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Beam-Foil Measurements of Singlet Levels in Bi IV and Some Newly-Assigned Levels in Bi V

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Abstract

The beam-foil technique has been used to measure the lifetimes of five levels in Bi IV and nine levels in Bi V, six of which are new assignments. Cascade correction has been applied to the analysis of the resonance levels $6s6p\ ^1P_1$ in Bi IV and $6p\ ^2P_{1/2,3/2}$ in Bi V.

1. Introduction

We have recently published lifetime measurements for the resonance transitions in the Hg I and Au I isoelectronic sequences of the ions Hg I and II [1], Pb III and IV [2] and Bi IV [3]. We were prevented from doing the same in Bi V by a problem in spectral assignment. This has now been resolved, at least for the lower-lying levels, independently by Joshi *et al.* [4] and ourselves, and we are now in a position to publish the Bi V results as far as the assignments are confirmed. We have also measured lifetimes of the cascade system for the Bi IV resonance line, i.e., the Bi IV singlet system. Preliminary results for this system were presented at a recent conference [3].

The techniques used for ion beam generation, data collection and analysis are essentially the same as those described in the earlier lead and bismuth reports [2, 3] and will not be repeated here. The only major difference in the experiment is the use of an incident ion energy of 1100 keV, made possible by reducing the deflection angle of the analyzing magnet. The lower mass resolving power is still sufficient to resolve Bi^+ from Sn_2^+, the only close mass peak when a Bi–Sn alloy is used in the field-emission ion source. Accurate lifetime measurements are dependent on a good velocity estimate, and this in turn requires a knowledge of the energy loss of the ions passing through the carbon foil. We have since confirmed the estimates and measurements made for Bi in the earlier work [3] by an independent post-foil velocity measurement for Hg ions [1], whose mass is almost as great as that of bismuth, and we therefore believe that the beam velocity is known to better than 3%, this figure being incorporated into our uncertainties in the reported lifetimes. All but two of these are less than 2 ns so that we have not encountered problems due to angular scattering at the foil. Our detection system views the whole beam without vignetting up to 40 ns from the foil if the half angle for scattering is assumed to be no more than 4°.

2. Spectral assignments

Before any lifetimes could be measured in the Bi V system the assignments had to be revised, as the $6p$–$6d$ transitions classified by Schoepfle [5] were missing from our spectra. This reclassification has now been done by Joshi *et al.* [4] but at the time this work was not available to us. It is worth noting that rather different techniques were used by the two groups: while spectra from the beam-foil source with a 1-metre normal incidence monochromator cannot compare in resolution with spark spectra and a high-resolution spectrograph, the beam-foil method offers the added dimension of good time resolution. This can be used to advantage in establishing levels through transitions that are expected to be unusually long- or short-lived, or through comparison of branch transitions, where decay curves can be measured for possible branches and selected by the requirement that the shape should be the same for each branch. (The conditions for establishing this are rather less stringent than the conditions for extracting an accurate lifetime from the curve, so a spectral assignment made in this way will not necessarily result in a lifetime measurement.) In the case of the Bi V spectra we used the line list originally compiled by Arvidsson [6] to improve the wavelength accuracy of the lines we assigned from our own spectra. The wavelengths measured by Joshi *et al.* [4] are more accurate, and differ by up to 0.02 Å from those reported by Arvidsson, for some lines, but the differences are too small to affect our analysis. Since Arvidsson's list has now been superseded, we have not listed our level assignments here. All wavelengths reported here are vacuum wavelengths.

The assignments for the $6d$, $5d^9 6s^2$ and $7p$ levels were made on the basis of isoelectronic extrapolations from Moore's tables [7] for Au I and Hg II, and from Gutmann and Crooker [8] for Tl III and Pb IV. The relatively strong lines we observed at 738.2 and 901.6 Å, with a satellite line at 929.8 Å, and assigned to the $6p$–$6d$ doublet gave immediate support to the regularity of the Au I isoelectronic sequences. The identification of the $5d^9 6s^2\ ^2D$ levels was also made on the basis of transitions to the $6p\ ^2P$ levels. These transitions are known to be long-lived (100 ns. for the $J = 1/2$–$3/2$ transition in Pb IV [2]) and do not appear in Joshi's new list. Spectra in a range of ± 50 Å from where these lines were expected to lie were therefore taken 4 to 8 cm downstream from the foil, corresponding to a delay time of 40 to 80 ns after excitation. All features whose lifetimes appeared too short or whose ionization stage seemed much to low were eliminated, leaving just two candidates for the $J = 1/2$–$3/2$ transition; only one of which, at 1313.3 Å, matched a corresponding long-lived transition (4275 Å from the $^2D_{5/2}$ level) which was consistent with the predicted $5d^9 6s^2\ ^2D$ splitting. We were unable to measure the lifetime of the latter level as the line is extremely weak; however it is certainly greater than 100 ns. The lifetime of the $^2D_{3/2}$ level was estimated using normal multi-exponential fitting to be 56 ns.

The assignment of the $7p\ ^2P$ levels relied on finding decay curves of the same shape for the $7s$–$7p$ and $6d$–$7p$ branches. In order to limit the search for possible lines we first chose a

Table I. *Lifetime measurements for Bi IV and Bi V and new assignments in Bi V*

Transition	Wavelength (Å)	Lifetime (ns)		
		This work	Other Experiments	Theory[a]
Bi IV:				
$6s^2\ ^1S_0$–$6s6p\ ^1P_1$	873	0.243 ± 0.013[b]	0.39 ± 0.08[c]	0.25[d], 0.15
$6s6p\ ^1P_1$–$6s6d\ ^1D_2$	1438	1.02 ± 0.11	–	0.58
–$6p^2\ ^1D_2$	969	0.173 ± 0.024	–	0.19
–$6s7s\ ^3S_1$	1207	0.255 ± 0.020	–	0.31
–$6s7s\ ^1S_0$	1150	0.453 ± 0.026	–	0.34
Bi V:				
$6s\ ^2S_{1/2}$–$6p\ ^2P_{1/2}$	1139	0.88 ± 0.10[b]	–	1.02[e], 0.62
$^2S_{1/2}$–$6p\ ^2P_{3/2}$	864	0.301 ± 0.016[b]	0.49 ± 0.08[c]	0.43[e], 0.28
$6p\ ^2P_{1/2}$–$6d\ ^2D_{3/2}$	738	0.15 ± 0.03	NEW	0.16[e], 0.14
$^2P_{3/2}$–$6d\ ^2D_{5/2}$	902	0.34 ± 0.10	NEW	0.21[e], 0.18
$^2P_{3/2}$–$7s\ ^2S_{1/2}$	850	0.145 ± 0.033	–	0.20
$^2P_{1/2}$–$6s^2\ ^2D_{3/2}$	1313	56 ± 3	NEW	–
$^2P_{3/2}$–$6s^2\ ^2D_{5/2}$	4275	> 100	NEW	–
$7s\ ^2S_{1/2}$–$7p\ ^2P_{1/2}$	3253	1.7 ± 0.3	NEW	1.25
–$7p\ ^2P_{3/2}$	2402	0.85 ± 0.14	NEW	0.58

[a] Numerical Coulomb approximation unless otherwise noted.
[b] ANDC (Cascade-corrected) result: includes population modelling for the $^2P_{1/2}$ level (see text).
[c] T. Andersen *et al.*, Ref. [12].
[d] J. Migdalek and W. E. Baylis, Ref. [13].
[e] Estimated from J. Migdalek and W. E. Baylis, Ref. [11].

small number of possible values for the $7p$ energy levels based on the lines in Arvidsson's list between 360 and 380 Å which appeared to be candidates for the $6s$–$7p$ transitions. Because of the extreme weakness of the transitions being sought in the region above 2000 Å we were able to positively identify only the $7p\ ^2P_{3/2}$ level, through comparison of lines at 2067 and 2402 Å. However our tentative assignment of the $J = 1/2$ level proved to coincide with that of Joshi *et al.* [4].

3. Lifetime measurements

Table I lists the results of lifetime measurements in the doublet system of Bi V. The $6s$–$6p$ resonance transitions have been analyzed by the ANDC technique [9] in which direct cascades from the $6d$ and $7s$ levels have been used to correct for repopulation of the primary level. The $6p\ ^2P_{3/2} - 5d^9 6s^2\ ^2D_{5/2}$ oscillator strength is too small to significantly affect any ANDC analysis, although the corresponding $J = 1/2 - 3/2$ component was included in the $^2P_{1/2}$ cascade scheme. We often find that levels that are subject to heavy cascading, such as the $6p$ levels in question here, yield lifetime parameters by multi-exponential fitting that are significantly longer than the ANDC lifetimes. Values obtained for the $^2P_{3/2}$ level, for example, are 0.49 ns and 0.30 ns respectively. The ANDC procedure should be the more acceptable one, provided that all the important direct cascades are included, as the fitting function more closely reflects the physical processes occurring than do the arbitrary terms in a multi-exponential fit.

In the case of the $^2P_{1/2}$ level the decay curves are fitted very well by a two-term function whose second exponential term is small, and the ANDC and multiexponential results consequently differed by only a small amount. This situation implied that there was significant cascading only from the long-lived $5d^9 6s^2$ level, which cannot really be so as two other cascades, $6p$–$6d$ and $6p$–$7s$, are seen quite strongly in our spectra. To clarify the ANDC problem we included all three cascades in ratios governed by a model with level populations proportional to $(2l + 1)/n^{*3}$. That is, we fixed their relative contributions rather than allowing them to be free parameters in the fit. (This procedure is documented in more detail in Ref. [10], where a similar problem was encountered in the homologous ion In III.) An acceptable fit was obtained with a population in the $5d^9 6s^2$ level double that given by the model, while the best fit resulted from a population about seven times that predicted. The larger uncertainty reported for the $^2P_{1/2}$ mean lifetime encompasses the results from the various trials, since we cannot rule out the possibility that an important cascade has yet to be discovered, and whose absence from the analysis could produce the same effect as the deviation from the rather simplistic model used.

Figure 1 illustrates the f-value trend for the $^2S_{1/2}$–$^2P_{3/2}$ transition. It can be seen that the present result seems to confirm the view expressed in our earlier paper [3] that the core polarization correction calculated by Migdalek and Baylis [11] is too large for the Au I isoelectronic sequence. However it should be noted that we have only estimated the correction for BiV, by extrapolation from lower members of the sequence, as the core polarizability is not known for this species [11]. The only other experimental measurement for the Bi V system [12] matches our multiexponential result for the $^2P_{3/2}$ level. The lifetimes of the other Bi V levels in Table I have been obtained by multi-exponential fitting, since the significant cascades are not known and, as a consequence, the standard deviations in the fits have been doubled to attempt to cover potential errors due to cascading. The $6d\ ^2D$ levels in particular show evidence of heavy cascading, probably from the as-yet unclassified $5f$ levels.

In the Bi IV singlet system we had already presented a preliminary result for the $6s^2\ ^1S_0$–$6s6p\ ^1P_1$ resonance transition [3]. This result is now confirmed by a more extensive ANDC analysis involving the four direct cascades that were evident in the Bi IV spectrum, and whose lifetimes are also

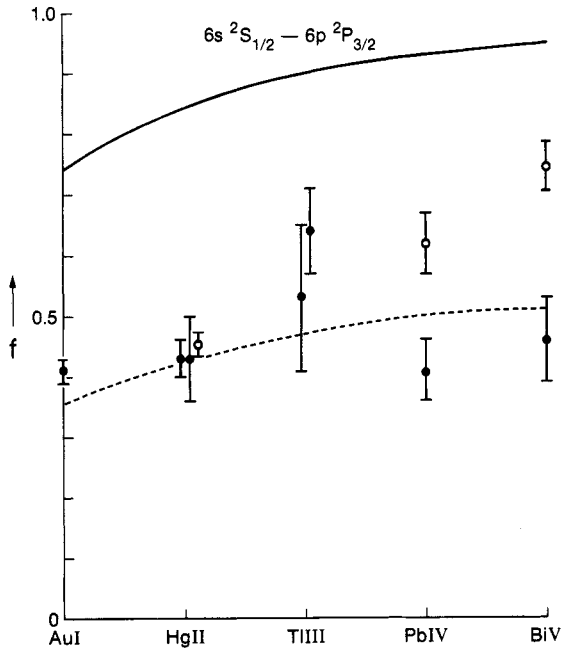

Fig. 1. f-value trend for the $6s\ ^2S_{1/2}$–$6p\ ^2P_{3/2}$ transition in the Au I isoelectronic sequence. The dashed and solid curves show the RHF calculation with and without core polarization (Ref. [11]). The open circles indicate this work and our earlier results (Ref. [1, 2]) and the solid circles are other experimental results (Refs. [12, 15–17]).

listed in Table I. The largest contribution to the cascade scheme came from the $6p^2\ ^1D_2$ and $6s7s\ ^1S_0$ levels. The other two levels were observed through branch transitions to the triplet system ($6s6p\ ^3P_1$–$6s6d\ ^1D_2$ at 924 Å and $6s6p\ ^3P_2$–$6s7s\ ^3S_1$ at 990 Å) as the direct transitions were masked by much stronger Bi II and III lines. These branch transitions both lie within 1 Å of rather stronger lines – 925 Å (III) and 968 Å (IV) respectively. In order to obtain accurate shapes for the required decays we had to include in the fits the shape of these weakly-blended lines, a procedure we have used in the past [1]. For both Bi IV and V, where more precise calculations [11, 13] are not available, we have carried out numerical Coulomb approximation (NCA) calculations using a recently-published series expansion for the radial integral [14]. (A minor error in that paper, namely the substitution of a negative sign for a positive one at the start of the last line of the final equation, has been noted.) The agreement is generally not very good, perhaps reflecting the fact that a fixed central potential is a poor model for a large core of some 78 electrons.

In contrast to the situation in the doublet system, excellent agreement exists between our ANDC result and the more recent calculation by Migdalek and Baylis [13] for the Bi IV $^1P_1$ level. This would suggest that the ANDC results should also be reliable for Bi V and therefore points to an interesting problem that is still to be resolved.

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