Precision measurement of the $K\alpha$ transitions in heliumlike Ge^{30+}

S. MacLaren, P. Beiersdorfer, D. A. Vogel, D. Knapp, R. E. Marrs, K. Wong, and R. Zasadzinski
High Temperature Physics Division, University of California, Lawerence Livermore National Laboratory, Livermore, California 94550
(Received 15 April 1991)

A measurement of the $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ resonance transition in heliumlike germanium (Ge^{30+}) has been made on the Lawrence Livermore National Laboratory electron-beam ion trap to a precision of 21 ppm. The result is compared with theoretical values and confirms a trend previously seen in the differences between experiment and theory for this transition as a function of Z. Results for the $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$ and $1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$ intercombination lines and for the $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ forbidden line are also presented and show similar differences with theoretical predictions.

PACS number(s): 32.30.Rj, 34.80.Kw

I. INTRODUCTION

Predicting the energy levels of a multielectron atom is considerably more difficult than solving the two-body problem of the hydrogenlike atom, as it involves many-body quantum-electrodynamical corrections, relativity, and electron-electron correlations [1]. The heliumlike ion, the simplest of the multielectron systems, provides an ideal setting for testing approaches to solving the many-body problem. As approaches tend to vary significantly in their treatment of correlation and relativistic effects, experimental results are necessary in order to assist the development of accurate theoretical approximations. Moreover, heliumlike transitions have been used in many instances as reference lines to determine the wavelengths of transitions from many-electron ions [2,3]. Accurate heliumlike wavelengths, therefore, are also crucial to making precision measurements of transitions in many-electron ions.

Studies of highly charged heliumlike ions require an experimental apparatus capable of creating the necessary conditions for these charge states to exist. This has been previously accomplished using beam-foil techniques in an accelerator and plasma spectroscopy with a vacuum spark source or a tokamak. Accelerators have been used to study transition energies of heliumlike sulfur [4], argon [5], iron [6], krypton [7], xenon [8], and, most recently, uranium [9]. The best precision among beam-foil measurements was 23 ppm [7]; unfortunately, the precision of the highest-Z measurements was much lower, with xenon measured to within 114 ppm and uranium to within 350 ppm [8,9]. The vacuum-spark-source-generated data for a wide range of atomic numbers from $Z = 16-39$ with a precision worse than 50 ppm [10]. A tokamak with an electron temperature of ≤ 5 keV was used to measure transition energies for potassium, scandium, titanium, vanadium, chromium, and iron [11]. The measurement of the transition in heliumlike iron achieved a precision of 30 ppm [11]. The highest precision measurement to date was attained with the recoil-ion technique in an accelerator setting. Here the transition was measured in argon with an error of only 12 ppm [12].

A survey of the data suggests systematic differences between the experimental values and several theoretical results; the wavelength of each transition measured in the range $19 \leq Z \leq 36$ was found to be less than the wavelength calculated [11]. These differences are small, however, and measurements with errors better than 30 ppm are needed to carefully examine this trend.

The electron-beam ion traps (EBIT-1 and EBIT-2) at Lawrence Livermore National Laboratory also provide the means to produce highly charged ions for precision x-ray spectroscopy [13,14]. Since the trapped ions are at rest, measurements can be made with high precision, unaffected by Doppler shifts and Doppler broadening. The EBIT-1 source was previously used to make a precision measurement of the self-energy contribution to the $2s$-$3p$ transition in neonlike ytterbium [15]. Here the transition energy was measured with an error of 85 ppm. In the present experiment, an 11-keV electron beam was used to generate and excite heliumlike germanium (Ge^{30+}). The transitions in heliumlike germanium were calibrated by hydrogenlike copper x rays, and a precision of 21 ppm was attained in the measurement of the wavelength of the $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ resonance transition.

II. EXPERIMENT

Low-charge germanium and copper ions are produced and injected into EBIT-2 by a metal vapor vacuum arc (MeVVA) [16]. In particular, a MeVVA was constructed with an anode made from a germanium-aluminum alloy and a copper trigger wire. By exchanging the anode and trigger leads during the run, measurements of germanium and copper x rays could be made successively while the ion trap was in operation. In addition, two MeVVA's, one containing only germanium and one containing only copper, were constructed for the experiment, and successive spectra were measured by interchanging the two MeVVA's.

Interactions in the trap take place along a 2-cm-long region within the 60-μm-diam electron beam. A von Hámos spectrometer resolves and focuses the x-ray spectrum. EBIT's x-ray-emission pattern is very well suited to the von Hámos geometry since a von Hámos spectrometer ordinarily requires an entrance slit. A detailed

description of the spectrometer can be found in Ref. [17]. The x-ray spectra were taken with a LiF(220) crystal bent to a 75-cm radius. The spectrum in Fig. 1(a) is a typical example of a germanium spectrum taken in first order at a Bragg angle of 17°. The spectrum has a resolution of about $\lambda/\Delta\lambda=3000$ and represents data collected over a 2-h period.

The spectrum in Fig. 1(a) shows the germanium $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ transition, along with the $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$, $1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$, and $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ transitions. These lines are labeled *w*, *x*, *y*, and *z*, respectively, using the notation of Gabriel [18]. The 1-3 transitions in hydrogenlike copper were used as calibration lines. Figure 1(b) shows a spectrum that represents 24 h of data. The count rate for the copper x rays was very slow for two reasons: the excitation cross sections for the 1-3 transitions are relatively small, and a high concentration of hydrogenlike ions in the trap is more difficult to maintain than either bare or heliumlike ions. The longer run time was needed to produce a statistically significant number of counts in each peak. From Fig. 1 it is clear that the germanium *w* line and the copper Ly_{β_2} line are nearly coincident, with the Ly_{β_1} line appearing only 20 channels (about 10 eV) away. This grouping implies that the copper lines are an excellent reference for the germanium line, since any errors in the dispersion are virtually eliminated.

With the spectrometer positioned for first order, three runs acquiring Ge data were interspersed with two runs acquiring Cu to check for drifts in either the hardware or electronics. Separate spectra were also taken in second order acquiring Ge and Cu x rays concurrently. Unlike the previous Yb measurement on the EBIT-1 apparatus [15], no drifts were discovered in the present spectra.

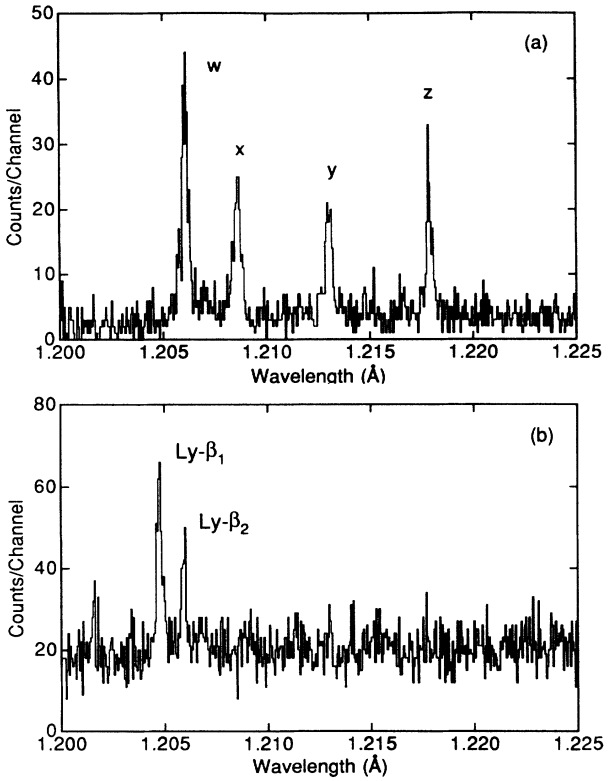

FIG. 1. Typical spectra observed with the high-resolution von Hámos spectrometer: (a) $n=2\rightarrow 1$ transitions in heliumlike germanium; (b) $n=3\rightarrow 1$ transitions in hydrogenlike copper. Notice the proximity of the copper lines to the line *w* of germanium. This coincidence enabled a very precise measurement.

III. ANALYSIS

In order to arrive at an experimental value for the germanium line using the copper spectra, the difference in Bragg angle between the two wavelengths is needed. Through an understanding of the von Hámos geometry, a dispersion relationship can be derived to enable the calculation of this angle. Referring to Fig. 2 we can describe the wavelength of a line whose Bragg angle differs by $\Delta\theta$ from the reference Bragg angle θ_0 by

$$\lambda=2d\sin(\theta_0+\Delta\theta)\ , \tag{1}$$

where

$$\Delta\theta=\arctan\left[\frac{\Delta x}{2D}\right]=\arctan\left[(N-N_0)\frac{b}{2D}\right]\ . \tag{2}$$

Here, Δx is the change in position on the face of the detector, D is the distance from the crystal to the detector, N and N_0 are the centroids of the two wavelengths in channel numbers, and b is the distance per channel across the face of the detector. Defining the dispersion constant K,

$$K=\frac{b}{2D}\ , \tag{3}$$

the Bragg equation becomes

$$\lambda=2d\sin\{\theta_0+\arctan\,[K(N-N_0)]\}\ . \tag{4}$$

Inverting this equation, the dispersion constant can be expressed in terms of the difference in Bragg angle be-

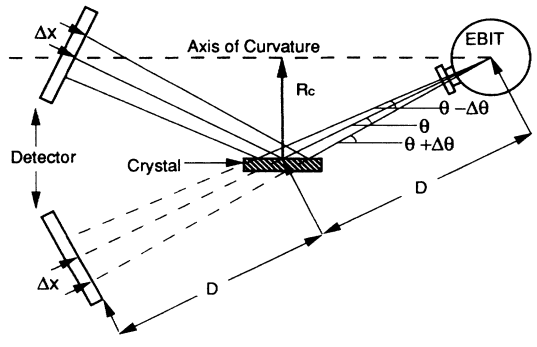

FIG. 2. Schematic of the spectrometer layout on EBIT. The detector is oriented perpendicular to the line connecting the center of the crystal with the center of the detector. X rays incident upon the crystal are not dispersed linearly on the face of the detector; instead the difference in angle $\Delta\theta=$ arctan $(\Delta x/2D)$.

TABLE I. Comparison of measured wavelengths of $K\alpha$ transitions in Ge^{30+} with theory. All values are in angstroms. The wavelengths of the Cu^{28+} Ly_β reference lines are set to 1.204 73 and 1.205 87 Å.

Transition	Label	λ_{expt}	λ^a	λ^b	λ^c
$1s2p\ ^1P_1 \rightarrow 1s^2$	w	1.205 99 (±21 ppm)	1.206 14	1.206 06	1.206 03
$1s2p\ ^3P_2 \rightarrow 1s^2$	x	1.208 48 (±36 ppm)	1.208 59	1.208 57	1.208 47
$1s2p\ ^3P_1 \rightarrow 1s^2$	y	1.212 94 (±34 ppm)	1.213 02	1.213 07	1.212 90
$1s2p\ ^3S_1 \rightarrow 1s^2$	z	1.217 76 (±51 ppm)	1.217 90	1.217 88	1.217 78

[a]L. A. Vainshtein and U. I. Safronova, Ref. [24].
[b]G. W. F. Drake, Ref. [25].
[c]E. V. Aglitsky *et al.*, Ref. [10]; values for x, y, and z have been shifted as discussed in the text.

tween two reference lines:

$$K = \frac{\tan[\arcsin(\lambda/2d - \theta_0)]}{N - N_0} . \quad (5)$$

There are thus two separate ways to determine the dispersion constant K. First, physical measurements can be made of b and the total x-ray path length for use in Eq. (3). Second, the centroids for two x-ray peaks of known wavelengths, such as the two hydrogenlike 1-3 copper transitions, can be found and used in Eq. (5). The latter method was used previously on EBIT to determine the wavelengths of transitions in neonlike ytterbium and thorium [15,19], as well as the wavelengths of fluorinelike, oxygenlike, and nitrogenlike barium and of the dielectronic satellite lines of heliumlike vanadium [20,21]. For the present analysis, however, the first method was employed, since the physical measurements of the spectrometer were more precise than the measurement of the distance between the centroids of the Ly_{β_1} and Ly_{β_2} lines of copper. The resulting value of K was then used in Eq. (4) along with weighted averages of the centroids of the two reference lines to determine the wavelength for each germanium line.

The closeness of line w to the hydrogenic reference lines virtually eliminates contributions from the uncertainty in the dispersion to the overall uncertainty of its measured wavelength. Uncertainties in its measured wave length arise instead from the statistical uncertainty in its line position as well as that of the reference lines. Line positions determined in separate measurements are found to be consistent with the variation expected from statistical analysis of the number of counts observed in a given line and its width. Adding in quadrature uncertainties in the dispersion (3 ppm) and in the line positions of w and the reference lines (20 ppm) we obtain an experimental precision of 21 ppm or $\pm 2.5 \times 10^{-5}$ Å. Uncertainties in the dispersion affect line z the most. Furthermore, it is also located closest to the edge of the spectrum and is affected by vignetting. The overall uncertainty of 51 ppm comprises 33 ppm from uncertainties in the dispersion and 39 ppm from uncertainties in the line positions. The overall estimated uncertainties of x and y are 36 and 34 ppm.

Theoretical values for the copper transitions are those of Erickson [22]. However, in order to account for subsequent revisions in the values of atomic constants, we have replaced Erickson's ground-state energy by the one given by Johnson and Soff [23]. This decreases the wavelengths of Cu Ly_β lines calculated by Erickson by 0.02 mÅ. The resulting values we use are 1.204 73 Å for Ly_{β_1} and 1.205 87 Å for Ly_{β_2}. Theoretical values for the wavelengths of the heliumlike germanium transitions were computed by Vainshtein and Safronova [24] using the Z-expansion method and by Drake [25] using a nonrelativistic variational approach. An updated set of theoretical wavelengths for the heliumlike resonance lines has been published by Aglitsky *et al.* in Ref. [10] that incorporates an additional term into the theory of Vainshtein and Safronova. For Ge^{30+} the additional term amounts to a 0.98-eV increase in the theoretical value. The term affects only the ground-state energy and leaves the energy of the excited state the same. Because the forbidden and intercombination lines have the same ground level as the resonance line, we have shifted their transition energies by this amount as well. The resulting theoretical wavelength values are shown in Table I.

IV. DISCUSSION

In a study of the wavelength of line w, Beiersdorfer *et al.* [11] noted the possibility of a systematic discrepancy between experimental results and theory. The study showed that, for the range of atomic numbers 16–36, the experimental wavelengths tended to lag behind the calculated values as Z increased. This discrepancy was largest when the data were compared to the values calculated with the Z-expansion technique by Vainshtein and Safronova [24]; it was smaller when compared to values calculated by Drake [25], who used a variational approach, or to those calculated by Indelicato with a MCDF code [26]. The result obtained with EBIT for germanium agrees with this trend: the measured wavelength of the Ge^{30+} w line falls 53 ppm below the theoretical value of Drake and 123 ppm below the theory of Vainshstein and Safronova. Based on the observation [11] that transition energies calculated by Indelicato are about 10–20 ppm larger than those of Drake for elements with $20 \leq Z \leq 36$, we conjecture that our measured value for the Ge^{30+} w line would fall about 30–40 ppm below the wavelength value calculated with this MCDF code, should a calculation be made. A recent calculation by Indelicato [27] of the transition energies of the triplet lines in Ge^{30+} affirms our ex-

pectation, as the transition energies of x, y, and z calculated by Indelicato with the MCDF method are 0.18, 0.21, and 0.12 eV higher, respectively, than those of Drake in Ref. [25].

Similar to the results for the resonance line, we find that the measured wavelengths for the intercombination and forbidden lines are also shorter than predicted by the calculations of Drake or Vainshtein and Safronova. By contrast, comparison with values of Vainshtein and Safronova that were adjusted for a shift in the $1s^2$ ground-state energy shows very good agreement with the data; except for the measured wavelength of w, which is shorter than predicted, measured and predicted wavelengths agree within experimental error limits. Better agreement with Drake and experiment would also be achieved, if the values calculated by Drake were increased by about 0.8–1.0 eV.

V. CONCLUSION

The germanium w wavelength reported here represents the most precise transition energy measurement on EBIT to date. The precision compares well with similar measurements on other sources of highly charged ions. It is about four times higher than the Yb^{60+} measurement reported earlier and carried out on EBIT-1 [15]. This improvement was achieved by substituting a 75-cm-radius crystal for a 30-cm crystal, thus increasing the resolving power by a factor of 2.5. Additional improvement resulted from the elimination of a 0.5-eV day-to-day spectral drift noted in the earlier measurement.

Taking into account the error bars, a significant discrepancy between our experiment and the theoretical wavelengths in Refs. [24] and [25] was observed. This confirms previous observations [11] and perhaps points to the need for including additional interactions in the theoretical treatment of the ground state.

ACKNOWLEDGMENTS

We are grateful to E. Magee and D. Nelson for their expert technical support. Discussions with Dr. Paul Indelicato are acknowledged with much appreciation. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

[1] P. Indelicato, in *X-ray and Inner-Shell Processes, Knoxville, 1990,* AIP Conf. Proc. No. 215, edited by T. A. Carlson, M. O. Krause, and S. T. Manson (AIP, New York, 1990), p. 591.

[2] P. Beiersdorfer, M. Bitter, S. von Goeler, S. Cohen, K. W. Hill, J. Timberlake, R. S. Walling, M. H. Chen, P. L. Hagelstein, and J. H. Scofield, Phys. Rev. A **34**, 1297 (1986).

[3] P. Beiersdorfer, S. von Goeler, M. Bitter, E. Hinnov, R. Bell, S. Bernabei, J. Felt, K. W. Hill, R. Hulse, J. Stevens, S. Suckewer, J. Timberlake, A. Wouters, M. H. Chen, J. H. Scofield, D. D. Dietrich, M. Gerassimenko, E. Silver, R. S. Walling, and P. L. Hagelstein, Phys. Rev. A **37**, 4153 (1988).

[4] L. Schleinkofer, F. Bell, H. -D. Betz, G. Trollmann, and J. Rothermel, Phys. Scr. **25**, 917 (1982).

[5] J. P. Briand, J. P. Mossé, P. Indelicato, P. Chevallier, D. Girard-Vernhet, and A. Chetioui, Phys. Rev. A **28**, 1413 (1983).

[6] J. P. Briand, M. Tavernier, P. Indelicato, R. Marrus, and H. Gould, Phys. Rev. Lett. **50**, 832 (1983).

[7] P. Indelicato, O. Gorceix, M. Tavernier, J. P. Briand, J. P. Desclaux, R. Marrus, and M. Prior, Z. Phys. D **2**, 149 (1986).

[8] J. P. Briand, P. Indelicato, A. Simionovici, V. San Vicente, D. Liesen, and D. Dietrich, Europhys. Lett. **9**, 225 (1989).

[9] J. P. Briand, P. Chevallier, P. Indelicato, K. P. Ziock, and D. Dietrich, Phys. Rev. Lett. **65**, 2761 (1990).

[10] E. V. Aglitsky, P. S. Antsiferov, S. L. Mandelstam, A. M. Pain, U. I. Safronova, S. A. Ulitin, and L. A. Vainshtein, Phys. Scr. **38**, 136 (1988).

[11] P. Beiersdorfer, M. Bitter, S. von Goeler, and K. W. Hill, Phys. Rev. A **40**, 150 (1989).

[12] R. D. Deslattes, H. F. Beyer, and F. Folkmann, J. Phys. B **17**, L689 (1984).

[13] R. E. Marrs, M. A. Levine, D. A. Knapp, and J. R. Henderson, Phys. Rev. Lett. **60**, 1715 (1988).

[14] M. A. Levine, R. E. Marrs, J. N. Bardsley, P. Beiersdorfer, C. L. Bennett, M. H. Chen, T. Cowan, D. Dietrich, J. R. Henderson, D. A. Knapp, A. Osterheld, B. M. Penetrante, M. B. Schneider, and J. H. Scofield, Nucl. Instrum. Methods B **43**, 431 (1989).

[15] P. Beiersdorfer, M. H. Chen, R. E. Marrs, and M. A. Levine, Phys. Rev. A **41**, 3453 (1990).

[16] I. G. Brown, J. E. Galvin, R. A. MacGill, and R. T. Wright, Appl. Phys. Lett. **49**, 1019 (1986).

[17] P. Beiersdorfer, R. E. Marrs, J. R. Henderson, D. A. Knapp, M. A. Levine, D. B. Platt, M. B. Schneider, D. A. Vogel, and K. L. Wong, Rev. Sci. Instrum. **61**, 2338 (1990).

[18] A. H. Gabriel, Mon. Not. R. Astron. Soc. **160**, 99 (1972).

[19] P. Beiersdorfer, Nucl. Instrum. Methods B **56/57**, 1144 (1991).

[20] R. Hutton, P. Beiersdorfer, A. L. Osterheld, R. E. Marrs, and M. B. Schneider, Phys. Rev. A **44**, 1836 (1991).

[21] P. Beiersdorfer, M. H. Chen, R. E. Marrs, M. B. Schneider, and R. S. Walling, Phys. Rev. A **44**, 396 (1991).

[22] G. W. Erickson, J. Phys. Chem. Ref. Data **6**, 831 (1977).

[23] W. R. Johnson and G. Soff, At. Data Nucl. Tables **33**, 405 (1985).

[24] L. A. Vainshtein and U. I. Safronova, Phys. Scr. **31**, 519 (1985).

[25] G. W. F. Drake, Can. J. Phys. **66**, 586 (1988).

[26] P. Indelicato, Nucl. Instrum. Methods B **31**, 14 (1988).

[27] P. Indelicato (private communication).