Precision Measurement of the $3s_{1/2}$-$3p_{3/2}$ Transition Energy in Na-like Platinum Ions

T. E. Cowan, C. L. Bennett, D. D. Dietrich, J. V. Bixler, C. J. Hailey, J. R. Henderson, D. A. Knapp, M. A. Levine,[a] R. E. Marrs, and M. B. Schneider

University of California, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

(Received 20 July 1990)

We report a measurement of the $3s_{1/2}$-$3p_{3/2}$ transition energy in Na-like $_{78}Pt^{67+}$ ions of 653.44 ± 0.02(stat) ± 0.05(syst) eV. The x rays were observed from ions in an electron-beam ion trap. The uncertainty in our result corresponds to 1% of the total estimated quantum electrodynamic radiative contribution to this transition energy. This value differs significantly from extrapolations based on previous lower-Z data, and establishes a benchmark for calculations of high-Z multielectron radiative and relativistic effects.

PACS numbers: 31.30.Jv, 12.20.Fv, 32.30.Rj

There is a great deal of interest in the atomic energy levels of highly charged ions in the Na-like isoelectronic sequence. The relative calculational simplicity of treating a single electron outside of a closed shell enables accurate theoretical calculations of all contributions to the energy except the quantum electrodynamic (QED) radiative corrections. QED corrections have only been calculated for hydrogenic ions for the $1s$, $2s$, and $2p$ states.[1] For $n=3$ the theoretical treatment is incomplete, although it is believed that, apart from an overall $1/n^3$ scaling, the $n=2$ and 3 radiative corrections are approximately the same. For the more complex Na-like ions the residual differences between measured energies and the energies calculated without radiative corrections exhibit the same approximate Z^4 scaling as the hydrogenic Lamb shifts but are somewhat smaller. Accounting for this "screening" of the Lamb shift is one of the outstanding unsolved problems in the atomic physics of highly charged ions.

The multiconfiguration Dirac-Fock (MCDF) code of Grant *et al.*[2] includes a phenomenological estimate of the radiative corrections, and has been compared to a variety of measurements. When differences between experiment and calculation arise, it is difficult to determine whether they are due to an inadequate treatment of the relativistic many-body effects or of the QED effects. Recent many-body perturbation theory (MBPT) calculations by Johnson, Blundell, and Sapirstein[3-5] are fully relativistic but do not contain radiative corrections. The accuracy reported for these calculations is sufficiently high that residual differences between theory and measurements are dominated by QED effects.

Extension of experimental measurements to high Z is particularly important because of the Z^4 scaling of relativistic and radiative corrections. Previous observations of the Na-like sequence extended to $_{64}Gd^{53+}$ for the $3s_{1/2}$-$3p_{3/2}$ transition, and to $_{54}Xe^{43+}$ for the $3s_{1/2}$-$3p_{1/2}$ transition.[6] In this work, we extend the range of precision measurements for the $3s_{1/2}$-$3p_{3/2}$ transition to $_{78}Pt^{67+}$. Na-like Pt was chosen because the near degeneracy of this transition with the Ly-α transitions in hydrogenic oxygen provides an excellent absolute-energy calibration.

The Na-like platinum ions were produced in the electron-beam ion trap (EBIT) at the Lawrence Livermore National Laboratory. EBIT has been described in detail elsewhere.[7] Briefly, low-charge Pt ions were injected into a cylindrical electrostatic well where they were further ionized and collisionally excited by an 18.5-keV electron beam. The deexcitation x rays were observed at 90° with respect to the beam direction using a Bragg-crystal spectrometer. The kinetic-energy spread of the trapped Pt^{67+} ions was less than 1.0 keV,[8] resulting in a negligible Doppler shift or broadening of the observed x-ray lines.

The x-ray spectrometer consisted of a cylindrically curved rubidium acid phthalate (RAP) crystal (2×2 cm^2 area) in a Johann geometry, with a position-sensitive detector on the Rowland focal circle oriented normal to the incident x rays, as indicated in Fig. 1. The 70-μm-diam, 2-cm-high column of trapped Pt ions in EBIT was located on the Rowland circle (to <0.5 mm accuracy) and oriented perpendicular to the diffraction plane. Data were taken over a broad x-ray energy range by con-

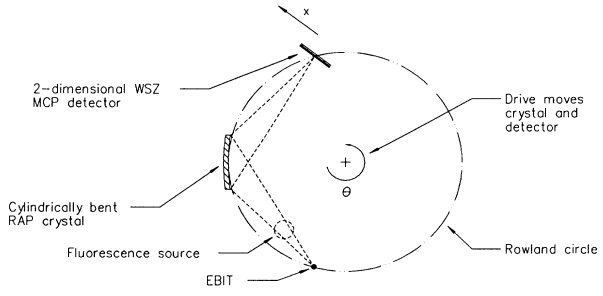

FIG. 1. Schematic diagram of the Johann spectrometer, showing the RAP crystal, MCP detector, and fluorescence source which rotate as a unit about the center of the Rowland circle.

tinuously rotating the spectrometer assembly back and forth about the center of the Rowland circle for Bragg angles near 46°, which corresponds to the ~650-eV energy of the Pt $3s_{1/2}$ to $3p_{3/2}$ transition. The detector consisted of three stacked microchannel plates (MCP) coated with a CsI photocathode and backed by a wedge and strip anode plane which gave X and Y positions on an event-by-event basis for each detected x ray. The instrumental line shape, dominated by the resolving power of the RAP crystal ($E/\Delta E \sim 700$), was well described by a Voigt profile approximately 1 eV wide.

The wavelength scale of the spectrometer was calibrated in two steps. First, the dispersion was determined from characteristic fluorescence x rays of Mn in ninth and tenth orders, and F in first order. Foils of Mn and KF were positioned in the line of sight between the Bragg crystal and the ion source, and were fluoresced by an intense x-ray source located out of the focal plane. The measured dispersion agreed to better than 0.2% with that determined from the crystal geometry (58 cm radius of curvature, 26.121 Å $2d$ spacing[9]) and spatial dispersion of the detector (0.037 mm/channel), which was verified mechanically by rotating the detector assembly about the center of the Rowland circle by known amounts and measuring the shift of a given calibration line along the detector face.

Second, the absolute-energy scale was accurately determined by measuring the Ly-α transition of H-like O produced in EBIT. The near degeneracy (within 0.18 eV) between this transition and the $3s_{1/2}$-$3p_{3/2}$ transition in Na-like Pt provided an excellent calibration. H-like $1s$-$2p$ transitions have been previously used as high-accuracy calibration lines[10] and can be calculated with very little uncertainty. Throughout all the calibrations, the EBIT magnetic fields remained at the Pt run settings and the spectrometer was continuously scanned in Bragg angle. Thus, any possible shifts in the detected line position resulting from the spatially varying magnetic field or mechanical stresses on the spectrometer were treated in a consistent fashion for both the calibration and Pt data.[11]

In order to obtain a precise measurement of the Na-like Pt $3s_{1/2}$-$3p_{3/2}$ line position, to guard against shifts in the detector image, and to minimize other time-varying sources of systematic error, we alternated Pt data-taking runs (typically ~2 h) with H-like O calibration runs (typically 30 min). For the O runs, the Pt-ion source was switched off, the electron-beam energy was reduced to 3.6 keV, and oxygen gas was injected into EBIT. In Fig. 2 the centroids of the measured Na-like Pt lines and Ly-α O lines are plotted versus the corresponding run number. The data exhibit a six-channel shift (~0.3 eV) after run 1241. Similar shifts were observed in the fluorescence-source calibration lines from F and Mn before and after run 1242. The shift appears to be correlated with a mechanical adjustment of the spectrometer and a change in the EBIT magnetic fields. Only data taken after run 1242 are used in the following analysis. During this time, the scatter in the oxygen and platinum peaks was consistent with statistical variations about a constant value; no systematic deviation of the line centroids is apparent.

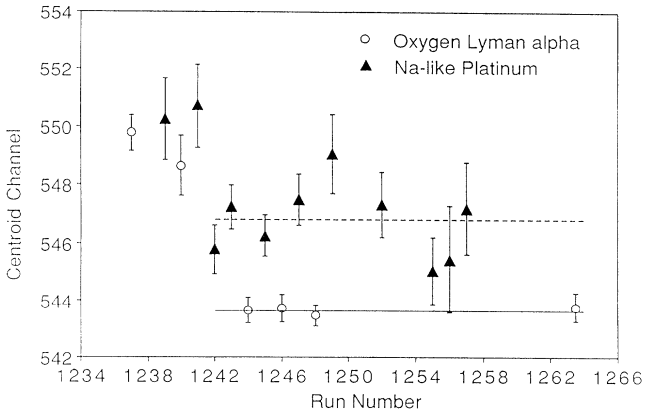

FIG. 2. Line centroids for the Pt 3-3 transition (triangles) and oxygen Ly-α (circles) in channel numbers plotted vs run number. One channel corresponds to approximately 0.05 eV.

The total spectra obtained from summing the data for the Pt and O runs are shown in Fig. 3. Also shown is a spectrum from the Mn fluorescence calibration source. The O line is actually an unresolved doublet, corresponding to the $1s_{1/2}$-$2p_{1/2}$ and $1s_{1/2}$-$2p_{3/2}$ transitions, with calculated[1] energies of 653.494 and 653.680 eV, respectively. Since the Bragg angle is near 45°, the crystal reflectivity is very small for x rays polarized in the diffraction plane, and the centroid of the observed doublet depends on the polarization of each line. While the $1s_{1/2}$-$2p_{1/2}$ decay is unpolarized, the $1s_{1/2}$-$2p_{3/2}$ emission has a theoretical polarization of 0.116.[12] Given a 1:2 admixture of the $2p_{1/2}$ and $2p_{3/2}$ intensities, and including adjustments for (1) the angular distribution of the polarized radiation, (2) the crystal reflectivity for longitudinal and transverse polarizations, and (3) the depolarizing effects of the 340-eV electron temperature,[12] the mean energy of the doublet is 653.623 ± 0.004 eV. (The uncertainty reflects uncertainties in the electron temperature and crystal reflectivity.)

Fitting Voigt line shapes to the data of Figs. 3(a) and 3(b) yields a 0.18 ± 0.02-eV difference between the $3s$-$3p$ Na-like Pt line centroid and the O Ly-α line centroid. Using this value, we obtain a Pt $3s_{1/2}$-$3p_{3/2}$ transition energy of 653.44 ± 0.02(stat) eV. Because of the proximity of the Pt and O lines, errors from uncertainties in the spectrometer dispersion are negligible.

Apart from the O Ly-α polarization uncertainty discussed above, the only other possible sources of significant systematic error would be a shift of the observed Pt line position from unresolved underlying transitions or

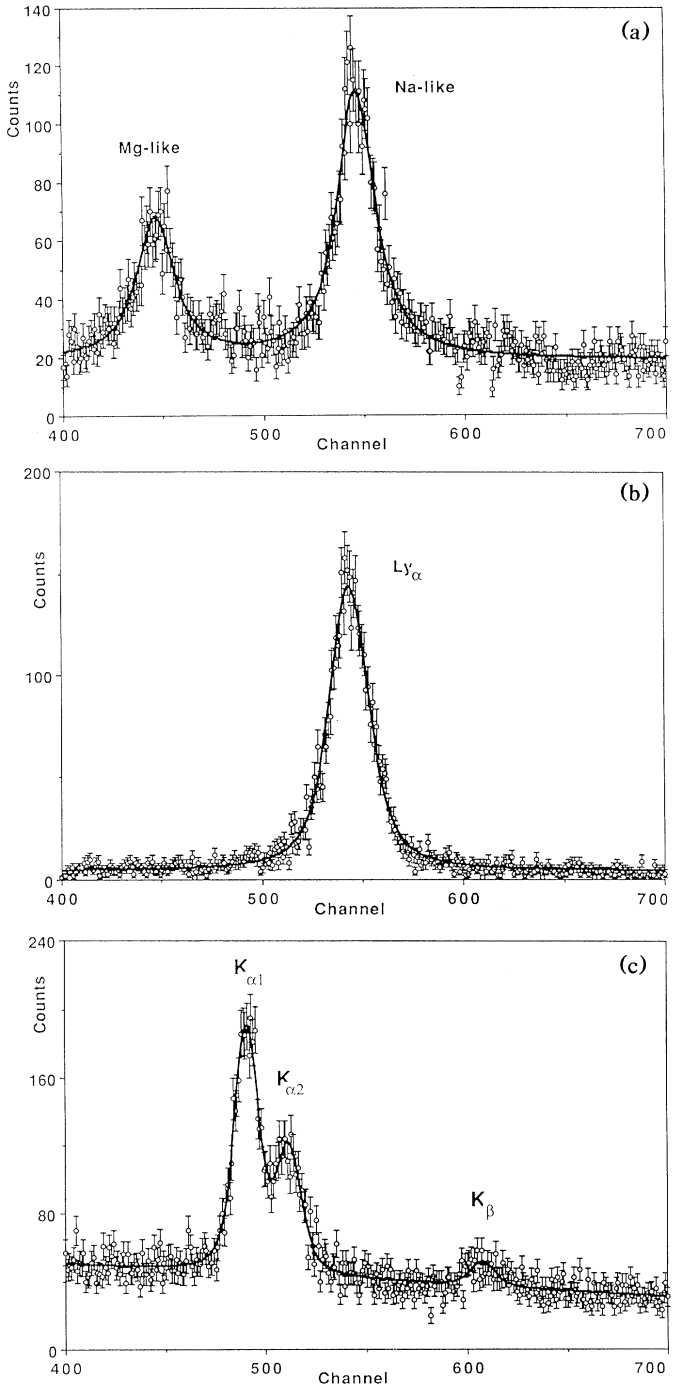

FIG. 3. Summed spectrum of (a) Pt $3s_{1/2}$-$3p_{3/2}$ transitions taken with 18.5-keV electron-beam energy; (b) O Ly-α taken with 3.6-keV electron-beam energy; and (c) calibration lines, Mn $K\alpha$ in ninth order and Mn $K\beta$ in tenth order, produced by x-ray fluorescence of a solid target.

from nearly complete polarization of the Pt radiation in the dispersion plane. We have investigated the first possibility by operating the EBIT trap under the Pt run conditions with (1) no injected ions, in which case Ba and Hg contaminant ions slowly fill the trap, and (2) while injecting Au ions, which closely imitates the conditions obtained with Pt ions. In both cases, no statistically significant deviations from a smooth background were observed at the Pt line position. In particular, there was no evidence for trace contributions of the oxygen Ly-α transition. From broader energy scans[13] no other known Pt transitions, from any diffraction order or ionization state, are expected in the 1-eV energy interval spanned by this peak. For the second possibility, if the Pt radiation were almost entirely polarized in the diffraction plane, the line shape might be skewed by the energy dependence of the reflectivity of the RAP crystal near 45° Bragg scattering. However, the symmetric shape of the Na-like Pt line, its intensity, and its width are all consistent with the instrumental response to mostly unpolarized radiation. Considering the uncertainty in the theoretical values for the O line polarization, we estimate that a conservative upper limit of the systematic error in our measurement is 0.05 eV.

The MBPT calculations are expected to accurately include all important contributions to the Na-like transition energies except the QED effects.[4] Subtracting the MBPT calculation from the experimental result therefore provides a determination of the radiative contributions in $n=3$ (the Na-like analog of the hydrogenic Lamb shift). The hydrogenic Lamb shift in platinum, scaled from $n=2$, is 6.44 eV.[1] Grant's phenomenological estimate[2] of the screening correction to the self-energy reduces the predicted Lamb-shift contribution to this transition to 4.84 or 4.93 eV depending upon whether one performs the calculation in the extended average level or optimized level mode.[6] Subtracting the MBPT result from our experimental value, we obtain 5.32 ± 0.05 eV for the radiative correction to the $3s_{1/2}$-$3p_{3/2}$ transition energy in Na-like platinum.

In Fig. 4 we compare our present measurement to previous lower-Z measurements of the Na-like $3s_{1/2}$-$3p_{3/2}$ transition and to theoretical and semiempirical calculations. Throughout the range of Z so far explored, the phenomenological estimate of the screened Lamb shift employed in the MCDF code of Grant *et al.*[2] (solid line) systematically underestimates the magnitude of the measured radiative corrections. The semiempirical extrapolation of the transition energy by Seely and Wagner,[6] based on lower-Z data obtained in tokamak and laser-produced-plasma measurements (dashed curve), significantly disagrees with our experimental result at $Z=78$, and in particular shows that the radiative corrections do not converge to the Grant code estimate for high Z as previously suggested.[6] Additional data from high-Z measurements should enable a considerably more accurate empirical fit of the radiative corrections.

In summary, we report a precision measurement of the $3s_{1/2}$-$3p_{3/2}$ transition energy in Na-like platinum ions. Our overall uncertainty corresponds to a 77-ppm measurement of the transition energy, and a 1% measure-

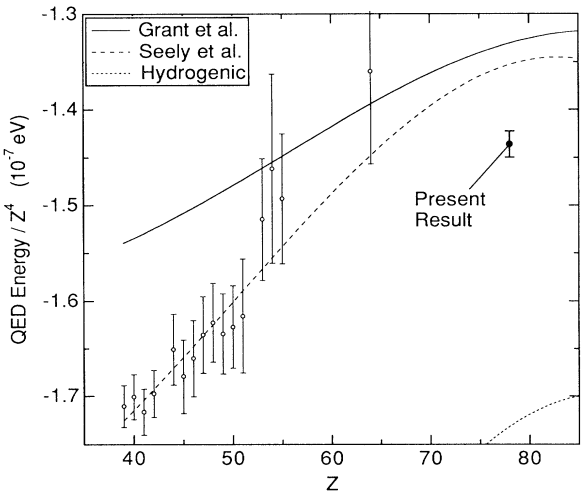

FIG. 4. Comparison of theoretical and measured energies for the Na-like $3s_{1/2}$-$3p_{3/2}$ transition. The total QED contribution (transition energy minus calculated MBPT value) is shown divided by the expected Z^4 scaling of the radiative correction. The solid and dotted curves are the screened QED corrections and hydrogenic Lamb shift, respectively. The dashed line is an empirical fit to the low-Z experimental values (open circles) taken from Ref. 8 (Table II, columns 8 and 9, respectively). The solid circle is the present result.

ment of the $n=3$ Lamb shift in Na-like Pt. Our work extends precise measurements of the Na-like isoelectronic sequence to $Z=78$ from the previous high-Z limit of $Z=64$, and we find a significant disagreement with semiempirical extrapolations from lower-Z data of the screened radiative corrections.

The authors wish to thank R. Keville and J. Geier for their technical support in the implementation of the vacuum crystal spectrometer and D. Nelson and E. Magee for their help in maintaining EBIT in excellent working condition. We are also indebted to the continuing support and encouragement of Dr. R. J. Fortner and Dr. M. J. Eckart. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

[a]Permanent address: Lawrence Berkeley Laboratory, 4-230, Berkeley, CA 94720.

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

[2]I. P. Grant, B. J. McKenzie, P. H. Norrington, D. F. Mayers, and N. C. Pyper, Comput. Phys. Commun. **21**, 207 (1980); B. J. McKenzie, I. P. Grant, and P. H. Norrington, Comput. Phys. Commun. **21**, 233 (1980).

[3]W. R. Johnson, S. A. Blundell, and J. Sapirstein, Phys. Rev. A **37**, 2764 (1988).

[4]W. R. Johnson, S. A. Blundell, and J. Sapirstein, Phys. Rev. A **38**, 2699 (1988).

[5]W. R. Johnson, S. A. Blundell, and J. Sapirstein, Phys. Rev. A **42**, 1087 (1990).

[6]J. F. Seely and R. A. Wagner, Phys. Rev. A **41**, 5246 (1990).

[7]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 Phys. Res., Sect. B **43**, 431 (1989).

[8]M. B. Schneider, M. A. Levine, C. L. Bennett, J. R. Henderson, D. A. Knapp, and R. E. Marrs, in *International Symposium on Electron Beam Ion Sources and Their Applications,* edited by Ady Hershcovitch, AIP Conference Proceedings No. 188 (American Institute of Physics, New York, 1988), p. 158.

[9]D. M. Barrus, R. L. Blake, H. Felthauser, E. E. Fenimore, and A. J. Burek, in *Low Energy X-Ray Diagnostics—1981,* edited by D. T. Attwood and B. L. Henke, AIP Conference Proceedings No. 75 (American Institute of Physics, New York, 1981).

[10]B. Edlen and L. A. Svensson, Ark. Fys. **28**, 427 (1964).

[11]A comparison of the O calibration line with the Mn lines gives a precise measurement of the index of refraction correction for RAP and photon energies near 630 eV. The average 1.08 ± 0.3-eV shift of the first-order oxygen line from the ninth-order Mn $K\alpha$ lines ($E/9=655.42$ eV) and tenth-order Mn $K\beta$ line ($E/10=649.05$ eV) yields a value for the index of refraction correction to the Bragg angle of 6.34 ± 0.3 arcmin. This is slightly higher than the calculation of Ref. 9, of 5.63 arcmin at 653.58 eV.

[12]E. Haug, Solar Phys. **71**, 77 (1981).

[13]C. L. Bennett *et al.* (to be published).