Decay Scheme of Co^{62}†

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A study of the decay of Co^{62} has been made using β- and γ-scintillation techniques. The Co^{62} was produced by a (d,α) reaction on nickel oxide enriched in Ni^{64}. A half-life of 13.91 minutes with a calculated standard deviation of ± 0.05 minute was measured. Two beta groups of 0.88 ± 0.04 and 2.88 ± 0.03 Mev energy were found, with relative abundances of 25% and 75%, respectively. Both β-ray transitions appear to be allowed. Gamma rays of 1.17 ± 0.01, 1.47 ± 0.02, 1.74 ± 0.03, and 2.03 ± 0.03 Mev were measured, with relative percentages of 100% and 82% for each member of the 1.17-Mev doublet, and 18%, 18%, and 7% for the others, respectively. A much weaker γ ray with an energy of $\sim 2.5\pm 0.2$ Mev and an intensity of less than 2% was also noted. A level scheme incorporating these data is presented. All energy errors are estimated standard deviations.

I. INTRODUCTION

ONLY a few reports in the literature refer to the decay of Co^{62} and the energy levels of its decay product, Ni^{62}. In 1949 Parmley and co-workers[1] found that the half-life of the Co^{62} ground state decay was 13.9 minutes. They measured a maximum β-ray energy of 2.3 Mev by absorption, and noted the presence of γ rays of about 1.3 Mev. They also found a much shorter-lived activity of 1.6 minutes that emitted both β and γ rays and assigned it to an isomeric state of Co^{62}.

In 1954 Nussbaum *et al.*[2] measured a maximum β-ray energy of 2.8 ± 0.2 Mev for Co^{62} in addition to a number of γ rays (Table I). Kraushaar *et al.*[3] have also recently found a similar group of γ rays (Table I) in connection with the positron decay of Cu^{62}. Since over 98% of the Cu^{62} decay is to the ground state of Ni^{62}, the values reported for these γ rays are somewhat tentative. Recently Spencer *et al.*[4] have found evidence of excited states in Ni^{62} at energies of 1.171, 2.047, and 2.304 Mev by inelastic scattering of protons from nickel foils enriched in Ni^{62}. A search of the literature up to March, 1957 has revealed no further work on this isotope.

II. EXPERIMENTAL METHODS

The Co^{62} was produced by the (d,α) reaction on a nickel oxide target enriched in Ni^{64}. The enriched target material was obtained from the Isotope Research and Production Division, Union Carbide and Carbon Chemicals Company, Oak Ridge, Tennessee. Table II lists the isotopic percentages, along with the spectrographic analysis for the target material. Usually about 50 mg of the oxide were enclosed in a 1.5-mil aluminum envelope for the bombardment in the 7.8-Mev deuteron beam of the University of Michigan cyclotron. A chemical separation was necessary to separate the cobalt from the copper and nickel activities produced by (d,n) and (d,p) reactions in the target element as well as from the products of these reactions on impurity elements. Information on the characteristics of the isotopes that might be produced by low-energy deuteron bombardment of nickel isotopes is available in the literature.[5] Bombardment products of the oxygen in the target caused no interference.

The nickel oxide target was dissolved in 10*N* HCl. It was then placed on an ion-exchange column with a Dowex-2 resin-bed 8 mm in diameter and 140 mm tall that had been previously washed with concentrated HCl. The nickel was first removed by elution with 8*N* HCl, and then the cobalt removed with 4*N* HCl. The copper remains on the column. The cobalt fraction was mounted for γ-ray measurements by evaporation onto a thin cover glass. For β-ray measurements the cobalt fraction was evaporated to dryness, taken up in water, and finally mounted on $\frac{1}{4}$-mil aluminum-coated Mylar films.

The radiations were examined with the γ-ray scintillation spectrometer and coincidence apparatus described

TABLE I. Radiations emitted during the decay of Co^{62} and Ni^{62}. Relative abundances are given in parentheses.

	Energy in Mev		
	This work[a]	Nussbaum *et al.*[b]	Kraushaar *et al.*[c]
γ_1	1.17 ± 0.01 (182)	1.0 (40) 1.17 ± 0.03 (100)	1.18 ± 0.02 (~ 1)
γ_2	1.47 ± 0.02 (18)	1.5 (5)	1.36 ± 0.02 1.46 ± 0.03 1.55 ± 0.02
γ_3	1.74 ± 0.03 (18)	1.7 (10)	1.67 ± 0.02
γ_4	2.03 ± 0.03 (7)	2.0 (15)	1.98 ± 0.03
γ_5	2.5 ± 0.2 (<2)	2.5 (~ 3)	2.24 ± 0.03 0.66 ± 0.03 (~ 1) 0.86 ± 0.03 (~ 1)
β_1	0.88 ± 0.04 (25 ± 3)		
β_2	2.88 ± 0.03 (75 ± 3)	2.8 ± 0.2	

[a] Errors are standard deviations, estimated in the case of β rays.
[b] See reference 2.
[c] See reference 3.

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[1] Parmley, Moyer, and Lilly, Phys. Rev. **75**, 619 (1949).
[2] Nussbaum, Wapstra, van Lieshout, Nijgh, and Ornstein, Physica **20**, 571 (1954).
[3] Kraushaar, Brun, and Meyerhof (private communication to K. Way in June, 1955). See reference 5, p. 80.
[4] Spencer, Phillips, and Young, Bull. Am. Phys. Soc. Ser. II, **2**, 105 (1957).
[5] *Nuclear Level Schemes*, $A=40$—$A=92$, compiled by Way, King, McGinnis, and van Lieshout, Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).

previously.[6] Since the half-life of Co^{62} is relatively short, a photographic method was used to obtain coincidence information.[7] For this method one channel of the coincidence spectrometer was set on a group of pulses while the second channel was allowed to scan the entire spectrum. Pulses from the linear amplifier of the second channel were at the same time fed to an oscilloscope after first passing through a 4-μsec delay line. The output of the coincidence analyzer would trigger a monostable multivibrator whose output was a 20-μsec square wave. This square wave was applied to the Z axis of the oscilloscope so that when a coincidence occurred the oscilloscope's trace would be illuminated, and thus display only the pulse causing the coincidence with the first channel.

The β-ray spectrum was measured by using a specially constructed hollow plastic scintillator which will be described in detail elsewhere. This particular scintillator was designed to handle a maximum β-ray energy of 3.6 Mev. Corrections were made for the resolution of the instrument,[8] for the energy loss in air and in the sample cover, and also for the γ-ray background.

The Kurie analyses were carried out on an IBM 650 digital computer located at the University of Michigan. Tables of the Fermi function and screening correction were taken from *Tables for the Analysis of Beta Spectra*.[9]

The $\gamma-\gamma$ coincidence studies were carried out using two $1\times1\frac{1}{2}$ in. NaI (Tl) crystals. A 1.6-g/cm^2 Al absorber was placed between the sample and each crystal. For the $\beta-\gamma$ coincidence studies, one of the crystals was replaced by the plastic scintillator previously described and no absorber was used between the source and this scintillator.

Calibration of the γ-ray spectrometer was accomplished by using γ rays of known energy from the following isotopes: In^{114}, Sn^{113}, Cs^{137}, Zn^{65}, and Co^{60}. The β-ray spectrometer was calibrated in the following way. A preliminary calibration was first made by using the conversion electron peaks of In^{114}, Sn^{113}, and Cs^{137}. Next a known β-ray spectrum was run by using a beta emitter of appropriate energy (such as In^{114} or Sr^{90}-Y^{90}). A Kurie plot of the known spectrum was then made, and examined for the proper end point and shape. In this way drift in the spectrometer could be detected and corrected for, although in only a few cases was drift found.

TABLE II. Analysis of nickel oxide target material.

Mass analysis	
Nickel isotope	Atom percent enriched[a]
58	1.99±0.10
60	1.20±0.05
61	0.14±0.01
62	0.77±0.03
64	95.90±0.16
Spectrographic analysis	
Element	Percent
Cu	0.05
Fe	0.02
Mn	0.01

[a] This mass analysis was furnished by the Isotope Research and Production Division, Y-12 Research Laboratory, Union Carbide and Carbon Chemicals Company, Oak Ridge, Tennessee (C. P. Keim, private communication).

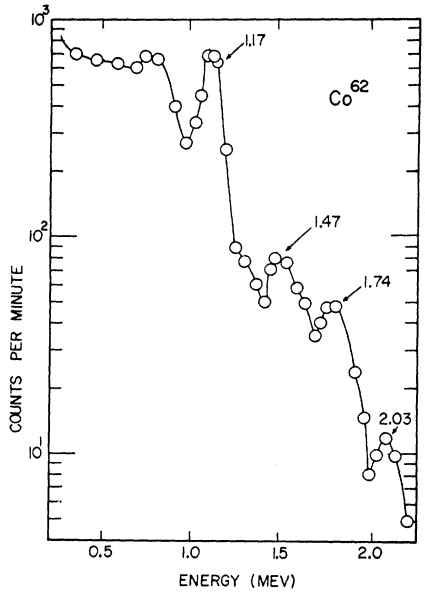

FIG. 1. Gamma-ray spectrum of Co^{62}.

III. RESULTS

The half-life of Co^{62} was determined to be 13.91 ±0.05 minute (calculated standard deviation by least squares) by following the decay of the γ rays in a scintillation-well-type counter. The decay curve showed only a small amount of the 2.56-hour Ni^{65} and the 12.8-hour Cu^{64} present. No other cobalt activity could be seen.

Gamma-ray energies were measured primarily by photographing oscilloscope presentations of the output of the linear amplifier, and also by plotting the output of a counting-rate meter which was connected to the single-channel pulse-height analyzer. Figure 1 shows a typical γ-ray spectrum of Co^{62} taken from a series of measurements by the latter method. The γ-ray energies and errors listed in Table I were obtained by averaging a number of photographic measurements (e.g., 32 measurements for the 1.17-Mev γ ray).

An abundant γ-ray transition was found at 1.17±0.01 Mev in addition to four higher energy γ rays at 1.47 ±0.02, 1.74±0.03, 2.03±0.03, and 2.5±0.2 Mev. The last four γ rays had abundances of 11%, 11%, 4%, and <1%, respectively, relative to 100% for the 1.17-Mev

[6] W. A. Cassatt and W. W. Meinke, Phys. Rev. **99**, 760 (1955).
[7] D. G. Gardner and R. W. Shideler, Atomic Energy Commission, Report AECU-3397, April, 1957 (unpublished).
[8] J. P. Palmer and L. J. Laslett, Atomic Energy Commission Report AECU-1220, March, 1951 (unpublished).
[9] *Tables for the Analysis of Beta Spectra*, U. S. National Bureau of Standards, Applied Mathematics Series No. 13 (U. S. Government Printing Office, Washington, D. C., 1955).

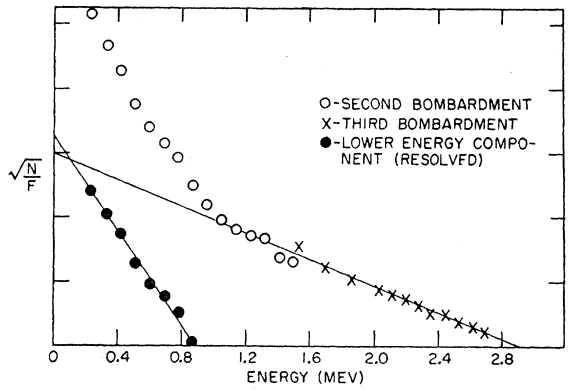

FIG. 2. Kurie plot of Co^{62}.

γ ray. The abundances were obtained by integration of the areas under the photopeaks after subtraction of the Compton distribution of the higher energy γ rays and the background. The areas were then corrected for the "photoelectric yield" of the crystal by use of the curves of McLaughlin and O'Kelley.[10]

A tentative decay scheme based on the γ-ray information, permitted three β-ray groups: transitions with end points 0.8 Mev, 2.3–2.5 Mev, and 2.8 Mev. A complete β-ray spectrum with good statistical reproducibility could not be obtained on one single sample because of the short half-life of the Co^{62}. Therefore, it was necessary to combine the results of two bombardments to obtain the one beta spectrum shown in Fig. 2. Each point on the curve was corrected for the 14-minute Co^{62} decay both throughout the course of the entire plot and during the time of an individual count. Correction was also made for the γ-ray background in the plastic scintillator.

Since the higher energy end of the β-ray spectrum yielded a Kurie plot straight down to 1.5 Mev, the 2.3–2.5 Mev transition postulated above was presumed to be absent. The total Kurie plot, when corrected for instrument resolution, could be resolved into two components: a 0.88 ± 0.04 and a 2.88 ± 0.03 Mev transition with relative abundances of $25\pm3\%$ and $75\pm3\%$, respectively. The $\log(ft)$ values of 4.5 and 5.8, respectively, for these β rays indicate that both transitions are allowed. This conclusion is borne out, in the case of the 2.88-Mev β ray, by the shape of the Kurie plot. While the shape of the lower energy group also appears to be allowed, it is subject to the usual subtraction errors.

If it is assumed that the 2.88-Mev β-ray group populates the 1.17-Mev γ-ray level, the γ-ray intensities calculated from the observed β-ray intensities differed from the observed γ-ray intensities by about a factor of 2. Furthermore, the total disintegration energy for Co^{62} predicted from β-ray systematics is about 5 Mev, whereas the 2.88-Mev β-ray and the 1.17-Mev γ-ray transitions add up to only about 4 Mev. These difficulties are resolved if it is assumed that a cascade doublet follows the higher energy β ray. Both γ rays would have an energy of about 1.17 Mev with an energy difference of only a few percent. The corrected percentage abundances for the 1.17 (doublet), 1.47, 1.74, 2.03, and 2.5-Mev γ rays then become 100% and 82% for the doublet, 18%, 18%, 7%, and <2%, respectively.

Information obtained photographically by $\beta-\gamma$ coincidence measurements showed only the 1.17-Mev γ ray in coincidence with β rays above 1.2 Mev. Measurements of $\gamma-\gamma$ coincidences with the 1.17-Mev γ ray showed strong coincidences with a γ ray at 1.17 Mev, and also with higher energy γ rays.

IV. CONCLUSIONS

The above information has been correlated into the level diagram shown in Fig. 3. In the nuclide $_{27}Co_{35}{}^{62}$ the ground-state configuration of the protons is $[(1f_{7/2})^{-1}]_{7/2}$, using the notation of Mayer. The ground-state configuration of the neutrons is somewhat less uniquely predictable. Here both the $(2p_{3/2})$ and the $(1f_{5/2})$ levels are relatively close together in energy.[11] A consideration of the other nuclides in this neutron range indicates that the probable configuration is $[(2p_{3/2})^{-1}]_{3/2}[(1f_{5/2})^{-2}]_0$. According to Nordheim's "weak" rule,[12] the proton and neutron spins will tend to add, giving a resultant spin of 4 or 5 and even parity.

In the case of $_{28}Ni_{34}{}^{62}$, the $(1f_{7/2})$ proton shell is clearly filled with a resultant spin of 0. Again the neutron configuration is unclear, but is probably $[(2p_{3/2})^{-2}]_0[(1f_{5/2})^{-2}]_0$ so that the ground state of Ni^{62} would have 0 spin and even parity. The first excited state of Ni^{62} is very probably 2+. The second excited

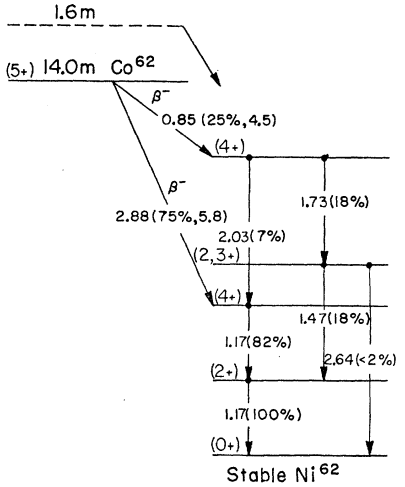

FIG. 3. Decay scheme of Co^{62}.

[10] P. W. McLaughlin and G. D. O'Kelly, Atomic Energy Commission Report MTA-40, September, 1953 (unpublished).

[11] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley and Sons, Inc., New York, 1955).

[12] L. A. Nordheim, Revs. Modern Phys. **23**, 322 (1951).

state at 2.34 Mev and the fourth at 4.37 Mev are both required to have high spins and even parity since the ground state of the parent is 4+ or 5+ and both β-ray transitions are allowed. A spin of 4+ for the second excited state is reasonable from the shell model.

The 2.5-Mev γ ray is too intense to be the result of a crossover transition from the second excited state to the ground state and therefore must arise from the third excited level. Hence the order of the 1.74- and 1.47-Mev γ rays given in Fig. 3 is the most likely. This would require a spin of 2 or 3 for the third level. The fact that the third level is not populated by β decay, together with the ratio of the intensities of the 1.74- and 2.03-Mev γ rays, suggest the following level assignments: spin 3+ or 2+ for the third level, spin 4+ for the fifth level, and spin 5+ for the ground state of Co^{62}.

The 1.6-min isomer of Co^{62} found by Parmley[1] was not found here due to the length of time required by the chemical separation. It is quite reasonable to expect, however, that the first excited state of Co^{62} would have a proton configuration of $[(1f_{7/2})^{-1}]_{7/2}$, and a neutron configuration of $[(1f_{5/2})^{-3}]_{5/2}$. These would couple to give a spin of 1+, producing an isomeric state with an energy not much above ground state. This first excited state would have a high probability of decaying directly to the ground state of Ni^{62}. For the sake of completeness this hypothetical excited level has been included in Fig. 3.

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Time-Dependent Hartree-Fock Theory of Nuclear Collective Oscillations*†

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A theory of nuclear collective oscillations is presented which does not involve introducing extra variables and subsidiary conditions. This time-dependent self-consistent field method is applied to the breathing mode of a spherically symmetric nucleus and yields a value for the frequency of oscillation which is more accurate than that from a previous treatment in terms of one-nucleon excitation, but which becomes identical to the latter in the case of weak nucleon-nucleon interaction. In cases where nucleon exchange can be neglected, the new estimate reduces to the frequency derived from the simple classical theory of a compressible fluid. By means of an electric monopole sum rule which is derived for $T=0\rightarrow T=0$ transitions, it is shown that in general the classical formula overestimates the breathing mode frequency. From the sum rule it also follows that the 6.06-Mev 0^+ state in O^{16} is related only indirectly to the breathing mode, which must itself be at a higher excitation energy.

I. INTRODUCTION

IN an earlier publication[1] it was shown how a collective oscillation in a nucleus could be identified as the coherent superposition of one-nucleon excitations. This identification depended on an approximate treatment of the Hill-Wheeler-Griffin[2] wave function. The purpose of the present note is to outline in a very idealized case a time-dependent self-consistent field treatment of collective oscillations which can be formulated within the framework of the shell model, but which does not suffer from the approximation made in reference 1. In order to emphasize the essential features of the approach, we shall limit ourselves to the breathing mode (the simplest type of nuclear oscillation) in a fictitious mass-twelve nucleus composed of a vacant $1s$ shell and a filled $1p$ shell. This has enough nucleons to exhibit collective effects without the complication of coupled shell vibrations. The fact that such a nucleus (actually an excited state of C^{12}) would in fact be unstable need not concern us here, since we can consider that the parts of the nuclear interaction which would give rise to $1p-1s$ transitions have been removed from the Hamiltonian. This procedure does not affect the $1p-2p$ transitions, which are the ones involved in the breathing mode.

II. MONOPOLE SUM RULE

The degree of the inaccuracy of the one-nucleon approximation to a breathing mode excitation can be most easily exhibited by considering a sum rule for electric monopole transitions. Following Sachs and Austern,[3] we consider the double commutator of the

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† A report on this work has been presented at the 1957 New York Meeting of the American Physical Society [Bull. Am. Phys. Soc. Ser. II, 2, 26 (1957)].
[1] R. A. Ferrell and W. M. Visscher, Phys. Rev. **102**, 450 (1956).
[2] References 3 and 4 of reference 1.
[3] R. G. Sachs and N. Austern, Phys. Rev. **81**, 705 (1951).