In particular for $|k|=1$ (the only case for which the corrections are significant), we have

$$Y(p_{\frac{1}{2}})=1-3\left(\frac{1-\rho}{1+\rho}\right)[1-Y(s_{\frac{1}{2}})]. \qquad (V,9)$$

VI. COMPUTATION OF THE NUCLEAR MAGNETIC MOMENT OF $_{80}Hg^{199}$

As an illustrative example, we shall compute the nuclear magnetic moment of $_{80}Hg^{199}$ starting from the ground state $6s\,{}^2S_{\frac{1}{2}}$ of the $_{80}Hg^{199}$ II ion. For this state, the quantities involved in the (I,1) formula are: $n_*=1.703\,396$; $Z_i=80$; $Z_0=2$; $\chi(\frac{1}{2},80)=2.257\,306$; $(1-d\sigma/dn)=1.236\,539$ (determined by the method of finite differences and by the extrapolation of the resulting series on the basis of the D'Alembert convergence criterion). The interval factor a_{6s} determined by the hyperfine structure[5] is 1.358 cm^{-1}. With these data, we find the following value for μ_0:

$$\mu_0=0.442\,149\mu_N. \qquad (VI,1)$$

In order to compute Y we take into account the fact that the nuclear state of $_{80}Hg^{199}$ is given by the odd neutron $p_{\frac{1}{2}}$ and that $_{80}Hg^{199}$ fits in Schmidt's diagram. The characteristic values which are included in the expression of Y are: $\alpha_L=0$; $\alpha_S=1$, $r_0=1.216\times10^{-13}A^{\frac{1}{3}}$ cm, $(5/3)\langle(R/R_0)^2\rangle_{Av}\approx1$. The value of Y is

$$Y=0.879\,825. \qquad (VI,2)$$

On the other hand, the magnetic resonance test gives

$$\mu_R=0.4993\cdots, \qquad (VI,3)$$

while the diamagnetic correction D is

$$D=0.990\,348. \qquad (VI,4)$$

By using the ratios (I,3), we obtain the following values for the moment:

(1) From hyperfine structure,

$$\mu=\mu_0/Y=0.5031. \qquad (VI,5)$$

(2) From magnetic resonance,

$$\mu=\mu_R/D=0.5041. \qquad (VI,6)$$

[5] S. Mrozowski, Phys. Rev. **57**, 207 (1940).

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Excited Levels in Mn^{56}†

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The half-lives of the first three excited levels of Mn^{56} have been measured by looking at the cascade gamma rays from neutron capture in Mn^{55}. They are found to be 10.7^{+2}_{-3} mμsec, 4.9±0.6 mμsec, and ⩽0.5 mμsec. A fairly plausible assignment of spins and parities to the first, second, and third excited levels of Mn^{56} would seem to be 2^+, 1^+, and 2^+, respectively. The technique described in the paper should be useful in those cases in which excited levels of unstable nuclei cannot be reached through beta decay.

I. INTRODUCTION

Excited states of Mn^{56} were investigated by Green *et al.*[1] by means of the $Mn^{55}(d,p)Mn^{56}$ reaction. More recently, gamma-ray spectra from neutron capture in resonances of Mn^{55} have been investigated by Kennett *et al.*[2] In Fig. 1, from the paper of Kennett *et al.*, are shown the first three excited states of Mn^{56} and the transitions observed following neutron capture in Mn^{55}. The 210-kev level and the 109-kev level are fed directly from the capture state. The 210-kev level is fed predominantly at the 1080-ev ($J=3^-$) resonance; the 109-kev level at the 337-ev ($J=2^-$) resonance. The ground level of Mn^{56} is known to be a 3^+ state.[3,4]

This paper describes the measurement of the half-lives of the first three excited levels of Mn^{56}. A beam

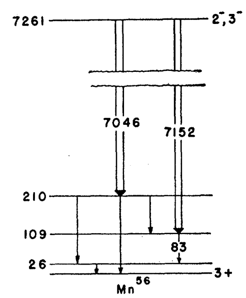


FIG. 1. Excited states of Mn^{56} and the transitions observed following neutron capture in Mn^{55}.

† This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] Green, Smith, Buechner, and Mazari, Phys. Rev. **108**, 841 (1957).

[2] Kennett, Bollinger, and Carpenter, Phys. Rev. Letters **1**, 76 (1958).

[3] Childs, Goodman, and Kieffer, Phys. Rev. Letters **1**, 296 (1958).

[4] Strominger, Hollander, and Seaborg, Revs. Modern Phys. **30**, 628 (1958).

of thermal neutrons from the Argonne CP-5 reactor irradiates a thin Mn target and the delay between following capture gamma rays is measured with a fast time-to-amplitude converter of the kind described by Green and Bell.[5]

II. EXPERIMENTAL SETUP

The neutron beam from the Argonne CP-5 reactor is collimated by means of lead and brass cylinders with holes $\frac{3}{8}$ in. in diameter and Cd slits with holes of the same size. A Pb absorber about 3 in. thick is placed in the beam to reduce the gamma-ray background from the reactor. The target is a thin Mn foil, 3 cm×3 cm and ~15 mg/cm² thick, set at approximately 45° to the direction of the beam.

Two scintillation counters are set 5 cm apart on a line perpendicular to the neutron beam. Lead bricks shield the counters from the gamma-ray background in the room and from the radiation from the reactor. In addition, paraffin and Cd are used between the reactor and the counters (Fig. 2). To detect the "prompt" gamma ray, a plastic scintillator $1\frac{1}{2}$ in. high and 2 in. in diameter is used with an RCA-6342 photomultiplier. The "delayed" gamma ray is detected by a

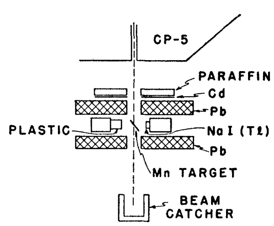


FIG. 2. Experimental setup (not to scale).

NaI(Tl) crystal, $\frac{1}{4}$ in. thick and $1\frac{1}{2}$ in. in diameter, viewed by an RCA-6810A photomultiplier. The time-to-amplitude converter is essentially like the one described by Green and Bell. It is based on a 6BN6 tube working at unusually low electrode voltages. A supervisory diode coincidence avoids double-valued time-to-amplitude conversion. A fast-slow coincidence system allows the energy selection of the pulses from the two photomultipliers. The pulses from the time-to-amplitude converter are amplified and recorded in an Argonne-type 256-channel analyzer.

III. RESULTS

As a check on the equipment, the half-life of the first excited level of W^{182} was measured by use of a Ta^{182} sample obtained by irradiating Ta^{181} with thermal neutrons. The value obtained is 1.4±0.2 mμsec, in agreement with a previous determination.[6] Then the half-lives of the first three excited levels of Mn^{56} were measured.

An energy spectrum of the gamma radiation from the Mn target under neutron bombardment is given in

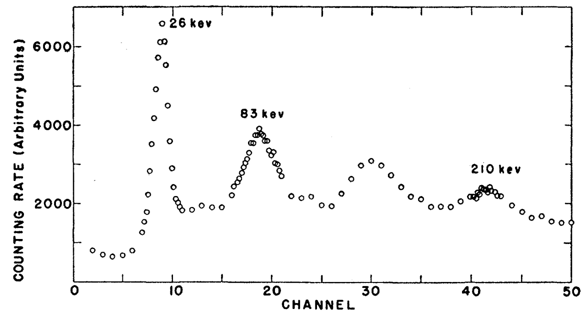


FIG. 3. Energy spectrum of the gamma radiation from the Mn target. (Data obtained with NaI crystal.)

Fig. 3. It was obtained with the NaI(Tl) crystal. The energy scale was calibrated by means of the radiation from Mn and from the Ta^{182} source used for the initial check of the equipment. Three of the four peaks in Fig. 3 were attributed to the 26-, 83-, and 210-kev gamma rays from Mn^{56}. The peak at about 140 kev was probably due to gamma rays from neutron capture in the iodine of the NaI(Tl) crystal. That it was not due to gamma rays from the Mn target was proved with an absorption measurement. The peak at 83 kev was completely absorbed by 5 mm of Pb, while the one at about 140 kev was very slightly affected. Absorption measurements with thin Pb absorbers definitely proved that the 26-kev peak was due to gamma rays from the Mn target.

After these preliminary measurements, an attempt was made to measure the half-lives of the first three excited levels of Mn^{56}. In each case it was required that the energy spent in the NaI(Tl) crystal by the "delayed" gamma ray should be within a fairly narrow window centered at 26, 83, and 210 kev, respectively. A comparison run was always made with a "prompt" source which was either a Co^{60} source inserted in place of the Mn target, or the gamma background in the room, which gave "prompt" coincidences when a high-energy gamma ray suffered a Compton scattering in the plastic scintillator and the scattered gamma was detected in the NaI(Tl) crystal. The energy spent by the "prompt" gamma in the plastic scintillator was required to be above a few hundred kev.

The half-lives of the first and second excited levels were measured in two different ways: (a) from the slope of the "delayed" curve far from the "prompt" peak, and (b) by an extension of Newton's[7] method to the case in which the recorded coincidences are due to a superposition of a "prompt" and a "delayed" source. The decay constant of the delayed radiation is given in such a case by

$$\lambda=\frac{[F(x_1)-F(x_0)]-A_2[P(x_1)-P(x_0)]}{\int_{x_0}^{x_1}[F(x)-P(x)]dx},$$

[5] R. E. Green and R. E. Bell, Nuclear Instr. **3**, 172 (1958).
[6] V. S. Dzelepov and L. K. Peker, Atomic Energy of Canada Limited Report AECL-457, 1957 (unpublished).
[7] T. D. Newton, Phys. Rev. **78**, 490 (1950).

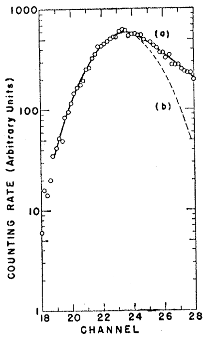
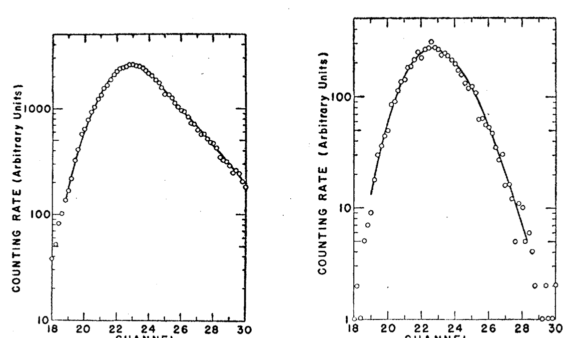


FIG. 4. (a) "Delayed" curve for the first excited level of Mn^{56} (solid curve and experimental points). (b) "Prompt" curve for the first excited level of Mn^{56} (dashed curve).

where the notation is the same as in Newton's paper, and A_2 is the fraction of the total radiation which is "prompt." In Figs. 4(a) and 5(a) are given the results for the first and the second excited levels of Mn^{56}; Figs. 4(b) and 5(b) are the corresponding "prompt" curves. The results shown in Figs. 6 and 7 were obtained under the same conditions as for Figs. 4(a) and 5(a), except one of the two pulses feeding the time-to-amplitude converter was delayed to observe the very end of the tail of the "delayed" distributions, far from the "prompt" peak. Analysis of the data for the second excited level gives a value of $T_{\frac{1}{2}}=4.9\pm0.6$ mμsec, when looking at the slope of the curve in Fig. 7. Newton's method would give a half-life between ~4.8 and ~5.8 mμsec. The fairly close agreement between the two determinations seems to indicate that the measured half-life is indeed that of the 83-kev radiation and not of a higher energy radiation which suffered an energy loss of ~83 kev in the crystal. To exclude this possibility, however, the same runs were repeated as in Figs. 5(a) and 5(b), except that the window of the pulse-height analyzer for the energy of the "delayed" gamma ray was moved a few channels above the peak at 83 kev. The results of the measurements for the "delayed" source and for the "prompt" source are given in Figs. 8(a) and 8(b), respectively. It is immediately obvious, by comparison of Figs. 5(a) and 8(a), that a few channels above the peak at 83 kev the



(a) (b)

FIG. 5. (a) "Delayed" curve for the second excited level of Mn^{56}. (b) "Prompt" curve for the second excited level of Mn^{56}.

ratio of delayed to prompt coincidences strongly decreases.

The first excited level has been analyzed in a similar way. Newton's method gives a half-life between ~8 and ~11 mμsec. From the slope of the "delayed" curve far from the "prompt" peak one gets $T_{\frac{1}{2}}=10.7\pm2$ mμsec. This value might be somewhat high because the first excited level is sometimes fed through the

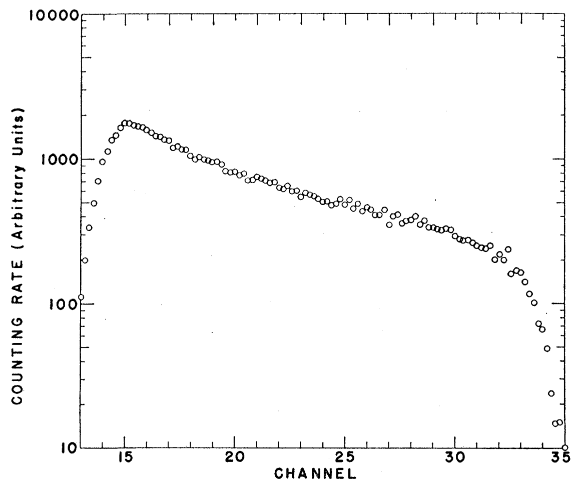


FIG. 6. "Delayed" curve for the first excited level of Mn^{56}. One of the two pulses to the time-to-amplitude converter is artificially delayed.

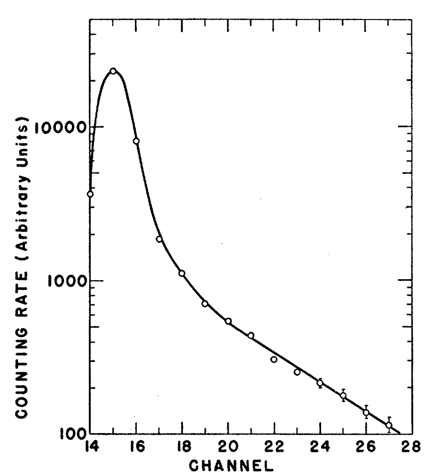


FIG. 7. "Delayed" curve for the second excited level of Mn^{56}. One of the two pulses to the time-to-amplitude converter is artificially delayed.

de-excitation of the second level, which has a half-life of 4.9 mμsec. The correction for this effect can be calculated easily for the case in which the first level is fed by the 83-kev gamma ray and the "prompt" gamma is from de-excitation of the capture state. For such a case, which obviously represents a limit to the actual situation, the "true" half-life of the first level would be about 1 mμsec smaller than the value observed

as described above. Thus one may reasonably assume that $T_{\frac{1}{2}}=10.7^{+2}_{-3}$ mμsec for the first level. From Figs. 9(a) and 9(b) one can obtain an upper limit of ~0.5 mμsec for the half-life of the third level. The ratio of the intensity of the "delayed" to that of the "prompt" radiation at ~210 kev is too small to allow a smaller upper limit than the one above.

IV. CONCLUSIONS

The results of Sec. III allow an assignment of the spins and parities of the first three excited levels of Mn^{56}. The levels at 109 and 210 kev are fed directly from the capture states. The 7046- and 7152-kev transitions are most likely $E1$ transitions. The parities of the 109- and 210-kev levels, therefore, should both be positive. From the relative intensities of the transitions observed after neutron capture in manganese resonances, it appears that the 109-kev level is fed predominantly from the 2^- capture state and the

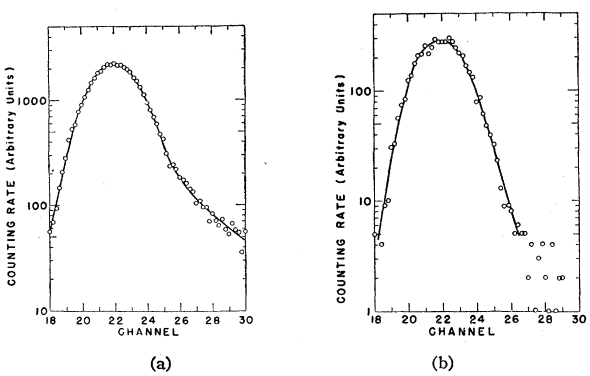


FIG. 8. (a) "Delayed" curve with the window of the pulse-height analyzer of the "delayed" gamma slightly above 83 kev. (b) "Prompt" curve. The window of the pulse-height analyzer is the same as in (a).

210-kev level from the 3^- level. The 109-kev level could then be either a 1^+, 2^+, or 3^+ state, and the 210-kev level a 2^+, 3^+, or 4^+ state. According to Weisskopf's[8] predictions, the 83-kev transition from the 109-kev to the 26-kev level, with a half-life of 4.9 mμsec, is very likely an $M1$ transition. The same should be true for the 26-kev transition, with a half-life of 10.7 mμsec. These statements are supported by the fact that, in this region of the periodic table, half-lives for $M1$ transitions are fairly close to Weisskopf's predictions.[6] The 109-kev transition from the 109-kev level to the 3^+ ground level has not been observed.

[8] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 627.

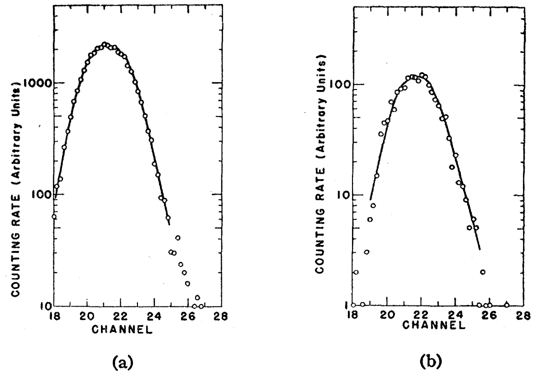


FIG. 9. (a) "Delayed" curve for the third excited level of Mn^{56}. (b) "Prompt" curve for the third excited level of Mn^{56}.

This fact supports the view that the 109-kev level is 1^+. The 26-kev level, decaying through an $M1$ transition, could be a 2^+, 3^+, or 4^+ state. The transition to it from the 109-kev level is $M1$ so the only choice seems to be 2^+.

For the third excited level one finds $T_{\frac{1}{2}}\leqslant 0.5\times 10^{-9}$ sec. The transition from the 210-kev to the ground level, between two states of positive parity, cannot be $E1$. The half-lives for the 210-kev transition predicted by Weisskopf's formulas for $M1$ and $E2$ transitions are $\sim 2\times 10^{-12}$ sec and $\sim 5\times 10^{-9}$ sec, respectively. These values may well be smaller than the actual ones (perhaps as small as a hundredth of them), but it is unlikely that they are greater. It would then seem reasonable to assume that the 210-kev transition is $M1$. If the transition from the 210-kev to the 109-kev level were an $E2$ or a higher multipole (the next possible would be an $M3$), it probably would not be observed at all because the 210-kev level decays through an $M1$ transition of higher energy (210 kev). If it is assumed that the transition from the 210-kev to the 109-kev level is $M1$, then, because the 109-kev level is 1^+, the only possibility left for the 210-kev level would seem to be 2^+.

In conclusion, a fairly plausible assignment of spins and parities to the first, second and third excited levels of Mn^{56} would seem to be 2^+, 1^+, and 2^+, respectively.

It should be noted that the technique described in this paper might turn out to be useful in all those cases in which, as in Mn^{56}, the excited levels of an unstable nucleus cannot be reached directly by beta decay.

ACKNOWLEDGMENT

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