Measurement of the $2s\ ^3S_1-2p\ ^3P_2$ transition energy in heliumlike krypton

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We report the first measurement of the $1s\,2s\ ^3S_1-1s\,2p\ ^3P_2$ transition in heliumlike krypton produced by beam-foil interaction at 34.31 MeV/amu. Measurement is sensitive to higher-order relativistic contributions and to quantum electrodynamic effects. The accuracy corresponds to about 5% of the Lamb shift.

Accurate tests of relativistic effects and quantum electrodynamics in strong fields may be obtained from wavelength measurements of the $1s\,2s\,^3S_1$-$1s\,2p\,^3P_J$ transitions in high-Z heliumlike ions. In such two-electron ions there are two sorts of interactions: the electron-nucleus interaction, including the QED correction as vacuum polarization and selfenergy, and the e-e interaction including the Breit terms. The complexity of the problem comes mainly from the fact that exact calculations cannot be performed. The contribution of each effect has to be taken into account within a given perturbation order. The precise wavelength measurement of the $1s\,2s\,^3S_1$-$1s\,2p\,^3P_J$ transitions can be useful when trying to choose between different theoretical approaches and calculations.

In earlier high-energy beam-foil spectra[1] these transitions were observed in the light species C V, N VI, O VII, and Ne IX. Divergences from theoretical values, oversimply calculated at the time, had already been noticed and demands were made for more refined theoretical approaches. Since then, accurate measurements in the heliumlike ions of many elements between beryllium and argon have been performed. Comparisons with the best existing calculations after including one-electron Lamb shifts showed that there is an approximately Z^3-dependent discrepancy which may be due to screening of the radiative effect by the second electron.[2] In more recent work which we did at CEV Orsay[3–5] and at GSI Darmstadt[6] on higher-Z ions Cr^{22+}, Fe^{24+}, Cu^{27+} the energy of the $2s\,^3S_1$-$2p\,^3P_2$ transition is observed to be about 300 cm^{-1} higher than the calculated values of DeSerio *et al.*[7] This gap could be explained by the difficulties encountered in evaluating the two-electron QED corrections and some Breit terms. Comparison of measurements and calculations of the $^3S_1$-$^3P_2$ transition energy for heliumlike ions of $Z \leq 26$ are presented by Galvez *et al.*[8] in the discussion of their very recent results on Ti XXI. References to all previous experimental data can be found herein.

More measurements at even higher Z are required to test this assumption. This is why we measured the $1s\,2s\,^3S_1$-$1s\,2p\,^3P_2$ transition wavelength of heliumlike Kr XXXV as a more stringent test of the theory. We report here on this experiment, done at GANIL (Grand Accelerateur National d'Ions Lourds, in Caen) using the beam-foil technique. Our measured value agrees with the multiconfiguration Dirac-Fock calculated value[9] and is the highest -Z test of the two-electron QED and higher-order relativistic effects to date.

The incoming $^{84}Kr^{26+}$ ion beam had an energy of 34.31 MeV/nucleon (2.882 GeV). A typical particle current on target was 30—50 nA. At this energy cross sections for electron loss and capture in solid are very weak, so that the equilibrium thickness for carbon foil is several mg/cm^2. At 6 mg/cm^2 the outgoing charge states were found to be 36^+ (54%), 35^+ (43%), and 34^+ (3%). Thus it is easy to work in nonequilibrium conditions and to adjust the foil thickness to produce the proper outgoing charge state. Moreover, by varying the foil thickness it is possible to change the charge-state distribution which is a help for line identification.

Spectra were obtained using a McPherson 2.2-m grazing incidence vacuum ultraviolet monochromator, with angle fixed at 86°, detecting the radiation emitted at an angle near 90° to the beam direction. The 600 grooves/mm platinum-coated grating was blazed at 116 Å. The detector was a channeltron associated with a photon-counting system. The counting time was controlled by the beam current integrated in a Faraday cup.

Several spectra were recorded between $\lambda = 45$ and 300 Å with Kr^{26+} incident ions for different carbon-foil thicknesses (200—650 μg/cm^2). The extensive analysis of these spectra is in progress and will be published later. A typical low-statistics spectrum is displayed in Fig. 1. It was obtained with a 400-μg/cm^2 foil, a slit width of 300 μm and a 0.7-Å step. Within the scanned range 60—160 Å the more intense line is the resonance transition $2s\,^2S_{1/2}$-$2p\,^2P_{3/2}$ of lithiumlike Kr XXXIV. Other intense lines correspond to the $2s^2\,^1S_0$-$2s\,2p\,^1P_1$ and $2s\,2p\,^3P_1$-$2p^2\,^3P_2$ transitions of the berylliumlike Kr XXXIII in first and in second order. The more interesting part of the spectrum is located between 105 and 115 Å where the heliumlike Kr XXXV $2s\,^3S_1$-$2p\,^3P_2$ line

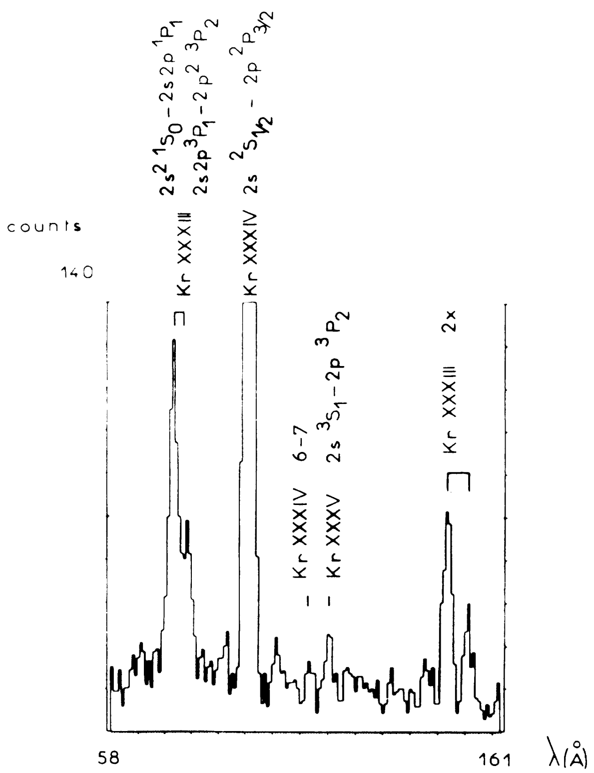

FIG. 1. Spectrum of foil-excited krypton showing beryllium-like, lithiumlike, and heliumlike lines in first and second (2×) orders. Energy of Kr^{26+} incident beam, 34.31 MeV/amu. Foil thickness, 400 $\mu g/cm^2$.

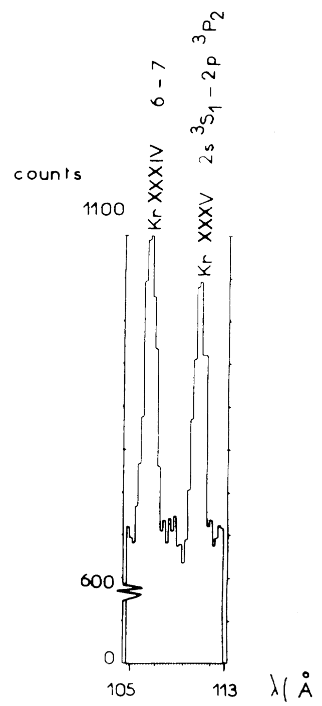

FIG. 2. Spectrum used in the Kr XXXV $2s\,^3S_1$-$2p\,^3P_2$ wavelength determination. Kr^{26+} beam at 34.31 MeV/amu as in Fig. 1 but foil thickness 650 $\mu g/cm^2$.

appears near the transition between Rydberg states $n=6$ and 7 of Kr XXXIV.

With the object of eliminating the $2s2p\,^3P_2$-$2p^2\,^3P_2$ Kr XXXIII line at about 112 Å in the higher-wavelength wing of the heliumlike line to be measured it was desirable to strip the krypton beam more efficiently by using a 650-$\mu g/cm^2$ carbon foil. The relative percentages for 35^+, 34^+, 33^+, ad 32^+ ions were measured and found to be 10%, 60%, 25%, and 4% respectively. With this target the lithiumlike and heliumlike lines had only very low contamination from transitions due to lower charge states. Under these conditions we obtained simpler spectra, such as the one displayed in Fig. 2 with a slit width of 150 μm (line width 1.2 Å) and a 0.25-Å step. Between 105 and 113 Å we observed only two well-separated lines, the 6-7 transition in Kr XXXIV and the $2s\,^3S_1$-$2p\,^3P_2$ transition in Kr XXXV.

The signal count rate was corrected for the background and a Gaussian profile was fitted to these corrected experimental points. Accurate measurement of the wavelengths of the heliumlike lines necessitated a calibration of the spectrometer and the use of well-known spectral lines as wavelength references. The dispersion curve was determined using a Penning gauge situated just in front of the entrance slit of the instrument. Many lines, observed from 240–700 Å in He I, He II, Ne I, and Ne II, were treated as wavelength standards. This "static" calibration is accurate to about 0.01 Å. Because the Doppler effect shifts and broadens the lines emitted by fast ions, it was necessary to used foil-excited lines as references. The $2s\,^2S_{1/2}$-$2p\,^2P_{3/2}$ resonant line of Kr XXXIV at 91.00 Å is known to ±0.02 Å extrapolating from Edlen.[10] The 6-7 transition of Kr XXXIV is also a good candidate because Rydberg energies are precisely calculated in the lithium sequence. However, further corrections are needed because of the dependence of line centroids and shapes on the way the grating is illuminated and consequently on the lifetimes of upper levels. After taking all these uncertainties and corrections into account, our final result for the wavelength of the $2s\,^3S_1$-$2p\,^3P_2$ transition in Kr XXXV is 111.15±0.08 Å.

As far as we know, no previous energy measurement is available for comparison. Thus, in Table I, our experimental energy and wavelength are compared only to theoretical values. Details of our own calculation are displayed in the first row of Table I. For the nonrelativistic part of the transition energy calculated in a Z expansion we used the coefficients of Blanchard.[11] The total relativistic energy has been developed in a double expansion in increasing powers of Z^{-1} and $(\alpha Z)^2$. The whole hydrogenic relativistic term, the Breit term in $Z^{-1}\,(\alpha Z)^4$ and the $Z^{-2}\,(\alpha Z)^4$ term have been taken into account. The mass polarization was obtained by extrapolation from the values of Ermolaev and Jones.[12] The one-electron QED contribution was from Mohr.[13] The two-electron Lamb-shift screening was extrapolated from the recent data given by Hata and Grant.[14]

TABLE I. Comparison between experimental and theoretical values for the $1s2s\,^3S_1-1s2p\,^3P_2$ transition in Kr XXXV. Energies are in cm^{-1} and wavelength in Å.

Experiment		Theory				
λ	Energy	Nonrelativistic + relativistic	One-electron QED	Two-electron QED	Total energy	λ
111.15±0.08	899 685 (650)	912 548	−12 668	696 [e]	900 576 [a]	111.04
		912 382.1 [b]	−12 784.9 [b]	340 [f]	899 937.2	111.12
		914 067	−12 478		901 589 [c]	110.92
				672	899 709 [d]	111.147

[a]Our calculation.
[b]DeSerio *et al.* (Ref. 7).
[c]Safronova (Ref. 15).
[d]Desclaux (Ref. 9).
[e]Value extrapolated from Hata and Grant (Ref. 14).
[f]Value extrapolated from DeSerio *et al.* (Ref. 7).

Detailed calculations have been published by DeSerio *et al.*[7] and by Safronova[15] who also used a double-series expansion formalism. Safronova included a simple one-electron QED contribution although DeSerio added an estimated two-electron QED correction. Calculations disagree mainly in the relativistic and QED parts of the energies. However, we have noted also some non-negligible difference between the nonrelativistic part deduced from Blanchard and from Safronova. Our calculation of the relativistic contribution has only been extended to the first terms of the series, which may explain the difference with the more complete calculation of Deserio.

The recent multiconfiguration Dirac-Fock result of Desclaux[9] is in very satisfactory agreement with our experiment. This calculation includes the magnetic interaction, correlation effects, the retardation in the *e*-*e* interaction, the mass polarization, the one-electron QED and its screening. The present experimental error in the $1s2s\,^3S_1$-$1s2p\,^3P_2$ energy in Kr XXXV (650 cm^{-1}) is equivalent to 5% of the one-electron QED contribution and is about as large as the screening by the second electron as determined by Desclaux. In order to measure this last contribution experimentally, some improvements need to be made to the method and technique used. Such improvements are at present being implemented in our laboratory.

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