

## Nuclear Moments of Mo<sup>95</sup>, Mo<sup>97</sup>, Zr<sup>91</sup>, I<sup>127</sup>, Sb<sup>121</sup>, and Sb<sup>123</sup>

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The hyperfine structure (hfs) of the spectrum of Mo I was studied, and it was found that both Mo<sup>95</sup> and Mo<sup>97</sup> have nuclear spins equal to 7/2. Substituting this in the *g*-values of Mo<sup>95</sup> and Mo<sup>97</sup> given in the literature, the magnetic moments  $\mu(\text{Mo}^{95}) = -1.2736 \text{ nm}$  and  $\mu(\text{Mo}^{97}) = -1.3006 \text{ nm}$  (without diamagnetic correction) are obtained. Hfs investigation of the spectrum of Zr yielded the result that  $\mu(\text{Zr}^{91}) = -1.9 \pm 0.2 \text{ nm}$ . The quadrupole moment of I<sup>127</sup> as derived from the hfs of the visible spectrum and as derived from the atomic beam resonance technique published in the literature is discussed, and it is concluded that  $Q(\text{I}^{127}) = (-0.69 \pm 0.03) \times 10^{-24} \text{ cm}^2$  including the polarization correction due to Sternheimer. Data concerning the hfs of the spectrum of Sb II are discussed, and it is shown that they support the values  $Q(\text{Sb}^{121}) = (-0.53 \pm 0.10) \times 10^{-24} \text{ cm}^2$  and  $Q(\text{Sb}^{123}) = (-0.68 \pm 0.10) \times 10^{-24} \text{ cm}^2$  (including the polarization correction) that were deduced previously.

### I. NUCLEAR MOMENTS OF Mo<sup>95</sup> AND Mo<sup>97</sup>

USING separated isotopes, Arroe<sup>1</sup> studied the hyperfine structure (hfs) of the spectrum of Mo I and found that the most probable values of the nuclear spins of Mo<sup>95</sup> and Mo<sup>97</sup> are 5/2. Woodward<sup>2</sup> repeated the same kind of experiment as Arroe<sup>1</sup> and determined the spins of Mo<sup>95</sup> and Mo<sup>97</sup> to be 5/2. Proctor and Yu<sup>3</sup> measured the *g*-values of Mo<sup>95</sup> and Mo<sup>97</sup> by nuclear induction and found that

$$g(\text{Mo}^{95}) = -0.3639, \quad g(\text{Mo}^{97}) = -0.3716, \quad (1)$$

$$\mu(\text{Mo}^{97})/\mu(\text{Mo}^{95}) = 1.0210 \pm 0.0001, \quad (2)$$

using Mack's<sup>4</sup> finding that  $\mu(\text{Mo}^{97})/\mu(\text{Mo}^{95}) = 1.07 \pm 0.05$ .

A critical review of the published spectroscopic data reveals that the conclusion about the spins is not so convincing. The present investigation was undertaken in order to determine the spins of Mo<sup>95</sup> and Mo<sup>97</sup> more definitely.

A hollow-cathode discharge tube described previously<sup>5</sup> was used as the light source and a Fabry-Pérot etalon was used in order to resolve the hfs. In order to get sharp hfs components, the discharge current was made as small as possible, although the time of exposure was much prolonged.

Molybdenum is known to consist of seven isotopes<sup>6</sup>: 92 (15.86), 94 (9.12), 95 (15.7), 96 (16.5), 97 (9.45), 98 (23.75), and 100 (9.62). The abundance in percent is in parentheses. Shift of these isotopes in the line Mo I  $\lambda 5888 (4d^4 5s^2 \ ^5D_3 - 4d^5 \ ^6S) 5p \ ^5P_2$  is shown schematically in Fig. 1. Appreciable isotope shift anomaly, such as observed in the spectra of Sn<sup>7,8</sup> and Cd,<sup>8-11a</sup> was not

observed in Mo I. It follows from Fig. 1 that the mean shift per two neutron difference in the transition  $5s^2 - 4d^5 p$  is about  $0.014 \text{ cm}^{-1}$ . Arroe<sup>1</sup> detected a shift of Mo<sup>95</sup>-Mo<sup>97</sup> ranging from  $0.0113$  to  $0.0143 \text{ cm}^{-1}$  in the group of lines  $4d^4 5s^2 \ ^5D - 4d^5 p \ ^5P$ . We may assume that the mean shift per two neutron difference in  $4d^5 5s - 4d^5 p$  is about  $0.007 \pm 0.002 \text{ cm}^{-1}$ . This assumption and the ratio (2) were used in interpreting the hfs of  $\lambda 3903 [4d^5 \ (^6S) 5s \ ^7S_3 - 4d^5 \ (^6S) 5p \ ^7P_2]$  which is shown in Fig. 2.

According to the analysis of the low even configurations given by Trees and Harvey,<sup>12</sup> the levels  $4d^5 \ (^6S) 5s \ ^7S_3$  and  $^5S_2$  are not perturbed (the wave functions are pure). The former level is expected to have a larger splitting of the odd isotopes. A perturbation calculation shows that the upper level of  $\lambda 3903$  has a

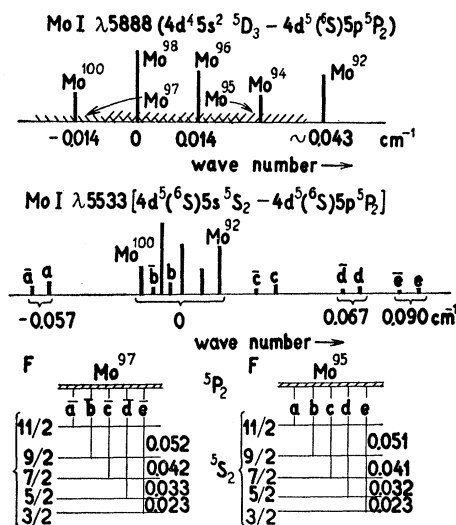


FIG. 1. Hfs of the lines Mo I  $\lambda 5888$  and Mo I  $\lambda 5533$ .

<sup>1</sup> S. Arroe, *Studier over Spektralliniere Struktur*, Copenhagen, 1951 (unpublished).

<sup>2</sup> E. C. Woodward, *Phys. Rev.* **93**, 954 (1954).

<sup>3</sup> W. G. Proctor and F. C. Yu, *Phys. Rev.* **81**, 20 (1951).

<sup>4</sup> J. E. Mack, quoted in reference 3.

<sup>5</sup> K. Murakawa, *J. Phys. Soc. (Japan)* **9**, 391 (1954).

<sup>6</sup> D. Williams and P. Yuster, *Phys. Rev.* **69**, 556 (1946).

<sup>7</sup> K. Murakawa, *J. Phys. Soc. (Japan)* **9**, 876 (1954).

<sup>8</sup> Hindmarsh, Kuhn, and Ramsden, *Proc. Phys. Soc. (London)* **117**, 478 (1954).

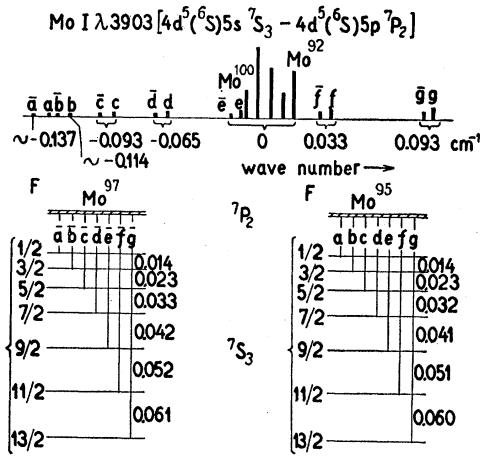
<sup>9</sup> K. Murakawa, *Phys. Rev.* **93**, 1232 (1954); *J. Phys. Soc. (Japan)* **10**, 319 (1955).

<sup>10</sup> E. C. Woodward and D. R. Speck, *Phys. Rev.* **96**, 529 (1954).

<sup>11</sup> W. M. Cloud, *Phys. Rev.* **99**, 623(A) (1955).

<sup>11a</sup> Note added in proof.—See also J. Blaise, *Z. Physik* **141**, 87 (1955).

<sup>12</sup> R. E. Trees and M. M. Harvey, *J. Research Natl. Bur. Standards* **49**, 397 (1952).

FIG. 2. Hfs of the line Mo I  $\lambda$ 3903.

total splitting of the order of 0.000 to  $-0.060 \text{ cm}^{-1}$ . Thus the hfs of the line  $\lambda$ 3903 is the most suited for determining the spins. The tail components  $\bar{a}$ ,  $a$ ,  $\bar{b}$ , and  $b$  (Fig. 2) were not resolved, but the intensity distribution shows that this tail consists of at least three components, so the final level in  $\text{Mo}^{95}$  and  $\text{Mo}^{97}$  splits into seven hyperfine levels; the spin 5/2 is therefore excluded. The sums of intensities  $\bar{a}+a+\bar{b}+b$  and  $\bar{c}+c$  (instead of the intensity of an individual component) were measured directly. The intensity ratio  $(\bar{a}+a+\bar{b}+b)/(\bar{c}+c)$  was measured to be  $0.93 \pm 0.10$ . This ratio should be 1.00 for the spin 7/2 and 1.25 for the spin 9/2. We conclude, therefore, that the spins of  $\text{Mo}^{95}$  and  $\text{Mo}^{97}$  are 7/2.<sup>13</sup>

The observed hfs of the line  $\lambda$ 5533 [ $4d^5(6S)5s^2 5S_2 - 4d^5(6S)5p^2 5P_2$ ] is shown schematically in Fig. 1. A calculation shows that the upper level has a negligible splitting of the odd isotopes, so the interpretation of the hfs is simple. Here again the observed hfs is consistent only with the assumption of the spins 7/2 for  $\text{Mo}^{95}$  and  $\text{Mo}^{97}$ .

From the measured splittings of  $d^5s^2 7S_3$  and  $5S_2$  we get by the aid of the  $LS$ -coupling formulas  $A[d^5(6S)s^2 7S_3] = \frac{1}{6}a(s)$ ,  $A[d^5(6S)s^2 5S_2] = -\frac{1}{6}a(s)$  a consistent value  $a(5s) = -0.0574 \text{ cm}^{-1}$  for  $\text{Mo}^{95}$ . The assumption of  $I=5/2$  would meet with a difficulty in this respect. Putting this  $a(5s)$  and  $Z=42$ ,  $Z_0=1$ ,  $F$  (relativity correction factor) = 1.20,  $1-\delta$  (nuclear finite volume correction) = 0.978 and  $(dn^*/dn)/n^{*3} = 0.376$  in the modified Goudsmit-Fermi-Segrè formula,

$$a(s) = \frac{ZZ_0^2(1-\delta)F}{117.8} \frac{dn^*/dn}{n^{*3}} \frac{\mu}{I}$$

we get  $\mu(\text{Mo}^{95}) = \mu(\text{Mo}^{97}) = (-1.3 \pm 0.2) \text{ nm}$ . They are in good agreement with the more accurate values that

<sup>13</sup> In Fig. 2 the hfs transition scheme is drawn, assuming that the interval factor of the initial level is strictly zero. If this has a finite value, the splitting of the final level shown in Fig. 2 will have to be slightly corrected, but the conclusion regarding the nuclear spins would not be changed at all.

are obtained by putting 7/2 in the nuclear induction  $g$ -values [Eq. (1)]:

$$\mu(\text{Mo}^{95}) = -1.2736 \pm 0.0002 \text{ nm},$$

$$\mu(\text{Mo}^{97}) = -1.3006 \pm 0.0002 \text{ nm}.$$

They include no diamagnetic correction. These magnetic moments with spin 7/2 are not in agreement with the prediction of the single particle shell model.

## II. NUCLEAR MOMENT OF $\text{Zr}^{91}$

Using a sample enriched in  $\text{Zr}^{91}$ , Arroe and Mack<sup>14</sup> studied the hfs of the spectrum of  $\text{Zr I}$  and determined the nuclear spin of  $\text{Zr}^{91}$  to be 5/2. Using a natural sample, Suwa<sup>15</sup> studied the hfs of the lines of  $\text{Zr I}$  that are suited for determining the magnetic moment and calculated it to be  $\mu(\text{Zr}^{91}) = -1.3 \pm 0.3 \text{ nm}$ . However his calculation is somewhat inaccurate, so his limit of error of  $\mu$  must be somewhat widened.

In the present investigation the hfs of the group of lines  $4d^3 5s^2 5F - 4d^3 5p^2 5G$  was studied.<sup>16</sup> The observed hfs of the line  $\lambda$ 4788.7 ( $4d^3 5s^2 5F_5 - 4d^3 5p^2 5G_5$ ) is shown schematically in Fig. 3. Both the initial and the final levels are of good  $LS$ -coupling, so the interval factors can be expressed by

$$A(d^3 s^2 5F_5) = (1/10)[a(s) + 8a_d' + a_d'' + 8a_d'''],$$

$$A(d^3 p^2 5G_5) = (1/600)(401a_d' + 49a_d'' + 248a_d''') \\ + (1/40)(9a_p' + a_p''),$$

$$a_d' = a(d_{5/2}), \quad a_d'' = a(d_{3/2}), \quad a_d''' = a(d_{5/2, 3/2}),$$

$$a_p' = a(p_{3/2}), \quad a_p'' = a(p_{1/2}), \quad a_p''' = a(p_{3/2, 1/2}).$$

The value of  $\mu(\text{Zr}^{91})$  can be calculated by the usual procedure, using these formulas. It is only to be remarked that  $(dn^*/dn)/n^{*3} = 0.266$  for the 5s electron of  $\text{Zr I}$ . The result of the calculation is

$$\mu(\text{Zr}^{91}) = -1.9 \pm 0.2 \text{ nm}.$$

The same value with the same accuracy can be obtained from the hfs of the line  $\lambda$ 4239 ( $4d^3 5s^2 5F_4 - 4d^3 5p^2 5F_4$ ) measured by Suwa.<sup>15</sup> It may be noted that the above-mentioned value of  $\mu(\text{Zr}^{91})$  is nearly coincident with the Schmidt limit, as in the case of  $\text{O}^{17}$  that was measured by Alder and Yu.<sup>17</sup>

## III. QUADRUPOLE MOMENT OF $\text{I}^{27}$

In a previous work<sup>18</sup> the hfs of the visible lines of  $\text{I I}$  was studied, and the value of  $Q(\text{I}^{27})$  was deduced to be  $-0.72 \times 10^{-24} \text{ cm}^2$  (including the polarization correction due to Sternheimer<sup>19</sup>) from the level  $5p^4 6s^4 P_{5/2}$ , and  $-0.76 \times 10^{-24} \text{ cm}^2$  from the level  $5p^4 6s^4 P_{3/2}$ . It was shown that the former is far more trustworthy than the latter. In the mean time an accurate measurement

<sup>14</sup> H. Arroe and J. E. Mack, Phys. Rev. **76**, 873 (1949).

<sup>15</sup> S. Suwa, J. Phys. Soc. (Japan) **8**, 734 (1953).

<sup>16</sup> The classification of the spectrum of  $\text{Zr I}$  was given by C. C. Kiess and H. K. Kiess, J. Research Natl. Bur. Standard **6**, 621 (1931).

<sup>17</sup> F. Alder and F. C. Yu, Phys. Rev. **81**, 1067 (1951).

<sup>18</sup> K. Murakawa and S. Suwa, Z. Physik **137**, 575 (1954).

<sup>19</sup> R. Sternheimer, Phys. Rev. **84**, 244 (1951); **86**, 316 (1952).

(atomic beam resonance method) of the hfs of the ground level  $5p^5\ ^2P_{3/2}$  of I r has been published by Jaccarino *et al.*<sup>20</sup> Using the spectroscopic notation to describe the hfs multiplet<sup>20,21</sup> in the form

$$E = E_0 + \frac{1}{2}AK + BK(K+1) + C[K^3 + 4K^2 + \frac{4}{5}K\{-3I(I+1)J(J+1) + I(I+1) + J(J+1) + 3\}],$$

$$K = F(F+1) - I(I+1) - J(J+1).$$

Their result can be summarized as follows:  $A = 827.265$  Mc/sec =  $0.0275755$  cm<sup>-1</sup>,  $B = 0.47765 \times 10^{-3}$  cm<sup>-1</sup>,  $C = 0.00454 \times 10^{-6}$  cm<sup>-1</sup>. The constant  $B$  determines  $Q(I^{127})$ . From the data of Jaccarino *et al.* Jache, Blevins, and Gordy<sup>22</sup> obtained  $Q(I^{127}) = -0.819 \times 10^{-24}$  cm<sup>2</sup>. If the wave function of  $5p^5\ ^2P_{3/2}$  of I r were pure, then  $\langle 1/r^3 \rangle_{av}$  could be simply eliminated from the expression for  $B$ , using the value of  $A$  and the nuclear induction value of  $\mu(I^{127})$ ; then the aforementioned value<sup>22</sup> of  $Q$  would be obtained. However in reality the wave function is perturbed in such a way that the expression for  $A$  is strongly modified and that for  $B$  is somewhat affected.

The configuration  $5s5p^56s$  gives rise to several levels, among which  $^2P_{3/2}^a$  and  $^2P_{3/2}^b$  must be given special consideration. In the spectrum of I r<sup>23</sup> the levels  $5s5p^5\ ^3P_2$  and  $5s^25p^36s\ ^5S_2$  lie  $81916$  cm<sup>-1</sup> and  $81040$  cm<sup>-1</sup> respectively higher than the ground level  $5s^25p^4\ ^3P_2$ . Then we can assume that in the case of I r the levels from the configuration  $5s5p^56s$  lie approximately  $10^5$  cm<sup>-1</sup> higher than the ground level. A calculation similar to that of Fermi and Segrè<sup>24</sup> and Koster<sup>25</sup> shows that  $A(5s^25p^5\ ^2P_{3/2})$  is diminished by a finite amount owing to the mixture of  $5s5p^56s\ ^2P_{3/2}^a$  and  $^2P_{3/2}^b$ . It is therefore not acceptable to use the value of  $A$  in the calculation of  $Q$ . We have therefore to use the value of  $B$  only, and the formula given by Koster<sup>25</sup> gives  $Q(I^{127}) = -0.68 \times 10^{-24}$  cm<sup>2</sup>, if we assume  $Z_p^* = 53 - 4 = 49$ , and  $Q(I^{127}) = -0.69 \times 10^{-24}$  cm<sup>2</sup>, if we assume  $Z_p^* = 53 - 3 = 50$ .

It is to be remarked that Koster's formula for  $Q$  is valid only when the configuration  $5s5p^56s$  is of  $LS$ -coupling. In reality this is not the case, and the true value of  $Q$  would be slightly larger than the above mentioned one. Giving larger weight to  $Q$  from  $5p^5\ ^2P_{3/2}$

than  $Q$  from  $5p^46s\ ^4P_{5/2}$ , we might consider

$$Q(I^{127}) = (-0.69 \pm 0.03) \times 10^{-24} \text{ cm}^2$$

the best value available at present.

#### IV. QUADRUPOLE MOMENTS OF Sb<sup>121</sup> AND Sb<sup>123</sup>

Using separated isotopes Sb<sup>121</sup> and Sb<sup>123</sup>, the author studied<sup>26</sup> the hfs of the level  $5p6s\ ^3P_2$  of Sb II and obtained the quadrupole moments  $Q(\text{Sb}^{121}) = (-0.52 \pm 0.10) \times 10^{-24}$  cm<sup>2</sup> and  $Q(\text{Sb}^{123}) = (-0.67 \pm 0.10) \times 10^{-24}$  cm<sup>2</sup>. When the polarization correction due to Sternheimer<sup>19</sup> is applied, they become

$$Q(\text{Sb}^{121}) = (-0.53 \pm 0.10) \times 10^{-24} \text{ cm}^2,$$

$$Q(\text{Sb}^{123}) = (-0.68 \pm 0.10) \times 10^{-24} \text{ cm}^2.$$

Using natural sample, Sprague and Tomboulia<sup>27</sup> studied the hfs of the levels of Sb II with  $J=1$ . They studied among others the level  $5p6s\ ^3P_1$  and concluded that this is perturbed by a close-lying level, and calculated the quadrupole moments to be  $Q(\text{Sb}^{121}) = -1.3 \times 10^{-24}$  cm<sup>2</sup> and  $Q(\text{Sb}^{123}) = -1.7 \times 10^{-24}$  cm<sup>2</sup>.

ST deduced the hfs of  $5p6s\ ^3P_1$  from the line  $\lambda 5895$  ( $5p6s\ ^3P_1 - 5p6p\ ^3P_0$ ). The hfs measurement of this line is disturbed by the strong helium line  $\lambda 5876$ , when the hollow cathode is cooled. The intensity of the disturbing helium line is suppressed only when the cathode is hot, but then the hfs components of  $\lambda 5895$  become somewhat diffuse.

In the present investigation some plates that were taken using a hot hollow cathode were measured, and it was found that a probable error of  $\pm 0.003$  cm<sup>-1</sup> must be admitted for the hfs. Since ST used a hot hollow cathode, one would be permitted to ascribe a probable error of  $\pm 0.003$  cm<sup>-1</sup> to their measurement. ST's virtual level, which should be  $133$  cm<sup>-1</sup> distant away from the level  $5p6s\ ^3P_1$ , was carefully searched for in the present work, and it was found that this is definitely nonexistent. Then the quadrupole moments can be calculated by the usual procedure without the assumption of perturbation of a close-lying level, and from ST's measurement of the hfs of  $\lambda 5895$ , it follows<sup>28</sup> that  $Q(\text{Sb}^{121}) = (-0.2 \pm 0.6) \times 10^{-24}$  cm<sup>2</sup> and  $Q(\text{Sb}^{123}) = (-1.2 \pm 0.6) \times 10^{-24}$  cm<sup>2</sup>. They agree, within the experimental error, with those derived from the level  $5p6s\ ^3P_2$ . However, as remarked in the previous work,<sup>26</sup> the level  $5p6s\ ^3P_1$  is not favorable for our purpose, owing to its small quadrupole effect. The same remark applies to the hfs of the level  $5p6p\ ^3D_1$  measured by ST. Thus the values of the quadrupole moments originally given by ST become invalid.

Loomis and Strandberg<sup>29</sup> calculated the upper and the lower limits of  $Q(\text{Sb}^{121})$  and  $Q(\text{Sb}^{123})$ , using their microwave data. In their calculation they used  $Q(I^{127})$

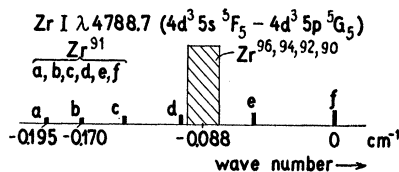


FIG. 3. Hfs of the line Zr I  $\lambda 4788.7$ .

<sup>20</sup> Jaccarino, King, Satten, and Stroke, Phys. Rev. **94**, 1798 (1954).

<sup>21</sup> H. B. G. Casimir and G. Karreman, Physica **9**, 214 (1942).  
C. Schwartz, Phys. Rev. **97**, 380 (1955).

<sup>22</sup> Jache, Blevins, and Gordy, Phys. Rev. **97**, 680 (1955).

<sup>23</sup> K. Murakawa, Z. Physik **109**, 162 (1938).

<sup>24</sup> E. Fermi and E. Segrè, Rendiconti della R. Acad. d'Italia **4**, 18 (1933); Z. Physik **82**, 729 (1933).

<sup>25</sup> G. F. Koster, Phys. Rev. **86**, 148 (1952).

<sup>26</sup> K. Murakawa, Phys. Rev. **91**, 1232 (1954).

<sup>27</sup> G. Sprague and D. H. Tomboulia, Phys. Rev. **92**, 105 (1953). This paper will be referred to as ST.

<sup>28</sup> K. Murakawa and S. Suwa, Phys. Rev. **76**, 433 (1949).

<sup>29</sup> C. C. Loomis and M. W. P. Strandberg, Phys. Rev. **81**, 798 (1951).

as a standard. When the new value derived in Sec. III of the present paper is substituted in their formula, their limits become  $Q(\text{Sb}^{121}) = (-0.52 \text{ to } -0.75) \times 10^{-24} \text{ cm}^2$ ,  $Q(\text{Sb}^{123}) = (-0.67 \text{ to } -0.93) \times 10^{-24} \text{ cm}^2$ , which agree satisfactorily with the values deduced here.

In the same way the discrepant values of  $Q$  published by Gordy<sup>22</sup> can be modified and brought into agreement with those obtained in the present work.

*Note added in proof.*—In the meantime the hfs of the line  $\text{Mo I } \lambda 4979$  ( ${}^5S_2 - {}^7D_1$ ) has been measured, and  $A[{}^5d^5({}^6S) {}^5S_2] = 0.011_2 \text{ cm}^{-1}$  and therefore  $a(5s) = -0.067 \text{ cm}^{-1}$  was obtained for  $\text{Mo}^{95}$ , where this  $A$  was obtained purely empirically. Comparing this with the nuclear induction value of  $\mu$ , we see that  $(dn^*/dn)/n^{*3}_{5s} (\text{Mo I}) = 0.44$  instead of  $0.37_5$  that was deduced purely spectroscopically in this article.

### Decay Scheme of $\text{In}^{107}\dagger$

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The gamma radiations of  $\text{In}^{107}$  have been investigated with a scintillation spectrometer. The  $\text{In}^{107}$  was produced in a cyclotron by a  $(d,n)$  reaction on electromagnetically enriched  $\text{Cd}^{106}$ . Beta-gamma and  $\gamma$ - $\gamma$  coincidence experiments showed, in addition to the annihilation radiation, only one  $\gamma$  ray of 0.22-Mev associated with the 2-Mev positron.

#### I. INTRODUCTION

THE radioisotope  $\text{In}^{107}$  was first reported by Mallary and Pool<sup>1</sup> as a product of deuteron and proton bombardment of cadmium enriched in  $\text{Cd}^{106}$ . They observed a positron activity with a 33-minute half-life and an energy of 2 Mev. While they report  $\gamma$  rays accompanying this decay, they give no energy values. The only other reference to this activity in the literature to date is one to a mass spectrometer study by Maclure<sup>2</sup> who confirmed the mass assignment of Mallary and Pool. No mention was made, however, of positron or  $\gamma$ -ray energy measurements.

Information on the radiations of the other isotopes formed in low-energy deuteron bombardments of cadmium is available in the literature.<sup>3</sup>

TABLE I. Mass analysis of cadmium oxide target materials.

Cadmium isotope	Atom percent	
	Natural <sup>a</sup>	Enriched <sup>b</sup>
106	1.215	19.94
108	0.875	0.65
110	12.39	7.21
111	12.75	39.16
112	24.07	11.85
113	12.26	4.14
114	28.86	15.25
116	7.58	1.80

<sup>a</sup> See reference 3.

<sup>b</sup> C. P. Keim (private communication), Head, Isotope Research and Production Division, Y-12 Research Laboratory, Carbide and Chemical Company, Oak Ridge, Tennessee.

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<sup>1</sup> E. C. Mallary and M. L. Pool, *Phys. Rev.* **76**, 1454 (1949).

<sup>2</sup> K. C. Maclure as given by reference 3.

<sup>3</sup> Hollander, Perlman, and Seaborg, *Revs. Modern Phys.* **25**, 469 (1953).

#### II. EXPERIMENTAL METHODS

Radioactive indium isotopes were produced by a  $(d,n)$  reaction in bombardments of cadmium oxide with 7.8-Mev deuterons in the University of Michigan cyclotron. Fifty milligram samples of Baker and Adams reagent-grade cadmium oxide were used initially while for the final bombardments 10–15 mg samples of cadmium oxide electromagnetically enriched in  $\text{Cd}^{106}$  were used. The enriched samples were obtained from the Isotope Research and Production Division, Carbide and Carbon Chemicals Corporation, Oak Ridge, Tennessee. Mass analyses of the materials are given in Table I. The indium was chemically separated from cadmium and silver activities produced by  $(d,p)$  and  $(d, \alpha)$  reactions upon cadmium and from activities arising from neutron reactions on impurities such as lead and zinc in the cadmium oxide target. Bombardment products of the oxygen in the target caused no interference.

The cadmium oxide target was dissolved in concentrated nitric acid containing carriers of silver, indium, lead, thallium, bismuth, zinc, copper, and gallium. The chlorides of silver, thallium, and lead were precipitated with a few drops of 1*N* HCl, digested, filtered and discarded. From the filtrate, indium, gallium, lead, and bismuth hydroxides were precipitated with concentrated  $\text{NH}_4\text{OH}$ , filtered and washed. They were dissolved in 6*N*  $\text{H}_2\text{SO}_4$  and boiled to precipitate  $\text{PbSO}_4$ , which was discarded. Finally the filtrate was made basic with concentrated NaOH to reprecipitate the bismuth and indium hydroxides, leaving the gallium in solution as the soluble gallate ion. Bismuth was removed from the indium by dissolving these hydroxides in 5% HCl, precipitating bismuth cupferrate with an excess of cupferron (ammonium phenylnitrosohydroxylamine) and filtering. Each carrier was again added and the