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Lifetimes and Oscillator Strengths for Be I- Be III

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ABSTRACT.
In contemporary fusion research beryllium (Be) plays an important role. It is being assessed as a suitable low Z material for plasma-facing walls, limiters and divertors. Several authors have already made detailed spectroscopic studies of Be in tokamak plasmas. In the present report a critical evaluation has been made of radiative transitions in neutral, singly and doubly ionized Be (Be I - Be III), with emphasis on the needs for diagnostic measurements in plasmas. In addition to an extensive literature survey we also report new experimental and theoretical results. The former were obtained by means of the beam-foil excitation technique, whereas the theoretical analyses were performed using the superposition of configurations (SOC) method of Cowan. On the basis of available theoretical and experimental data critically evaluated oscillator strengths and transition probabilities are presented for a number of transitions in Be I - Be III.

1. INTRODUCTION

The use of beryllium as a suitable plasma-facing material for limiters and divertors in tokamaks has been discussed for several years. Pilot studies on ISX-B [1] and UNITOR [2] led to the major experimental programme on beryllium in JET [3]. This programme has continued and the new pumped divertor at JET (presently under construction) will initally have solid beryllium target elements [4]. Detailed observations and modelling of the spectral emission from beryllium ions have been carried out in the original machine configuration of JET [5]. However, spectroscopic diagnostics will be of particular importance for the divertor plasma, and wide wavelength coverage with spatial and temporal resolution is planned. Cool relatively high density conditions are sought for the divertor and there will be high concentrations of neutral deuterium. A strongly recombining environment should be experienced by inflowing impurity ions from the bulk plasma while released neutral species from the strike zones will be ionising. For populations of excited states of beryllium ions, collisional mixing, charge transfer and dynamic development of metastable states matter. These features allow extended diagnostic spectral measurements, but require comprehensive 'collisional-radiative' modelling [5] and fundamental reaction data of high quality.

In the present report an evaluation of lifetimes and transition probabilities for Be I - Be III is presented. We will also report on new experimental and theoretical studies of these quantities. This critical study of the available theoretical and experimental material is further motivated by the fact that the existing critical compilation, by Wiese *et al.* [6] is more than 25 years old and thus severely outdated. For instance, in 1966 there were no experimental lifetimes (or oscillator strengths) available for Be, and also the theoretical data could suffer from serious shortcomings, being usually based on single-configuration approximations. However, at the end of the 1960's the experimental situation underwent important improvements, mainly thanks to the introduction of the method of beam-foil spectroscopy (BFS). Similarly, the development of powerful computer codes for configuration interaction (CI), multi-configuration Hartree-Fock (MCHF) and other modern methods for atomic structure calculations have drastically changed the theoretical picture.

It should also be noted that the knowledge about experimental wavelengths and excitation energies has increased in recent years. All relevant high-resolution data on wavelengths and energies can be found in Refs.[7-10] (Be I), [8,10] (Be II) and [11,12] (Be III).

2. EARLY BEAM-FOIL WORK

In the late 1960's and early 1970's two groups, in Aarhus and Stockholm, made experimental determinations of lifetimes in neutral and ionized Be, using the method of beam-foil spectroscopy (BFS) [13-21]. Somewhat later a lifetime measurement for Be I, using laser excitation was reported [22]. These are (as far as we know) the only lifetime measurements performed for levels in Be I - Be III, with the exception of a number of studies of inner-shell excited (or doubly excited) levels, e.g. those belonging to the 1s2sn*l* and 1s2pn*l* configurations in Be II or the 2sn*l* or 2pn*l* configurations in Be III. For a review of such work, see Mannervik [23].

It was pointed out by Kerkhoff *et al.* [22], more than 10 years ago, that the number of experimental studies of Be I lifetimes is small in comparison with the publications that report new theoretical results. The situation has not changed in recent years, e.g. there are at least 20 theoretical papers dealing with Be I, the main emphasis being placed on the $2s^2\ ^1S$ - $2s2p\ ^1P$ resonance line.

In the early days of beam-foil spectroscopy, a number of sources of systematic uncertainties were unknown or underestimated. Consequently, the error estimates given in the early papers are sometimes too optimistic. Among the error sources, cascading and line blending are particularly serious. They both result in decay curves which are sums of exponential functions. It is well known that the decomposition of such data involves substantial numerical problems and may lead to large uncertainties. For some years there appeared tendencies to discard a very large fraction of all available beam-foil data and primarily rely on theoretical results. However, already in 1971 remedies were found for the cascade problems [24] and it became also possible to markedly increase the spectral resolution

[25]. These methods (and their further developments) have now been routinely used for many years. Their applications to Be-like ions have been discussed by several authors, e.g. Engström *et al.* [26] and Reistad and Martinson [27].

In this report we present beam-foil data for Be I - Be III, obtained at the 400 kV heavy ion accelerator at the Research Institute of Physics (now called the Manne Siegbahn Institute), Stockholm. The experimental work was performed in 1973 and 1974, but only a fraction of the data has been published so far [21]. The results now presented have been reanalyzed by means of modern methods.

3. EXPERIMENT

The 400 kV accelerator in Stockholm gave good beams of Be which could be accelerated to several energies and directed through a carbon foil or a gas cell where excitation, ionization or capture could take place. In the experiments discussed here the light emitted by the ions was analyzed with a Heath 35 cm EUE monochromator, equipped with a Peltier-cooled EMI 6256 photomultiplier. Some typical spectra, obtained with the setup are displayed in the paper by Hontzeas *et al.* [19]. A somewhat more recent spectrum of Be, also recorded with the same equipment, is shown in Fig. 1. Note the favourable signal-to-noise and the strong transitions from doubly-excited levels in Be II. At the time of the lifetime measurements (reported here) the velocity of the ions was calculated, using known data for the energy loss in the foil. More refined checks, performed in 1975, by means of the quantum beat method and direct measurements using an electrostatic analyzer, essentially confirmed the computed velocities. Thus, we asume that the velocities were known with an uncertainty of 2 %. Lifetimes were measured for the 2p ^2P level in Be II (3130 Å) and the Be I levels 2s4d ^1D (3813 Å), $2p^2$ ^3P (2650 Å), 2s3s ^3S (3321 Å), and 2s3d ^3D (2494 Å). These lifetimes have been determined earlier, but in a number of cases the various results differ somewhat and, moreover, they are not quite consistent with the theoretical predictions.

The decay curves were analyzed in Lund, using two computer programs, DISCRETE [28] and DECFIT [29]. Examples of decay curves are shown in Figs. 2-4. The results are included in Tables I-III, together with previous experimental and theoretical lifetime data. In most theoretical publications oscillator strengths (f-values) are presented. In converting these data to lifetimes, we have consistently used experimental transition wavelengths.

In addition to the lifetime measurements we also carried out theoretical calculations of f-values for Be I, using the superposition-of-configurations method of Cowan [30]. The program was run in the *ab initio* mode, except for the default scaling of 85% and 90% for the electrostatic and spin-orbit integrals, respectively. For the 2sn$l$ system we performed calculations for n = 2-7 and l = 0-3, and also included the $2p^2$ configuration. In the calculation of the 2pn$l$ system (n = 3-5 and l = 0-3) we also included the continuum states 2sεl (l = 0-4) in order to obtain correct lifetimes for the autoionizing levels in the 2pn$l$ configuration. Our theoretical results are included in Table III.

4. DISCUSSION

4.1. Be III

The experimental and theoretical results for Be III are summarized in Table I. Very accurate calculations of energy levels and f-values can be carried out for two-electron ions. The theoretical f-values, from the available calculations [31-37], may often have uncertainties as low as 1%. or less. It is therefore very difficult to perform experiments that really test the theoretical values, and indeed no such data are available in the case of Be III. However, a successful such measurement of this kind was reported by Astner *et al.* [38], who - using beam-foil spectroscopy - determined a lifetime in He I with an uncertainty of 0.26%. The result was in excellent agreement with theory. Since calculations for Be III should not be more complicated than in the He I case, this result provides additional support to the theoretical data for Be III. A study of Table I indicates a marked difference between the various theoretical results (which all are consistent) and the experimental lifetime for the 1s2p ^3P term. The latter is from a very early experiment, and the discrepancy is probably due to experimental problems,notably Rutherford scattering of ions in the foil which leads to a divergent beam after the foil, loss of intensity and consequently a too short lifetime. A remeasurement would here be motivated.

A very interesting case is given by the $1s^2\ ^1S_0$ - $1s2p\ ^3P_1$ intercombination line, first observed in JET some years ago [5]. Such transitions, which become possible because of violations of the LS-coupling approximation, are more difficult to calculate than the $\Delta S = 0$ electric dipole ones, because the amount of spin-orbit induced mixing (here between the $^1P_1$ and $^3P_1$ levels) strongly affects the lifetime. No measurements exist for Be III, but we refer to a beam-foil study of the same transition in the isoelectronic spectra of C V and N VI [39] which yielded data in excellent agreement with Drake's calculations [40] for these ions. The latter should therefore be quite reliable also in the case of Be III.

4.2. Be II

The Be II singly excited system, with one active electron outside the $1s^2$ shell, is not expected to present significant theoretical problems or difficulties. Thus, the theoretical transition probabilities should be judged as quite reliable. Several sets of such data exist, based on *ab-initio* Hartree-Fock calculations [41,42] or semiempirical model potential or Coulomb approximation calculations [37,43,44]. From Table II, where these results are compared with experimental lifetimes [13-19] it can be noted that the various experimental results are in reasonable accord with the theoretical lifetimes, with a few exceptions. In cases when the early beam-foil data are not internally quite consistent, the most recent results, by Hontzeas *et al.* [19], tend to lie closest to the theoretical predictions. Only for the 6f ^2F level does a discord appear, here the problem is most likely on the experimental side. A more fundamental problem concerns the 2s ^2S - 2p ^2P resonance transition. Here our new measurement is in very good agreement with theory [37,41-44], indicating that the previous experimental data may have suffered from some small systematic errors (Rutherford scattering, underestimation of cascading, etc). This transition in Li-like ions has been throughly investigated in recent years, largely because there persisted a small but significant discrepancy for Li I between the results obtained from very accurate experimental work [45,46] and theoretical *ab initio* studies. However, more recent theoretical calculations [47] seem to have bridged this small gap.

4.3. Be I

The spectrum of Be I with two electrons outside a core presents much more difficult theoretical problems than Be III or Be II, discussed above. Here configuration interaction effects can be substantial, and single-configuration calculations may therefore result in values of poor accuracy. A well known example is the $2s^2\ ^1S$ - $2s2p\ ^1P$ resonance transition, for which the results f = 1.8 (dipole length value) or f = 0.95 (dipole velocity value) are obtained when configuration interaction is neglected. On the other hand, the geometric mean of these values 1.31 is fairly close to the best theoretical and experimental values. In certain cases series perturbations, for instance the interaction of the $2p^2\ ^1D$ term with the 2snd ^1D series may play a significant role.

In Table III we present a summary of experimental and theoretical data for Be I lifetimes. (In some cases two different theoretical values are given by the same author, being based on the dipole-length and dipole-velocity approximation, respectively). While there indeed exists a wealth of experimental [13,14,16-19,21,22] and theoretical [6,37,48-74] data, several problems and inconsistencies seem to remain.

Of fundamental importance in Be I and Be-like ions are the n = 2, Δn = 0 transitions. In the present case we are concerned with the $2s^2\ ^1S$ - $2s2p\ ^1P$ resonance multiplet, and the $2s2p\ ^1P$ - $2p^2\ ^1D$ and $2s2p\ ^3P$ - $2p^2\ ^3P$ combinations. Note that the $2p^2\ ^1S$ level lies above the first ionization limit of Be I and is autoionizing. This had been suggested in several theoretical studies, and the experimental proof was provided by Clark *et al.* [75] in a laser experiment. The line at 3455 Å, which for many years was assigned to the $2s2p\ ^1P$ - $2p^2\ ^1S$ radiative transition is due to the $2s3p\ ^1P$ - $2p3p\ ^1P$ combination, as first predicted by Weiss [50] and subsequently confirmed in two beam-foil experiments [17,19] .

As shown in Table III a wide variety of results can be found for the $2s^2$ ^1S - $2s2p\ ^1P$ resonance line (2348 Å). On the experimental side, the most accurate value is given in Ref. [21], and it is in very good agreement with several theoretical results, for instance [53,54,57,60,68]. Here the calculations of Sims and Whitten [53] are of particular interest, because these authors were able to obtain rigorous upper and lower bounds to the theoretical f-values.

The f-value for the 2s2p ^1P - $2p^2$ ^1D transition is predicted to be very small because of cancellation in the dipole matrix element. Thus, the various theoretical results have large uncertainties. Note also, that no experimental lifetime is available, only a lower limit has been obtained in a beam-foil experiment [18]. It has further been discussed in recent years whether in Be I there exists a well-defined $2p^2$ ^1D state at all, an alternate interpretation being that $2p^2$ ^1D is distributed over the whole 2snd ^1D series [76,77]. However, a multiconfiguration Hartree-Fock (MCHF) calculation of Froese Fischer [78] shows that the lowest ^1D state is predominatly $2p^2$ ^1D. In contrast to these problems, several theoretical and experimental results are available for the 2s2p ^3P - $2p^2$ ^3P transition. Table III shows that practically all the data are consistent for this multiplet. This is not surprising, however. The effects of configuration interaction are not dominant for this transition, while (from the experimental point of view) the multiplet is very intense and the cascade effects are limited.

No experimental decay data have been reported for the 2sns ^1S states. However, the theoretical data of Weiss [50] are expected to be reliable, because the method used, superposition of configurations (SOC), has been found to yield data that are in good agreement with experiment for other levels in Be I. Furthermore, the results of Weiss are consistent with more recent calculations [62,67,73]. Nor does experimental material exist for 2s3p ^1P and higher ^1P terms (Table III). Here, also, calculated values are available. However, the f-values for transitions to the ground state ($2s^2$ ^1S - 2snp^1P, n = 2,3,4..) are relatively small, and for these the various theoretical values differ substantially). On the other hand, the decays to higher states (e.g. 2s3s ^1S) largely determine the lifetimes of the 2snp ^1P terms.

In the triplet system, there is a fairly large amount of experimental data for the 2sns ^3S, 2snp ^3P and 2snd ^3D decay times. For instance, the 2s2p ^3P - 2s3s ^3S multiplet (at 3321 Å) has been investigated experimentally by several authors, and the data are in agreement with each other and also with theory. We have now remeasured this decay, and our data also yield an experimental lifetime for the 2s3p ^3P level, determined from the cascade in the 3321 Å decay curve, see Fig. 4. The 2s3s ^3S - 2s3p ^3P transition lies in the infrared region (14650 Å) and it cannot be easily detected in a beam-foil experiment. On the other hand, in the studies of tokamak spectra, the 3321 Å line plays an important role [1,2,5] and the repopulation of the 2s3s ^3S term by cascading from 2s3p ^3P must be carefully studied.

In Table III we also present data for the doubly excited states 2pn*l* ^1L and 2pn*l* ^3L with n = 3,4...These lie above the first ionization limit and would autoionize via the Coulomb interaction mechanism. However, this decay mode is not possible for levels with l = L, and these mainly decay by radiative transitions to lower states. Typical examples are the 2p3p ^1P level, mentioned above, 2p3d ^1D, 2p3p ^3P and 2p3d ^3D, see [9,19,49]. Comparisons of experimental and theoretical lifetimes here show that the latter are often longer. The principal explanation is here that besides radiative decay to the 2sn*l* levels the doubly excited levels have additional decay mechanisms, notably spin-orbit induced autoionization.

5. RECOMMENDED TRANSITION PROBABILITIES

By analyzing the experimental and theoretical material discussed above and presented in the Tables I-III, we have compiled a set of recommended f-values and transition probabilities (Einstein A-coefficients) for a number of fundamental transitions in Be I - Be III, primarily resonance lines and transitions between low-lying levels. These data are presented in Tables IV-VI.

In the case of Be III (where as noted the theoretical data are consistent and more accurate than the available experimental results) we have mainly selected the f-values given by Schiff *et al.* [33] which are generally considered as the most precise ones. However, for higher values of n the fairly recent calculations, by Fernley *et al.* [36] are probably more accurate than other theoretical results. In the case of the $1s^2\ ^1S_0$ - $1s2p\ ^3P_1$ intercombination line, the value of Drake [40] has been used, realizing that the other theoretical results are very similar (see the discussion by Summers *et al.* [5]). For transitions involving the 1snd levels the calculations of Kono and Hattori [31] were selected. Note also that Theodosiou [37] gives theoretical lifetimes for many levels in Be III (in very good agreement with other data, Table I) whereas no transition probabilities are included in Ref. [37].

Similar data for Be II are given in Table V. Here, also, the calculations of Theodosiou [37] are very extensive, but as in the Be III case limited to lifetimes only. Whenever possible, we have in Table V adopted these data, but in cases when a given upper level decays to more than one lower level, the f-values of Lindgård and Nielsen [44] have been selected in Table V. As pointed out earlier (see also Table II) the results of Refs. [37] and [44] are in excellent agreement, although the latter are based on a more sophisticated theoretical treatment.

The theoretical complexities being largest for Be I, it is natural that the calculations sometimes result in quite different f-values. This holds in particular for weaker lines where cancellations in the dipole matrix element play a significant role. In Table VI a set of recommended f-values is given. In selecting these data, emphasis has been placed on comparisons with experimental results. For the $2s^2\ ^1S$ - $2s2p\ ^1P$ resonance line we have selected the value of Sims and Whitten [53] which agrees with other accurate theoretical calculations, notably [54,56,57,62,68,69] and with experiment [21]. For the other transitions within the $n = 2$ and $n = 3$ shells we have usually taken mean values of the theoretical results based on elaborate configuration-interaction or model-potential calculations. In most cases more recent theoretical data were preferred. As an example, for the $2s3s\ ^3S$ - $2s3p\ ^3P$ transition, we have selected the data of Hibbert [58], Chang and Tang [73] and Bartschat *et al.* [74], the mean value of which is given in Table VI.

6. CONCLUDING REMARKS

Although the available data on lifetimes and f-values is quite extensive, a number of problems merit additional study. Besides being motivated by the data needs in fusion research, much of this work is of great importance for basic atomic physics. Thus, the structure of Be is nowadays being theoretically studied by means of very advanced non-relativistic and relativistic atomic-structure codes [79,80]. A number of Be I and Be II lines (notably those at 2494 Å, 2650 Å, 3130 Å and 3321 Å) are of interest in astrophysics, in connection with determination of Be abundances in solar and stellar atmospheres.

For Be III and Be II additional lifetime measurements are primarily motivated if uncertainties as low as 1% - 2% can be reached and comparisons with theory can become meaningful. For Be I the situation is different, here less precise measurements will continue to be quite useful. Besides the 2sns ^1S and 2snp ^1P levels, mentioned above, also the 2snd ^1D levels merit further study. These ^1D levels have been discussed recently [78-80], and it appears that careful lifetime measurements may solve some of the present differences between theoretical and experimental data. Furthermore, additional studies of the levels of the 2pn$l$ configuration will most likely provide interesting insight into J-dependent decay rates of excited levels. Such work has recently been initiated [81].

The critically evaluated data on transition probabilities are being incorporated together with electron collision rate coefficients in specific files for Be^0, Be^{+1} and Be^{+2} in the JET atomic data and analysis structure (ADAS). Extensive tables of derived theoretical quantities for spectroscopic measurement interpretation such as photon efficiencies and ratios of line emissivities have been computed with collisional-radiative models. These are available on request.

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Table I. Lifetimes in Be III.

Upper level	Wavelength (Å)	Lower level	Lifetime of upper level (ns) Experiment[a]	Theory
$1s3s\ ^1S$	767.8	$1s2p\ ^1P$	1.2 (1) [20]	1.14 [33] 1.19 [34] 1.16 [36] 1.15 [37]
$1s3d\ ^1D$	746.2	$1s2p\ ^1P$	0.21 (2) [20]	0.194 [34] 0.195 [37] 0.196 [31]
$1s3s\ ^3S$	725.2	$1s2p\ ^3P$	1.11 (6) [20]	0.923 [33] 0.877 [34] 0.921 [36] 0.911 [37]
$1s2p\ ^3P$	3722.2	$1s2s\ ^3S$	22.3 (10) [14]	29.24 [33] 28.19 [34] 29.17 [36] 29.30 [37] 29.23 [32] 29.16 [35]
$1s3p\ ^3P$	582.1	$1s2s\ ^3S$	0.74 (4) [20]	0.603 [33] 0.632 [34] 0.604 [36] 0.611 [37] 0.605 [35]
$1s3d\ ^3D$	675.6	$1s2p\ ^3P$	0.18 (2) [20]	0.177 [34] 0.180 [37] 0.178 [31]

[a] The numbers in parentheses represent experimental uncertainties, i.e. 1.2 (1) stands for 1.2 ± 0.1, etc., while the numbers in square brackets refer to the list of references.

Table II. Lifetimes in Be II

Upper level	Wavelength (Å)	Lower level	Lifetime of upper level (ns)	
			Experiment	Theory
3s ^2S	1776.2	2p ^2P	3.3 (3) [14] 2.0 (2) [15] 2.5 (3) [16]	2.511 [44] 2.473 [37] 2.37 [41] 2.38 [42]
4s ^2S	5270.6	3p ^2P	4.4 (3) [14] 4.1 (3) [16] 3.77 (10) [13] 4.2 (3) [19]	4.254 [44] 4.196 [37]
4s ^2S	1197.1	2p ^2P	4.9 (3) [15] 5.0 (3) [16] 3.8 (4) [19]	
5s ^2S	3241.7	3p ^2P		7.213 [37] 7.311 [44]
2p ^2P	3130.6	2s ^2S	8.1 (4) [14] 9.5 (2) [16] 9.29 (20) [13] 8.7 (2) [*]	8.939 [44] 8.930 [37] 8.62 [41] 8.63 [42] 8.77 [43]
3p ^2P	1036.3	2s ^2S	6.7 (8) [19]	5.615 [44] 5.431 [37] 5.58 [41] 5.55 [42]
4p ^2P	3274.6	3s ^2S	8.1 (8) [14] 8.5 (9) [19]	8.312 [44] 8.030 [37]
4p ^2P	4828.2	3d ^2D	8.2 (8) [19]	
3d ^2D	1512.4	2p ^2P	0.83 (8) [15] 0.92 (6) [16] 1.0 (1) [19]	0.911 [44] 0.911 [37] 0.876 [41] 0.878 [42]
4d ^2D	4360.9	3p ^2P	2.3 (2) [14] 2.12 (9) [16] 2.22 (6) [13]	2.069 [44] 2.081 [37]
4d ^2D	1143.0	2p ^2P	2.30 (9) [16] 2.4 (2) [19]	

$5d\ ^2D$	3046.6	$3p\ ^2P$	5.1 (3) [14] 5.4 (5) [17] 3.5 (4) [19]	3.940 [44] 3.971 [37]
$5d\ ^2D$	1026.9	$2p\ ^2P$	3.2 (4) [19]	
$6d\ ^2D$	6279.6	$4p\ ^2P$	8.0 (8) [14]	6.688 [44] 6.754 [37]
$6d\ ^2D$	2618.1	$3p\ ^2P$	7.3 (8) [19]	
$4f\ ^2F$	4673.4	$3d\ ^2D$	7.0 (4) [14] 4.9 (2) [16] 5.02 (14) [13]	4.523 [44] 4.522 [37]
$5f\ ^2F$	3197.1	$3d\ ^2D$	9.7 (7) [14] 10.8 (10) [17] 9.0 (8) [19]	8.737 [44] 8.739 [37]
$6f\ ^2F$	2728.9	$3d\ ^2D$	9.3 (10) [19]	14.93 [44] 14.93 [37]

*This work

Table III. Lifetimes in Be I

Upper level	Wavelength (Å)	Lower level	Lifetime of upper level (ns)	
			Experiment	Theory$^{\$}$
2s3s ^1S	8254.1	2s2p ^1P		26.8; 28.2 [50] 22.9 [62] 24.3 [67] 27.9 [73] 19.9 [*]
2s4s ^1S	4407.9	2s2p ^1P		48.1; 47.2 [50] 42.9 [62] 47.6 [73] 31.8 [*]
2s5s ^1S	3736.3	2s2p ^1P		56.5; 80.0 [50] 80.3 [73] 71.8 [62] 47.6 [*]
2s6s ^1S	3476.5	2s2p ^1P		145; 147 [50]
2s2p ^1P	2348.6	$2s^2$ ^1S	2.05 (6) [13] 2.3 (1) [14] 2.5 (2) [16] 1.80 (15) [19] 1.85 (7) [21]	1.76 [48] 1.743; 1.790 [51] 1.99; 2.18 [52] 1.810; 1.802 [54] 1.846 [53] 2.231; 2.192 [55] 1.800 [56] 1.790; 1.801 [57] 2.11 [59] 1.808 [62] 2.207 [64] 1.69 [67] 1.824; 1.699 [65] 1.824 [60] 1.735; 1.938 [61] 1.830 [68] 1.839 [69] 1.75 [73] 1.762; 1.707 [74]
2s3p ^1P	1661.5	$2s^2$ ^1S		25.8 [67] 58.8 [73] 38.3 [62] 45.5; 40.1 [74]

$2p^2\ ^1D$	6982.7	$2s2p\ ^1P$	>380 [18]	12000 [50] 609; 761 [52] 19000; 26000 [54] 40000 [57] 1450 [49,62] 7500; 12000 [71] 24300 [73]
$2s3d\ ^1D$	4572.7	$2s2p\ ^1P$	12.0 (3) [13] 10.0 (2) [14] 12.3 (4) [16] 10.4 (10) [18]	11.7 [49,62] 12.7 [48] 12.9; 12.2 [71] 12.8; 12.6 [74] 10.3 [67] 11.9 [73] 11.7 [*]
$2s4d\ ^1D$	3813.4	$2s2p\ ^1P$	18.8 (5) [13] 13.6 (2) [14] 19.3 (5) [16] 14.0 (15) [18] 18.6 (10) [*]	18.3 [49] 23.8 [67] 19.6 [73] 14.2 [*]
$2s5d\ ^1D$	3515.5	$2s2p\ ^1P$	19 (2) [18]	33.7 [49] 44.8 [67] 35.1 [73] 22.8 [*]
$2s6d\ ^1D$	3367.6	$2s2p\ ^1P$	38 (4) [18]	53.4 [49] 82.9 [67] 57.3 [73] 35.6 [*]
$2p3p\ ^1P$	3455.1	$2s3p\ ^1P$	5.35 (14) [13] 5.0 (2) [14] 5.4 (2) [16]	6.69; 6.11 [50] 6.24 [49] 4.15 [*]
$2p3p\ ^1P$	4526.4	$2s4p\ ^1P$	5.6 (7) [19]	
$2p4p\ ^1P$	3208.6	$2s4p\ ^1P$	3.9 (5) [19]	8.59 [49] 1.62 [*]
$2p5p\ ^1P$	3160.7	$2s5p\ ^1P$	5.3 (5) [19]	6.34 [49] 0.38 [*]
$2p3d\ ^1D$	2738.1	$2p^2\ ^1D$	0.69 (9) [19]	3.91 [49] 0.43 [*]
$2s3s\ ^3S$	3321.2	$2s2p\ ^3P$	5.95 (16) [13] 7.3 (2) [14] 6.2 (2) [16] 6.4 (2) [22] 6.5 (3) [*]	6.05 [62] 6.76; 6.66 [58] 6.64; 6.41 [74] 6.98 [67] 6.64 [73] 5.97 [68] 5.13 [*]

2s4s ^3S	2350.8	2s2p ^3P		18.4 [74] 19.1 [67] 17.5 [73]
2s5s ^3S	2125.6	2s2p ^3P	10.5 (5) [14]	39.2 [67] 38.2 [73] 32.5 [*]
$2p^2$ ^3P	2650.6	2s2p ^3P	2.42 (6) [13] 2.3 (2) [14] 2.2 (1) [*]	2.320 [48] 2.330; 2.341 [54] 2.342; 2.298 [57] 2.06 [59] 1.806 [68] 2.356 [62] 2.305; 2.124 [74] 2.00 [*]
2s3p ^3P	14643.9	2s3s ^3S	75 (5) [*]	82.2; 85.9 [58] 73.8 [68] 83.7; 87.5 [74] 83.2 [67] 85.1 [73] 66.3 [*]
2s4p ^3P	6786.6	2s3s ^3S		283 [73]
2s3d ^3D	2494.6	2s2p ^3P	5.00 (14) [13] 4.9 (2) [14] 5.4 (2) [16] 5.2 (2) [22] 5.0 (1) [*]	5.11 [62] 5.79; 6.04 [58] 5.68; 6.01 [74] 5.52 [*] 5.42 [67] 5.23 [73] 5.21 [*]
2s4d ^3D	2175.1	2s2p ^3P	11.5 (5) [14] 10.8 (4) [16] 11.2 (6) [22]	12.6; 12.8 [74] 12.4 [67] 11.7 [73] 11.7 [*]
2p3p ^3P	3019.6	2s3p ^3P	1.5 (2) [17] 6.9 (1) [17] 2.3 (2) [19] 6.0 (7) [19]	7.10; 6.47 [50] 7.99 [62]
2p3d ^3D	2898.1	$2p^2$ ^3P	2.6 (2) [14] 1.7 (2) [19]	
2p3d ^3D	3110.9	2s3d ^3D	6.8 (2) [14] 1.6 (2) [19]	

$ Whenever two values are given, they were obtained by the dipole length and dipole velocity approximation, respectively.

* This work.

Table IV. Oscillator strengths (f) and transition probabilities (A) for some Be III transitions

Transition	Wavelength (Å)	f	A (10^8 s^{-1})
$1s^2\ ^1S_0$ - $1s2p\ ^1P_1$	100.26	0.55155	1206
- $1s3p\ ^1P_1$	88.31	0.1269	361.8
- $1s4p\ ^1P_1$	84.75	0.0493	152.6
- $1s2p\ ^3P_1$	101.70	$1.857 \cdot 10^{-6}$	$3.993 \cdot 10^{-3}$
$1s2s\ ^1S_0$ - $1s2p\ ^1P_1$	6142.01	0.14854	0.08754
- $1s3p\ ^1P_1$	661.32	0.3059	15.55
$1s2s\ ^3S$ - $1s2p\ ^3P$	3721.8	0.2131	0.3421
- $1s3p\ ^3P$	582.08	0.2526	16.58
$1s2p\ ^1P$ - $1s3s\ ^1S$	767.75	0.07737	8.755
- $1s3d\ ^1D$	746.23	0.7088	50.94
$1s2p\ ^3P$ - $1s3s\ ^3S$	725.59	0.08871	10.83
- $1s3d\ ^3D$	675.59	0.6391	56.04

Table V. Oscillator strengths (f) and transition probabilities (A) for some Be II transitions.

Transition	Wavelength (Å)	f	A (10^8 s^{-1})
2s ^2S - 2p ^2P	3130.6	0.4935	1.120
- 3p ^2P	1036.3	0.0800	1.655
2p ^2P - 3s ^2S	1776.2	0.0637	4.04
- 3d ^2D	1512.4	0.6277	10.98
3s ^2S - 4p ^2P	3274.6	0.0677	0.1404
3p ^2P - 4s ^2S	5270.6	0.1339	0.9638
- 5s ^2S	3247.7	0.02162	0.4114
- 4d ^2D	4360.9	0.5128	1.079
- 5d ^2D	3046.6	0.1288	0.555
3d ^2D - 4f ^2F	4673.4	1.014	2.211
- 5f ^2F	3197.1	0.157	0.731

Table VI. Oscillator strengths (f) and transition probabilities (A) for some Be I transitions.

Transition	Wavelength (Å)	f	A (10^8 s^{-1})
$2s^2$ ^1S - $2s2p$ ^1P	2348.6	1.344	5.417
- $2s3p$ ^1P	1661.4	0.021	0.172
$2s2p$ ^1P - $2s3s$ ^1S	8254.1	0.1223	0.359
- $2s4s$ ^1S	4407.9	0.101	1.04
- $2s3d$ ^1D	4572.6	0.415	0.794
- $2s4d$ ^1D	3813.4	0.186	0.512
$2s2p$ ^3P - $2p^2$ ^3P	2650.6	0.451	4.28
- $2s3s$ ^3S	3321.2	0.0833	1.51
- $2s4s$ ^3S	2350.7	0.0115	0.416
- $2s3d$ ^3D	2494.6	0.271	1.74
- $2s4d$ ^3D	2175.1	0.092	0.775
$2s3s$ ^3S - $2s3p$ ^3P	14643.9	1.137	0.118

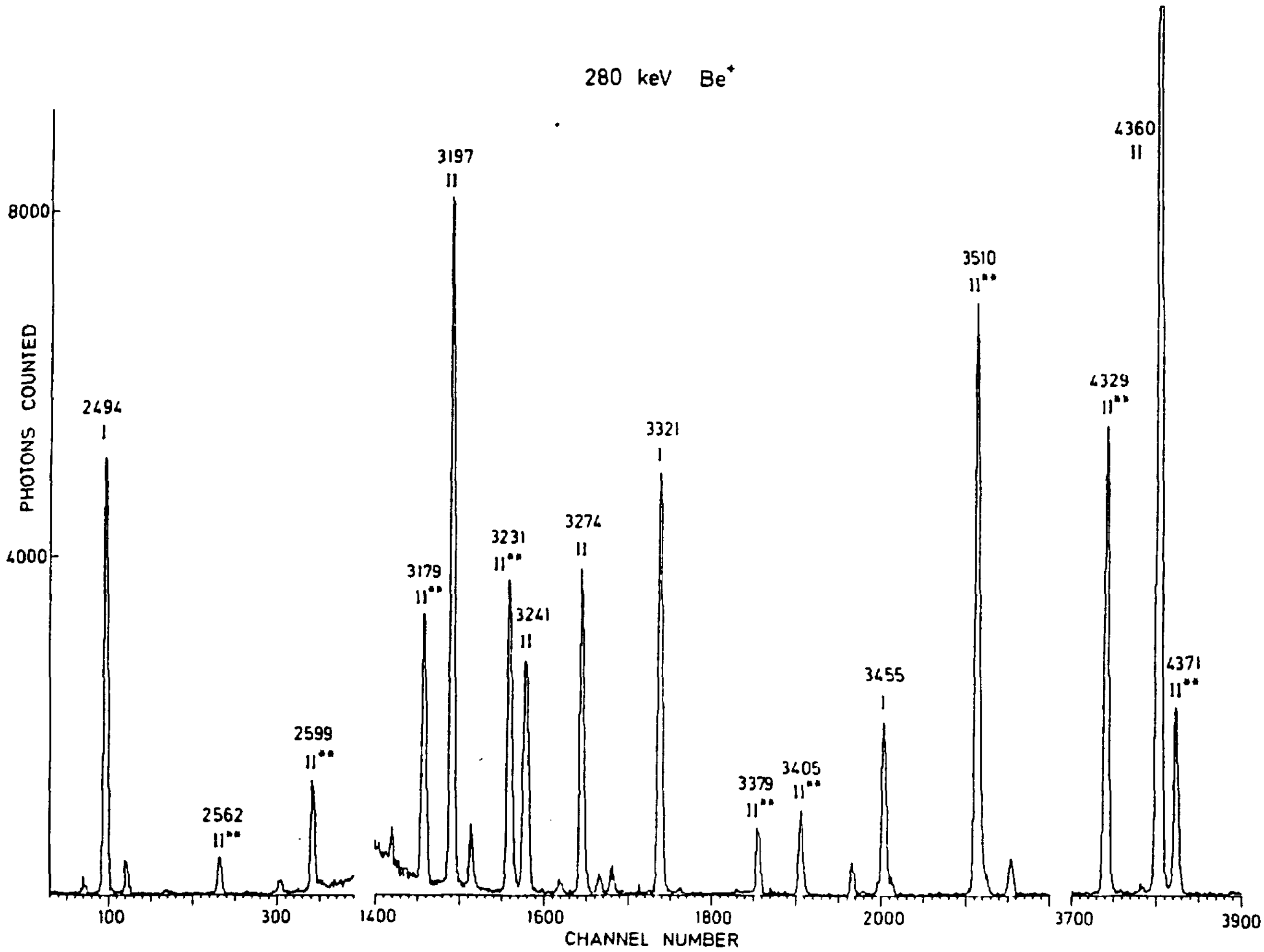

Fig. 1. Beam-foil spectrum of Be, recorded with 280 keV Be^{+} ions from the Stockholm 400 kV heavy ion accelerator and a 35 cm Heath monochromator. Although this particular spectrum (S. Mannervik, I. Martinson and B. Jelenkovic, J. Phys. **B 14** (1981) L275) was taken a few years after the lifetime studies, the equipment used was identical.

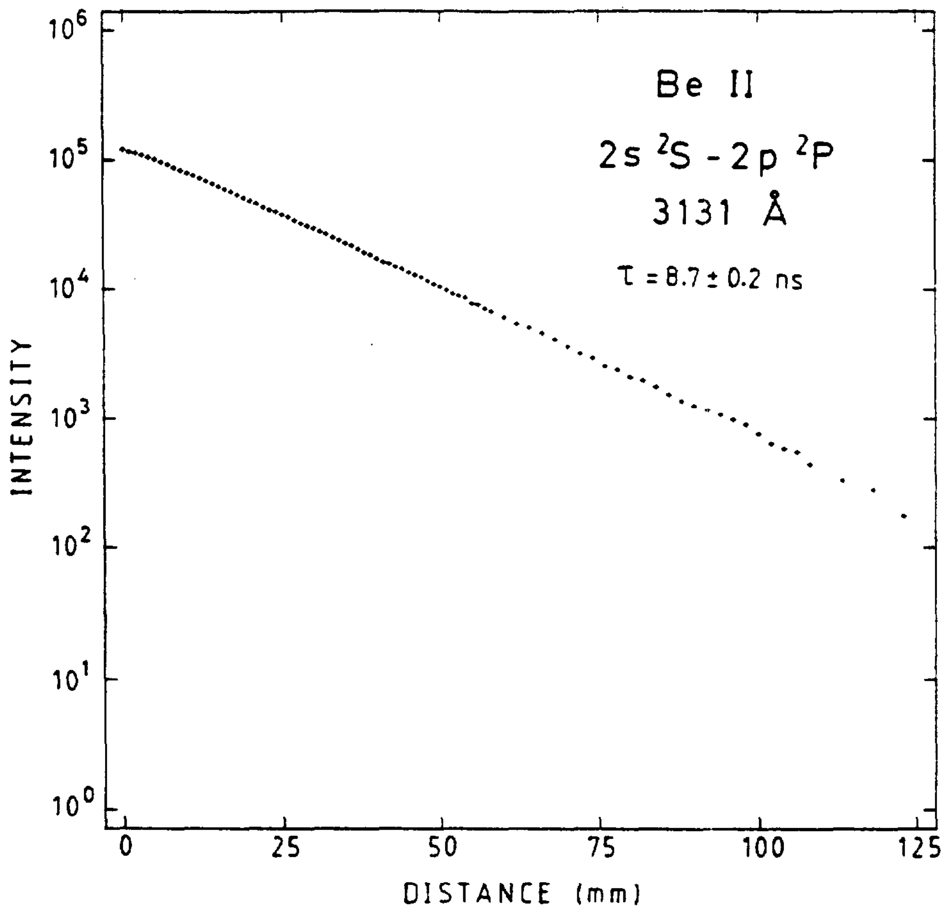

Fig. 2. Intensity decay of the 2s ^2S - 2p ^2P transition (3131 Å) in Be II.

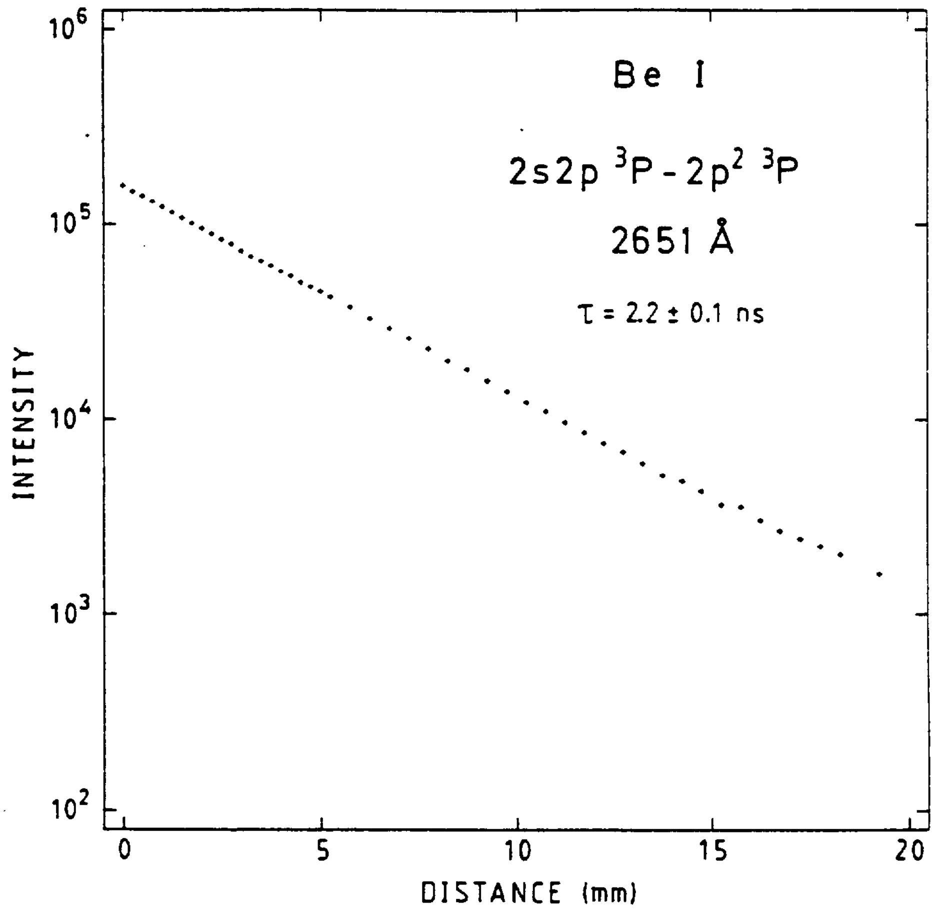

Fig. 3. Intensity decay of the 2s2p ^3P - $2p^2$ ^3P transition (2651 Å) in Be I.

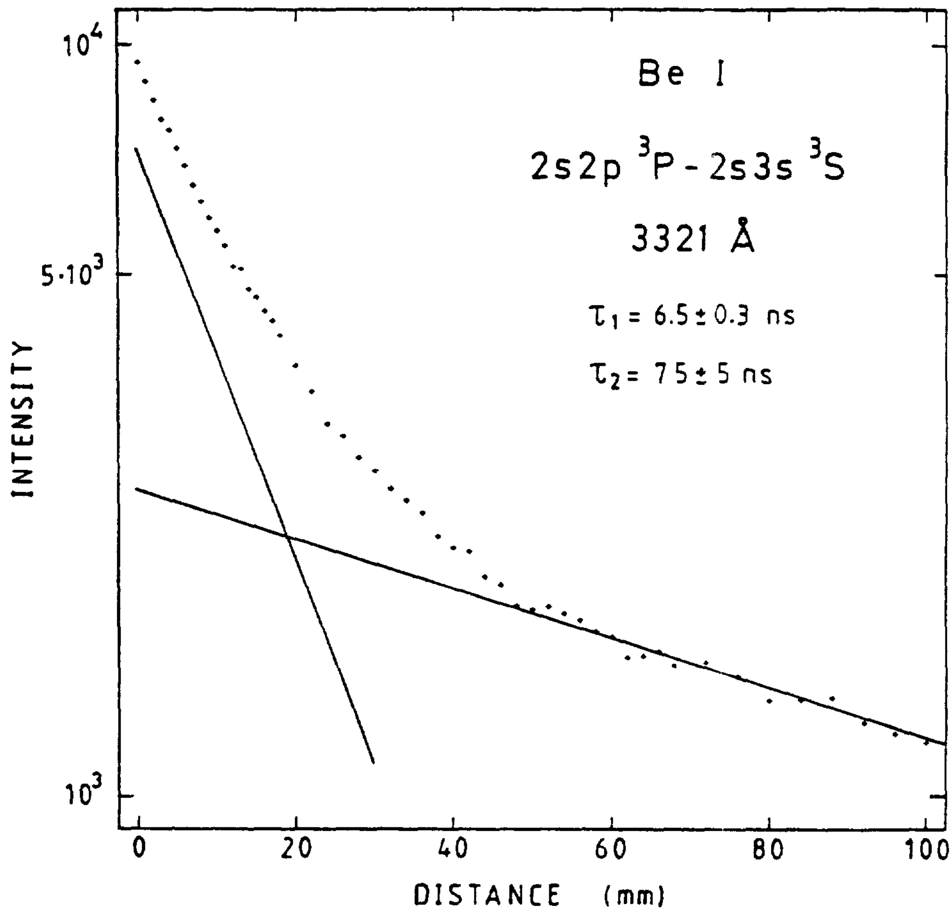

Fig. 4. Intensity decay of the 2s2p ^3P - 2s3s ^3S in Be I (3321 Å). The decay curve is composed of two exponentials, corresponding to lifetimes 6.5 ± 0.3 and 75 ± 5 ns. Of these the latter value is ascribed to the decay of the 2s3p ^3P term (see text).

Appendix I

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