HIGH-RESOLUTION MEASUREMENTS OF THE ISOTOPE SHIFT, FINE-STRUCTURE SPLITTING, AND ENERGY OF THE K_α MUONIC X RAYS OF Mo^{96} AND Mo^{98} †

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The development of lithium-drifted germanium gamma-ray detectors makes it possible to measure muonic x rays in the MeV region with greater accuracy and higher resolution than has been obtained previously. One of these detectors has been used to study the K_α muonic x-ray spectra of Mo^{96} and Mo^{98}, especially the isotope shift in the $2p_{3/2} \rightarrow 1s_{1/2}$ transition. The measurements yielded energies of 2713.3 ± 1.1 keV and 2707.1 ± 1.1 keV for the $2p_{3/2} \rightarrow 1s_{1/2}$ transition for Mo^{96} and Mo^{98}, respectively, and an average fine-structure-splitting energy of 23.5 ± 0.9 keV. An isotope shift, i.e., the energy difference between the $2p_{3/2} \rightarrow 1s_{1/2}$ transitions, $\Delta(Mo^{96}\text{-}Mo^{98})$ has been found to be +6.2 ± 0.7 keV. Calculations of this isotope shift by Pustovalov[1] and by Ford and Wills[2] show that for a spherical distribution of nuclear charge having a radius proportional to $A^{1/3}$, the nuclear penetration by the muonic orbits is expected to result in an energy shift (corrected for the reduced mass effect) of $\Delta(Mo^{96}\text{-}Mo^{98}) = +7.5$ keV.

A schematic diagram of the experimental apparatus is presented in Fig. 1. The muon beam from the Nevis cyclotron was slowed down by the polyethylene absorber, and a fraction of these muons was stopped in the molybdenum target. A stopped muon was signaled by a $123\bar{4}$ coincidence. The two targets were each 60 grams of MoO_3 made from Mo^{96} or Mo^{98}. The target material was obtained from Oak Ridge National Laboratory and had the following isotopic enrichment: $Mo^{96} > 96\%$; $Mo^{98} > 98\%$. Each of these targets was in a separate Lucite pillbox, and the two pillboxes were alternately placed in the beam at intervals of 10 minutes by an automatic sample-changing mechanism. About 30 $123\bar{4}$ events were recorded per second, 15 of which were attributed to muon capture in the molybdenum.

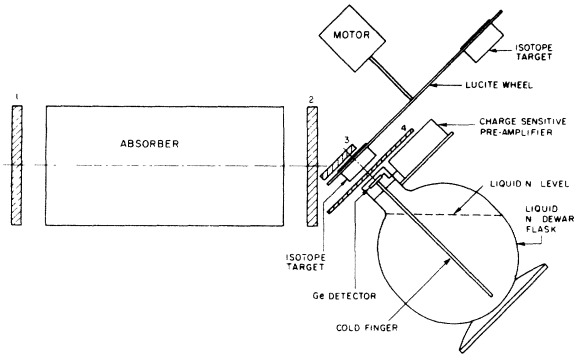

FIG. 1. Experimental apparatus; the muon beam enters from the left.

The lithium-drifted germanium gamma-ray detector, which was made at Brookhaven, has a sensitive volume of approximately 3.5 cm^3. It was mounted in a cryostat of a type described elsewhere,[3] and was positioned so as to present the largest practicable solid angle to the target, about 2%. The pulses from the gamma-ray detector were amplified by a conventional preamplifier-amplifier system and were routed by the target-switching mechanism to either the first or second 200-channel group of a 400-channel pulse-height analyzer, depending upon which target was positioned in the beam. As a systematic check of the system, the two targets were interchanged in the sample changer, and consistent results were observed.

Muonic x-ray spectra, as shown in Fig. 2, were recorded in the energy region of the second escape peaks, which occur at $2m_e c^2 = 1.022$ MeV less than the full x-ray energy. At the energy of the muonic K_α x ray in Mo (≈2.7 MeV), these second escape peaks are considerably more prominent than the full-energy peaks. Spectra recorded with radioactive sources having gamma rays of similar energy showed that the continuous Compton background under the second escape peaks has only about $\frac{1}{10}$ the amplitude of the peaks. In the spectra presented in Fig. 2, the background amplitude is also only about $\frac{1}{10}$ that of the $2p_{3/2} \rightarrow 1s_{1/2}$ peaks, indicating that other sources of background were unimportant. The energy interval of interest

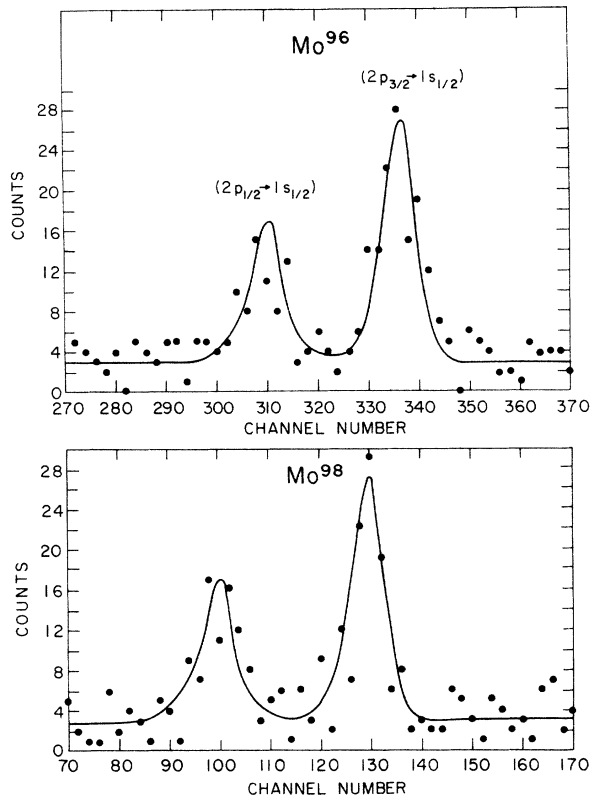

FIG. 2. K_α muonic x-ray spectrum. The line shapes were obtained from calibration sources. Data from one of two similar 18-hour runs are included in this Figure.

was calibrated relative to the (2614.45 ± 0.10)-keV line[4] of ThC'' and the (2753.5 ± 1.0)-keV line of Na^{24}.[5] The intermediate energy region was calibrated by interpolation with a precision potentiometer and mercury pulser, according to a method which has been described previously.[6] Calibrations performed at the beginning and end of each run indicated that electronic drifts were smaller than 0.5 keV.

Data analysis was performed by two independent methods: centroid analysis, and graphical fit to standard line shapes. The two techniques agreed well; reported errors (see Table I) reflect the internal consistency of these methods and also include estimated possible systematic errors.

The measured isotope shift is only slightly smaller than predicted by a model in which the nuclear charge radius is spherically symmetric and varies as $A^{1/3}$. This is particularly interesting in that recent measurements[7] of similar isotope shifts in Ca, Sn, and O all indicate that the shifts are less than half of what is predicted by this simple model. The isotope shift as measured by optical spectroscopy[8] is also considerably less than expected on the basis of the $A^{1/3}$ model. However, experiments[9] on electron scattering from two isotopes of nickel find results in agreement with the $A^{1/3}$ law.

Calculations of the magnitude of the fine-structure splitting agree with experiment, and the observed doublet pattern provides further confirmation (if any were needed) that the muon has spin $\frac{1}{2}$. The data on the fine-structure splitting for the two isotopes appears to be somewhat different. However, the associated errors are such that no firm conclusions can be reached. The intensity ratio of the $2p_{3/2} \rightarrow 1s_{1/2}$ transition to that of the $2p_{1/2} \rightarrow 1s_{1/2}$ transition was found to be 1.6 ± 0.4, a value which is only marginally consistent with the $2p$ levels being populated according to their statistical weight.

Good agreement is found between the absolute energy value for the $2p_{3/2} \rightarrow 1s_{1/2}$ transition and

Table I. Experimental results (all energies in keV).

	Experiment	Calculation	
		Ford and Wills[a]	Pustovalov[b]
X-ray energy			
$Mo^{96}(2p_{3/2} \rightarrow 1s_{1/2})$	2713.3±1.1	2715	2718
$Mo^{98}(2p_{3/2} \rightarrow 1s_{1/2})$	2707.1±1.1		
Isotope shift $(2p_{3/2} \rightarrow 1s_{1/2})$			
$\Delta(Mo^{96}-Mo^{98})$	+6.2±0.7	+7.5	+7.5
Fine-structure splitting $[(2p_{3/2} \rightarrow 1s_{1/2})-(2p_{1/2} \rightarrow 1s_{1/2})]$			
Mo^{96}	22.5±1.2	25	23.8
Mo^{98}	24.6±1.2		
Intensity ratio $(2p_{3/2} \rightarrow 1s_{1/2})/(2p_{1/2} \rightarrow 1s_{1/2})$	1.6±0.4		

[a]See reference 2. [b]See reference 1.

that calculated by Pustovalov[1] and Ford and Wills[2] using nuclear parameters based on the analysis of high-energy electron scattering. Agreement with previous measurements[10,11] of the energy of the K_α line in Mo is also good if it is considered that both of these earlier measurements used targets of natural Mo, not separated isotopes. It may be noted that the separation of the two components of the K_α line makes possible a more meaningful comparison between theory and experiment than previous experimental work in which the fine-structure splitting was unresolved.

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PROMPT ELECTRON SPECTRA FROM Cf^{252} FISSION FRAGMENTS*

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Recent measurements of the spectra of prompt gamma rays accompanying fission[1] have pointed out the possibility of extending the methods of nuclear spectroscopy into the region spanned by the prompt-fission products of Cf^{252}. We have followed up this advance with the measurement of the electron spectra originating from the internal conversion of prompt gamma rays from Cf^{252} fission fragments of selected mass in the energy range extending from 30 to 1000 keV. The initial results are quite encouraging with respect to the possibility of charge identification and internal-conversion-coefficient measurement, and it is expected that these studies will yield considerable information concerning the de-excitation processes of primary fission fragments.

An inhomogeneous magnetic field of configuration proposed by Malmfors[2] was used to steer the electrons around a block of lead, which shielded the electron detector from fission fragments and gamma rays. In our case, a wide range of energies and a large solid angle of electrons precess in trochoidal orbits in the fringing field of a large electromagnet. A weightless Cf^{252} source was mounted inside a brass vacuum chamber, which was positioned between the pole faces of the magnet. A lithium-drifted silicon electron detector was mounted inside the vacuum chamber 90° around the magnet from the fission source. This arrangement allowed the detection of electrons without the interference of fission fragments and gamma rays. The fragment energies were measured by two phosphorus-diffused silicon detectors mounted on both sides of the fission source on a line perpendicular to the median plane and at a distance of 1.8 cm.

A triple coincidence was required between the two fragments and the electrons. For geometrical reasons only electrons emitted within one nsec can precess into the detector. That is, the high-magnetic-field configuration prevents electrons more distant than about 1 cm from the median plane from reaching the electron detector. The data (E_{f_1}, E_{f_2}, E_β) were recorded individually, event by event, in a multi-dimensional pulse-height analyzer and stored on magnetic tape. The neutron-corrected masses were then deduced by a method of suc-