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OBSERVATION OF THE MAGNETIC QUADRUPOLE DECAY ($2^3P_2 \rightarrow 1^1S_0$) OF HELIUM-LIKE Ar XVII AND LIFETIME OF THE 2^3P_2 STATE*

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Abstract:

The magnetic quadrupole transition $(1s2p)2^3P_2 \rightarrow (1s^2)1^1S_0$ of the helium-like 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 helium-like 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 associated 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 helium-like ions beyond chlorine (Z = 17) the dominant decay mode is magnetic quadrupole emission. For argon (Z = 18), the calculated rate is $A_{M2}(2^3P_2) = 3.14 \times 10^8 \text{ sec}^{-1}$.

In this letter we report the first observation of the M2 transition $(1s2p)2^3P_2 \rightarrow (1s^2)1^1S_0$ in the helium-like 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 reliably compare a measured rate with a theoretical rate that is calculated from first principles. Since highly accurate rate calculations are possible in hydrogen-like and helium-like 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[11] and will be reviewed only briefly here. Ions of ^{40}Ar in the +14 charge state are obtained from the Berkeley 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 (lithium-like, +16 (helium-like), +17 (hydrogen-like), and +18 (fully stripped) charge states. In this non-equilibrium 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 ($\sim 10^{-14}$ sec) to the ground and long-lived levels, with a sizeable fraction of the helium-like 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 count rate is normalized to the integrated beam current. The foil is mounted on a moveable 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 hydrogen-like atoms and $2^1S_0 \rightarrow 1^1S_0$ of helium-like 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 the M2 transition $(1s2p)2^3P_2 \rightarrow (1s^2)1^1S_0$ dominates the observed decay at small distances.

The only decays of hydrogen-like and helium-like 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 hydrogen-like $2^2S_{1/2}$ 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 to 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, from the helium-like 2^3S_1 states, overlaps closely the M2 line but because this state has such a long mean lifetime ($\tau \cong 172$ nsec),[11] 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 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[10,16] and our measurement[11] 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 ($\sim 2\%$), count-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 accurately correct the data for cascading effects, there is evidence that these effects are quite small.

Recently, Drake[16] 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

$$\frac{1}{\tau} = A_{E1} + A_{M2} \quad ,$$

yields the predicted value $\tau = 1.49 \times 10^{-9}$ sec, which agrees with our measurements within the experimental error.

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FOOTNOTES AND REFERENCES

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Table I. Forbidden Decays in Hydrogen-Like and Helium-Like Argon

Ion	Transition	Mode	Approx. Trans. Prob.	Ref.
Ar XVII	$(1s2p)2^3P_2 \rightarrow (1s^2)1^1S_0$	M2	$\sim 3 \times 10^8$ sec^{-1}	5
($E \cong 3.1$ keV)	$(1s2s)2^3S_1 \rightarrow (1s^2)1^1S_0$	2E1	$\sim 3 \times 10^3$	12
		M1	$\sim 6 \times 10^6$	10
	$(1s2s)2^1S_1 \rightarrow (1s^2)1^1S_0$	2E1	$\sim 4 \times 10^8$	13
Ar XVII	$(1s)2^2s_{1/2} \rightarrow (1s)1^2s_{1/2}$	2E1	$\sim 3 \times 10^8$	14
($E \cong 3.3$ keV)		M1	$\sim 8 \times 10^6$	10

Note: 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[15] of the E1 transitions $(1s2p)2^3P_{2,0} \rightarrow (1s^2)1^1S_0$ is not present for the isotope ^{40}Ar.

FIGURE CAPTIONS

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.

Fig. 2. Typical decay curve obtained by plotting the intensity of the peak vs 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.

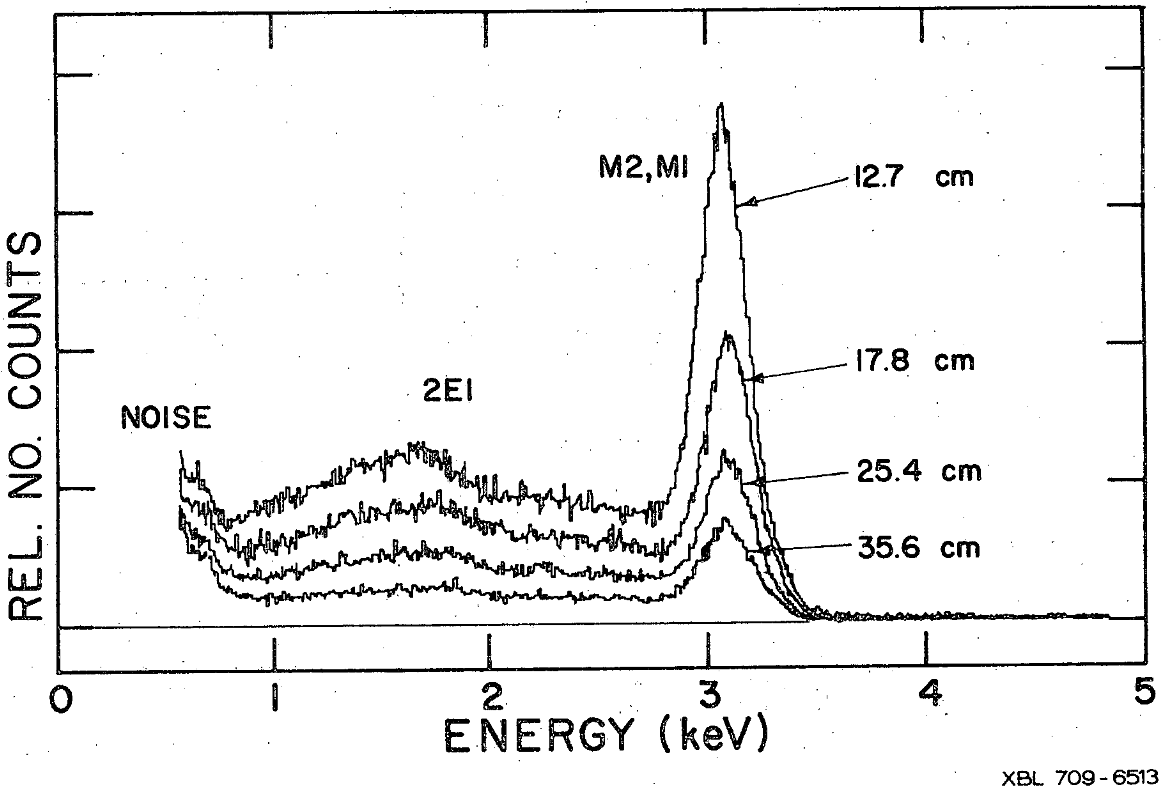
REL. NO. COUNTS
ENERGY (keV)
0
1
2
3
4
5
NOISE
2E1
M2,M1
12.7 cm
17.8 cm
25.4 cm
35.6 cm
XBL 709-6513

Fig. 1

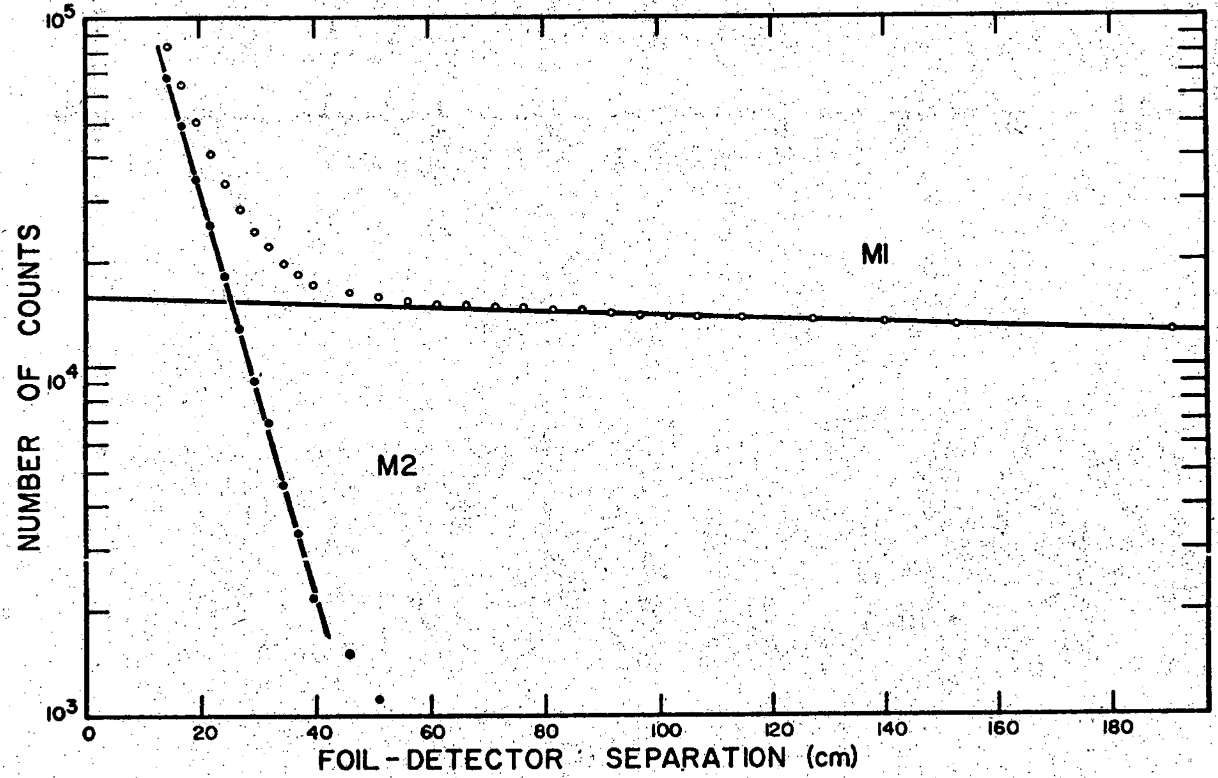

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Fig. 2

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