Lifetime of the $2\,^1S_0$ state of heliumlike Ni^{26+}

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We report the observation of the two-photon decay of the $2\,^1S_0$ level in heliumlike Ni^{26+} and a measurement of the lifetime of this state. We find a lifetime of 150(16) ps, in agreement with the theoretical calculation of G. W. F. Drake [Phys. Rev. A **34**, 2871 (1986)] which yields 154.3(5) ps.

The $2\,^1S_0$ state of heliumlike ions is forbidden to decay by single-photon emission to the $1\,^1S_0$ ground state because of the angular momentum conservation in the decay. The decay mode for this state is the simultaneous emission of two $E1$ photons. While a precise calculation of the decay rate of such states, including relativistic corrections, has been performed by Drake,[1] the only experiment sensitive to these relativistic corrections is a recent measurement of the $2\,^1S_0$ state lifetime in heliumlike Kr^{34+} by Marrus *et al.*,[2] which is in mild disagreement with the theoretical result. This decay rate has also been measured in He by Van Dyck *et al.*,[3] in Li^+ by Prior and Shugart,[4] and in Ar^{16+} by Gould and Marrus.[5] We report here the first measurement of the lifetime of the $2\,^1S_0$ state in Ni^{26+}. The calculation by Drake predicts a lifetime of 154.3(5) ps for this level. The relativistic corrections are about 3%.

In our experiment, a beam of 346-MeV nickel ions from the Argonne Tandem Linac (ATLAS) is stripped in a 200-μg/cm^2 carbon foil and the 26+ charge state is magnetically analyzed and directed into the experimental area. About 20% of the beam incident on the foil emerges in the 26+ charge state. The other charge states are distributed as follows: 23+(10%), 24+(29%), 25+(40%), and 27+(1%). In the experimental area the 26+ beam (0.5 particle nA) is incident on a thin carbon target (5–10 μg/cm^2) which excites some of the ions to the $2\,^1S_0$ state. The decay radiation from the beam after passing through the target is observed with a Si(Li) detector.[6] A collimator in front of the detector allows detection of photons emitted only in a 2-mm-long region along the beam. The solid angle of the detection system is about 0.1% of 4π. The target is moved relative to the detector by means of a precision translator. The rate of decay from the $2\,^1S_0$ state (normalized to the beam current) is measured as a function of foil-detector separation in order to determine the lifetime. The foil-detector distance was varied from 0 to 25 mm. Based on theory, one decay length at the present beam velocity is 5.16 mm (25 mm corresponds to about 5 lifetimes). The beam energy was measured to ±0.2% by a time-of-flight energy analyzer. The correction for energy loss[7] in the 200-μg/cm^2 foil is 5.8 MeV.

A typical spectrum observed in the Si(Li) detector, taken using a 10-μg/cm^2 foil and a foil-detector separation of 5 mm, is shown in Fig. 1. The counting time was 5 min and the accumulated Faraday cup charge was 3.6 μC. The two-photon decay ($2E1$) of the $2\,^1S_0$ state forms a continuum with a broad maximum at half the transition energy of 7.8 keV and drops to zero at both end points. The peak at the high-energy end results from the heliumlike $2\,^3P_2$ and $2\,^3S_1$ states which decay to the ground state by single-photon emission ($M2$ and $M1$, respectively). The peaks at low energy result from transitions in three-electron nickel. These single-photon peaks persist out to the largest foil-detector separations. In the case of

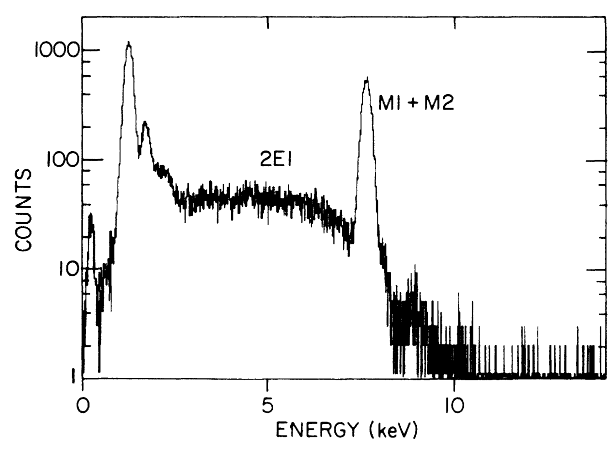

FIG. 1. Typical Si(Li) spectrum taken with a 346-MeV beam of Ni^{26+} incident on a 10-μg/cm^2 foil at a foil-detector separation of 5 mm. The line at 7.8 keV is predominantly from the ground-state decays of the $2\,^3P_2$ ($M2$) and $2\,^3S_1$ ($M1$) levels of heliumlike nickel. The two-photon decay ($2E1$) forms a broad continuum with a maximum at 3.9 keV.

the 7.8-keV peak, this persistence is due to the metastable $2\,^3S_1$ level which has a decay length of about 75 mm. The long lifetimes of the three-electron lines are presumably due to cascading from high-lying Rydberg states. In Fig. 2(a) we show a spectrum taken with a thicker foil (19 $\mu g/cm^2$) at the same foil-detector separation which shows an increase in the two-electron $M1$ transition relative to the three-electron lines. We also measured some spectra with a Ni^{27+} beam directed into the target chamber. A typical spectrum is shown in Fig. 2(b) for a 5-$\mu g/cm^2$ target at a foil-detector distance of 5 mm. In this case, the three-electron lines are considerably reduced.

Another contribution to the Si(Li) spectrum comes from any hydrogenlike Ni^{27+} excited to the $2S_{1/2}$ level in the target. The $2S_{1/2}$ state of Ni^{27+} also decays to the ground state by the emission of two $E1$ photons and, since the transition energy is near 8 keV, these decays are indistinguishable from the two-photon decays of the heliumlike state. The contribution from the hydrogenlike component was minimized by our procedure of prestripping the Ni beam to the 26 + charge state and then using a thin target to excite the $2\,^1S_0$ state. We correct the data for any remaining $2S_{1/2}$ component using the fact that the hydrogenlike $2S_{1/2}$ state also decays to the ground state by emission of a single $M1$ photon (branching ratio =0.17). This decay produces a peak at the end point which is about 300 eV higher in energy than the

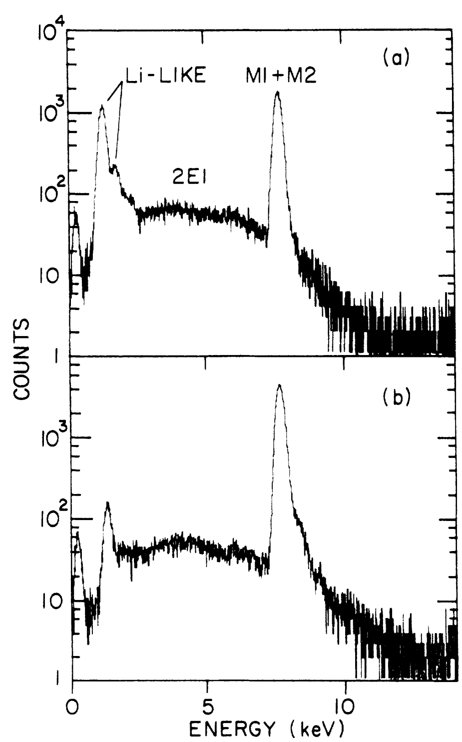

FIG. 2. (a) Si(Li) spectrum for a 346-MeV beam of Ni^{26+} incident on a 19-$\mu g/cm^2$ carbon foil at a foil-detector separation of 5 mm. The peaks at 1.4 and 1.9 keV are believed to be predominantly from decay of Li-like Ni^{25+} following single-electron capture. (b) Spectrum for a Ni^{27+} beam incident on a 5-$\mu g/cm^2$ carbon foil.

heliumlike single-photon peaks. Since the resolution of the Si(Li) detector is 270 eV in this region we can, in principle, determine the hydrogenlike contribution by fitting the single-photon region to two peaks. Consequently, from the number of hydrogenlike $M1$ counts and the known branching ratio and the shape of the two-photon decay, the hydrogenlike contribution to the two-photon continuum can be subtracted. For the data taken with heliumlike Ni^{26+} incident on the target, we saw no statistically significant hydrogenlike $M1$ contribution, so the fitting procedure produced only an upper limit for this correction. The data taken with Ni^{27+} incident on the target do show a contribution from the hydrogenlike $M1$ as can be seen in Fig. 2(b), but these data were not used in the lifetime measurement reported here.

Another systematic effect to be considered is the repopulation of the $2\,^1S_0$ state by cascades from higher-lying n states. These cascades have a branch to the $1\,^1S_0$ state which gives rise to peaks in the Si(Li) spectrum between 9.5 and 11 keV. Using the number of counts in these peaks and the known branching ratios to $2\,^1S_0$, we determined a correction to the data for the cascade contribution.

At each foil-detector separation, data were taken for a fixed quantity of charge collected on the Faraday cup. Periodically, we returned to the same foil-detector separation (5 mm) to monitor changes in the foil and check the overall consistency of the data. Analysis of these repeated points indicates a random fluctuation in the number of counts in the two-photon spectrum that was significantly larger than that expected from counting statistics.

Five separate measurements of the lifetime were made using different foils and different collimator geometries. In the Si(Li) spectrum obtained at each foil-detector separation we first subtract counts associated with a tail from the single-photon line. The tail shape is a characteristic of the Si(Li) detector which was measured using radioactive sources. After subtraction of the tail shape, the counts in the spectral region from 4 to 7.5 keV were fit to a single exponential and a constant background. A typical decay curve is shown in Fig. 3. The upper data points are the raw data after subtraction of the tail factor while the lower curve shows the data minus the background; the solid line is the fit. The combined results for the five runs together with the corrections and uncertainties are given in Table I. The error in the average of the lifetimes determined from the three-parameter fits is derived from the standard deviation for the five runs. The pure statistical error is an order of magnitude smaller than this. The final result is 150(16) ps which is in agreement with the Drake calculation.

We also analyzed the data by breaking the energy spectra up into four bins, each of which was fit to a single exponential plus a constant background. The average lifetime for each run was the same using this procedure but in four of the runs the lowest energy bin (4–5 keV) gave a lifetime which was 3–6 % longer than the average of the other three bins. This effect is not understood but it is likely due to a background which varies with foil position. Further evidence for such a background comes

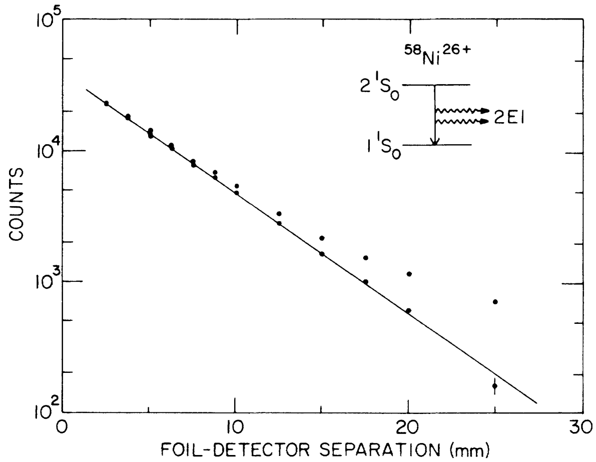

FIG. 3. Decay curve showing data after subtraction of a tail factor from the single-photon peak (upper curve), and after subtraction of a constant background determined by the fit (lower curve). The solid line is the single exponential obtained from the fit.

from examining the spectra at large foil-detector separation which show a deviation from the expected two-photon shape in the low-energy region of the Si(Li) spectrum. Because of this problem, we included an uncertainty in Table I to account for position-dependent backgrounds.

In order to search for systematic effects, several other fitting functions were tried, including the addition of a second exponential. In most cases these functions did not lead to improved fits. One exception was a function which included an exponential term plus a parameter times the counts in the single-photon peak at 7.8 keV. Although this function gave the same result for the average lifetime as the three-parameter fit with a constant background, the standard deviation of the results for the five runs was reduced by a factor of 4, suggesting that this fit corrects for random sources of background under the two-photon continuum. Following this procedure, the final error in our measurement, after taking into account the additional uncertainties of Table I, could be decreased by a factor of 2. However, since we could not fully justify the use of this fitting function, our quoted error reflects the more conservative fit to an exponential plus a constant background. The result shown in Table I is also in agreement with the value obtained by an alternate fitting procedure, in which the data in each Si(Li) spectrum were fit to a theoretical two-photon energy distribution plus background and the resulting amplitudes were fit to a single exponential.

TABLE I. Final lifetime result and uncertainties (ps).

Five runs combined (standard deviation σ)	150 ± 14
Hydrogenic $2S_{1/2}$ contamination	0 ± 6
Cascade correction	-0.3 ± 2
Position-dependent background	0 ± 4
Distance measurement	0 ± 2
Velocity measurement	0 ± 0.4
Energy loss in 200-μg/cm^2 foil (uncertainty)	0 ± 0.4
Final result	150 ± 16

An improved experimental procedure is clearly needed in order to critically compare the measured lifetime with the theoretical prediction. We are planning another experiment which will measure the two photons in coincidence, thus eliminating the systematic errors associated with spurious backgrounds. In addition, we will use an x-ray detector at a fixed foil-detector distance for normalization.

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