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Electron-Impact Excitation Cross-Sections for High-Lying Even Levels of the Dysprosium Atom

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Abstract

The method of extended crossing beams has been used to study electron-impact excitation of the dysprosium atom energy levels that belong to the $4f^{10}6s7s$ configuration. Ninety-one excitation cross sections have been measured at incident electron energy of 30 eV. Cross-section measured are within the range of 10^{-18} to 10^{-19} cm^2 in most cases. Spontaneous emission rises as a result of both allowed and forbidden transitions from the excited levels covered in the study.

Keywords: rare-earth elements, dysprosium atom, inelastic collision, cross-section, energy level, spectral line

1 Introduction

Spectra of rapidly oscillating chemically peculiar stars (roAp stars) are often dominated by spectral lines belonging to rare-earth (RE) elements [8]. The abundance of individual RE elements, including dysprosium, in some roAp stars may exceed their abundance in the solar atmosphere by two orders of magnitude (the examples being HD 122970, HD 24712 stars [4]). In the case of the HD 101065 star, the first of roAp stars discovered by A. Przybylski in 1961 [12], this difference reaches three orders of magnitude. roAp stars remain a subject of intense ongoing studies.

Furthermore, successful laser generation was reported in 2002 [5] using two dysprosium atom transitions in the near-IR part of the spectrum. A major problem faced by designers of RE vapor lasers (except for Yb, Eu, Tm, Sm) is the need for adequate high-temperature gas-discharge tube designs as vapors of these elements only reach the characteristic vapor-laser pressure of ~1 Torr at temperatures nearing T = 2000 K. Staunch cells operational at temperatures up to T = 2070 K were used in [5], enabling successful laser generation at λ = 1032.81 nm with holmium atom vapor in 1999 [6]. In the case of dysprosium atom, laser generation was obtained with λ = 849.0 ± 0.1 nm and 917.2 ± 0.1 nm lines at T = 1470–1670 K. Spectral properties of the dysprosium atom provided in [6] only allowed to identify the transition for the former line. As the entire wealth of data on DyI energy levels (on the middle of 2017) proved helpless for identifying the transition responsible for the longer-wavelength line, there are arguably significant gaps in the interpretation of the dysprosium optical spectrum.

The most exhaustive treatment of dysprosium atom and singly-charged ion spectra was provided in the report [13] covering 22000 DyI and DyII spectral lines in the wavelength range λ = 230–1140 nm. The same report provides some tentative analysis of DyI and DyII energy levels. Nevertheless, the most detailed data on DyI and DyII spectra presented in publicly available journals [7] is limited to 4584 dysprosium lines and their temperature classification. DyI and DyII energy level systems obtained in the report [13] were reproduced fully in the journal article [3] where energies and internal quantum number J values are stated for 141 even and 197 odd DyI levels as well as 14 even and 214 odd DyII levels. These values were used in [3] to classify 1952 spectral lines of the dysprosium atom and 1000 spectral lines of the singly-charged dysprosium ion.

J.-F. Wyart’s work, starting with his doctoral thesis [18], contributed significantly to the understanding of the dysprosium atom spectrum. These findings, including unpublished materials (1975, 1976), are compiled in [9]. They lead to significant revision of both DyI energy levels and their theoretical interpretation. In particular, 71 odd levels missing from [3] have been added in the 17500–30500 cm^{-1} energy range. Furthermore, several dozen new levels have been added in the E = 30500–47400 cm^{-1} energy range. Of more than 320 DyI even levels with E > 28000 cm^{-1} listed in the compilation [9], only 30 have been classified so far. Particularly, four levels with energies 28300 < E < 29600 cm^{-1} have been identified to represent the $4f^96s^26p$ configuration while nine levels in the E = 36700–37900 cm^{-1} range have been tentatively assigned to the $4f^{10}6s6d$ configuration. The remaining 17 levels situated in the E = 30500–42500 cm^{-1} range have been reliably identified as belonging to the $4f^{10}6s7s$ configuration. As for odd levels, the compilation [9] adds 26 new levels with E = 12300–23400 cm^{-1} to those in [3] while excluding 31 levels listed in [3]. Findings from [9] are reproduced in entirety in the NIST Atomic Spectra Database.

However, in the meantime after the publication [9], a further five odd and 38 even levels have been located in the range E = 32000–39700 cm^{-1}, and their internal quantum numbers J have been determined as well [11]. The new levels have been used in [11] to classify more than 280 DyI spectral lines in the λ = 329–1655 nm wavelength range. Additionally, as stated in [11]: “We measured over 24500 lines in the spectrum of the Dy/Ar hollow cathode discharge between 194 nm and 3.6 μm. The first step of the analysis was to classify as many of the lines as possible using known energy levels. The energy levels taken from the NIST Atomic Spectra Database…were used to make a list of wavenumbers of all possible electric dipole transitions…Hence a large tolerance was used initially, resulting in a large number of spurious coincidences between observed and Ritz wavenumbers. This tolerance was reduced by deriving new energy level values from the observed wavelengths with the ELCALC computer program…A new list of classified lines was then made using the improved energy levels, with a much smaller tolerance and with fewer spurious coincidences between observed and Ritz wavenumbers. This list was then used to reoptimize the energy level values. Over 4800 DyI lines and 4000 DyII lines were classified with the improved energy level values. The improved values for the previously known energy levels will be published separately" [11, P. 464]; however we were unable to find the respective publication.

Only two experimental studies of the dysprosium atom excitation have been published so far. A study of excitation of UV lines in DyI is presented in [14] while a recent paper [15] elaborates on the excitation of $4f^96s^26p$ and $4f^{10}6p^2$ configurations. However, even though the levels investigated in [14] lie rather high (up to E = 40400 cm^{-1}), not one belongs to the $4f^{10}6s7s$ configuration whose excitation is studied in this paper. Similar to our preceding experiments, we have used the method of extended crossing beams as described in greater detail in recent publications [16, 17]. For that reason we find it superfluous to present details of our experimental method and technique in this paper and will only note some basic conditions pertinent to the dysprosium atom experiment proper.

2 Main experimental condition

99.7% pure dysprosium placed in a crucible of tantalum was vaporized by heating the surface of the metal under study to temperature T = 1450 K. Because the melting point of dysprosium lies at 1650 K, evaporation proceeded from a solid phase. Atom concentrarion within the crossing zone of atom and electron beams was 3.2×10^{10} cm^{-3} throuout the main part of experiment. The electron beam current density did not exceed 1.0 mA/cm^2 over the whole operating range of electron energy E = 0–200 eV. The setup had an effective spectral resolution of about 0.1 nm within the short-wave part of a spectrum at $\lambda < 600$ nm, deteriorating to ~ 0.2 nm in the red at $\lambda > 600$ nm as the monochromator diffraction grating had to be replaced.

The ground level of dysprosium atom $4f^{10}6s^2\,{}^5I_8$ is separated from others low-lying levels by very significant energy intervals exceeding $\Delta E > 4000$ cm^{-1}; among REs, dysprosium shares this peculiarity with europium, holmium, erbium and thulium. In fact, the ground level of dysprosium atom behaves as an isolated level, serving as the initial level during electron-impact excitation. The population of the nearest excited even level, $4f^{10}6s^2\,{}^5I_7$ ($E > 4134$ cm^{-1}) is 1.46% of the total concentration of atoms in the beam as a result of thermal excitation owing to evaporation of atoms, whilr the population of the lowest-lying odd level $4f^9({}^6H^\circ)5d6s^2\,{}^7H^\circ_8$ (E = 7565 cm^{-1}) is unimportant at 0.055% (population have been estimated under assumption that Boltzmann distribution law is true).

Relative cross-section values have been measured with an error of 8–15%, depending on the intencity of lines and their positions in the spectrum. Absolute cross-section values have been established using benchmark cross-sections of a helium atom and determined with an error of 20–27%.

3 Results and discussion

Ninety-one excitation cross sections for transitions from levels belonging to the $4f^{10}6s7s$ configuration have been measured at incident electron energy of E = 30 eV. Inasmuch as levels of this configuration have the same parity as the pre-excitation ground state in our experimental setup, excitation cross-sections of the $4f^{10}6s7s$ configuration are expected to be comparatively small. Consequently it has proved impossible to record optical excitation functions (OEFs) for transitions originating from these levels. The sole exception is the λ = 415.931 nm line corresponding to the $4f^{9}5d6s^{2}\,{}^{7}H^{\circ}_{7}$–$4f^{10}6s7s_{8}$ transition with an upper level energy E = 32554 cm^{-1} giving an excitation cross-section Q_{30} greater than 10^{-17} cm^{2}. While [18] ascribes this level to the $4f^{10}6s7s$ configuration, it is not reported in [9]. Furthermore, a somewhat later publication [1] states: “The ΔT value of (Z – 14) mK for the 32554 cm^{-1} is too high for a $4f^{10}6s7s$ configuration, whereas ΔT = (Z – 70) mK for the 37591 cm^{-1} level confirm the configuration assignment to $4f^{10}6s6d$”. Thus it is likely that the initial assignment of the level E = 32554 cm^{-1} to the $4f^{10}6s7s$ configuration was a mistake. This level is marked with an asterisk in our Table.

The Table presents the findings from our experiment supplemented with necessary spectroscopic reference data. The Table lists wavelengths λ, transitions, inner quantum numbers for lower J_{low} and upper J_{up} levels, energies of lower E_{low} and upper E_{up} levels and excitation cross-section values Q_{30} at incident electron energy of 30 eV. Reference data in columns 1 to 5 have been sourced from [7, 9].

In some instances, especially in the short-wave part of the spectrum at $\lambda <$ 634 nm, lines recorded in our experiment have been missing altogether from all publications available to the author. For such lines we have performed a tentative classification of transitions based on the information on energy levels of the dysprosium atom available in [9, 11]. This classification was then used for a more precise wavelength computation. In all these cases, properties listed in columns 1 to 5 are put in parentheses. This part of the spectrum contains some lines interpreted in [10] as belonging to the singly-charged dysprosium ion whereas our classification puts them into the DyI spectrum. It should be noted that spectral excitation conditions in studies covered by the compilation [10] were such as to favor DyII lines over DyI.

A different development takes place in the long-wave part of the spectrum at $\lambda >$ 630 nm. A significant number of lines occurring here have temperature classifications in [7] whereas their transitions have not been classified. Our classification values are listed in parentheses in columns 2 to 5 for such lines. While there is no doubt that spectral lines classified in our study are covered in the follow-up material promised in [11], we have been unable to find this later publication by the authors of [11] as noted in the Introduction.

A partial state diagram for the dysprosium atom with transitions studied by us is plotted in the Figure. To make the plot more comprehensible, terms are shown without *J*-split. Vertical dashed lines separate states with different parities. Configuration labels are put beneath the horizontal axis while the term notation is

Table. Excitation cross-sections of dysprosium atom **(**$4f^{10}6s7s$ configuration)

λ nm	Transition	J_{low}–J_{up}	E_{low} cm^{-1}	E_{up} cm^{-1}	Q_{30} 10^{-18} cm^2
1	2	3	4	5	6
(365.440	$4f^{9}5d6s^{2}\,{}^{7}H^{\circ}$–$4f^{10}6s7s$ (7,1)	8–8	7565	34922)	0.13
(366.904	$4f^{9}5d6s^{2}\,{}^{7}H^{\circ}$–$4f^{10}6s7s$ (6,0)	5–6	12298	39545)	0.14
366.917	-	-	-	-	
400.059	$4f^{9}5d6s^{2}\,{}^{7}H^{\circ}$–$4f^{10}6s7s$	8–8	7565	32554*	2.33
415.931	$4f^{9}5d6s^{2}\,{}^{7}H^{\circ}$–$4f^{10}6s7s$	7–8	8519	32554*	13.5
423.390	$4f^{9}5d6s^{2}\,{}^{7}I^{\circ}$–$4f^{9}5d6s6p$	7–7	14367	37980	0.26
423.413	-	-	-	-	
(423.426	$4f^{9}5d6s^{2}\,{}^{7}P^{\circ}$–$4f^{10}6s7s$ (5,1)	4–4	16412	40023)	
(425.454	$4f^{9}5d6s^{2}\,{}^{5}I^{\circ}$–$4f^{10}6s7s$ (6,1)	8–7	14625	38123)	0.47
(425.458	$4f^{9}5d6s^{2}\,{}^{7}F^{\circ}$–?	5–6	14153	37650)	
428.358	($4f^{9}5d6s^{2}\,{}^{7}I^{\circ}$–$4f^{10}6s7s$ (5,1)	5–4	16684	40023)	0.23
437.475	($4f^{10}6s6p$ (8,1)°–$4f^{10}6s7s$ (6,0)	7–6	16693	39545)	0.98
443.044	$4f^{10}6s^{2}\,{}^{5}I$–?°	8–8	0	22564	0.58
(443.049	$4f^{9}5d^{2}6s\,{}^{9}G^{\circ}$–?	8–8	18472	41037)	
443.061	$4f^{9}5d6s^{2}\,{}^{7}I^{\circ}$–$4f^{10}6s7s$	9–8	9990	32554*	
(443.922	$4f^{9}5d6s^{2}\,{}^{7}D^{\circ}$–$4f^{10}6s7s$ (5,1)	5–4	17502	40023)	0.45
(446.125	$4f^{9}5d6s^{2}\,{}^{5}F^{\circ}$–$4f^{10}6s7s$ (5,1)	5–5	17804	40213)	0.57
(449.682	$4f^{9}5d6s^{2}\,{}^{7}I^{\circ}$–?	7–8	14367	36599)	0.41
(449.691	$4f^{9}5d6s^{2}\,{}^{5}G^{\circ}$–$4f^{10}6s7s$ (6,1)	6–5	15862	38093)	
1	2	3	4	5	6
(464.297	$4f^{9}5d6s^{2}\,{}^{7}G^{\circ}$–$4f^{10}6s7s$ (6,1)	6–7	16591	38123)	0.73
(464.306	$4f^{9}5d6s^{2}\,{}^{7}K^{\circ}$–$4f^{10}6s6d$	8–8	16288	37820)	
(464.315	$4f^{10}6s6p$ (8,1)°–?	8–7	16733	38264)	
(464.336	$4f^{9}5d6s^{2}\,{}^{7}I^{\circ}$–	5–6	16684	38214)	
464.344	? ?–?°	8–9	0	21529?	
(467.748	$4f^{9}5d6s^{2}\,{}^{5}H^{\circ}$–$4f^{10}6s7s$ (6,0)	6–6	18172	39545)	0.25
(467.758	$4f^{9}5d6s^{2}\,{}^{7}G^{\circ}$–$4f^{9}5d6s6p$	7–7	12655	34027)	

Table. (Continued): Excitation cross-sections of dysprosium atom **(**$4f^{10}6s7s$ configuration)

(477.469	$4f^95d6s^2\,{}^5H^\circ$–$4f^{10}6s7s$ (4,1)	5–4	20921	41859)	0.38
477.480	-	-	-	-	
(478.071	$4f^95d6s^2\,{}^7H^\circ$–$4f^95d6s6p$	5–6	12298	33210)	0.36
(478.088	$4f^95d6s^2\,{}^5F^\circ$–?	5–6	17804	38715)	
478.102	($4f^95d6s^2\,{}^7G^\circ$–?	6–7	16591	37501)	
(478.131	$4f^95d^26s\,{}^3F^\circ$–$4f^{10}6s7s$ (5,1)	6–5	19304	40213)	
479.828	$4f^{10}6s6p$ (8,1)°–$4f^95d6s6p$	9–8	15972	36807	0.13
479.842	-	-	-	-	
(479.852	$4f^{10}6s6p$ (8,2)°–$4f^{10}6s7s$ (6,0)	6–6	18711	39545)	
479.867	$4f^{10}6s6p$ (8,1)°–$4f^96s^26p$	7–8	16693	37527	
(479.868	$4f^95d6s^2\,{}^7K^\circ$–$4f^96s^26p$	8–9	16288	37121)	
486.005	-	-	-	-	0.15
486.019	$4f^95d6s^2\,{}^7I^\circ$–$4f^{10}6s7s$ (8,1)	9–9	9990	30560	
(486.373	$4f^95d6s^2\,{}^5G^\circ$–$4f^95d6s6p$	6–7	15862	36417)	0.074
(486.381	$4f^95d6s^2\,{}^7I^\circ$–$4f^{10}6s7s$ (7,1)	7–8	14367	34922)	
486.536	$4f^95d6s^2\,{}^7I^\circ$–$4f^{10}6s7s$	8–8	12007	32554*	0.29
(486.667	$4f^95d6s^2\,{}^7G^\circ$–$4f^{10}6s7s$ (5,1)	5–4	19480	40023)	0.12
(486.715	$4f^95d6s^2\,{}^7F^\circ$–?	5–6	14153	34693)	
(487.438	$4f^95d6s^2\,{}^5I^\circ$–$4f^{10}6s7s$ (7,1)	8–7	14625	35135)	0.10
(487.464	$4f^95d6s^2\,{}^5G^\circ$–?	4–3	20474	40983)	
(490.059	$4f^{10}5d6s\,{}^3[9]$–$4f^95d6s7s^\circ$	8–9	20193	40594)	0.15
(490.078	$4f^95d6s^2\,{}^5H^\circ$–$4f^{10}6s7s$ (5,1)	5–5	19813	40213)	
(490.454	$4f^95d6s^2\,{}^7I^\circ$–?	6–5	14970	35354)	0.11
(490.487	$4f^95d6s^2\,{}^5G^\circ$–?	6–6	15862	36244)	
(490.489	$4f^95d6s^2\,{}^7K^\circ$–$4f^{10}6s7s$ (6,1)	7–6	17687	38070)	
(493.875	$4f^{10}6s6p$ (8,2)°–?	8–7	18021	38264)	0.13
(493.892	$4f^95d6s^2\,{}^5I^\circ$–?	6–5	20554	40796)	
(493.893	$4f^95d^26s\,{}^3F^\circ$–$4f^{10}6s7s$ (6,0)	6–6	19304	39545)	
(494.267	$4f^95d6s^2\,{}^5H^\circ$–$4f^{10}6s7s$ (7,1)	7–6	15194	35421)	0.27
494.285	-	-	-	-	
(520.337	$4f^95d6s^2\,{}^7H^\circ$–$4f^{10}6s7s$ (6,1)	7–6	18857	38070)	0.22
(524.499	$4f^95d6s^2\,{}^7G^\circ$–$4f^{10}6s7s$ (6,0)	7–6	20485	39545)	0.094
524.516	($4f^95d6s^2\,{}^7I^\circ$–$4f^95d6s6p$	5–6	16684	35744)	
524.542	$4f^95d6s^2\,{}^5K^\circ$–$4f^{10}6s7s$	9–8	13495	32554*	0.10

1	2	3	4	5	6
(525.312	$4f^95d6s^2\,{}^7H^\circ$–$4f^{10}6s7s$ (6,1)	8–7	19092	38123)	0.37

Table. (Continued): Excitation cross-sections of dysprosium atom ($4f^{10}6s7s$ configuration)

(528.631	$4f^{9}5d6s^{2}\,{}^{7}K^{\circ}$–?	7–8	17687	36599)	0.11
(528.632	$4f^{9}5d6s^{2}\,{}^{7}G^{\circ}$–$4f^{9}5d6s6p$	6–5	18561	37472)	
(528.640	$4f^{9}5d6s^{2}\,{}^{7}K^{\circ}$–$4f^{10}6s7s$ (6,1)	6–5	19182	38093)	
529.271	-	-	-	-	0.13
(529.287	$4f^{9}5d^{2}6s\,{}^{9}G^{\circ}$–?	7–6	18528	37416)	
(529.297	$4f^{9}5d6s^{2}\,{}^{7}H^{\circ}$–$4f^{9}5d6s6p$	8–7	19092	37980)	
(529.307	$4f^{9}5d6s^{2}\,{}^{7}K^{\circ}$–$4f^{10}6s7s$ (6,1)	6–6	19182	38070)	
(535.904	$4f^{9}5d6s^{2}\,{}^{7}F^{\circ}$–?	4–4	20430	39084)	0.15
(535.922	$4f^{9}5d^{2}6s\,{}^{9}G^{\circ}$–$4f^{10}6s7s$ (6,0)	5–6	20891	39545)	
(535.926	$4f^{10}6s6p$ (8,2)°–$4f^{9}5d6s6p$	6–7	18711	37366)	
(535.937	$4f^{10}6s6p$ (8,2)°–$4f^{9}5d6s6p$	7–8	18433	37087)	
(537.798	$4f^{9}5d6s^{2}\,{}^{7}G^{\circ}$–$4f^{10}6s7s$ (6,1)	5–6	19480	38070)	0.18
(539.110	$4f^{9}5d6s^{2}\,{}^{7}G^{\circ}$–$4f^{10}6s7s$ (7,1)	6–7	16591	35135)	0.11
539.120	-	-	-	-	
(539.137	$4f^{9}5d6s^{2}\,{}^{5}I^{\circ}$–?	6–7	20554	39097)	
(547.301	$4f^{9}5d6s^{2}\,{}^{7}H^{\circ}$–$4f^{10}6s7s$ (6,1)	6–7	19856	38123)	0.12
(547.306	$4f^{9}5d6s^{2}\,{}^{7}H^{\circ}$–$4f^{9}6s^{2}6p$ (13/2,3/2)	7–6	8519	26785)	
(547.309	$4f^{9}5d6s^{2}\,{}^{5}I^{\circ}$–?	6–6	20554	38820)	
(550.705	$4f^{10}5d6s\,{}^{3}[6]$–?°	7–7	18094	36248)	0.39
	$4f^{9}5d^{2}6s\,{}^{9}G^{\circ}$–$4f^{10}6s7s$ (6,0)	6–6	21392	39545)	
(550.707	$4f^{10}6s6p$ (8,2)°–?	6–7	18711	36865)	
(577.740	$4f^{9}5d^{2}6s\,{}^{3}F^{\circ}$–?	6–7	19304	36608)	0.23
	$4f^{10}6s6p$ (8,2)°–?	7–7	18433	35737)	
(577.750	$4f^{10}6s6p$ (7,1)°–$4f^{10}6s7s$ (6,1)	7–6	20766	38070)	
(577.775	$4f^{10}6s^{2}\,{}^{5}I$–$4f^{9}5d^{2}6s\,{}^{9}G^{\circ}$	6–7	7050	24353)	
(584.082	$4f^{9}5d6s^{2}\,{}^{5}I^{\circ}$–?	5–5	22294	39411)	0.42
(584.091	$4f^{9}5d^{2}6s\,{}^{9}F^{\circ}$–$4f^{10}6s7s$ (6,1)	7–6	20954	38070)	
630.420	($4f^{10}6s6p$ (6,1)°–$4f^{10}6s7s$ (6,0)	6–6	23687	39545)	0.31
633.335	-	-	-	-	0.79
(633.343	$4f^{10}6s6p$ (6,2)°–?	4–4	24841	40625)	
633.349	$4f^{9}5d6s^{2}\,{}^{5}H^{\circ}$–$4f^{10}6s7s$ (8,1)	7–8	15194	30979	
	($4f^{10}6s^{2}\,{}^{3}K2$–?°	8–8	19019	34803)	
644.415	($4f^{10}6s6p$ (7,0)°–$4f^{10}6s7s$ (7,1)	7–6	19907	35421)	0.12
648.660	$4f^{10}6s6p$ (8,0)°–$4f^{10}6s7s$ (8,1)	8–8	15567	30979	0.60
659.168	($4f^{10}6s6p$ (6,0)°–$4f^{10}6s7s$ (6,1)	6–7	22956	38123)	0.17
661.471	($4f^{10}5d6s\,{}^{3}[6]$–?°	7–8	21778	36892)	0.26
661.491	($4f^{10}6s6p$ (6,0)°–$4f^{10}6s7s$ (6,1)	6–6	22956	38070)	
662.697	($4f^{10}6s6p$ (5,0)°–$4f^{10}6s7s$ (5,1)	5–5	25127	40213)	0.22

Table. (Continued): Excitation cross-sections of dysprosium atom **(**$4f^{10}6s7s$ configuration)

1	2	3	4	5	6
665.804	$4f^{9}5d6s^{2}\,{}^{7}H$°–$4f^{9}6s^{2}6p$ (15/2,3/2)	7–8	8519	23534	0.53
665.836	$4f^{10}6s6p$ (7,0)°–$4f^{10}6s7s$ (7,1)	7–8	19907	34922	
666.164	$4f^{10}6s6p$ (8,1)°–$4f^{10}6s7s$ (8,1)	9–8	15972	30979	0.45
666.786	$4f^{10}6s6p$ (8,0)°–$4f^{10}6s7s$ (8,1)	8–9	15567	30560	0.74
671.157	($4f^{10}6s6p$ (5,0)°–$4f^{10}6s7s$ (5,1)	5–4	25127	40023)	0.16
672.471	$4f^{9}5d6s^{2}\,{}^{5}I$°–$4f^{10}6s7s$ (7,1)	6–6	20554	35421	0.29
674.793	$4f^{10}6s6p$ (8,1)°–$4f^{10}6s7s$ (8,1)	7–7	16693	31509	0.27
676.589	$4f^{10}6s6p$ (8,1)°–$4f^{10}6s7s$ (8,1)	8–7	16733	31509	0.64
682.178	($4f^{10}6s6p$(7,1)°–$4f^{10}6s7s$ (7,1)	7–6	20766	35421)	0.37
685.296	$4f^{10}6s6p$ (8,1)°–$4f^{10}6s7s$ (8,1)	9–9	15972	30560	1.25
685.646	$4f^{10}6s6p$(7,1)°–$4f^{10}6s7s$ (7,1)	8–8	20341	34922	0.57
687.512	($4f^{10}6s6p$ (6,1)°–$4f^{10}6s7s$ (6,1)	5–5	23552	38093)	0.49
687.901	$4f^{10}6s6p$ (8,2)°–$4f^{10}6s7s$	8–8	18021	32554*	0.23
688.231	($4f^{10}6s6p$ (5,1)°–$4f^{10}6s7s$ (5,1)	4–5	25687	40213)	0.32
693.965	($4f^{10}6s6p$ (6,1)°–$4f^{10}6s7s$ (6,1)	6–5	23687	38093)	0.36
694.862	($4f^{10}6s6p$ (5,1)°–$4f^{10}6s7s$ (5,1)	6–5	25825	40213)	0.51
697.359	($4f^{10}6s6p$ (5,1)°–$4f^{10}6s7s$ (5,1)	4–4	25687	40023)	0.35
699.810	$4f^{10}6s6p$ (8,1)°–$4f^{10}6s7s$ (8,1)	7–8	16693	30979	1.46
701.742	$4f^{10}6s6p$ (8,1)°–$4f^{10}6s7s$ (8,1)	8–8	16733	30979	0.38
706.230	$4f^{10}6s6p$ (7,1)°–$4f^{10}6s7s$ (7,1)	7–8	20766	34922	0.17
707.966	$4f^{10}6s6p$ (8,2)°–$4f^{10}6s7s$	7–8	18433	32554*	0.12
708.500	($4f^{10}6s6p$ (5,1)°–$4f^{10}6s7s$ (5,1)	5–4	25912	40023)	0.23
723.004	$4f^{10}6s6p$ (8,1)°–$4f^{10}6s7s$ (8,1)	8–9	16733	30560	0.21
741.237	$4f^{10}6s6p$ (8,2)°–$4f^{10}6s7s$ (8,1)	8–7	18021	31509	0.44
748.303	$4f^{10}6s6p$ (7,2)°–$4f^{10}6s7s$ (7,1)	7–6	22061	35421	0.44
754.373	$4f^{10}6s6p$ (8,2)°–$4f^{10}6s7s$ (8,1)	9–8	17727	30979	1.75
755.300	$4f^{10}6s6p$ (7,2)°–$4f^{10}6s7s$ (7,1)	8–7	21899	35135	0.56
756.426	($4f^{10}6s6p$ (6,2)°–$4f^{10}6s7s$ (6,1)	7–7	24906	38123)	0.12
759.130	$4f^{9}5d6s^{2}\,{}^{5}I$°–$4f^{10}6s7s$ (8,1)	7–7	18339	31509	0.51
759.486	$4f^{10}6s6p$ (6,2)°–$4f^{10}6s7s$ (6,1)	7–6	24906	38070	0.39
760.917	$4f^{10}6s6p$ (6,2)°–$4f^{10}6s7s$ (6,1)	6–6	24931	38070	0.25
761.155	$4f^{10}6s6p$ (7,2)°–$4f^{10}6s7s$ (7,1)	6–6	22286	35421	0.84
761.621	$4f^{9}5d6s^{2}\,{}^{5}I$°–$4f^{10}6s7s$ (7,1)	5–6	22294	35421	0.31
761.770	$4f^{10}6s6p$ (6,2)°–$4f^{10}6s7s$ (6,1)	8–7	24999	38123	0.38
764.109	$4f^{10}6s6p$ (7,2)°–$4f^{10}6s7s$ (7,1)	9–8	21838	34922	1.16
764.123	$4f^{10}6s^{2}\,{}^{5}I$–$4f^{9}5d6s^{2}\,{}^{5}I$°	5–5	9211	22294	
764.587	$4f^{10}6s6p$ (8,2)°–$4f^{10}6s7s$ (8,1)	7–7	18433	31509	0.42
764.664	$4f^{10}6s6p$ (7,2)°–$4f^{10}6s7s$ (7,1)	7–7	22061	35135	

Table. (Continued): Excitation cross-sections of dysprosium atom **(**$4f^{10}6s7s$ configuration)

766.236	$4f^{10}6s6p$ (8,2)°–$4f^{10}6s7s$ (8,1)	10–9	17513	30560	0.75
767.669	$4f^{10}6s6p$ (7,2)°–$4f^{10}6s7s$ (7,1)	8–8	21899	34922	0.27
1	2	3	4	5	6
768.190	($4f^{10}6s6p$ (5,2)°–$4f^{10}6s7s$ (5,1)	6–5	27199	40213)	0.32
768.271	$4f^{10}6s6p$ (8,2)°–$4f^{9}5d6s6p$	9–8	17727	30739	
768.320	($4f^{10}6s6p$ (6,2)°–$4f^{10}6s7s$ (6,1)	5–5	25082	38093)	
771.533	$4f^{10}6s6p$ (8,2)°–$4f^{10}6s7s$ (8,1)	8–8	18021	30979	0.51
777.342	$4f^{10}6s6p$ (7,2)°–$4f^{10}6s7s$ (7,1)	7–8	22061	34922	0.14
778.089	$4f^{10}6s6p$ (7,2)°–$4f^{10}6s7s$ (7,1)	6–7	22286	35135	0.35
781.206	$4f^{10}6s6p$ (8,2)°–$4f^{10}6s7s$ (8,1)	6–7	18711	31509	0.58
787.064	$4f^{9}5d6s^{2}\ ^{5}H$°–?	7–8	15194	27896	0.21
787.074	($4f^{10}6s6p$ (4,1)°–$4f^{10}6s7s$ (5,1)	3–4	27321	40023)	
787.115	($4f^{9}5d6s^{2}\ ^{7}I$°–$4f^{9}6s^{2}6p$ (13/2,3/2)	7–6	14367	27068)	
790.939	$4f^{9}5d6s^{2}\ ^{5}I$°–$4f^{10}6s7s$ (8,1)	7–8	18339	30979	0.38
797.313	$4f^{10}6s6p$ (8,2)°–$4f^{10}6s7s$ (8,1)	8–9	18021	30560	0.19

shown in the plot area. *J* values are indicated in two cases: 1) when only a single level of the respective term is present in the Table; 2) when the particular level is shown in [9] to be isolated and not part of any term together with other levels. Regarding term labels, they are presented both in *LS* notation and J_1j-coupling notation in accordance with the data from [9].

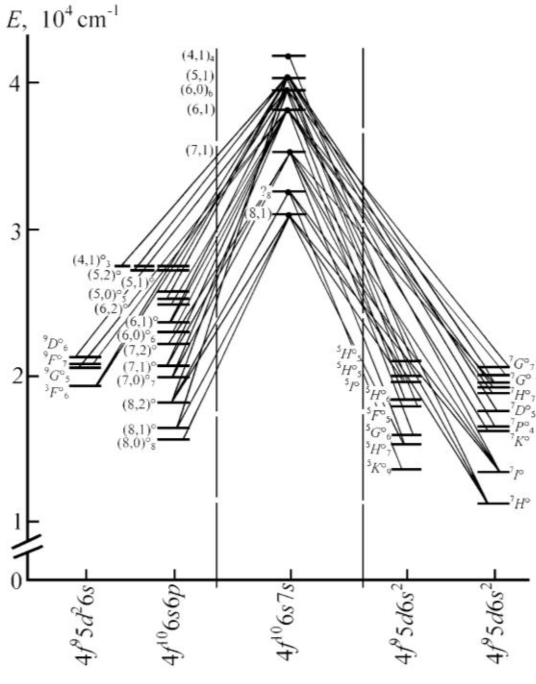

Figure. Partial state diagram of dysprosium atom

As mentioned earlier, ground level $4f^{10}6s^2\ {}^5I_8$ is the initial level for excitation in our experimental setup, with electron-impact excitation of $4f^{10}6s7s$ configuration levels resulting from optically forbidden single-electron transition $6s \rightarrow 7s$. Subsequent spontaneous radiative transitions terminate at low-lying odd levels belonging to $4f^95d^26s$, $4f^{10}6s6p$ and $4f^95d6s^2$ configurations. Fully allowed are spontaneous transitions to $4f^{10}6s6p$ levels accomplished by means of $7s \rightarrow 6p$ valence electron transfer. Transitions from $4f^{10}6s7s$ configuration levels to $4f^95d^26s$ and $4f^95d6s^2$ levels are quite unlikely as they would be accompanied with a complex restructuring of the electron shell. $4f^{10}6s7s$ configuration levels are almost pure in the J_1j-coupling notation, with leading component percentages of 99–81%. However the probability of such transitions may increase dramatically as a result of significant configuration mixing at lower-lying, odd levels.

4 Conclusion

Even levels of the dysprosium atom that belong to the $4f^{10}6s7s$ configuration are the highest-lying classified levels of DyI. Nevertheless their excitation is feasible both in research and state-of-the-art industrial setups using electron beams. The findings can be used as reference data in beam plasma performance calculations. Interpretation of experimental findings detailed in this paper is severely hampered by the absolute lack of the corresponding theoretical treatment of the dysprosium atom.

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