Measurement of $1s2s\ ^3S_1-1s2p\ ^3P_{2,0}$ wavelengths in heliumlike neon

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We have measured the vacuum-ultraviolet $1s2s\ ^3S_1-1s2p\ ^3P_{2,0}$ transition wavelengths in heliumlike neon by photographic spectroscopy of a recoil-ion source. The results are 1248.10±0.01 and 1277.74±0.04 Å, respectively, and are a sensitive test of present relativistic and quantum-electrodynamic calculations. Earlier photographic data have been reanalyzed for comparison with these results.

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INTRODUCTION

The $1s2s\ ^3S_1-1s2p\ ^3P_{2,1,0}$ transitions in heliumlike ions have been studied over a wide range of nuclear charge (Z) in recent years. This work is motivated by the large contributions to the intervals of relativistic and quantum-electrodynamic effects. Of particular theoretical interest are two-electron radiative corrections whose leading term scales as Z^3 [1] and contributions to the single-electron self-energy which scale as Z^6 and above [2]. Because of this scaling, less precise measurements at higher Z can yield comparable information to more precise experiments at low Z, provided the relativistic contributions to the intervals are sufficiently well known. Very precise measurements at low Z using fast-beam laser resonance spectroscopy [3–5] and beam-foil measurements on heliumlike krypton [6] and xenon [7] have recently been reported.

This paper describes photographic spectroscopy of neon ($Z=10$) and argon ($Z=18$) recoil ions, yielding measurements of the Ne^{8+} $1s2s\ ^3S_1-1s2p\ ^3P_{2,0}$ wavelengths. These wavelengths have been measured before in a number of sources (see Table III) but our spectra have the highest resolution, and the measurement of the $^3P_2$ wavelength is the most precise so far. Agreement with recent calculations is good.

EXPERIMENT

It is well known [8] that highly charged ions with velocities of order 10^4 m s^{-1} are produced by bombardment of a target gas by a highly charged heavy-ion beam. The most highly charged ions recoil almost at right angles to the beam so that the most favorable viewing geometry is axial [9]. Even in transverse observation the Doppler broadening $\delta\nu/\nu$ is only of order 10^{-5}. The success of earlier photographic work on tokamak [10] and recoil-ion [11] sources prompted us to use photographic detection to take advantage of these narrow linewidths. The Kodak 101-01 film we use has a grain size of about 1 μm [12] and is insensitive to radiation from nuclear events, which can lead to troublesome background in photoelectric detectors.

We performed the experiment at the Lawrence Berkeley Laboratory (LBL) heavy-ion linear accelerator (Super-HILAC), where high currents of heavy ions are available. The recoil-ion source is intrinsically weak and long photographic exposures of the order of 1 day were required. This is in contrast to the tokamak work where $\frac{1}{10}$ s or so was sufficient, and is consistent with our estimate of signal strengths based on measured cross sections [13].

A Hilger and Watts E766 normal-incidence 1-m concave-grating spectrometer fitted with a camera and a 1200-lines/mm osmium-coated grating was used to observe the radiation from a specially constructed open gas cell. This was situated just after the last radio frequency cavity of the accelerator. In three days of beam time we took three exposures with a lanthanum (element 57) ion beam. The exposure conditions are listed in Table I. Many transitions in low-charge states were excited. Those used as calibration lines are listed in Table II,

TABLE I. Exposure conditions.

Target	Pressure (torr)	Beam energy (MeV/amu)	Mean charge state	Charge delivered (C)
Ne-Ar	0.6	6	45+	0.384
Ne-Ar	0.6	3.5	37+	0.337
Ar	0.1	6	45+	0.700

TABLE II. Calibration and heliumlike lines.

$m\lambda$ (Å)		λ (Å)	Reference	Density	FWHM (μm)
1195.4002	Ar II	597.7001	[17]	1.3	27
1205.7168	Ar II	602.8584	[17]	1.1	25
1215.67	H I Lyman α			1.3	25
1217.5614	Ne II	405.8538	[17]	1.0	20
1221.4128	Ne II	407.1376	[17]	0.9	19
1224.7430	Ar II	612.3715	[17]	1.2	18
1248.10	Ne IX	$1s2s\,^3S_1-1s2p\,^3P_2$		0.5	16
1248.63	Ne V	416.21	[10]	0.5	16
1253.6464	Ne I	626.8232	[17]	0.4	15
1259.4776	Ne I	629.7388	[17]	0.3	14
1264.827	Ne IV	421.609	[18]	0.4	14
1268.483	Ar II		[18]	0.5	14
1274.56	Ar III	637.28	[18]	1.3	17
1277.74	Ne IX	$1s2s\,^3S_1-1s2p\,^3P_0$		0.2	17
1280.225	Ar II		[18]	0.6	10
1283.62	Ar III	641.81	[18]	1.1	13
1284.793	Ar II		[18]	0.3	12
1286.52	Ar III	643.26	[18]	0.7	12
1302.1686	O I		[17]	0.5	12
1304.8575	O I		[17]	0.4	11
1323.7378	Ar II	661.8689	[17]	1.3	20
1329.1244	Ar II	664.5622	[17]	1.1	15
1332.0216	Ar II	666.0108	[17]	1.2	17
1335.1191	Ne II	445.0397	[17]	0.7	15

along with the density and full width at half maximum (FWHM) on the strongest exposure.

ANALYSIS

The films were analyzed in Oxford using a modified Joyce-Loebl microdensitometer [11]. This instrument can measure the density of our films to within a few percent with a positional accuracy of approximately 1 μm. The densities were converted to an exposure level using a characterization of the film [12]. The line shapes were fitted to Gaussian functions with FWHM's of order 20 μm, corresponding to linewidths of 170 mÅ. Since energy differences of a few thousandths of an eV can be resolved in our spectra, we do not expect the line shapes of the heliumlike lines to be complicated by satellite transitions, in contrast to x-ray spectra of recoil-ion sources [14,15]. This would require significant population of states with very high principal quantum number n. We note that Rydberg transitions are absent: for example, the Ne VIII $n=4-5$ multiplet, which is prominent in the beam-foil spectra obtained by Berry and Hardis [16]. On the other hand, the vacuum-ultraviolet spectrum is very rich, raising the possibility of blending with other lines. Figure 1 is a densitometer trace showing the weak $^3P_0$ line and Fig. 2 shows a Gaussian line-shape fit of the $^3P_2$ line. What appear to be weak background lines can also be seen and they may ultimately limit the usefulness of the recoil-ion technique for accurate emission spectroscopy. Photographic spectra which we have taken of a beam-foil source do not show these features.

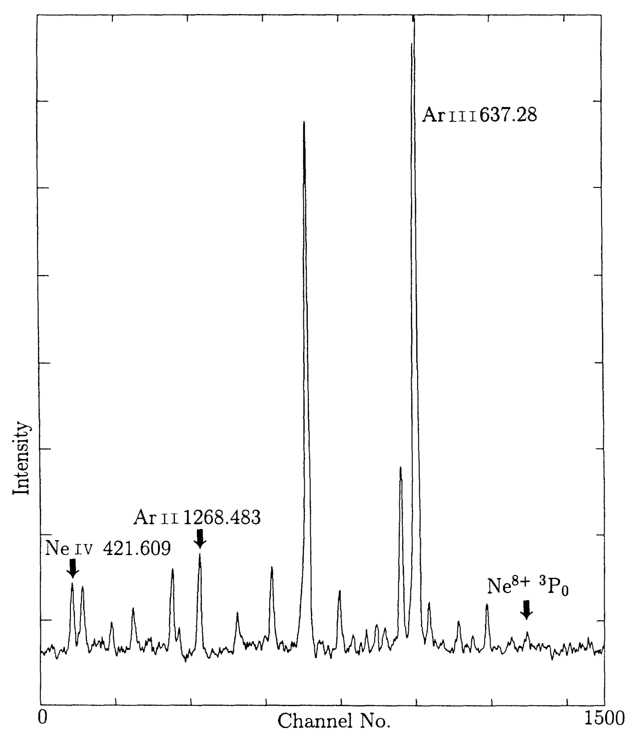

FIG. 1. Densitometer scan of film showing vacuum-ultraviolet spectrum of a neon-argon recoil-ion source. Each channel corresponds to a distance of 1.26 μm on the film. The weak Ne^{8+} $1s2s\,^3S_1-1s2p\,^3P_0$ line is indicated.

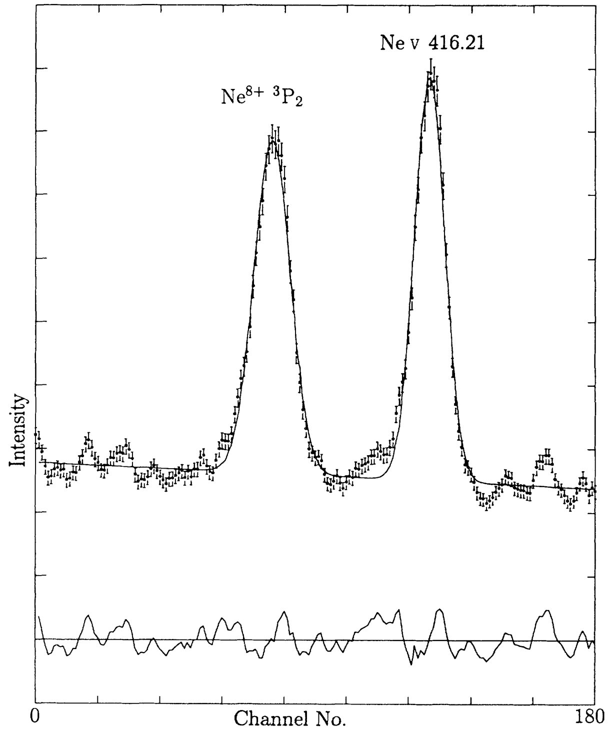

FIG. 2. Gaussian line-shape fit to a densitometer scan of the Ne^{8+} $1s2s\ ^3S_1-1s2p\ ^3P_2$ line on the stronger of the two neon-argon exposures.

Several densitometer scans of different sections of each film were analyzed. Figure 3 shows a typical set of residuals from a linear fit of wavelength against line centroid. These residuals are larger than expected from the statistical errors in the line shape fits, suggesting some source of systematic error. Besides the presence of weak lines in the spectrum, this may be due to nonlinear stretching of the film or thermal drifts during densitometry. However,

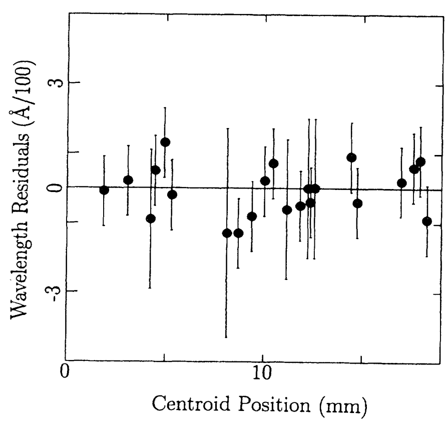

FIG. 3. Wavelength residuals from a linear fit of wavelength against centroid position for a typical scan of one of the films. The error bars were chosen to reflect the errors in the literature values and centroid fits. In fact, the fitted $^3P_2$ wavelength is insensitive to the relative weighting of calibration lines.

none of the calibration lines show significant shifts at the 0.01-Å level, and the scans from the same film yield almost identical wavelengths for the Ne^{8+} lines. The possibility of blends with the heliumlike lines was investigated in earlier recoil-ion measurements by Klein *et al.* [19], who used photoelectric detection. They found yields of the Ne^{8+} $1s^2\ ^1S_0-1s2p\ ^3P_1$ x ray which closely followed those of $1s2s\ ^3S_1-1s2p\ ^3P_2$ as a function of projectile beam energy. In addition the neon and argon exposures we took at different ion-beam energies yield the same wavelength for Ne^{8+} $1s2s\ ^3S_1-1s2p\ ^3P_2$. Comparison with the argon exposure shows that there is no blending with a line in the argon spectrum. The Ne^{8+} lines are weaker on the film taken at lower energy and $^3P_0$ is barely above the background. The value we quote is taken from the stronger exposure, where the heliumlike lines are in the expected statistical ratio. The larger quoted error reflects the fact that the fitted wavelength is 0.03 Å higher on the weaker exposure, suggesting a blend. The results are listed with previous measurements in Table III.

EARLIER PHOTOGRAPHIC MEASUREMENTS

Earlier measurements of the Ne^{8+} $^3P_2$ transition using the recoil-ion technique were made by Brown and coworkers [11,20] and are included in Table III. Both these values have been confirmed by redensitizing the original data. The provisional value [11] from an analysis of films obtained on the Oxford Nuclear Physics Department tandem Van de Graaff accelerator must now be in doubt due to the contamination of the neon target gas by krypton. This was not appreciated at the time of publication. A spectrum of pure krypton under similar conditions would be required to rule out an unfortunate blend, which is suggested by the line shape of the $^3P_2$ line. The experiment was repeated in 1985 at LBL [20] using a Au^{49+} ion beam and yields a value close to that from the present experiment. This value for $^3P_2$ has not been published before. The error reflects the weaker exposure and absence of close-lying calibration lines compared with the latest recoil-ion films.

The films obtained on the TCA tokamak in Lausanne by Peacock, Stamp, and Silver [10] were originally analyzed using an Abbe comparator, and we have confirmed the results of this analysis by densitizing the original data. This is an important check as the lines on the tokamak films are Doppler broadened with widths in excess of 80 μm and the $^3P_2$ line is not fully resolved from the Ne v 416.21-Å transition in third order. The tokamak and recoil-ion values for this line agree, yielding a slightly longer wavelength than the early measurement by Paul and Polster [29]. The discrepancy between the $^3P_2$ wavelengths is not understood. In particular, the radial geometry employed should have ruled out significant Doppler shifts from the expected bulk motion of the plasma.

COMPARISON WITH THEORY

Probably the most complete published calculations of these intervals are those by Drake [24]. These use accu-

TABLE III. Summary of results for Ne^{8+} $1s2s\ ^3S_1-1s2p\ ^3P_{2,0}$ (Å)

Source	Technique	$^3P_2$	$^3P_0$
	Experiment		
This work	Recoil ion	1248.104±0.010	1277.74±0.04
Beyer *et al.* [21]	Recoil ion	1248.07±0.02	
Berry and Hardis [16]	Beam-foil	1248.11±0.03	1277.75±0.05
Brown (LBL) 1990 [20]	Recoil ion	1248.11±0.02	
Brown *et al.* (Oxford) [11]	Recoil ion	1248.15±0.02	
Peacock *et al.* [10]	Tokamak	1248.076±0.013	1277.71±0.02
Klein *et al.* [19]	Recoil ion	1248.16±0.03	1277.79±0.08
Sandlin and Tousey [22]	Solar	1248.15±0.04	1277.70±0.04
Engelhardt and Sommer [23]	Theta pinch	1248.12±0.02	1277.68±0.04
	Theory		
Johnson and Sapirstein [32]		1248.098	1277.738
Drake [24]		1248.10±0.02	1277.70±0.02
Indelicato [25]		1248.28	1278.04
Hata and Grant[a] [26]		1248.13	1277.64
DeSerio *et al.* [27]		1248.11	1277.69

[a]Corrected according to Hata and Grant [28].

rate variational calculations of the nonrelativistic energy, while the relativistic operators are evaluated in two different perturbation schemes, appropriate to the low- and high-Z regimes. The method interpolates between the two, keeping track of each term in a double expansion in the perturbation parameters $(1/Z)$ and $(Z\alpha)$. Radiative corrections include an evaluation of the two-electron Bethe logarithm using variational basis sets [1] and all one-electron effects included in the tabulation by Johnson and Soff [30] of Lamb shifts in hydrogenic ions. These incorporate the numerical calculations of the one-electron self-energy by Mohr [31]. The uncertainties in Drake's calculations for $Z>2$ are thought to be dominated by uncalculated relativistic corrections which scale as $(Z\alpha)^4$ a.u.

Johnson and Sapirstein [32] have recently used many-body perturbation theory to calculate relativistic corrections to the $1s2s\ ^3S_1-1s2p\ ^3P_{2,0}$ energies from the so-called no-pair Hamiltonian of QED. This included a calculation of the most important $(Z\alpha)^4$ terms and accounts for the discrepancy with Drake's calculation of the $1s2p\ ^3P_0$ energy. The radiative corrections were taken from Drake.

As Table III shows, our result for the $^3P_2$ wavelength is in excellent agreement with these two calculations [24,32], while our measurement of $^3P_0$, though less precise, is in better agreement with Johnson and Sapirstein's result. Improved experimental results over a range of Z will be needed to investigate the $(Z\alpha)^4$ contributions, bearing in mind that a complete calculation of two-electron radiative corrections to this order has not been carried out.

Multiconfiguration Dirac-Fock (MCDF) calculations have been published by Gorceix, Indelicato, and Desclaux [33] and Indelicato [25], following earlier work by Hata and Grant [26]. Agreement with experiment is on the whole poorer for the MCDF calculations at low Z due to the difficulty of including enough orbitals to take adequate account of correlation effects. Attempts to correct for this [26,25] by substituting correlation energies from nonrelativistic variational calculations [34] seem to be only partially successful at low Z.

POSSIBLE OBSERVATION OF Ar^{16+} $1s2s\ ^3S_1-1s2p\ ^3P_{2,0}$

The Ar^{16+} $1s2s\ ^3S_1-1s2p\ ^3P_{2,0}$ wavelengths were first measured by Davis and Marrus [35] using the beam-foil

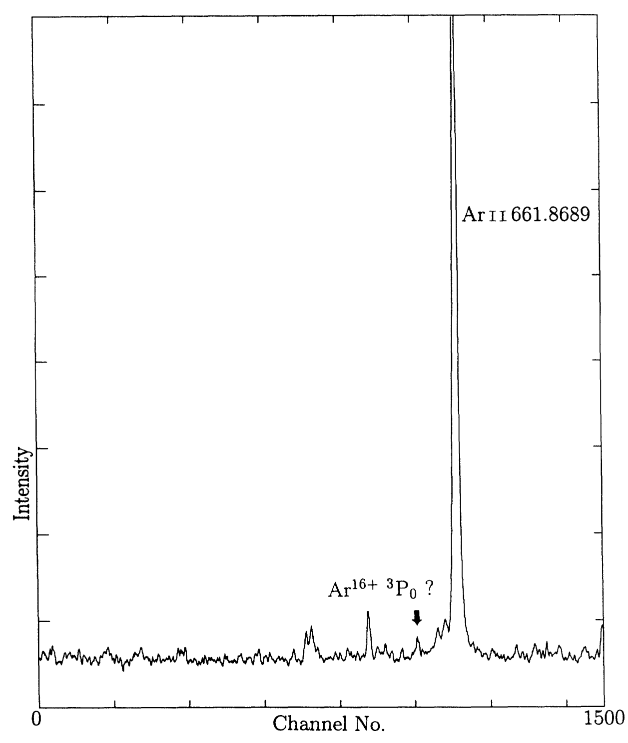

FIG. 4. Densitometer scan showing a line previously identified as the Ar^{16+} $1s2s\ ^3S_1-1s2p\ ^3P_0$ transition by Beyer *et al.* [21].

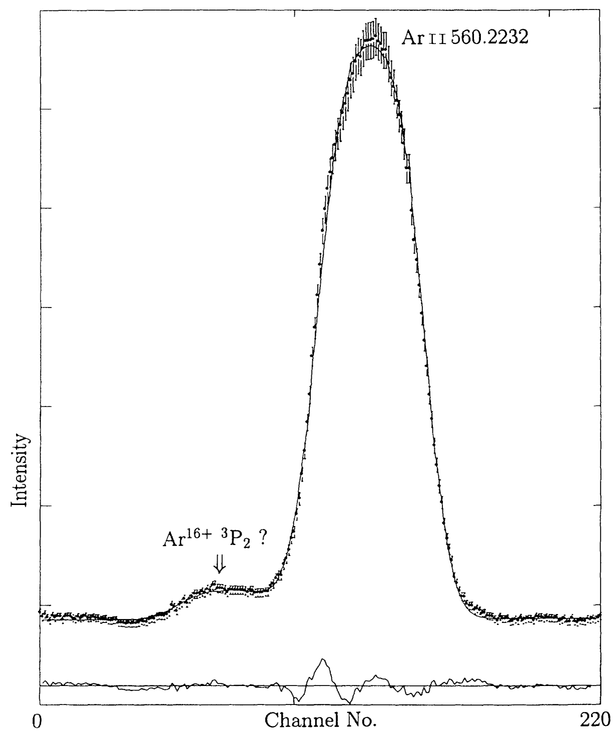

FIG. 5. Densitometer scan showing a line previously identified as Ar^{16+} $1s2s\,^3S_1-1s2p\,^3P_2$ by Beyer *et al.* [21]. Note that the film is not as well focused in this region.

technique. Beyer, Folkman, and Schartner [21] observed weak spectral lines in a recoil-ion source excited by a pulsed uranium ion beam which they identified with these transitions. Photoelectric detection was used, allowing some degree of time resolution against prompt transitions from lower charge states. We have identified lines in our spectra whose wavelengths are consistent with these observations. Although very weak, with densities of around 0.2, our data is of higher resolution and statistical quality (see Figs. 4 and 5). However, due to the presence of many weak lines and the lack of corroborative measurements in other sources, we do not feel sufficiently confident of their identification to quote wavelengths for these transitions.

IMPROVED MEASUREMENTS

The development of high-power lasers operating in the region of 1200 Å may make a laser resonance measurement of the Ne^{8+} intervals possible. This technique has been used successfully to measure the Lamb shift in hydrogenic ions at longer wavelengths [36,37] and could lead to a substantial improvement in precision over emission spectroscopy.

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[1] S. P. Goldman and G. W. F. Drake, J. Phys. B **17**, L197 (1984).
[2] P. J. Mohr, Ann. Phys. **88**, 26 (1974).
[3] Ping Zhao *et al.*, Phys. Rev. Lett. **63**, 1593 (1989).
[4] E. Riis *et al.*, Phys. Rev. A **33**, 3023 (1986).
[5] T. P. Dinneen *et al.*, Phys. Rev. Lett. **66**, 2859 (1991).
[6] S. Martin *et al.*, Europhys. Lett. **10**, 645 (1989).
[7] S. Martin *et al.*, Phys. Rev. A **42**, 6570 (1990).
[8] C. L. Cocke and R. E. Olson, Phys. Rep. **205**, 153 (1991).
[9] J. M. Laming and J. D. Silver, Phys. Lett. A **123**, 395 (1987).
[10] N. J. Peacock, M. F. Stamp, and J. D. Silver, Phys. Scr. **T8**, 10 (1984).
[11] J. S. Brown *et al.*, Nucl. Instrum. Methods B **9**, 682 (1985).
[12] W. M. Burton, A. T. Hatter, and A. Ridgeley, Appl. Opt. **12**, 1851 (1973).
[13] A. S. Schlacter *et al.*, Phys. Rev. A **26**, 1373 (1982).
[14] H. F. Beyer, R. D. Deslattes, F. Folkmann, and R. E. LaVilla, J. Phys. B **18**, 207 (1985).
[15] R. D. Deslattes, H. F. Beyer, and F. Folkmann, J. Phys. B **17**, L689 (1984).
[16] H. G. Berry and J. E. Hardis, Phys. Rev. A **33**, 2778 (1986).
[17] B. Edlén and V. Kaufman, J. Phys. Chem. Ref. Data **3**, 825 (1974).
[18] R. L. Kelly and L. J. Palumbo, Naval Research Laboratory Report No. 7599, 1973.
[19] H. A. Klein, *et al.* J. Phys. B **15**, 4507 (1982).
[20] J. S. Brown (private communication).
[21] H. F. Beyer, F. Folkmann, and K. -H. Schartner, Z. Phys. D **1**, 65 (1986).
[22] G. D. Sandlin and R. Tousey, Astrophys. J. **227**, L107 (1979).
[23] W. Engelhardt and J. Sommer, Astrophys. J. **167**, 201 (1971).
[24] G. W. F. Drake, Can. J. Phys. **66**, 586 (1988).
[25] P. Indelicato Nucl. Instrum. Methods B **31**, 14 (1988).
[26] J. Hata and I. P. Grant, J. Phys. B **16**, 523 (1983).
[27] R. DeSerio, *et al.*, Phys. Rev. A **24**, 1872 (1981).
[28] J. Hata and I. P. Grant, J. Phys. B. **17**, 931 (1984).
[29] F. W. Paul and H. D. Polster, Phys. Rev. **59**, 424 (1941).
[30] W. R. Johnson, and G. Soff, At. Data Nucl. Data Tables **33**, 405 (1986).

[31] P. J. Mohr, Phys. Rev. A **26**, 2338 (1982).
[32] W. R. Johnson and J. Sapirstein, Phys. Rev. A **46**, R2197 (1992).
[33] O. Gorceix, P. Indelicato, and J. P. Desclaux, J. Phys. B **20**, 639 (1987).
[34] P. Blanchard, Phys. Rev. A **13**, 1698 (1976).
[35] W. A. Davis and R. Marrus, Phys. Rev. A **15**, 1963 (1977).
[36] A. P. Georgiadis, *et al.*, Phys. Lett. A **115**, 108 (1986).
[37] J. Gassen *et al.*, Phys. Lett. A **147**, 385 (1990).