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Muonic Interactions in Zn^{66} and Zn^{68} †

D. A. Jenkins and R. J. Powers
Virginia Polytechnic Institute, Blacksburg, Virginia 24061
and
A. R. Kunselman
University of Wyoming, Laramie, Wyoming 82070

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We have looked for the $J^P = 0^+$ nuclear excitation of Zn^{68} in muonic atoms as suggested by Henley and Wilets. Zn^{68} was chosen because the energy of the 0^+ excitation is close to the energy difference of the $2s$-$1s$ muonic levels, thus allowing a dynamic interaction between a muon in a $2s$ state and the nucleus in the ground state. We find that the $2s$-$1s$ level difference is 20 keV less than the nuclear excitation energy and, as a result, the dynamic interaction is too small for us to observe. We measure the Zn^{66}-Zn^{68} isotope shift to be $\delta R/\delta R_{\mathrm{std}} = 0.47 \pm 0.11$.

1. INTRODUCTION

The purpose of our measurement was to look for a dynamic interaction between a muon in a $2s$ atomic state and a nucleus in a 0^+ excited state. The measurement was suggested by Henley and Wilets as a means for investigating the nuclear Coulomb monopole transition matrix element.[1] They suggested Zn^{68} for a target because the muonic $2s$-$1s$ energy difference is close to the excitation energy of the 0^+ nuclear level in Zn^{68}, and they predicted that the 0^+ excitation could be observed by looking for an additional splitting in the $2s \to 2p$ muonic transition. The effect of the interaction is shown in Fig. 1, in which the muonic energy levels and transitions without a nuclear interaction are shown by solid lines. The nuclear interaction causes a splitting of the $2s$ level, and the dashed lines indicate the new transitions which are introduced. The effect of the interaction can be measured by observing both the energy and relative intensities of the $2s \to 2p$ transitions. We have looked for the $2s \to 2p$ x ray, and we have measured the $2p \to 1s$ transition energy in order to estimate the muonic $2s$-$1s$ energy difference.

We have also measured the $2p \to 1s$ x-ray energy in Zn^{66}, which allows us to report the isotope shift in the muonic $2p \to 1s$ transition between Zn^{66} and Zn^{68}.

2. EXPERIMENTAL METHOD

The experiment was conducted at the National Aeronautics and Space Administration Space Radiation Effects Laboratory and proceeded in two parts. First, we searched for the $2s \to 2p$ transitions by looking for x rays in the region 20 to 60 keV with a silicon detector of 0.7-keV resolution (full width at half maximum). The targets were made up from 60 g of Zn^{68} and 100 g of Zn^{66} in the form of oxides; each target was at least 98% isotopically pure. A spectrum for the sum of the Zn^{66} and Zn^{68} x rays in this energy range is given in Fig. 2, in which we can see x-ray lines from transitions in both zinc and oxygen present in the ZnO target compound. The principal $2s_{1/2} \to 2p_{3/2}$ and $2s_{1/2} \to 2p_{1/2}$ x rays are predicted in our analysis, which is described below, to have an energy of 37.5 and 44.7 keV, respectively. The $2s_{1/2} \to 2p_{3/2}$ x ray is obscured by the 37.7-keV L_γ transition in oxygen; however, there is no statistically significant peak where the $2s_{1/2} \to 2p_{1/2}$ x ray is expected. The yield of the $2s \to 2p$ x rays in zinc is unknown, but, from these data, we estimate the yield to be less than 0.04 per cascading muon. The $2s \to 2p$ x ray has been observed in higher-Z isotopes to have a yield of approximately 0.02 per cascading muon.[2] We then proceeded to measure the $2p \to 1s$ transition energies so that we could determine the charge radius of the Zn^{68} nucleus and compute the $2s$-$1s$ energy difference. With this energy difference, we could then use the theory of Henley and Wilets to calculate the expected relative yield of the split $2s \to 2p$ x rays and establish whether or not a measurement of the splitting would be feasible.

The experimental arrangement for measuring the $2p \to 1s$ x-ray energies was similar to one which has been described for a pionic x-ray measurement.[3] To find the isotope shift, the $2p \to 1s$ x-ray energies in both Zn^{66} and Zn^{68} were measured. The linearity of the pulse analysis system was checked with nuclear γ rays of known energy,[4,5] and the γ rays in the region of interest are given in Table I. The total spectrum for Zn^{66} and Zn^{68} is shown in Fig. 3 with Gaussian curves which were used to fit the peak in the centroid determination. The x-ray energies are given in Table II; the largest contribution to the errors was an un-

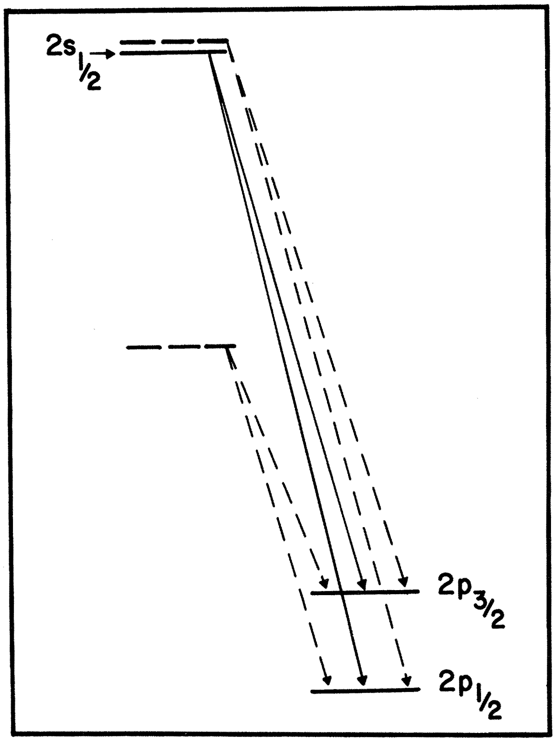

FIG. 1. Effect of the dynamic interaction on the $2s$ muonic level. The dynamic interaction splits the $2s$ level into the two levels shown by dashed lines. The splitting of the $2p_{3/2}$-$2p_{1/2}$ levels is 7 keV.

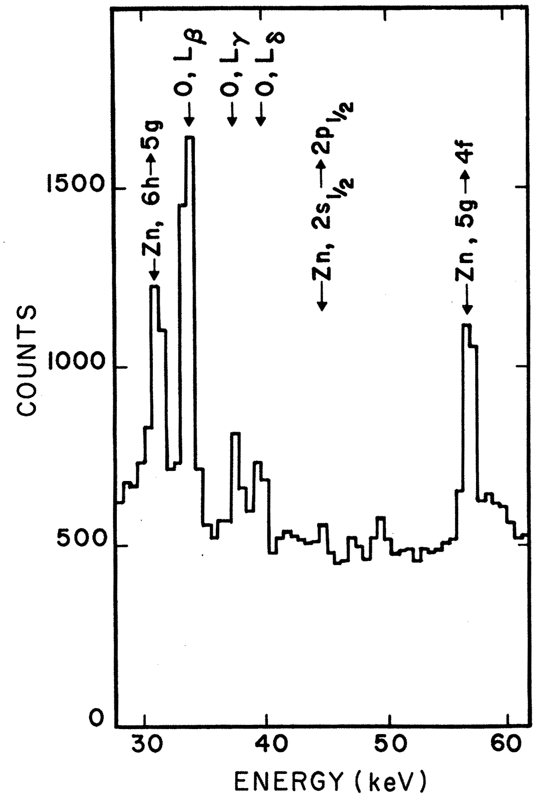

FIG. 2. Sum of the muonic x-ray spectra for Zn^{66} and Zn^{68}. The principal transitions in the spectrum are identified, and the expected position of the $2s_{1/2}\rightarrow 2p_{1/2}$ transition is indicated.

certainty of ±0.30 keV in the linearity. Our results are in agreement with NaI measurements of the x rays from natural zinc, which range from 1589.9 ± 4.5 to 1614 ± 6.2 keV. The numbers represent an average of the $2p_{1/2}\rightarrow 1s_{1/2}$ and $2p_{3/2}\rightarrow 1s_{1/2}$ x-ray energies, since the $2p_{3/2}\rightarrow 2p_{1/2}$ splitting was not resolved.[6]

3. DYNAMIC INTERACTION IN Zn^{68}

Henley and Wilets suggested that muons be used to measure the matrix element H' for the Coulomb excitation from the Zn^{68} ground state α to the 0^+ excited state β.[1] The Coulomb interaction between the muon and the nucleus causes a splitting in the $2s$ level of energy 2ϵ where

$$\epsilon = [H'^2 + (\tfrac{1}{2}\Delta)^2]^{1/2} , \qquad (1)$$

and

$$\Delta = E_{2s,\alpha} - E_{1s,\beta} . \qquad (2)$$

To find H', one must measure ϵ and Δ. In terms of measurable quantities, H' is given by

$$H' = 2\epsilon\sqrt{P}/(P+1) , \qquad (3)$$

where P is the ratio of the population of the muons in the two $2s$ levels. The effect of the dynamic interaction is to produce two sets of two lines each instead of the $2s_{1/2}\rightarrow 2p_{3/2}$ and $2s_{1/2}\rightarrow 2p_{1/2}$ lines seen when the interaction is not present, and H' is found by measuring the splitting and intensity ratio of these two sets of lines. To determine the size of the effect, we have measured the $2p\rightarrow 1s$ x-ray energy and obtained a value for Δ. Using Henley and Wilets' estimate for H' (2 keV), we then calculate ϵ and P from Eqs. (1) and (3).

A value for Δ was found by using the measured x-ray energies to find the charge distribution. We represented the charge distribution by a Fermi function,

$$\rho(r) = \rho_0/[1 + e^{(r-c)/s}] , \qquad (4)$$

TABLE I. Calibration sources. The energies are taken from Ref. 4, except for Bi^{212} from Ref. 5.

Source	Energy (keV)
Na^{22}	1274.53 ± 0.10
Th^{228}	1592.46 ± 0.10 (double escape)
Bi^{212}	1620.50 ± 0.10
Y^{88}	1836.08 ± 0.07

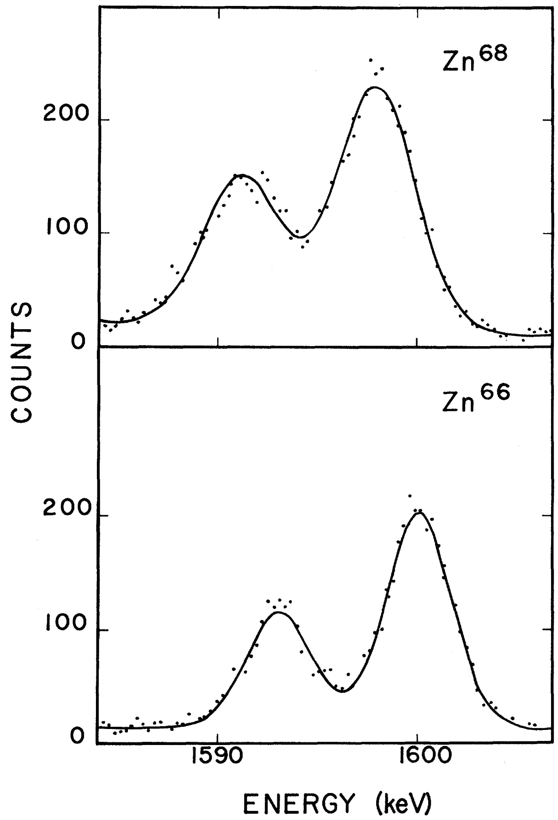

FIG. 3. The $2p \rightarrow 1s$ transitions for muons in Zn^{66} and Zn^{68}. The solid line represents the shape of the curve which was used in the centroid determination.

where c is the half-density radius, $t = s(4 \ln 3)$ is the skin thickness, and ρ_0 is a normalization factor. Analysis of higher-Z nuclei has shown that charge distributions represented by a Fermi function yield the correct $1s$, $2s$, and $2p$ binding energies.[2] Setting $t = 2.35$ F (an average value for nuclei in our range of atomic number[7]), we found $c = 4.423$ F from the x-ray data and used this charge distribution to compute the binding of a muon in a $2s$ state ($E_{2s,\alpha}$). The result was not significantly affected by changes of 10% in the value of t which was used in the calculation of c. We then assumed the binding energy of a $1s$ muon with the nucleus in the excited state β is equal, with an uncertainty of 1 keV, to the energy we measured for the binding of a $1s$ muon with the nucleus in the ground state α. The $2s$-$1s$ energy difference was found to be 1635.7 ± 1.1 keV. Our calculation included corrections due to vacuum polarization and the Lamb shift, but did not include the nuclear polarization, which is expected to be small (less than 1 keV[8]). The calculated transition energies are given in Table II. A recent measurement by Carter, Hamilton, Ramayya, and Pinajian of Zn^{68} nuclear excitation energies gives 1655.7 ± 1.0 keV for the 0^+ level.[9] We then arrive at a value for Δ of -20.0 ± 1.5 keV.

From Eqs. (1) and (3), we find $\epsilon = 10.2$ keV and $P = 101$. With our upper limit of 0.04 for the $2s \rightarrow 2p$ yield, we conclude that the low-intensity components of the $2s \rightarrow 2p$ transition, which must be seen, will have a yield of less than 4×10^{-4} per cascading muon. With present beam intensities, this transition would be difficult to observe.

4. Zn^{66}-Zn^{68} ISOTOPE SHIFT

We interpret the isotope shift in the manner described by Ehrlich.[10] The shift due to nuclear recoil (0.08 keV) is added to the isotope shift to obtain a volume shift of 2.01 ± 0.36 keV for the $K_{\alpha 1}$ line. The volume shift is then expressed as $\delta R/\delta R_{\rm std}$ where $R^2 = \frac{5}{3}\langle r^2 \rangle$ and $\delta R = R(A_2) - R(A_1)$; $\delta R_{\rm std}/R = (A_2^{1/3} - A_1^{1/3})/A_1^{1/3}$. To find δR, we set the skin thickness t equal to 2.35 F and held it constant while c was varied to obtain $(\partial E/\partial R)_t$. Defining

$$\delta R_t = \delta E/(\partial E/\partial R)_t ,$$

where δE is the isotope shift, we compute $\delta R_t/\delta R_{\rm std} = 0.47 \pm 0.08$. Including a model-dependent uncertainty of ± 0.08 due to variations in the skin thickness as calculated by Ehrlich, we find for the isotope shift

$$\delta R/\delta R_{\rm std} = 0.47 \pm 0.11 .$$

This result can be compared to isotope shifts measured by Ehrlich for elements of neighboring Z, where he found 0.60 for the shift in Cu^{63}-Cu^{65} and 0.55 for Ni^{60}-Ni^{62}. Consequently, we are unable

TABLE II. X-ray energies (in keV).

	$2p_{3/2} \rightarrow 1s_{1/2}$	$2p_{1/2} \rightarrow 1s_{1/2}$	$3d_{5/2} \rightarrow 2p_{3/2}$	$3d_{3/2} \rightarrow 2p_{1/2}$
Measured				
Zn^{66}	1600.15 ± 0.40	1592.97 ± 0.40	354.29 ± 0.25	360.75 ± 0.25
Zn^{68}	1598.22 ± 0.39	1591.22 ± 0.39	354.15 ± 0.25	360.59 ± 0.25
Shift	1.93 ± 0.36	1.75 ± 0.36	...	...
Calculated				
Zn^{68}	1598.25	1591.05	354.15	360.58

to detect a variation in the isotope shift for isotopes in this range of Z.

5. CONCLUSION

We have measured the charge radius of Zn^{68} and, from this, we have derived the $2s$-$1s$ muonic energy difference. The difference is compared with the 0^+ nuclear excitation of Zn^{68} and found to be 20.0 ± 1.0 keV too small, thus inhibiting the dynamic interaction described by Henley and Wilets. Instead of measuring the intensity ratios of the $2s \to 2p$ x rays, the dynamic interaction could be measured by determining Δ as we have done and then finding ϵ by looking for an energy shift in the principal pair of $2s \to 2p$ x rays. A shift of 0.2 keV is predicted from our analysis and would be barely observable with present-day techniques. Also, other corrections, such as nuclear polarization, would then become important. As a result, the interaction is difficult to observe in Zn^{68} under present experimental conditions. To see the 0^+ nuclear excitation in muonic atoms, other nuclei, such as Kr^{82} also suggested by Henley and Wilets, should be examined.

Our measurement of the isotope shift is consistent with the shift observed in other isotopes with $Z \simeq 30$.

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