High Resolution Spectroscopy of Prompt and Metastable Decaying Levels in Highly Ionized Argon, Especially of the Metastable $^3P_2$-State of Ar$^{16+}$ and the $^4P_{5/2}$-State of Ar$^{15+}$

H.-D. Dohmann, D. Liesen, and H. Pfeng
Gesellschaft für Schwerionenforschung, Darmstadt, Federal Republic of Germany

Received October 27, 1977

Besides the prompt x-ray emission of Ar-ions, the metastable decay of the heliumlike $^3P_2$- and the lithiumlike $^4P_{5/2}$-levels of highly ionized Ar$^{16+}$ and Ar$^{15+}$ atoms has been observed in a foil-excited beam using a flat-crystal spectrometer. Due to the high x-ray energy resolution of the spectrometer the two $^3P_2 \rightarrow ^1S_0$ and $^4P_{5/2} \rightarrow ^2S_{1/2}$ transitions could be resolved. The experiment yielded $(3128 \pm 2)$ eV for the $^3P_2 \rightarrow ^1S_0$ and $(3091 \pm 2)$ eV for the $^4P_{5/2} \rightarrow ^2S_{1/2}$ transition energy respectively. Using a time of flight technique the lifetimes of the $^3P_2$- and the $^4P_{5/2}$-states were determined to be $(1.44 \pm 0.09)$ ns and $(0.66 \pm 0.05)$ ns.

I. Introduction

The spectra of highly ionized atoms with intermediate atomic numbers up to $Z=28$ are of great interest in astrophysics, because the spectral lines of these elements are observed in the soft x-ray spectrum of solar flares [1]. Lifetime values of metastable states are needed for the determination of plasma properties of those active regions of the sun with very high temperatures of about $5 \times 10^7$ K [2].

There are theoretical calculations which give with high accuracy the energies of the transitions and the lifetimes of the levels in helium- and lithiumlike ions [3–6]. In these calculations contributions from correlations and quantum electrodynamic effects have been considered. The contribution of the former one decreases and the influence of the latter one increases with increasing $Z$-value. To test the reliability of these theoretical calculations the experimental determination of energies and decay times are necessary.

II. Apparatus

For this experiment an Ar$^{13+}$-beam of the UNILAC in Darmstadt, with a specific energy of 1.4 MeV/u was used. This beam was stripped by a movable 40 $\mu$g/cm$^2$ carbon foil. Measurements were made both looking perpendicular to the beam on the foil and at positions with various distances behind the foil. A sketch of the experimental arrangement is given in Figure 1. The x-rays emitted by the beam pass through a Soller-slit, constructed with tungsten-plates in order to get a high absorption for non-collimated x-rays. The measurements are made with two different Soller-slits with distances of 0.5 mm and 0.16 mm between the plates, respectively. With a length of 100 mm the angular resolution amounts to 0.3° and 0.1° FWHM.
The glancing angle of tungsten is 1.5° for an x-ray-energy of about 3 keV [7]. Therefore one would expect such a Soller-slit-system to give an angular resolution not much smaller than 1.5°, as x-rays with smaller angles will not be absorbed but reflected with high probability. But as the tungsten-plates consist of rolled material the surface is not planar, which has been demonstrated by a parallel laser-beam being reflected with a divergence of about 2°. The angular resolution of the spectrometer is slightly inferior to that given by the geometrical limitation. For the two Soller-slits FWHM-values of 0.38° and 0.14° were measured for the Mn-Kα₁, Kα₂ lines, compared to theoretically possible values of 0.3° and 0.1°. There are three reasons for the broadening of the lines:

1. Reflection and not absorption of the x-rays for angles smaller than the glancing angles.
2. The angular limitation of the x-ray-beam in the plane parallel with the Soller-plates is not zero.
3. The mosaic angle of the used Pentaerythrit-crystal seems to be greater than ~0.02° as given by Alexandropoulos [8].

The collimated x-ray-beam is reflected by the crystal with a lattice-spacing of 2d = 8.742 Å. This value was measured inside the vacuum chamber with known energy values of Kα₁- and Kα₂-lines of Mn in the first and second order of reflection. The x-ray-beam, reflected by the Bragg-condition, passes through a second Soller-slit with low angular resolution of 3° to reduce the background of scattered x-rays and is detected by a proportional-counter.

For monitoring, the ion-beam is stopped in a Faraday-cup. By charge integration measuring intervals can be defined. Two stepmotors move the crystal and the detector, where the detector rotates with twice the angular velocity of the crystal, into coordinated angular positions. The position of the crystal and the detector is measured by an absolute angular digitizer with a resolution of 0.01°.

III. Experimental Results and Interpretation

A. Determination of x-ray Energy

a) The Prompt Spectrum

The prompt K-x-ray spectrum of an Ar-beam passing a C-foil was observed with different energy resolution: 38 eV, 14 eV, and 8 eV. The first and third measurements were made with the Soller-slit of low resolution in first and second order of reflection for the crystal. The resolution of 14 eV is reached by the Soller-slit with higher angular resolution in first order reflection.

The measurements with 14 eV and 8 eV resolution are shown in Figure 2. The measured energy is corrected by 4.6 eV for the quadratic Doppler-effect. The single spectral-lines are not associated with single charge states but with the number of holes in the L-shell. For all lines there must exist one hole in the K-shell. The energy of the resonance line 1P → 1S₀ in helium-like Ar¹⁶⁺ is Eₚ = 3.141 keV [5]. This line has the highest energy in agreement with the fact that the counting rates for energies greater than E = Eₚ + ΔE are given by the background (ΔE = FWHM-value of the spectrometer). However, the first observed maximum at 3.130 keV is about 11 eV lower than the energy of the 1P → 1S₀-resonance line. The energy-shift can be explained as due to four spectator electrons in the M-shell. The value of 2.8 eV for one M-spectator electron is taken from the x-ray tables of House [9]. Another argument that the five lines, shown in the upper part of Figure 2, are not given by single configurations or charge states is the width of the line.

The line-shape, seen in Figure 2, can be fitted by a FWHM-value of 20 eV for the upper and 14 eV for the lower curve. That means, in both cases the observed FWHM-value is given by geometrically adding the FWHM-value of the spectrometer to that of a physical width of 12 eV which results from several unresolved transitions. A configuration of four spectator electrons in the M-shell is compatible with the line shape and shift. The energy separation of the single peaks shown in Figure 2 is in good agreement with the separation of the energy levels given by House [9] for additional spectator electrons in the L-shell.

To get absolute calculated energy-values, these differences due to the spectator electrons in the M-shell [9] must be added to the energy of the resonance line given by Johnson et al. [5]. All the measured energy values for the satellite-lines are shifted by (11 ± 1) eV to lower energies. The unshifted lines are indicated in Figure 2. It is not possible, however, to say which of the many lines of one charge state participate. (See for example Gabriel's table of lithiumlike satellite spectra [3].)

b) The Metastable Spectrum

In Figure 3 the simplified energy levels and decay schemes of heliumlike Ar¹⁶⁺ and lithiumlike Ar¹₅⁺ are shown. The observed spectra for two different distances behind the foil are shown in Figure 4. The magnetic quadrupole transitions (M2) 3P₂ → 1S₀ of heliumlike and 4P₅/₂ → 3S₁/₂ of lithiumlike ions are dominant. The measured energy of the 3P₂ → 1S₀