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Observation of the Magnetic-Quadrupole Decay ($2^3P_2 \to 1^1S_0$) of Heliumlike Ar XVII and Lifetime of the 2^3P_2 State*

Richard Marrus and Robert W. Schmieder

Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California 94720

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The magnetic-quadrupole transition $(1s2p)2^3P_2 \to (1s^2)1^1S_0$ of the heliumlike atom Ar XVII has been observed. A measurement of the lifetime of this state has been made by the beam-foil time-of-flight technique, with the result $\tau(2^3P_2) = (1.7 \pm 0.3)\times 10^{-9}$ sec.

In 1964, Mizushima[1] called attention to the possibility of magnetic-quadrupole ($M2$) transitions for spectral lines for which $\Delta S = \pm 1$. Subsequently, Mizushima[2] and Garstang[3] carried out numerical calculations of the lifetimes associated with $M2$ transitions that are of astrophysical significance. In recent publications Garstang[4] and Drake[5] have considered the decay of the level $(1s2p)2^3P_2$ of heliumlike atoms. In the neutral helium atom, the 2^3P_2 state decays to the 2^3S_1 state with a lifetime of 10^{-7} sec.[6] Since this is a fully allowed electric-dipole ($E1$) transition, this mode might be expected to be dominant throughout the helium isoelectronic sequence. However, the lifetime assoicated with this mode, $\tau_{E1}(2^3P_2)$, can be shown to scale roughly as Z^{-1} for high Z, whereas the rate associated with the $M2$ decay mode $A_{M2}(2^3P_2)$ scales roughly as Z^8. On the basis of numerical calculations, both Garstang and Drake conclude that, for the heliumlike ions beyond chlorine ($Z = 17$), the dominant decay mode is magnetic-quadrupole emission. For argon ($Z = 18$), the calculated rate is $A_{M2}(2^3P_2) = 3.14\times 10^8$ sec^{-1}.

In this Letter we report the first observation of the $M2$ transition $(1s2p)2^3P_2 \to (1s^2)1^1S_0$ in the heliumlike atom Ar XVII, and the measurement of the lifetime of the 2^3P_2 state using the beam-foil time-of-flight technique. The result is $\tau(2^3P_2) = (1.7 \pm 0.3)\times 10^{-9}$ sec (95% confidence).

Although magnetic-quadrupole transitions have been observed abundantly in nuclear physics, it has so far not been possible to compare reliably a measured rate with a theoretical rate that is calculated from first principles. Since highly accurate rate calculations are possible in hydrogenlike and heliumlike systems, we believe that this is the first experimentally measured $M2$ rate which is directly comparable with a theoretical rate derived from first principles.

A description and schematic diagram of the apparatus used in this work have been presented previously[7] and will be reviewed only briefly here. Ions of ^{40}Ar in the +14 charge state are obtained from the Berkeley heavy ion linear accelerator (HILAC) with energy 10.3 MeV/nucleon ($\beta \equiv v/c = 0.148$). The beam passes through a thin (10 μg/cm^2) carbon foil and emerges distributed among the +15 (lithiumlike), +16 (heliumlike), +17 (hydrogenlike), and +18 (fully stripped) charge states. In this nonequilibrium distribution, about 15% appear as +16 and a few percent as +17. The +15 and +18 ions produce no observable effects in our detectors. Initially the atoms may have large electronic excitation, but they decay rapidly (~10^{-14} sec) to the ground and long-lived levels, with a sizable fraction of the heliumlike ions appearing in the $(1s2p)2^3P_2$ state. The subsequent decay of these long-lived states is observed downstream of the foil with a high-resolution Si(Li) x-ray detector, and the counting rate is normalized to the integrated beam current. The foil is mounted on a movable track, and varying the foil-detector separation makes it possible to plot the decay curve over the range 15-200 cm. By fitting the observed decay with an exponential and knowing the beam velocity, we determine the lifetime.

Typical x-ray spectra taken with several foil-detector distances are shown in Fig. 1. They consist of a peak at an energy of 3.1 keV, and a continuous spectrum at energies between the noise level of the detector and the peak. Coincidence measurements reported elsewhere[8] have established the continuous spectrum as arising from the two-photon transitions $2^2s_{1/2} \rightarrow 1^2s_{1/2}$ of hydrogenlike atoms and $2^1S_0 \rightarrow 1^1S_0$ of heliumlike atoms. Within the Doppler-broadened width of the peak, it is possible to have contributions from several transitions, but we now give arguments which indicate that the $M2$ transition $(1s2p)2^3P_2 \rightarrow (1s^2)1^1S_0$ dominates the observed decay at small distances.

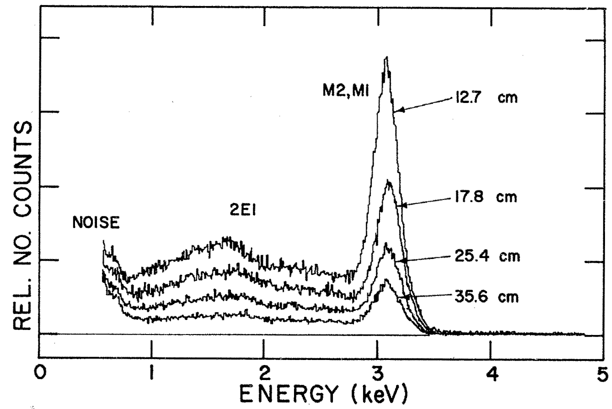

FIG. 1. Typical spectra obtained for several foil-detector separations. The shape of the two-photon spectrum has not been corrected for detector efficiency, so exhibits a large silicon absorption edge near 1.8 keV. The total number of counts within the right-hand half of the 3.1-keV peak was taken as a measure of the intensity of the peak. About half the linewidth is due to Doppler broadening.

The only decays of hydrogenlike and heliumlike atoms with sufficient energy to account for the 3.1-keV peak observed here are transitions to ground states, $1^2s_{1/2}$ and 1^1S_0, respectively. Moreover, with our apparatus geometry and the beam velocity of $4.4(1) \times 10^9$ cm/sec, the lifetime of a transition must be $\gtrsim 3 \times 10^{-10}$ sec in order to be observable. The only decays satisfying these conditions are listed in Table I. The $2E1$ decays give rise to the continuous spectra characteristic of two-photon emission, with intensities falling to zero at the end-point energies (3.1, 3.3 keV). Consequently, only a small fraction of the $2E1$ decays overlap the peak width, and this fraction can be estimated and subtracted as a small correction. The $M1$ decay from the hydrogenlike $2^2s_{1/2}$ state gives a line at 3.3 keV, and is a potential source of error, since the $2^2s_{1/2}$ state lifetime is comparable with the 2^3P_2 state lifetime. However, our observation of a "single" line at 3.1 keV shows that this contribution is small. Furthermore, the actual contribution to the peak can be estimated from the $2E1$ decay, and subtracted as another small correction. The other $M1$ decay,[14] .rom the heliumlike 2^3S_1 states, closely overlaps the $M2$ line, but because this state has such a long mean lifetime ($\tau \cong 172$ nsec),[7] this decay can be separated easily in the time-of-flight measurements. We conclude that the observed peak will decay with a fast and a slow component, the fast one being due to the $2^3P_2 \rightarrow 1^1S_0$ transition in Ar XVII.

That the observed peak actually consists of two

Table I. Forbidden decays in hydrogenlike and heliumlike argon.[a]

Ion	Transition	Mode	Approx. trans. prob. (sec^{-1})	Ref.
Ar XVIII	$(1s2p)2^3P_2 \rightarrow (1s^2)1^1S_0$	$M2$	$\sim 3 \times 10^8$	5
($E \cong 3.1$ keV)	$(1s2s)2^3S_1 \rightarrow (1s^2)1^1S_0$	$2E1$	$\sim 3 \times 10^3$	9
		$M1$	$\sim 6 \times 10^6$	10
	$(1s2s)2^1S_1 \rightarrow (1s_2)1^1S_0$	$2E1$	$\sim 4 \times 10^8$	11
Ar XVII	$(1s)2^2s_{1/2} \rightarrow (1s)1^2s_{1/2}$	$2E1$	$\sim 3 \times 10^8$	12
($E \cong 3.3$ keV)		$M1$	$\sim 8 \times 10^6$	10

[a]Only transitions to ground states are listed. E is the total energy available in the transition. The rate of the spin-orbit–induced $E1$ transition $(1s2p)2^3P_1 \rightarrow (1s^2)1^1S_0$ is $\sim 10^{12}$, i.e., too fast to be observable in the present apparatus. Nuclear spin inducement (Ref. 13) of the $E1$ transitions $(1s2p)2^3P_{2,0} \rightarrow (1s^2)1^1S_0$ is not present for the isotope ^{40}Ar.

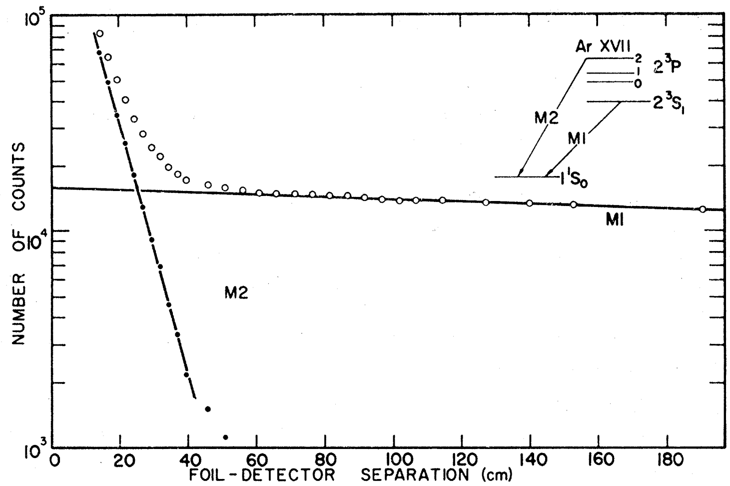

FIG. 2. Typical decay curve obtained by plotting the intensity of the peak versus foil-detector separation. By removing $M1$ contribution from the curve, we obtain the single exponential decay representing the $M2$ transition $2^3P_2 \rightarrow 1^1S_0$ in Ar XVII.

unresolved components is evident from the decay curve taken by varying the foil position. This decay curve, shown in Fig. 2, exhibits the fast mode associated with the $M2$ transition and the slow mode associated with the $M1$ transition. Our association of the slow mode with the $M1$ decay is based on recent calculations[10,15] and our measurement[7] of the $M1$ lifetime.

The lifetime of the 2^3P_2 state was extracted from the data in the following steps: First, the small $2E1$ and $M1$ contributions to the total counts under the right-hand half of the peak were subtracted for each point in the decay curve. Second, the long $M1$ component was removed leaving the single exponential decay. Third, a least-squares fit was made to an exponential, thus determining the mean decay length. Finally, dividing by the known velocity we obtain the mean $(1/e)$ lifetime, $\tau(2^3P_2) = (1.7 \pm 0.3) \times 10^{-9}$ sec.

The main contributions to the error are errors in beam velocity (~2 %), counting-rate normalization (3 %), $2E1$ and $M1$ corrections (3 %), and instrumental effects such as background, beam and detector drifts, foil tracking error, etc. (5 %). Although it is currently impossible to correct the data accurately for cascading effects, there is evidence that these effects are quite small.

Recently, Drake[15] has computed the electric-dipole rate, with the result $A_{E1} = (2^3P_2) = 3.55 \times 10^8$ sec^{-1}. Combining this with the value $A_{M2}(2^3P_2) = 3.14 \times 10^8$ sec^{-1} in the relation $1/\tau = A_{E1} + A_{M2}$ yields the predicted value $\tau = 1.49 \times 10^{-9}$ sec, which agrees with our measurements within the experimental error.

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