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Precision spectroscopic measurements in few-electron ions

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Abstract

We describe recent precision experiments in few-electron ions including measurements of the lifetimes of two-photon-emitting levels in Ni^{26+} and Ni^{27+}, a measurement of the lifetime of the 2^3S_1 level in Br^{33+} and measurements of the $2^3S_1 \rightarrow 2^3P_{0,1,2}$ transition energies in B^{3+}.

I. Introduction

Few-electron systems, particularly hydrogen-like and helium-like ions provide an important testing ground for our understanding of atomic structure. In the one-electron systems, there are no calculational uncertainties, so experiments in these systems provide tests of the underlying theory of Quantum Electrodynamics (QED). Current interest is in the question of whether there is a breakdown of QED in highly-charged one-electron atoms. The theory of the two-electron system is not as well understood. Here one has the additional problem of treating correlations between the two electrons and a complete Hamiltonian for the system does not exist [1]. The importance of the helium-like systems is that they are the simplest atoms in which the electron-electron correlations must be taken into account.

In this paper we describe four recent experiments done by our group which study the structure of one- and two-electron ions. The first two experiments are measurements of the lifetimes of the $2^2S_{1/2}$ level in one-electron Ni^{27+} and the 2^1S_0 level in two-electron Ni^{26+}, both of which decay primarily by two-photon emission. The third experiment is a measurement of the lifetime of the 2^3S_1 level in helium-like Br^{33+}, which decays to the ground state via a M1 transition. The final experiment is a precision measurement of the $2^3S_1 - 2^3P_{0,1,2}$ transition energies in two-electron B^{3+}. This experiment was done by driving resonances in a fast beam of metastable B^{3+} using a frequency doubled dye laser.

II. Two-Photon Decays in One- and Two-Electron Nickel

The 2^1S_0 level (see Fig. 1) in helium-like ions is forbidden to decay to the 1^1S_0 ground state by the emission of a single photon and so it decays via two-photon emission. The $2^2S_{1/2}$ level in hydrogen-like ions also decays to the ground state via two-photon emission although there is also a small M1 branch (17% in Ni^{27+}). We have measured the lifetimes of these two-photon emitting levels in one- and two-electron nickel [2]. Our technique is to measure the rate of two-photon coincidences as the distance between our detectors and the beam-foil is varied.

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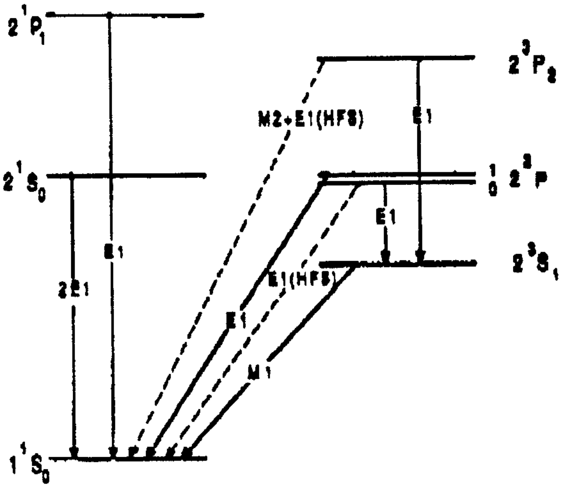

Fig. 1. Energy levels and decay modes for helium-like ions.

The data were taken using nickel beams from the Argonne Tandem-Linac (ATLAS). After acceleration, the ions were stripped in a thick carbon foil and the 26+ or the 28+ charge state was directed to the target area. The beam energy was measured by a time-of-flight energy analyzer and corrected for energy loss in the stripper foils [3]. In the target area, a thin carbon target (12 μg/cm²) is

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moved relative to three fixed Si(Li) detectors using a precision translation stage. Two of the Si(Li) detectors are collimated so they observe a region of length 5 mm along the beam path and subtend a solid angle of 0.1% at the beam. The third detector is not highly collimated and accepts photons into a solid angle of 1%. There is also a lower resolution silicon X-ray detector attached to the target holder which is used for normalization.

Events were recorded for coincidences between any two of the three Si(Li) detectors, but most of the coincidences are between one of the collimated detectors and the large solid-angle detector. The collimators serve to localize the events in position along the beam while the large solid-angle detector provides a good efficiency for detecting the second photon. In Fig. 2 we show a typical singles spectrum for one of the Si(Li) detectors for the case of Ni^{26+} incident on the target. The broad continuum extending out to 7.8 keV is mostly due to the decay of the 2^1S_0 level in helium-like Ni^{26+}. In Fig. 3 we show the sum-energy spectrum for true coincidences. In this case the sum of the energies of the two photons forms a peak at the transition energy. This peak is almost entirely from the helium-like two-photon decay. The spectrum taken with the 28+ beam is predominantly from the two-photon decay of hydrogen-like nickel but there is a small contamination from the helium-like sum energy peak which lies 300 eV lower in energy.

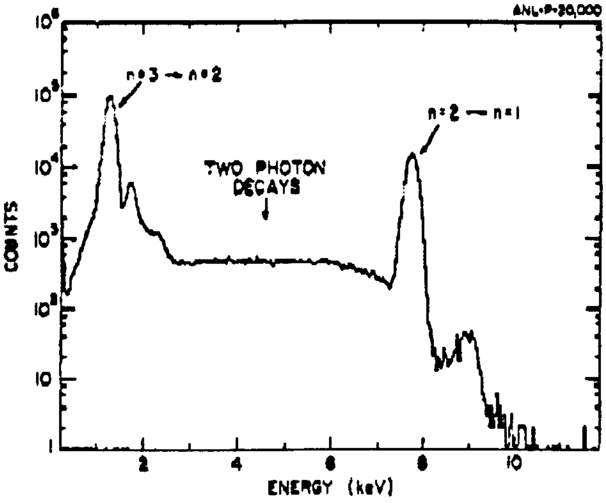

Fig. 2. Typical spectrum in the Si(Li) detector. Helium-like Ni^{26+} (670 MeV) incident on target.

The data are normalized using the count from the normalization detector and the decay curve is fit to a function with two parameters: a) the amplitude at the closest position and b) the lifetime. The lifetimes from these two component fits for each of the three detector pairs are combined and then corrected for time dilation to obtain the final result. A number of additional systematic effects were considered but found to be unimportant for these measurements including gain shifts, quenching in electric and magnetic fields, contributions from ions with high-lying spectator electrons [4] and backgrounds from coincidences caused by Compton scattering of Lyman-α photons between two of the Si(Li) detectors.

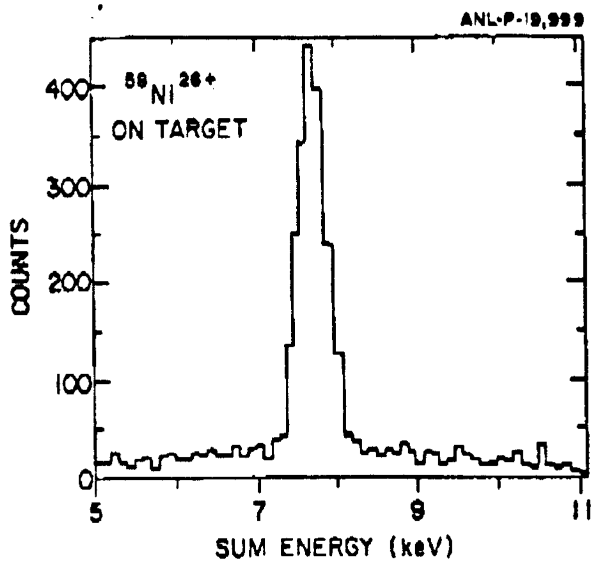

Fig. 3. Sum-energy spectrum for true coincidences with 670 MeV Ni^{26+} incident on target.

Two separate measurements were made for each of the two lifetimes. In each case, the measurements were consistent within errors and we simply combined them. For the helium-like decay the combined result is 156.1(1.6) ps which is in substantial agreement with the theoretical [5] value of 154.3(0.5) ps. For the decay of the $2^2S_{1/2}$ state in hydrogen-like Ni^{27+} we find a lifetime of 217.1(1.8) ps which agrees with the theoretical value [6] of 215.45 ps.

III. M1 Decay of the 2^3S_1 level $^{79}Br^{33+}$

The same apparatus has been used to measure the lifetime [7] of the 2^3S_1 level in helium-like $^{79}Br^{33+}$. This level decays to the 1^1S_0 ground state by a forbidden M1 transition. Bromine-79 is a good choice for the measurement of the lifetime of the helium-like 2^3S_1 level because, in this isotope, all of the other n=2 levels which decay by single-photon emission are much shorter lived and so there is a minimum of complication from the decay of other levels. An important factor here is that the $^3P_0$ level is quenched to the ground state by hyperfine mixing induced by the magnetic moment of ^{79}Br (I=3/2). This reduces the lifetime of this level from 1.48 ns (unquenched) to 5.6 ps (quenched).

The bromine beam was provided by the Argonne Tandem-Linac (ATLAS). The helium-like 33+ charge state is magnetically analyzed and directed to the experimental area. Two detectors were used for this experiment and they were collimated so that they observe a region 2 mm along the beam.

At each foil-detector separation, peaks near 12 keV in the Si(Li) detectors, which correspond to single-photon decays from the n=2 levels of Br^{33+} were fitted to a Gaussian line shape. The peak areas at each distance were divided by the count for the normalization detector and these data were fitted to a decay curve to obtain the lifetime. Our final result is $\tau(2^3S_1)$=224.1(7.1) ps, which agrees with the calculation by Drake [8] which gives 230(2) ps and the calculation by Johnson and Lin [9] which gives 228.2 ps.

IV. Laser Spectroscopy

Spectroscopic measurements in helium-like ions include high-precision measurements in helium [10] and lithium [11] which test the nonrelativistic parts of the interaction, and lower precision measurements in heavy ions which test the relativistic and QED corrections. A complete list of recent experiments is given by Drake [12] along with his most recent calculations. The measurements in lithium test relativistic corrections to higher precision than measurements in helium but are limited at present by uncertainties in the nonrelativistic calculations of the energy. We have recently completed precision laser measurements of the 2s to 2p transitions in B^{3+} where the relativistic and QED corrections are a larger fraction of the transition energy so they can be tested with less uncertainty arising from the nonrelativistic contribution to the calculations.

Metastable B^{3+} ions were produced in the Positive Ion Injector Electron Cyclotron Resonance (PII-ECR) source at ATLAS. The source was operated at 10 kV extraction voltage. Beam currents in the interaction region varied from 0.5 to 1.5 μA. Transitions from 2^3S_1 to $2^3P_{0,1,2}$ were driven by 282 nm laser light produced by intra-cavity frequency doubling of the 564 nm fundamental of a Coherent 699 ring dye laser. The maximum doubled output obtained from the dye laser was 7 mW.

The ion beam and laser beam were overlapped to take advantage of the increased interaction time and the velocity compression provided by the accelerated beam. The Doppler width (FWHM) was 1 GHz, corresponding to a beam energy spread of 21 eV. The transitions were monitored by detecting the fluorescence radiation emitted as the 2^3P levels decay back to the 2^3S_1 level. The sensitivity of the experiment was sufficient to allow most of the hyperfine components of $^{11}B^{3+}$ (nuclear spin I=3/2) to be observed. In order to make the Doppler correction, the laser light was reflected back through the interaction region and the laser was scanned over both the red and the blue Doppler-shifted components while simultaneously measuring an iodine absorption spectrum with the fundamental output of the dye laser. After making an absolute wavelength determination for one of the 2^3P_2 hyperfine transitions, all other transitions were measured relative to it.

To obtain hyperfine-free wavelengths it is necessary to measure all of the hyperfine components. Since the laser power stability was poor over large frequency scan ranges, a different technique was used to measure the hyperfine structure. This involved using the interaction region as a post acceleration section, and, keeping the laser frequency fixed, the ion-beam velocity was tuned through the resonances by varying the interaction region voltage. In this way all hyperfine components were obtained in a single spectrum as shown in Fig. 4.

The experiment resulted in precision laser measurements of the fine structure, the hyperfine structure and absolute wavelengths of the $(1s2s)^3S_1$ to $(1s2p)^3P_{0,1,2}$ transitions in helium-like boron. These results are being prepared for publication [13]. The measurements provide a precision at the level of 0.1% of the one-electron Lamb shift for the 2s → 2p transition.

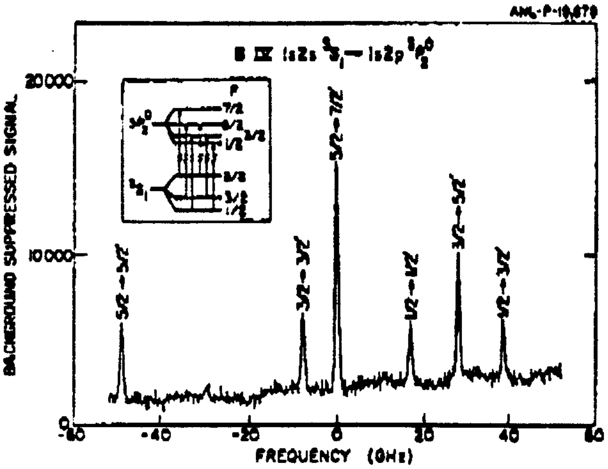

Fig. 4. Nearly complete hyperfine spectrum of the 2^3S_1 → 2^3P_2 transition in B^{3+}. The resonances were scanned by varying the potential in the light collection region from 0 to -800 volts.

V. Conclusion

We have discussed a number of experiments that are sensitive to the relativistic and QED effects in one- and two-electron ions. The measurements of the lifetimes of the two- photon emitting states in Ni^{26+} and Ni^{27+} used the coincidence technique which resulted in simple-decay curves that could be fit with only two parameters. In the future we will apply the coincidence technique to more highly-charged one- and two-electron ions. The experiment to measure the lifetime of the 2^3S_1 level in $^{79}Br^{33+}$ illustrates the potential of utilizing the hyperfine quenching effect to remove unwanted components from a blended line. We also described the first laser measurement of the 2^3S_1 → $2^3P_{0,1,2}$ transition in the B^{3+} system. With improved ion-beam intensity and metastable yield, there is potential for significant improvement in the precision of this experiment. We will also utilize this method to make measurements on other metastable helium-like ions which can be produced by our ECR ion source.

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