Letters to the Editor

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Identification of the Seven-Hour Mo^{93} Isomer

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THE seven-hour isomer of molybdenum is known[1,2] to decay by a 0.3-Mev lifetime determining transition followed by two cascade gamma-rays of 0.7 and 1.5 Mev. From the $K/(L+M)$ ratio of 2.8±0.3 and the energy 256 kev measured[3] by the group at Brookhaven, the isomeric transition was shown[4] by Goldhaber and Sunyar to be an $E4$ type. Ruby and Richardson later obtained[5] an energy of 262 kev and a $K/(L+M)$ ratio of 2.9±0.2 for the 7-hour transition and the values 692±11 kev and 1.51 ±0.035 Mev for the cascade gamma-rays.

Although a mass number 93 has been tentatively assigned[1] to this isomer, it is difficult to understand why the activity cannot be formed by the (d,p) or (n,γ) reactions on Mo^{92} or the (γ,n) reaction on Mo^{94}. Also, this mass number is not consistent with the predictions of shell theory, as pointed out[2] by Goldhaber and Hill. Recently, more evidence in favor of the mass 93 assignment was obtained[6] by Boyd and Charpie who studied the excitation functions for the production of 7-hour Mo and 10-day Nb^{92} formed by proton bombardment of Nb. Their data indicated that the first of these is due to the (p,n) reaction and the second due to the (p,pn) reaction on Nb^{93}. They concluded that the 7-hour isomer probably belongs to Mo^{93}.

We have made a direct mass assignment of this activity in the isotope separator at the Nobel Institute using sources obtained by bombarding Nb metal powder with deuterons. The cyclotron targets were prepared by forcing the powder under very high pressure into the surface of a copper block from which it could be scraped after the bombardment. Irradiations of 80 microampere-hours were made at a beam energy of 25 Mev, after which the active powder was introduced into a perforated lava tube and inserted in the separator ion source. This was arranged so that chlorine gas could pass through the powder and extract the activity in a manner somewhat similar to the technique used[7] by Keim at Oak Ridge. The lava tube was heated indirectly to a few hundred degrees by the ion source filament. It had been shown beforehand that the chlorine method gave strong lines from the stable isotopes of molybdenum when Mo metal powder was used in the ion source. With the bombarded niobium powder samples, stable Nb^{93} was also extracted by the chlorine and could be identified at once on the separator viewing screen by comparing the position of its line with those of the stable krypton isotopes and with three lines resulting from doubly-ionized $W^{182,183,184}$.

Separation of the Mo activity was carried out for 2 hours at a current of 1–3 microamperes on a 2.5 mg/cm² Al collector foil. A blackening of the foil at mass number 93 as a result of stable Nb^{93} was observed. By counting areas of the collector covering 10 successive mass units beginning with 88 and also from a radioautograph of the foil, it was established that the only activity present was at mass number 93.

A 6-mm wide strip at mass number 93 was then cut from the collector foil (adjacent masses in this region are about 9 mm apart) and examined in the double-focusing spectrometer. Figure 1 shows the internal conversion spectrum from this sample measured at a resolution of 0.8 percent. The energy of the transition is

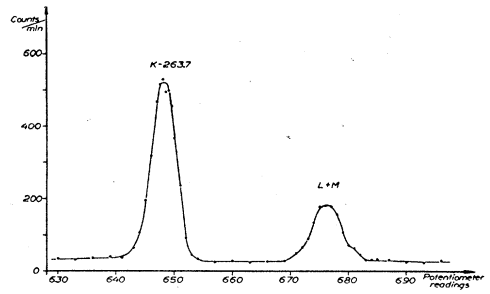

FIG. 1. Internal conversion spectrum of the Mo^{93} separated sample.

263.7±1.0 kev, and the $K/(L+M)$ ratio 2.79±0.15 is in favorable agreement with earlier results. The M line is not quite resolved but from the appearance of the curve probably accounts for 20–30 percent of the $L+M$ component. The half-life of 7 hours used to correct for decay was later checked by measuring the activity on the foil.

The gamma-rays from an unseparated portion of the active Mo were examined in the double-focusing spectrometer by observing the external conversion electrons from a 9-mg/cm² gold foil. Figure 2 shows the photolines and Compton electrons corresponding to the isomeric transition and two gamma-rays of 0.685±0.003 and 1.479±0.005 Mev. The total decay energy based on these measurements is 2.428±0.006 Mev.

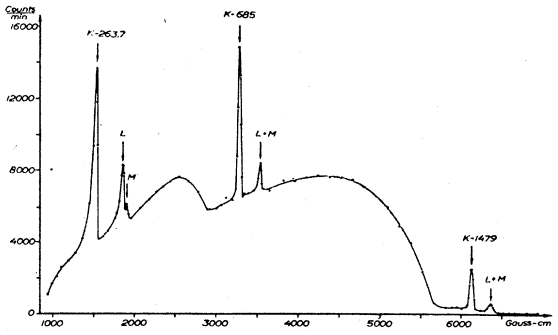

FIG. 2. External conversion of Mo^{93} gamma-rays in a 9-mg/cm² gold foil (unseparated sample).

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"Core Isomerism"—Remarks on Mo^{93m}†

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IT has been pointed out[1] that the 7-hr Mo isomer behaves in some respects as if it were an even-even nucleus. Now that this activity has been definitely assigned to an odd mass number, both by the study of the $Nb^{93}(p,n)$ excitation function[2] and by a direct mass spectrographic determination,[3] it seems appropriate to discuss the probable mode of excitation of Mo^{93m} further. This isomer lies outside the usual odd A "islands of isomerism," and it appears that we are dealing here with a case of "core isomerism" where the isomerism can be ascribed to an excitation of the

even-even core to a high spin state, probably 8+. This may be obtained by breaking a $g_{9/2}$ pair of protons and putting one of the protons into a $g_{7/2}$ state. The odd neutron probably remains in a $g_{7/2}$ state throughout the three-step isomeric transition while the core goes from $8+\rightarrow 4+\rightarrow 2+\rightarrow 0+$. Thus, the spin of Mo^{93m} may be as high as $(8+)+g_{7/2}=23/2+$, and this is supported by the absence of cross-over transitions.[4]

The total excitation energy of Mo^{93m}, 2.43 Mev,[3] is of the order expected on the assumption that it is due to the breaking of a $g_{9/2}$ proton pair (1–2 Mev) and the flipping of a spin $g_{9/2}\rightarrow g_{7/2}$ (spin orbit coupling energy $\sim$1.5 Mev). The low cross section of the $Nb^{93}(p,n)Mo^{93m}$ reaction[5] and the lack of success of attempts to produce Mo^{93m} by (d,p), (n,γ), and (γ,n) reactions (see reference 1) may be connected with the unusual character of this state. General consideration on even-even nuclei[6] indicate that "core isomerism" should be a rare phenomenon.[7]

My thanks are due Dr. Boyd, Dr. Charpie, Dr. Alburger, and Dr. Thulin for informing me of their results before publication.

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[3] D. E. Alburger and S. Thulin, preceding letter [Phys. Rev. **89**, 1146 (1953)]; R. Bernas and S. Beydon, Compt. rend. **236**, 194 (1953).
[4] A search for cross-over transitions was made by Alburger, der Mateosian, Friedlander, Goldhaber, Scharff-Goldhaber and Sunyar (unpublished) who used scintillation counters as well as (Be, D) photoneutron detectors.
[5] Blaser, Boehm, Marmier, and Preiswerk, Helv. Phys. Acta **24**, 441 (1951).
[6] G. Scharff-Goldhaber, Phys. Rev. **87**, 218 (1952); Physica (to be published); Phys. Rev. (to be published).
[7] The question may be raised: Where are the many excited states expected in this energy range ($\leq$2.4 Mev) from the one-particle excitation ($d_{5/2}$, $d_{3/2}$, $h_{11/2}$, $\cdots$) and from coupling of the $g_{7/2}$ neutron to the excited states of the core? They may, indeed, exist without showing up in the γ-ray transitions. If their energy does not differ considerably from the states which are populated in the decay of the isomer, they may be bypassed because transitions of minimum spin change win out. They should, however, be expected to show up under different excitation conditions.

Energy Loss and Čerenkov Radiation of a Relativistic Ionizing Particle

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IN the energy region where the bremsstrahlung is still not effective, the energy lost by a relativistic ionizing particle in traversing a material medium contributes essentially to the following three phenomena: (a) ionization of the atoms of the medium; (b) excitation of the atoms of the medium; (c) emission of the Čerenkov radiation.

At impact parameters larger than $\rho_0\approx 10^{-8}$ cm, the calculation of the energy lost in processes like (a) or (b) leads to the formula:

$$\left.\frac{dW_\sigma}{dx}\right|_{>\rho_0}=\frac{ne^2c}{\pi v^2}\int_0^\infty \frac{\sigma(\omega)}{|\epsilon(\omega)|^2}\left\{\log\frac{4v^2}{\gamma^2\omega^2|1-\epsilon(\omega)\beta^2|\rho_0^2}-\beta^2\,\mathrm{Re}[\epsilon(\omega)]\right\}d\omega, \quad (1)$$

where $\sigma(\omega)$ is the atomic cross section, related to the process considered, for a photon of frequency ω, n is the number of atoms per cm^3, and $\epsilon(\omega)$ is the frequency-dependent dielectric constant of the medium. All other symbols have the conventional significance. $\mathrm{Log}\gamma=0.577\cdots$.

The energy lost by direct excitation (that is, neglecting[1] reabsorption of the Čerenkov radiation) can be calculated by substituting in the preceding relation

$$\sigma(\omega)=-\mathrm{Re}[i\omega\epsilon(\omega)/cn]. \quad (2)$$

For the energy lost in processes (c) we have found the formula

$$\frac{dW}{dx}=\frac{e^2}{v^2}\int_{\text{Čerenkov}}\left[\beta^2-\frac{\mathrm{Re}[\epsilon(\omega)]}{|\epsilon(\omega)|^2}\right]\omega d\omega, \quad (3)$$

where the integration is to be performed over all frequencies for which

$$\mathrm{Re}[\epsilon(\omega)]>\beta^{-2} \quad \text{(Čerenkov frequencies)}. \quad (4)$$

It should be pointed out that, when the emitted radiation is to be observed at the distance ρ, the supplementary condition $\beta^2(\omega/v)\,\mathrm{Im}[\epsilon(\omega)]\rho\ll 1$ should be added.

When the damping constants are not too large, one gets, by adding Eq. (3) to Eq. (1) [and using (2)], the well-known Fermi[2] formula giving the total amount of energy emitted by the ionizing particle to a distance larger than ρ_0. The repartition of this energy between Eq. (3) and Eq. (1) [with (2)] depends critically on the value of the quantity

$$\Theta_i=mg_i\omega_i/4\pi Ne^2f_i, \quad (5)$$

where ω_i, f_i, and g_i are, respectively, the frequency, the oscillator strength, and the damping constants relating to the ith spectral line, and N=number of electrons per cm^3. When $\Theta_i\ll 1$ (dense media with narrow lines), the relativistic increase of the energy loss beyond the minimum relative to the ith line is caused by the emission of Čerenkov radiation, while the energy lost in excitation of the corresponding line does not show any increase (as in the case discussed by Schönberg,[3] who puts $g_i=0$). When $\Theta_i\ll 1$ (dense media with wide lines, or rarified gases) Eq. (1) [with (2)] gives

$$\left.\frac{dW_{exc}}{dx}\right|_{>\rho_0}=\frac{2\pi Ne^4}{mv^2}\sum_{i=1}^{r}f_i\left\{\log\frac{4v^2}{\gamma^2\omega_i^2\rho_0^2[(1-\beta+\beta^2D_i)^2+\beta^2\Theta_i^{-2}]^{\frac{1}{2}}}-\beta^2\right\}, \quad (6)$$

where

$$D_i\approx\frac{4\pi Ne^2}{m\omega_i^2}\sum_{j=1}^{i-1}f_j.$$

Hence, it is seen that the Bethe-Bloch formula is valid for energies E satisfying the condition

$$E^2\gtrsim\beta^{-2}(D_i^2+\Theta_i^{-2})^{-\frac{1}{2}}, \quad (7)$$

which determines the upper limit of the energy, below which there is no Čerenkov radiation from the corresponding band.

The expected behavior of the ionization may be discussed classically, considering the transition to the continuum as pertaining to wide bands ($\Theta_i\ll 1$) and therefore described by Eq. (6). According to the two following conditions:

Case I: $D_i>\Theta_i^{-1}$,
Case II: $D_i<\Theta_i^{-1}$,

the saturation of the ionization occurs gradually (I), as expected from the Halpern and Hall[4] formula, or more sharply (II). (See Fig. 1.)

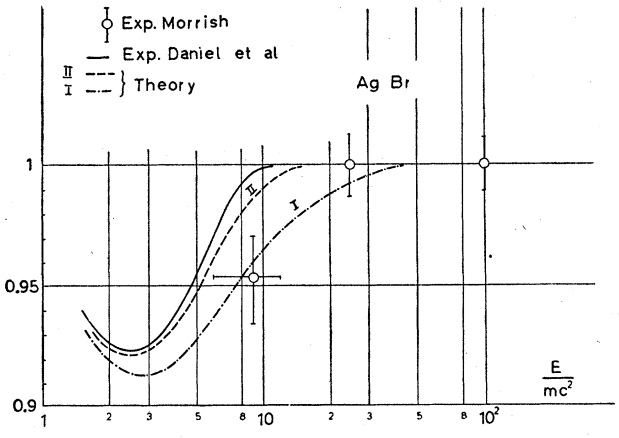

FIG. 1. Total rate of ionization in silver bromide (transfers less than 5 kev). The dashed curve II is computed with Eq. (6) and $D_i<\Theta_i^{-1}$. The dot-dash curve I is computed with Eq. (6) and $D_i>\Theta_i^{-1}$.