailed comparative analysis. 6. Compilations cannot always give a full account of all the studies on a given element and it is sometimes very useful to go back to the original references for a clear view of the state of the art.

In the forthcoming proceedings of the Colloquium on Atomic Spectra and Oscillator Strengths for Astrophysics and Fusion Research held in Amsterdam in August 1989, there is a paper by Rosa (1990) where some aspect of the importance of forbidden lines in astrophysics are discussed, while a review by Zeippen (1990) analyzes typical results obtained by recent theoretical calculations of forbidden transition probabilities. In particular, a detailed comparison of various sets of data concerning transitions in the $2p^{2,3,4}$ and $3p^{2,3,4}$ configurations is made. The numbers discussed were produced with the computer programs SUPERSTRUCTURE (Eissner *et al.*, 1974; Nussbaumer & Storey, 1978) and DIPOLE (Eissner & Zeippen, 1981), CIV3 (Hibbert, 1975; Glas & Hibbert, 1978), MCHF-BP (Froese Fischer, 1978 & 1983), the Cowan-Zealot suite of programs (Bromage, 1978), MCDF (Desclaux, 1975), NCMET (see, for example, Sinanoglu, 1969) and FOTOS (see, for example, Nicolaides & Beck, 1978). Recent studies of heavier species are mentioned: for example, the work of Biémont & Hansen (1986a & 1986b) on the $4p^{2,3,4}$ configurations or the treatment of *Fe II* by Nussbaumer & Storey (1980 & 1988).

Important points are still being debated today, among which is the question of the validity of those codes using the Breit-Pauli formalism as compared to the "fully-relativistic" programmes. Put in a provocative way, should the former be abandoned for lack of rigour? It is generally accepted that the fully-relativistic method cannot cope with neutrals (see, for example, Kaufman & Sugar, 1986) but it is often argued that the most rigorous method must be used in almost all other cases. The paper by Froese Fischer & Saha (1985) contains a very interesting discussion in relation to this problem. Following those authors, one can recall here that the basic point is the balance between correlation effects (CE) and relativistic effects (RE). For high Z , important CE arise only from configurations in the same complex as the one under consideration and RE must be taken into account as fully as possible. Therefore, the configuration basis set in the calculation may be kept to a comparatively small size but a formalism as fully relativistic as possible must be used. In this respect, the Breit-Pauli approximation loses its validity because of the dependence in Z^4 of its missing terms. For low Z , CE outside the complex of the configuration under consideration may be much bigger than RE but in all cases, the fine structure is mainly sensitive to RE.

In this type of work, the main internal test of a calculation is an assessment of the accuracy of calculated energy levels. Froese Fischer & Saha (1985) distinguish two cases when looking at term energy separations: terms arising from one configuration and terms arising from two different configurations. In the first case, CE outside the complex may be important for low Z , but RE may become big rather quickly, in particular through the spin-orbit operator. In the second case, CE are more important than RE for low Z . Finally, the fine structure is more sensitive to RE. The conclusion here must be that for low Z , a calculation based on the Breit-Pauli approximation and including much configuration interaction (CI) for an accurate representation of CE is preferable to a fully-relativistic calculation with poor CI. Now it should be remembered that for a given set of non-relativistic configurations, the corresponding number of relativistic configurations is much larger. Hence, the handicap of fully-relativistic methods where CI is the dominant factor. For high Z , fully-relativistic calculations are to be preferred. Of course, there remains the practical point of fixing the precise limits of validity of the various methods and this depends very much on the case treated.

Another debate concerns adjustable parameters. There are various semi-empirical ways to improve the calculated wavefunctions used to compute the probabilities. Some authors point out that much depends thereon on the care and experience of the physicists performing the calculation (see, for example, Saloman & Kim, 1989). This is of course a justified statement, but more rigorous methods (none is free of limitations) must also be used with caution, if only because of the smallness and sensitivity of the extra effects included, not to mention the fact that sometimes adjustable parameters are also present in the more refined formalisms even if they are appearing at a higher level. Thus, following Zeippen (1990), it can be said that a lot of work remains to be done in the field and that experienced human beings are of some importance in this game.

In conclusion, the present bibliography should be of help to producers of forbidden transition probabilities who want to assess the accuracy of their data or that of others, but also to users of the data who would like to know more about the probabilities available for a given case. A brief presentation of the bibliography is to be found in Section 2 of this paper.

• Presentation of the bibliography.

The aim of the present paper is simply to provide both producers and users of forbidden transition probabilities with a list of relevant papers published during the period 1968-1989, thus saving them some time better devoted to calculations or measurements. This project was started in view of the favourable comments of

many colleagues on the indexed bibliography on photoionisation prepared by Butler *et al.* (1988) for the second workshop in this series. The list we propose should not be considered as exhaustive : overlooking a reference is the easiest thing to do, and also no library possesses all the scientific journals or books (even though the selections available in Liège and Meudon are remarkably large). Apologies are due to colleagues whose work is missing from our list but of course any such omission is totally unintentional... Readers could be of great help in communicating their corrections and additions to any one of us so that further editions of the list for future workshops could be made more complete and accurate.

The present list was deliberately limited to papers which concern forbidden transition probabilities and which contain numerical data. Thus were excluded publications related to the topic of forbidden lines and which can be of great interest but should be considered in other reviews or bibliographies (theoretical or experimental methods, atomic energy levels, identifications of forbidden lines in astronomical objects or in fusion plasmas, models of astronomical objects, etc.). Following the philosophy behind the Atomic Data Workshop series of meetings, confusion and inflation had to be avoided as much as possible for the list to remain a useful and practical tool. Moreover, only those papers which at least one of us was able to check directly have been retained in the list. This accounts for possible gaps when the missing papers appear in books or journals unavailable to us.

Due to the strict selection rules applied, it was not thought necessary to print the titles of the papers in the bibliography, as they all concern a well defined topic. However, the usefulness of an index was not in question. This index has been arranged according to the species treated in each paper. Here again, we cannot claim that the result is totally free of errors but independent checks have convinced us that the accuracy should be good. Particular attention has been devoted to the np^2 configurations, owing to the amount of work performed on those cases in recent years, to their great importance in astrophysics and fusion and also to their challenge to physicists. On the subject of configurations, it is important to mention that, although a large majority of the papers listed deal with transitions within the ground configuration of the species considered, some references contain data on transitions within excited configurations or between two different configurations. Item 1 in the index refers to compilations or reviews. It should be noted that some of the compilations listed contain original results (some of them contain only a small fraction of non-original data) and that some of them are not concerned exclusively with forbidden transitions. Finally, a specific index item is devoted to those papers where magnetic quadrupole transitions are considered.

It is interesting to note that even for the most "popular" isoelectronic sequences, the number of references remains reasonable. Thus the present bibliography plus its index should allow for quicker assessments of which data are available and of what remains to be done for a given species.

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2. H, H-like ions ($1 e^-$).

53, 118, 147, 148, 150, 162, 205.

3. He, He-like ions ($2 e^-$).

5, 12, 38, 39, 40, 45, 48, 49, 51, 52, 55, 59, 61, 68, 74, 79, 81, 94, 95, 96, 97, 100, 101, 105, 116, 119, 120, 121, 132, 134, 135, 141, 142, 147, 148, 149, 150, 151, 162, 167, 199, 204, 207, 217, 225, 239.

4. Li, Li-like ions ($3 e^-$).

9, 15, 31, 32, 34, 35, 36, 38, 39, 48, 49, 50, 74, 104, 139, 140, 151, 162, 169, 194, 196, 208, 210, 216, 233.

5. Be, Be-like ions ($4 e^-$).

9, 15, 18, 43, 48, 74, 79, 81, 87, 88, 89, 90, 91, 109, 110, 126, 139, 140, 143, 144, 146, 151, 162, 168, 180, 182, 184, 194, 209, 222, 237, 238.

6. B, B-like ions ($5 e^-$, ground configuration : $2s^2 2p$).

Z = 5	B	I	69, 126, 224, 227, 234, 237.
Z = 6	C	II	69, 77, 126, 162, 186, 224, 227, 234, 237.
Z = 7	N	III	37, 69, 77, 126, 162, 183, 224, 227, 234, 237.
Z = 8	O	IV	37, 65, 69, 77, 126, 162, 224, 227, 234, 237.
Z = 9	F	V	37, 69, 126, 184, 227, 234, 237.
Z = 10	Ne	VI	37, 54, 69, 126, 162, 224, 227, 234, 237.
Z = 11	Na	VII	37, 54, 66, 69, 126, 227, 234, 238.
Z = 12	Mg	VIII	37, 54, 69, 122, 126, 224, 227, 234, 238.
Z = 13	Al	IX	37, 54, 69, 126, 224, 227, 234, 238.
Z = 14	Si	X	37, 54, 66, 69, 122, 126, 224, 227, 234, 238.
Z = 15	P	XI	37, 54, 69, 126, 227, 234, 238.
Z = 16	S	XII	37, 44, 54, 66, 69, 122, 126, 224, 227, 234, 238.
Z = 17	Cl	XIII	37, 54, 69, 126, 227, 234.
Z = 18	Ar	XIV	17, 37, 47, 54, 69, 122, 126, 224, 227, 234, 238.
Z = 19	K	XV	37, 54, 69, 126, 227, 234.
Z = 20	Ca	XVI	37, 47, 54, 69, 122, 126, 227, 234.
Z = 21	Sc	XVII	37, 69, 126, 151, 227, 234.
Z = 22	Ti	XVIII	15, 17, 37, 69, 122, 126, 140, 151, 224, 227, 234.
Z = 23	V	XIX	37, 69, 126, 151, 224, 227.
Z = 24	Cr	XX	37, 54, 60, 69, 122, 126, 140, 151, 227.
Z = 25	Mn	XXI	37, 54, 69, 122, 126, 151, 227.
Z = 26	Fe	XXII	17, 37, 54, 60, 69, 74, 122, 126, 140, 218, 224, 227.
Z = 27	Co	XXIII	37, 54, 69, 74, 126, 140, 227.
Z = 28	Ni	XXIV	37, 54, 60, 69, 74, 122, 126, 140, 224, 227.
Z = 29	Cu	XXV	37, 126, 224.
Z = 30	Zn	XXVI	37, 69, 126, 227.
Z = 31	Ga	XXVII	126.
Z = 32	Ge	XXVIII	17, 126.
Z = 33	As	XXIX	126.
Z = 34	Se	XXX	126.

Z = 35	Br	XXXI	37, 126.
Z = 36	Kr	XXXII	17, 37, 69, 126, 224, 227.
Z = 41	Nb	XXXVII	37.
Z = 42	Mo	XXXVIII	37, 69, 224, 227.
Z = 48	Cd	XLIV	37, 69, 227.
Z = 53	I	XLIX	37.
Z = 54	Xe	L	37, 69, 224, 227.
Z = 59	Pr	LV	37, 227.
Z = 63	Eu	LIX	227.
Z = 64	Gd	LX	37.
Z = 69	Tm	LXV	37.
Z = 74	W	LXX	37, 224.
Z = 79	Au	LXXV	37.
Z = 80	Hg	LXXVI	37.
Z = 82	Pb	LXXVIII	37, 224.
Z = 92	U	LXXXVIII	37, 224.

7. C, C-like ions ($6 e^-$, ground configuration : $2s^2 2p^2$).

Z = 6	C	I	73, 77, 126, 162, 172, 173, 176, 179, 211, 237.
Z = 7	N	II	73, 77, 126, 162, 171, 172, 173, 176, 179, 211, 237.
Z = 8	O	III	6, 13, 37, 73, 77, 125, 126, 162, 171, 172, 173, 176, 179, 187, 211, 237.
Z = 9	F	IV	37, 58, 73, 77, 126, 179, 237.
Z = 10	Ne	V	37, 54, 58, 73, 77, 124, 125, 126, 162, 176, 179, 237.
Z = 11	Na	VI	37, 54, 58, 73, 126, 176, 179, 238.
Z = 12	Mg	VII	37, 54, 58, 73, 124, 125, 126, 155, 176, 179, 238.
Z = 13	Al	VIII	37, 54, 58, 73, 126, 179, 238.
Z = 14	Si	IX	37, 54, 58, 73, 124, 125, 126, 155, 176, 179, 238.
Z = 15	P	X	37, 54, 58, 73, 126, 179, 238.
Z = 16	S	XI	37, 54, 58, 73, 124, 125, 126, 155, 176, 179.
Z = 17	Cl	XII	37, 54, 58, 73, 126, 179.
Z = 18	Ar	XIII	22, 37, 47, 54, 58, 73, 124, 125, 126, 176, 179, 238.
Z = 19	K	XIV	37, 54, 58, 73, 126, 179, 238.
Z = 20	Ca	XV	37, 47, 54, 58, 73, 124, 125, 126, 154, 176, 179, 238.
Z = 21	Sc	XVI	37, 58, 73, 126, 151, 179.
Z = 22	Ti	XVII	15, 22, 37, 58, 73, 124, 125, 126, 140, 151, 179.
Z = 23	V	XVIII	37, 58, 73, 126, 151, 179.
Z = 24	Cr	XIX	37, 46, 54, 58, 60, 73, 124, 125, 126, 140, 151, 179.
Z = 25	Mn	XX	37, 54, 58, 73, 126, 151, 179.
Z = 26	Fe	XXI	22, 37, 46, 54, 58, 60, 73, 74, 124, 125, 126, 140, 156, 176, 179.
Z = 27	Co	XXII	37, 54, 73, 74, 126, 140, 179.
Z = 28	Ni	XXIII	37, 46, 54, 60, 73, 74, 126, 140, 179.
Z = 29	Cu	XXIV	37, 46, 73, 126.
Z = 30	Zn	XXV	22, 37, 73, 126.
Z = 31	Ga	XXVI	126.
Z = 32	Ge	XXVII	126.
Z = 33	As	XXVIII	126.
Z = 34	Se	XXIX	22, 126.
Z = 35	Br	XXX	37, 126.
Z = 36	Kr	XXXI	22, 37, 126.
Z = 41, 42, 48, 53, 54, 59, 64, 69, 74, 79, 80, 82, 92 : 37.			

8. N, N-like ions ($7 e^-$, ground configuration : $2s^2 2p^3$).

Z = 7	N	I	33, 77, 92, 126, 162, 171, 172, 173, 211, 237, 243.
Z = 8	O	II	55, 77, 92, 126, 162, 171, 172, 173, 211, 237, 242, 243, 244.
Z = 9	F	III	11, 37, 77, 92, 126, 237, 243.
Z = 10	Ne	IV	11, 19, 37, 58, 77, 92, 126, 162, 237, 243.
Z = 11	Na	V	11, 37, 58, 92, 126, 162, 238, 243.
Z = 12	Mg	VI	11, 20, 37, 54, 58, 77, 92, 125, 126, 162, 238, 243.
Z = 13	Al	VII	11, 37, 54, 58, 126, 238, 243.

Z = 14	Si	VIII	11, 20, 37, 54, 58, 92, 124, 125, 126, 238, 243.
Z = 15	P	IX	11, 37, 54, 58, 126, 238, 243.
Z = 16	S	X	11, 20, 37, 54, 58, 92, 124, 125, 126, 238, 243.
Z = 17	Cl	XI	11, 37, 54, 58, 126, 243.
Z = 18	Ar	XII	11, 20, 37, 54, 58, 92, 124, 125, 126, 243.
Z = 19	K	XIII	11, 37, 54, 58, 126, 243.
Z = 20	Ca	XIV	11, 20, 37, 54, 58, 124, 125, 126, 243.
Z = 21	Sc	XV	11, 37, 58, 92, 126, 151, 243.
Z = 22	Ti	XVI	11, 15, 37, 58, 124, 125, 126, 140, 151, 243.
Z = 23	V	XVII	11, 37, 58, 126, 151, 243.
Z = 24	Cr	XVIII	11, 37, 46, 54, 58, 60, 124, 125, 126, 140, 151, 243.
Z = 25	Mn	XIX	11, 37, 54, 58, 126, 151, 243.
Z = 26	Fe	XX	11, 21, 37, 54, 58, 60, 74, 92, 124, 125, 126, 140, 218, 243.
Z = 27	Co	XXI	37, 126, 140.
Z = 28	Ni	XXII	37, 54, 60, 126, 140.
Z = 29	Cu	XXIII	37, 126.
Z = 30	Zn	XXIV	37, 92, 126.
Z = 31	Ga	XXV	126.
Z = 32	Ge	XXVI	126.
Z = 33	As	XXVII	126.
Z = 34	Se	XXVIII	126.
Z = 35	Br	XXIX	37, 126.
Z = 36	Kr	XXX	37, 126.
Z = 41, 42, 48, 53, 54, 59, 64, 69, 74, 79, 80, 82, 92 : 37.			

9. O, O-like ions ($8 e^-$, ground configuration : $2s^2 2p^4$).

Z = 8	O	I	7, 41, 42, 72, 77, 126, 127, 160, 162, 171, 172, 173, 211, 237.
Z = 9	F	II	7, 72, 77, 126, 237.
Z = 10	Ne	III	7, 37, 72, 77, 124, 126, 162, 237.
Z = 11	Na	IV	7, 37, 58, 72, 77, 126, 162, 238.
Z = 12	Mg	V	7, 37, 54, 58, 72, 124, 126, 162, 238.
Z = 13	Al	VI	7, 37, 54, 58, 72, 126, 238.
Z = 14	Si	VII	7, 14, 37, 54, 58, 72, 124, 125, 126, 238.
Z = 15	P	VIII	37, 54, 58, 72, 126, 238.
Z = 16	S	IX	7, 14, 37, 54, 58, 72, 124, 125, 126, 238.
Z = 17	Cl	X	37, 54, 58, 72, 126, 238.
Z = 18	Ar	XI	7, 14, 37, 54, 58, 72, 124, 125, 126, 238.
Z = 19	K	XII	7, 37, 54, 58, 72, 126.
Z = 20	Ca	XIII	7, 37, 44, 54, 58, 72, 124, 125, 126, 154.
Z = 21	Sc	XIV	37, 58, 72, 126, 151.
Z = 22	Ti	XV	7, 15, 37, 58, 72, 124, 125, 126, 140, 151.
Z = 23	V	XVI	37, 58, 72, 126, 151.
Z = 24	Cr	XVII	7, 37, 54, 58, 60, 72, 124, 125, 126, 140, 151.
Z = 25	Mn	XVIII	7, 37, 54, 58, 72, 126, 151.
Z = 26	Fe	XIX	7, 37, 54, 58, 60, 72, 74, 124, 125, 126, 140, 177.
Z = 27	Co	XX	37, 72, 74, 126, 140.
Z = 28	Ni	XXI	7, 37, 46, 54, 60, 72, 74, 126, 140, 177.
Z = 29	Cu	XXII	37, 72, 126.
Z = 30	Zn	XXIII	37, 72, 126.
Z = 31	Ga	XXIV	126.
Z = 32	Ge	XXV	126.
Z = 33	As	XXVI	126.
Z = 34	Se	XXVII	126.
Z = 35	Br	XXVIII	37, 126.
Z = 36	Kr	XXIX	7, 37, 72, 126.
Z = 41	Nb	XXXIV	37.
Z = 42	Mo	XXXV	37, 72.
Z = 48, 53, 54, 59, 64, 69, 74, 79, 80, 82, 92 : 37.			

10. **F, F-like ions ($9 e^-$, ground configuration : $2s^2 2p^5$).**

Z = 9	F	I	37, 126, 215, 234, 237.
Z = 10	Ne	II	37, 77, 126, 162, 234, 237.
Z = 11	Na	III	37, 126, 162, 234, 238.
Z = 12	Mg	IV	37, 77, 126, 162, 234, 238.
Z = 13	Al	V	37, 54, 126, 234, 238.
Z = 14	Si	VI	37, 54, 122, 126, 162, 234, 238.
Z = 15	P	VII	37, 54, 126, 234, 238.
Z = 16	S	VIII	37, 54, 122, 126, 234, 238.
Z = 17	Cl	IX	37, 54, 126, 234, 238.
Z = 18	Ar	X	37, 54, 122, 126, 234, 238.
Z = 19	K	XI	37, 44, 54, 126, 234, 238.
Z = 20	Ca	XII	37, 54, 122, 126, 154, 234, 238.
Z = 21	Sc	XIII	37, 126, 151, 234.
Z = 22	Ti	XIV	15, 37, 122, 126, 140, 151, 234.
Z = 23	V	XV	37, 126, 151, 234.
Z = 24	Cr	XVI	37, 54, 60, 122, 126, 140, 151, 234.
Z = 25	Mn	XVII	37, 54, 122, 126, 151, 234.
Z = 26	Fe	XVIII	37, 54, 60, 74, 122, 126, 140, 166, 218, 234.
Z = 27	Co	XIX	37, 54, 74, 126, 140.
Z = 28	Ni	XX	37, 54, 60, 74, 122, 126, 140.
Z = 29	Cu	XXI	37, 126.
Z = 30	Zn	XXII	37, 126.
Z = 31	Ga	XXIII	126.
Z = 32	Ge	XXIV	126.
Z = 33	As	XXV	126.
Z = 34	Se	XXVI	126.
Z = 35	Br	XXVII	37, 126.
Z = 36	Kr	XXVIII	37, 126.
Z = 37	Rb	XXIX	126.
Z = 38	Sr	XXX	126.
Z = 39	Y	XXXI	126.
Z = 40	Zr	XXXII	126.
Z = 41	Nb	XXXIII	37, 126.
Z = 42	Mo	XXXIV	37, 126.
Z = 48, 53, 54, 59, 64, 69, 74, 79, 80, 82, 92 : 37.			

11. **Ne, Ne-like ions ($10 e^-$).**

16, 62, 74, 79, 81, 85, 123, 130, 151, 152, 153, 212, 226.

12. **Na, Na-like ions ($11 e^-$).**

1, 25, 31, 32, 74, 93, 108, 137, 138, 151, 161, 162, 199, 220, 221, 232, 233.

13. **Mg, Mg-like ions ($12 e^-$).**

3, 43, 54, 74, 77, 79, 80, 81, 93, 111, 126, 141, 143, 162, 195, 213, 238.

14. **Al, Al-like ions ($13 e^-$, ground configuration : $3s^2 3p$).**

Z = 13	Al	I	114, 126, 234, 238.
Z = 14	Si	II	77, 114, 126, 162, 178, 234, 238.
Z = 15	P	III	114, 126, 234, 238.
Z = 16	S	IV	77, 114, 126, 162, 234, 238.
Z = 17	Cl	V	114, 126, 162, 234, 238.
Z = 18	Ar	VI	114, 126, 162, 234, 238.
Z = 19	K	VII	114, 126, 214, 234, 238.
Z = 20	Ca	VIII	54, 114, 122, 126, 214, 234, 238.
Z = 21	Sc	IX	114, 126, 151, 234.
Z = 22	Ti	X	114, 122, 126, 151, 234.
Z = 23	V	XI	114, 126, 151, 234.
Z = 24	Cr	XII	54, 114, 122, 126, 151, 213, 214, 234.

Z = 25	Mn	XIII	44, 54, 114, 122, 126, 151, 213, 214, 234.
Z = 26	Fe	XIV	24, 44, 54, 71, 74, 114, 122, 126, 154, 213, 214, 234.
Z = 27	Co	XV	44, 54, 74, 114, 126, 234.
Z = 28	Ni	XVI	44, 54, 74, 114, 122, 126, 213, 214, 234.
Z = 29	Cu	XVII	114, 126, 219, 234.
Z = 30	Zn	XVIII	114, 122, 126, 219, 234.
Z = 31	Ga	XIX	114, 122, 126, 219.
Z = 32	Ge	XX	114, 122, 126, 198, 219.
Z = 33	As	XXI	114, 126, 198, 219.
Z = 34	Se	XXII	114, 126, 219.
Z = 35	Br	XXIII	114, 126, 219.
Z = 36	Kr	XXIV	114, 126, 219.
Z = 37	Rb	XXV	114, 126, 219.
Z = 38	Sr	XXVI	114, 126, 219.
Z = 39	Y	XXVII	114, 126, 219.
Z = 40	Zr	XXVIII	114, 126, 219.
Z = 41	Nb	XXIX	114, 126, 219.
Z = 42	Mo	XXX	24, 114, 126, 219.
Z = 54	Xe	XLII	24, 114.
Z = 43 to 53 and 55 to 106 : 114.			

15. Si, Si-like ions ($14 e^-$, ground configuration : $3s^2 3p^2$).

Z = 14	Si	I	126, 162, 164, 231, 238.
Z = 15	P	II	113, 126, 164, 238.
Z = 16	S	III	23, 77, 113, 126, 162, 164, 238.
Z = 17	Cl	IV	77, 113, 126, 162, 164, 238.
Z = 18	Ar	V	23, 77, 113, 126, 162, 164, 238.
Z = 19	K	VI	77, 113, 126, 164, 214, 238.
Z = 20	Ca	VII	23, 54, 77, 113, 126, 164, 214, 238.
Z = 21	Sc	VIII	113, 126, 151, 164.
Z = 22	Ti	IX	23, 113, 126, 151, 164.
Z = 23	V	X	113, 126, 151, 164, 213.
Z = 24	Cr	XI	23, 54, 113, 126, 151, 164, 213, 214.
Z = 25	Mn	XII	54, 113, 126, 151, 164, 213, 214.
Z = 26	Fe	XIII	23, 54, 67, 74, 113, 126, 164, 213, 214.
Z = 27	Co	XIV	54, 74, 113, 126, 164.
Z = 28	Ni	XV	23, 44, 54, 74, 113, 126, 164, 213, 214.
Z = 29	Cu	XVI	113, 126, 219.
Z = 30	Zn	XVII	23, 113, 126, 219.
Z = 31	Ga	XVIII	113, 126, 219.
Z = 32	Ge	XIX	23, 113, 126, 219.
Z = 33	As	XX	113, 126, 198, 219.
Z = 34	Se	XXI	23, 113, 126, 219.
Z = 35	Br	XXII	113, 126, 219.
Z = 36	Kr	XXIII	23, 113, 126, 219.
Z = 37	Rb	XXIV	113, 126, 219.
Z = 38	Sr	XXV	23, 113, 126, 219.
Z = 39	Y	XXVI	113, 126, 219.
Z = 40	Zr	XXVII	23, 46, 113, 126, 219.
Z = 41	Nb	XXVIII	113, 126, 219.
Z = 42	Mo	XXIX	23, 113, 126, 219.
Z = 43	Tc	XXX	113.
Z = 44	Ru	XXXI	23, 113.
Z = 45	Rh	XXXII	113.
Z = 46	Pd	XXXIII	23, 113.
Z = 47	Ag	XXXIV	113.
Z = 48	Cd	XXXV	23, 113.
Z = 49	In	XXXVI	113.

Z = 50 Sn XXXVII 23, 113.
 Z = 51 to 106 : 113.

16. **P, P-like ions ($15 e^-$, ground configuration : $3s^2 3p^3$).**

Z = 15	P	I	126, 163, 238.
Z = 16	S	II	70, 77, 112, 126, 162, 163, 238.
Z = 17	Cl	III	77, 112, 126, 162, 163, 238.
Z = 18	Ar	IV	26, 77, 112, 126, 162, 163, 238.
Z = 19	K	V	77, 112, 126, 162, 163, 214, 238.
Z = 20	Ca	VI	26, 54, 112, 126, 163, 214, 238.
Z = 21	Sc	VII	112, 126, 151, 163.
Z = 22	Ti	VIII	26, 112, 126, 151, 163.
Z = 23	V	IX	112, 126, 151, 163.
Z = 24	Cr	X	26, 54, 112, 126, 151, 163, 214.
Z = 25	Mn	XI	54, 112, 126, 151, 163, 214.
Z = 26	Fe	XII	26, 54, 63, 74, 112, 126, 163, 213, 214.
Z = 27	Co	XIII	54, 74, 112, 126, 163.
Z = 28	Ni	XIV	26, 54, 70, 74, 112, 126, 163, 214.
Z = 29	Cu	XV	70, 112, 126, 219.
Z = 30	Zn	XVI	26, 112, 126, 219.
Z = 31	Ga	XVII	112, 126, 219.
Z = 32	Ge	XVIII	26, 70, 112, 126, 219.
Z = 33	As	XIX	112, 126, 219.
Z = 34	Se	XX	26, 70, 112, 126, 219.
Z = 35	Br	XXI	112, 126, 219.
Z = 36	Kr	XXII	26, 70, 112, 126, 219.
Z = 37	Rb	XXIII	112, 126, 219.
Z = 38	Sr	XXIV	26, 70, 112, 126, 219.
Z = 39	Y	XXV	112, 126, 219.
Z = 40	Zr	XXVI	26, 46, 70, 112, 126, 219.
Z = 41	Nb	XXVII	112, 126, 219.
Z = 42	Mo	XXVIII	26, 46, 70, 112, 126, 219.
Z = 43	Tc	XXIX	112.
Z = 44	Ru	XXX	26, 112.

Z = 45 to 92 : 112.

17. **S, S-like ions ($16 e^-$, ground configuration : $3s^2 3p^4$).**

Z = 16	S	I	28, 77, 126, 128, 159, 162, 165, 201, 202, 238.
Z = 17	Cl	II	28, 77, 126, 162, 165, 201, 202, 238.
Z = 18	Ar	III	28, 77, 126, 162, 165, 201, 202, 238.
Z = 19	K	IV	28, 77, 126, 162, 165, 201, 202, 214, 238.
Z = 20	Ca	V	28, 77, 126, 162, 165, 201, 202, 214, 238.
Z = 21	Sc	VI	28, 126, 165, 201, 202.
Z = 22	Ti	VII	28, 126, 151, 165, 201, 202.
Z = 23	V	VIII	28, 126, 151, 165, 201, 202.
Z = 24	Cr	IX	28, 44, 54, 126, 151, 165, 201, 202, 213, 214.
Z = 25	Mn	X	28, 54, 126, 151, 165, 201, 202, 214.
Z = 26	Fe	XI	28, 54, 74, 126, 154, 157, 165, 201, 202, 213, 214.
Z = 27	Co	XII	28, 54, 74, 126, 165, 201, 202, 213.
Z = 28	Ni	XIII	28, 54, 74, 126, 165, 201, 202, 213, 214.
Z = 29	Cu	XIV	28, 126, 201, 202, 219.
Z = 30	Zn	XV	28, 126, 201, 202, 219.
Z = 31	Ga	XVI	28, 126, 198, 201, 202, 219.
Z = 32	Ge	XVII	28, 126, 198, 201, 202, 219.
Z = 33	As	XVIII	28, 126, 201, 202, 219.
Z = 34	Se	XIX	28, 126, 201, 202, 219.
Z = 35	Br	XX	28, 126, 201, 202, 219.
Z = 36	Kr	XXI	28, 126, 198, 201, 202, 219.
Z = 37	Rb	XXII	28, 126, 201, 202, 219.

Z = 38	Sr	XXIII	28, 126, 201, 202, 219.
Z = 39	Y	XXIV	28, 126, 201, 202, 219.
Z = 40	Zr	XXV	28, 126, 201, 202, 219.
Z = 41	Nb	XXVI	28, 126, 201, 202, 219.
Z = 42	Mo	XXVII	28, 126, 201, 202, 219.
Z = 43 to 92 : 201, 202.			

18. **Cl, Cl-like ions ($17 e^-$, ground configuration : $3s^2 3p^5$).**

Z = 17	Cl	I	115, 126, 162, 234, 238.
Z = 18	Ar	II	115, 126, 162, 234, 238.
Z = 19	K	III	115, 126, 162, 214, 234, 238.
Z = 20	Ca	IV	115, 122, 126, 162, 214, 234, 238.
Z = 21	Sc	V	115, 126, 151, 234.
Z = 22	Ti	VI	115, 122, 126, 151, 234.
Z = 23	V	VII	115, 126, 151, 234.
Z = 24	Cr	VIII	54, 115, 122, 126, 151, 214, 234.
Z = 25	Mn	IX	54, 115, 122, 126, 151, 214, 234.
Z = 26	Fe	X	24, 44, 54, 74, 115, 122, 126, 154, 157, 213, 214, 230, 234.
Z = 27	Co	XI	54, 74, 115, 126, 234.
Z = 28	Ni	XII	44, 54, 74, 115, 122, 126, 213, 214, 234.
Z = 29	Cu	XIII	115, 126, 219, 234.
Z = 30	Zn	XIV	115, 122, 126, 219, 234.
Z = 31	Ga	XV	122, 126, 219, 234.
Z = 32	Ge	XVI	122, 126, 219, 234.
Z = 33	As	XVII	126, 219, 234.
Z = 34	Se	XVIII	115, 126, 219, 234.
Z = 35	Br	XIX	115, 126, 219.
Z = 36	Kr	XX	115, 126, 219.
Z = 37	Rb	XXI	115, 126, 219.
Z = 38	Sr	XXII	115, 126, 219.
Z = 39	Y	XXIII	126, 219.
Z = 40	Zr	XXIV	126, 219.
Z = 41	Nb	XXV	115, 126, 219.
Z = 42	Mo	XXVI	24, 115, 126, 219.
Z = 46	Pd	XXX	115.
Z = 47	Ag	XXXI	115.
Z = 48	Cd	XXXII	115.
Z = 50	Sn	XXXIV	115.
Z = 53	I	XXXVII	115.
Z = 54	Xe	XXXVIII	24, 115.
Z = 55, 56, 58, 62, 66, 70, 74, 78, 79, 80, 83, 86, 90, 92 : 115.			

19. **Ar, Ar-like ions ($18 e^-$).**

54, 64, 79, 81, 212, 213, 226, 228.

20. **K, K-like ions ($19 e^-$).**

1, 2, 30, 74, 76, 83, 107, 108, 136, 138, 162, 213, 232, 235, 238.

21. **Ca, Ca-like ions ($20 e^-$).**

8, 9, 10, 74, 77, 151, 162, 189, 213, 236.

22. **Sc, Sc-like ions ($21 e^-$).**

74, 77, 84, 151, 162, 181, 200, 213.

23. **Ti, Ti-like ions ($22 e^-$).**

74, 77, 106, 162, 213.

24. **V, V-like ions ($23 e^-$).**

56, 74, 151, 162, 192, 197, 213.

25. **Cr, Cr-like ions ($24 e^-$).**
74, 77, 84, 162, 213.
26. **Mn, Mn-like ions ($25 e^-$).**
74, 77, 78, 99, 103, 117, 151, 162, 185, 190, 191, 193, 213.
27. **Fe, Fe-like ions ($26 e^-$).**
74, 77, 98, 162, 213, 241.
28. **Co, Co-like ions ($27 e^-$).**
30, 74, 188, 213.
29. **Ni, Ni-like ions ($28 e^-$).**
9, 74, 213, 240.
30. **Zn, Zn-like ions ($30 e^-$).**
4, 9, 43, 80, 81.
31. **Ga, Ga-like ions ($31 e^-$, ground configuration : $4s^2 4p$).**
Z = 31 to 35 : 29, 234.
Z = 36 to 54 : 29.
32. **Ge, Ge-like ions ($32 e^-$, ground configuration : $4s^2 4p^2$).**
Z = 32 to 47 : 27.
33. **As, As-like ions ($33 e^-$, ground configuration : $4s^2 4p^3$).**
Z = 33 to 47 : 27.
34. **Se, Se-like ions ($34 e^-$, ground configuration : $4s^2 4p^4$).**
Z = 34 : 28, 129.
Z = 35 : 28.
Z = 36 : 28, 229.
Z = 37 to 47 : 28.
35. **Br, Br-like ions ($35 e^-$, ground configuration : $4s^2 4p^5$).**
Z = 35 to 42 : 24, 234.
Z = 43 to 54 : 24.
36. **Kr, Kr-like ions ($36 e^-$).**
212, 226.
37. **Rb, Rb-like ions ($37 e^-$).**
138, 174, 175, 232.
38. **Sr, Sr-like ions ($38 e^-$).**
8, 10, 223.
39. **Cd, Cd-like ions ($48 e^-$).**
80, 81, 141.
40. **In, In-like ions ($49 e^-$, ground configuration : $5s^2 5p$).**
Z = 49 to 52 : 234.
41. **Te, Te-like ions ($52 e^-$, ground configuration : $5s^2 5p^4$).**
Z = 54 : 102, 229.
42. **I, I-like ions ($53 e^-$, ground configuration : $5s^2 5p^5$).**
Z = 53 to 56 : 234.
43. **Xe, Xe-like ions ($54 e^-$).**
212.

44. Cs, Cs-like ions (55 e⁻).

9, 138, 203, 206, 232.

45. Ba, Ba-like ions (56 e⁻).

8, 131, 158.

46. Ir, Ir-like ions (77 e⁻).

57.

47. Pt, Pt-like ions (78 e⁻).

57.

48. Hg, Hg-like ions (80 e⁻).

80, 81, 141.

49. Tl, Tl-like ions (81 e⁻, ground configuration : 6s²6p).

Z = 81 : 170, 234.

Z = 82, 83 : 234.

50. Pb, Pb-like ions (82 e⁻, ground configuration : 6s²6p²).

Z = 82 : 86, 133.

51. At, At-like ions (85 e⁻, ground configuration : 6s²6p⁵).

Z = 84 : 234.

52. M2 transitions.

Note that the Z-values treated in each reference appear in brackets.

He-like : 38(17), 39(16), 48(18), 49(18), 52(2 to 10), 79(6, 10, 14, 18, 26), 81(2, 8, 18, 26), 96(23, 26),
 105(16 to 18, 22, 23, 26), 116(2 to 10),
 119(2 to 10, 12, 14, 16 to 18, 20, 22, 23, 26, 28, 30, 36, 40, 50, 60, 70, 80, 90, 100),
 120(5, 10, 16, 18, 26, 36, 60), 135(2 to 6), 141(2),
 142(2, 4, 6, 8, 10 to 30, 36, 42, 45, 50, 56, 65, 74, 80, 100), 143(2, 4, 6, 8, 10),
 148(16 to 18, 22, 23, 26), 149(18), 150(18).

Li-like : 35(6 to 10, 12, 14, 18, 22, 26, 30, 36, 42), 36(4 to 26), 39(16), 48(18), 49(18), 50(18), 104(13, 14),
 139(8 to 26), 196(3 to 18), 216(26, 41, 54, 65, 77, 83, 94).

Be-like : 79(26), 81(26), 87(6 to 10, 12, 14, 18, 20, 26), 90(36, 42), 91(22), 139(14, 20, 26), 143(4 to 8, 10, 12),
 144(4 to 10, 18, 26, 36, 42, 54, 64, 74, 82, 92), 168(4, 6, 8, 10, 12, 14, 16, 18, 20, 26, 28), 180(6),
 182(20, 26, 36, 42), 184(7 to 10), 209(6 to 30).

Ne-like : 62(10, 12, 14, 18, 26, 32, 50, 67, 74, 92), 79(26), 81(26), 123(14, 17 to 29), 130(24, 26, 28), 212(10).

Mg-like : 77(12), 79(26), 80(12), 81(12, 26), 111(13), 141(12), 143(12 to 17), 195(14).

Al-like : 71(26).

Ar-like : 79(26), 81(26), 212(18).

S-like : 157(26).

Cl-like : 157(26).

Zn-like : 4(30, 34, 36, 42, 48, 54, 64, 70, 74, 79, 80, 86, 92), 80(30), 81(30).

Kr-like : 212(36).

Cd-like : 80(48), 81(48), 141(48).

Xe-like : 212(54).

Hg-like : 80(80), 81(80), 141(80).