New Isomer: ^{68m}Cu†

T. E. WARD, H. IHOCHI, AND J. L. MEASON
Department of Chemistry, University of Arkansas, Fayetteville, Arkansas 72701

(Received 6 August 1969)

Irradiation of natural Zn, Ga, and enriched ^{68}Zn with 14.7-MeV neutrons was found to produce a new radioactivity with a half-life of 3.8±0.1 min which was assigned as an isomer of ^{68}Cu. The energies and relative intensities of those γ rays associated with the decay of 3.8-min ^{68m}Cu are: 0.085±0.001, 0.110±0.001, 0.153±0.001, 0.525±0.001, 0.577±0.002, 0.635±0.001, 1.078±0.002, 1.260±0.002, and 1.338±0.002 MeV, with relative intensities of 94.8±06., 25.7±1.0, 6.1±0.8, 100.00, ~2.4, 15.8 (some summing of 0.525–0.110 MeV), 83.3±1.3, 14.1±2.0, and 11.8±3.0, respectively. A maximum β-ray endpoint energy of 4.6±0.1 MeV was observed. Coincidence measurements of the 0.085- and 0.525-MeV, γ rays indicate that these γ rays are associated with an isomeric transition to the 30-sec ^{68}Cu ground state.

I. INTRODUCTION

INITIALLY, Flammersfeld[1] observed a 32±2 sec activity from fast-neutron bombardment of natural Zn and assigned the activity to ^{68}Cu. Later, Yythier and van Lieshout[2] and Bakhru and Mukherjee[3] studied the γ decay[2,3] and the β decay[3] of 30±1 sec ^{68}Cu, produced from 14-MeV neutron bombardment of natural Zn and Ga. Yythier and van Lieshout[2] reported observing γ rays of 1.08, 1.24, 1.52, 1.72, and 2.08 MeV, whereas Bakhru and Mukherjee[3] observed γ rays of 0.810, 1.08, 1.24, and 1.88 MeV and coincident β rays of 3.50, 2.70, and 2.25 MeV. In all of the previous studies no chemistry was performed.

Yamada and Matumoto[4] have estimated the β-decay Q-value of ^{68}Cu to be 4.5 MeV. Bakhru and Mukherjee[3] deduced a ^{68}Cu-^{68}Zn mass difference of 4.58±0.06 MeV from β-γ coincidence measurements of 30 sec ^{68}Cu.

In the present investigation, a new 3.8±0.1 min β- and γ-ray activity was radiochemically separated in the Cu fraction from fast neutron-irradiated samples of natural Zn and Ga. The new activity was found enhanced when 98.5% enriched ^{68}Zn was bombarded and analyzed and was assigned as an isomer of ^{68}Cu. Isomeric transitions from the 3.8-min state to the 30-sec ground state are indicated.

II. EXPERIMENTAL

The radioactive sources were produced through the (n, p) reaction on natural Zn and enriched ^{68}Zn, and through the (n, α) reaction on natural Ga using 14.7 MeV neutrons. The neutrons were generated by the University of Arkansas 400-kV Cockroft-Walton linear accelerator through the well-known $T(D,n)^4$He reaction. The neutron flux varied from 1×10^9 to 5×10^9 neutrons/cm^2 sec. The isotopic abundances of the 100-mg-enriched ^{68}Zn sample are given in Table I. The enriched sample was obtained from Union Carbide, Stable Isotope Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

The radioactive Cu sources obtained from the irradiated natural Zn oxide and Ga metal targets were radiochemically separated by reduction of the Cu fraction onto iron filings or iron sheet metal from 1–2N HCL solution. Decontamination of the Cu fraction from Ga, Zn, and Ni activities was very good, and the time required for separation was about 2 min. All samples were analyzed 4–5 min after bombardment to allow the 30-sec ^{68}Cu activity to decay away. In most cases five to ten bombardments were required to accumulate sufficient counts for each experiment.

TABLE I. Isotopic composition of enriched ^{68}Zn.

Isotopes	% abundance
^{64}Zn	0.8±0.1
^{66}Zn	0.46±0.05
^{67}Zn	0.16±0.05
^{68}Zn	98.5±0.1
^{70}Zn	<0.05

γ-ray spectra were obtained using a 4-cm^2-area by 5-mm-deep Ge(Li) detector in conjunction with a 4096-channel Nuclear Data 3300 analyzer system. β spectrometry was carried out using a $1\frac{1}{2}$-in. diam by $\frac{13}{16}$-in.-high cylindrical plastic detector. For γ-γ or β-γ coincidence measurements a 3-in.×3-in. NaI(Tl) detector or the plastic detector were used with a 3-in.×3-in. NaI(Tl) detector in conjunction with a 200-channel RIDL analyzer and a coincidence unit described by Kantele and Fink.[5] Gross β-decay measurements were performed using a two π end-window methane flow proportional counter. Gross γ decay was studied by analyzing the decay of the photo peaks from 16 consecutive multiscale spectra obtained using the Ge(Li) detector and the 4096-channel analyzer.

† Work supported by U.S. Atomic Energy Commission Contract No. At-(40-1)-3285.

[1] A. Flammersfeld, Z. Naturforsch **8a**, 274 (1953).
[2] C. Yythier and R. van Lieshout, J. Phys. Radium **21**, 470 (1960).
[3] H. Bakhru and S. K. Mukherjee, Nucl. Phys. **52**, 125 (1964).
[4] M. Yamada and Z. Matumoto, J. Phys. Soc. (Japan) **16**, 1497 (1961).
[5] J. Kantele and R. W. Fink, Nucl. Instr. Methods **15**, 69 (1962).

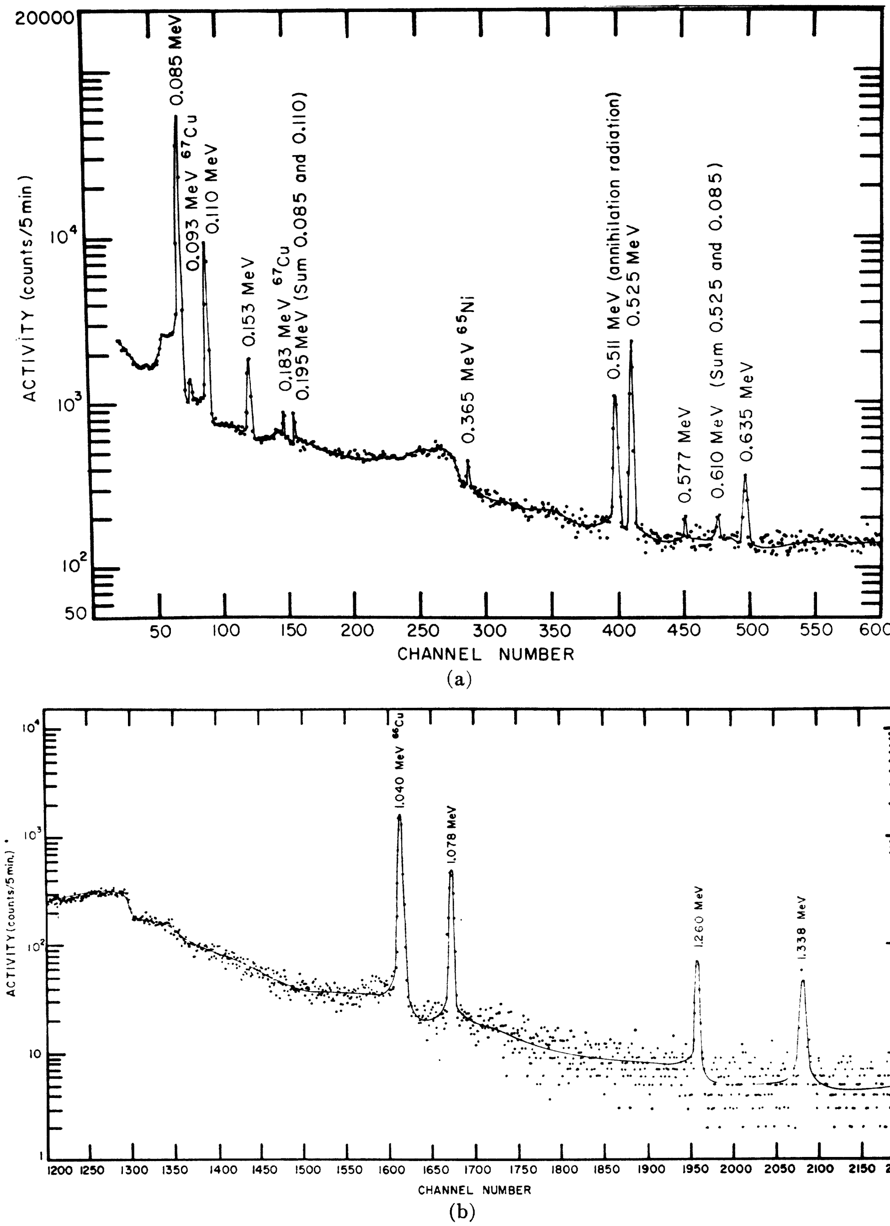

FIG. 1. Typical singles Ge(Li) γ-ray spectrum from irradiated enriched ^{68}Zn. The spectrum was obtained by accumulating counts from ten bombardments of the ^{68}Zn sample: (a) energy region 0.030 to 0.970 MeV; (b) energy region 0.970 to 1.54 MeV. The γ rays of 0.093 MeV and 0.183 MeV can be assigned to 61-h ^{67}Cu. The 0.365-, 1.115-, and 1.480-MeV γ rays can be assigned to 2.56-h ^{65}Ni. The 0.195- and 0.610-MeV γ rays were due to summing of the 0.085-MeV γ ray with the 0.110- and 0.525-MeV γ rays, respectively. The 1.040-MeV γ ray was assigned to 5.1 min ^{66}Cu.

III. RESULTS AND DISCUSSION

In Figs. 1(a) and 1(b), a typical Ge(Li) spectrum of irradiated enriched ^{68}Zn is shown. The spectrum was obtained by accumulating counts from ten 2-min bombardments for a counting period of 5 min from 4 min after bombardment. The γ rays of 0.085, 0.110, 0.153, 0.525, 0.577, 0.635, 1.087, 1.260, and 1.338 MeV are assigned to the 3.8-min activity and the relative intensities of those γ rays are listed in Table II. The γ rays of 0.195 and 0.610 MeV appeared to be entirely due to summing of the 0.085-MeV γ ray with the 0.110- and 0.525-MeV γ rays, respectively. The 0.635-MeV γ ray also indicated some summing of the 0.110- and 0.525-MeV γ rays.

Singles Ge(Li) γ-ray spectra of the Cu fraction radiochemically separated from natural Ga and Zn were also observed to have γ rays of 0.085, 0.110, 0.153, 0.525, and 1.078 MeV. Three additional γ rays of 0.635, 1.260, and 1.338 MeV were also observed in the Cu fraction from irradiated natural Zn. The relative intensities of γ_1, γ_2, γ_3, γ_4, and γ_7 listed in Table II remained essentially constant when natural Zn, Ga, or enriched ^{68}Zn was bombarded and analyzed.

The gross γ decay of the 0.085- and 0.110-MeV γ rays, obtained by analyses of 16 consecutive multiscale

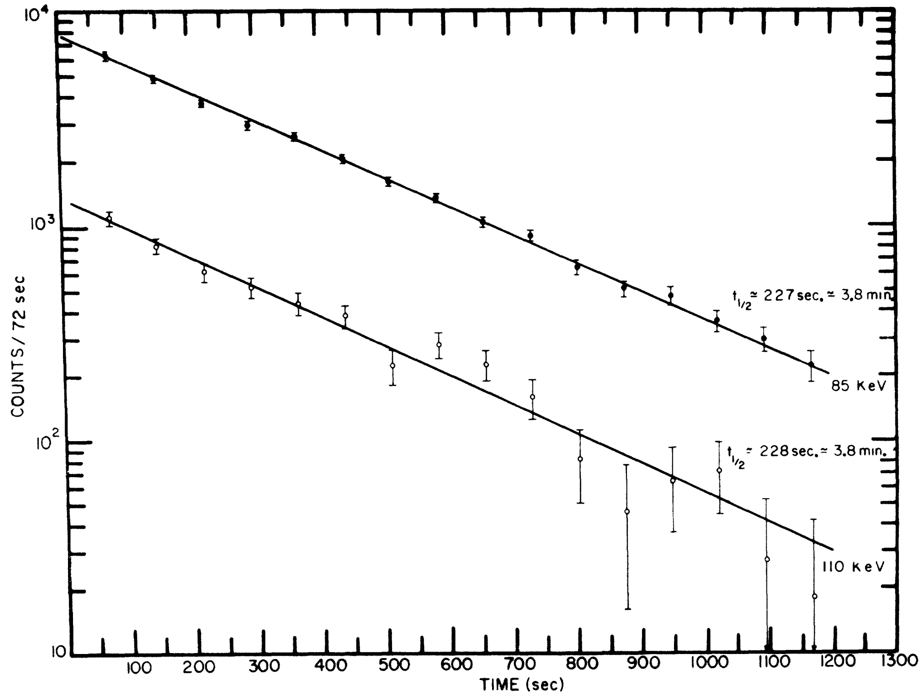

FIG. 2. Gross γ decay of the 0.085- and 0.110-MeV γ rays obtained by analyses of 16 consecutive multiscale Ge(Li) spectra of irradiated enriched ^{68}Zn.

spectra from irradiated enriched ^{68}Zn, is shown in Fig. 2. Both the 0.085- and 0.110-MeV γ rays decayed with a 3.8±0.1-min half-life. Gross β-decay analyses of irradiated enriched ^{68}Zn was observed to yield a 3.7±0.2-min activity after subtraction of a 95-min residual component. The residual component consisted of a possible mixture of ^{63}Zn (38 min), ^{69}Zn (55 min), and ^{65}Ni (2.56 h) activities produced through the ^{64}Zn$(n\,2n)^{63}$Zn, ^{70}Zn$(n,\,2n)^{69}$Zn and/or ^{68}Zn$(n,\,\gamma)^{69}$Zn, ϵ and ^{68}Zn$(n,\,\alpha)^{65}$Ni reactions.

The β spectrum of irradiated enriched ^{68}Zn is shown in Fig. 3. Fermi-Kurie analyses revealed a maximum β energy of 4.6±0.1 MeV which decayed with a 3.8±0.2 min half-life (the half-life was measured simultaneously by biasing the single-channel analyzer 3 MeV and greater and connecting the negative out to a scaler).

The γ-γ coincidence measurement on the 85±7-keV γ-ray region revealed only the 110- and 525-keV γ rays in coincidence (see Fig. 4), whereas β-γ coincidence measurements on the 85- and 525-keV γ-ray peaks indicated that these γ-rays were not in coincidence with any β rays.

Recently, the γ decay of 68.3 min ^{68}Ga was investigated by Carter *et al.*[6] They observed several excited levels in ^{68}Zn populated by the decay of ^{68}Ga ($I\pi = 1+$) and uniquely assigned the excited level at 1.656 MeV a spin of zero. The excited level scheme of ^{68}Zn populated by the decay of ^{68}Ga is shown in Fig. 5.

[6] H. K. Carter, J. H. Hamilton, and A. V. Ramayya, Phys. Rev. **174**, 1329 (1968).

The new 3.8-min activity observed in this investigation was assigned to a metastable state of ^{68}Cu based on the following: (a) The 3.8-min activity was observed to follow the Cu fraction radiochemically separated from fast-neutron-irradiated samples of natural Zn and Ga. The only Cu reaction products that could be produced from both natural Zn and natural Ga with such intensities are ^{66}Cu and ^{68}Cu. Other copper reaction products from Ga produced through the $(n,\,\text{He}^3)$, $(n,\,n\alpha)$, or $(n,\,2p)$ reactions are expected to have production cross sections several orders of magnitude

TABLE II. Radiations from 3.8 min ^{68}Cu.

Radiation	Energy (MeV)	Relative intensity
γ_1	0.085±0.001	94.8±0.6
γ_2	0.110±0.001	25.7±1.0
γ_3	0.153±0.001	6.1±0.8
γ_4	0.525±0.001	100.00
γ_5	0.577±0.001	~2.4
γ_6	0.635±0.001	15.8[a]
γ_7	1.078±0.002	83.3±1.3
γ_8	1.260±0.002	14.1±2.0
γ_9	1.338±0.002	11.8±3.0
β_{max}	4.6±0.1	

[a] Intensity of γ at 635 keV: some contribution from summing of 110- and 525-keV γ rays.

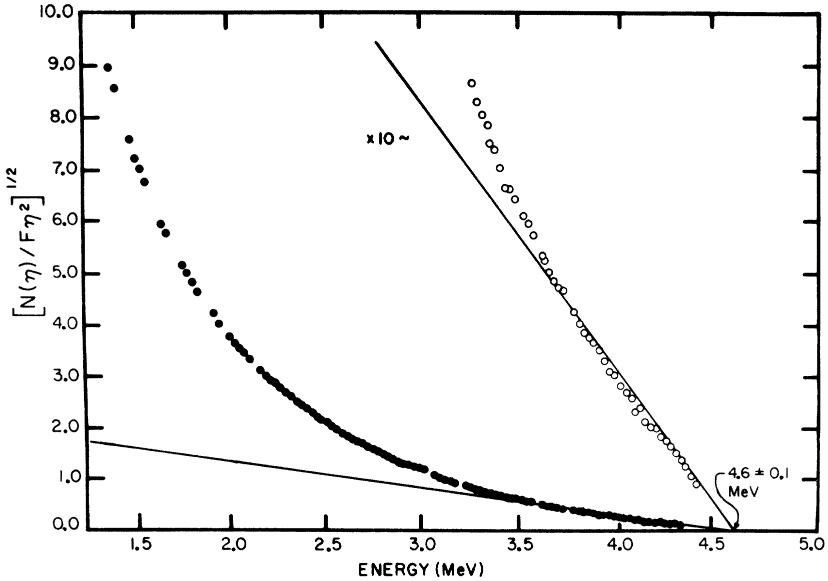

FIG. 3. Fermi-Kurie plot of β spectrum of 3.8-min ^{68}Cu from irradiated enriched ^{68}Zn.

smaller than the (n, α) reactions. (b) When 98.5% enriched ^{68}Zn was bombarded and analyzed the 3.8-min activity was found to be considerably enhanced over the 5.1-min activity of ^{66}Cu, indicating that the activity could be assigned to ^{68}Cu. (c) The 0.577-, 1.078-, and 1.260-MeV γ rays can be assigned to unique γ transitions from excited levels in ^{68}Zn (see Fig. 5). (d) The coincident nature of the 0.085- and 0.525-MeV γ rays and their apparent absence of coincident β rays indicates that these γ rays may be associated with an isomeric transition to the 30 sec ground state of ^{68}Cu. Also, the relative intensities of the γ rays listed in Table II lends support for such an isomeric transition since the absence of any high-energy high-intensity excited-state-to-ground-state transition would require the excited levels of ^{68}Zn to depopulate via the 1.078 MeV 2^+ level. (e) The maximum β-ray energy of 4.6$\pm$ 0.1 MeV is in excellent agreement with the estimated ^{68}Cu β decay Q value of 4.5 MeV[5] and the experimentally determined value of 4.58$\pm$0.06 MeV.[3]

Theoretically, the shell model assigns the 29th proton of ^{68}Cu a $J\pi=\frac{3}{2}^-$ and the 39th neutron a $J\pi=\frac{1}{2}^-$. Nordheims[7] coupling rules for odd-odd nuclei predicts a ground-state spin and parity of (1+) for ^{68}Cu. The existence of an isomeric state in ^{68}Cu could be explained as due to the coupling of the $2p\frac{3}{2}$ proton to either a $1g\frac{9}{2}$ neutron particle or to a $1f\frac{5}{2}$ neutron hole, giving a resultant spin of (3 or 6) or (1 or 4), respectively.

Although several of the γ rays we observe in this study can be assigned to transitions in ^{68}Zn, we will not at this time attempt to construct a decay scheme due to the lack of sufficient experimental data concerning the isomeric relationship between 3.8-min ^{68m}Cu and 30-sec ^{68g}Cu. It appears that a reinvestigation of the decay of 30 sec ^{68g}Cu is needed in view of the fact that there is observed a 4.6-MeV β ray that can best represent the 30-sec ^{68g}Cu β decay to the ^{68}Zn ground state.

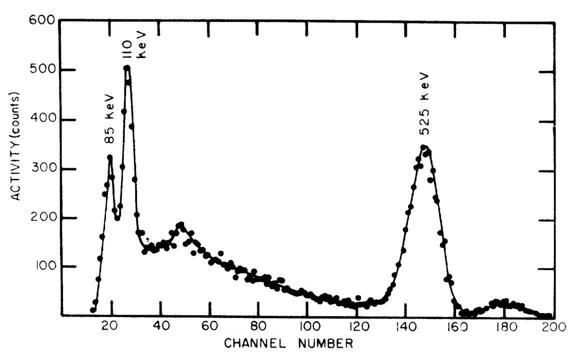

FIG. 4. γ-γ coincidence spectrum biased on the 0.085$\pm$ 0.007-MeV γ-ray region.

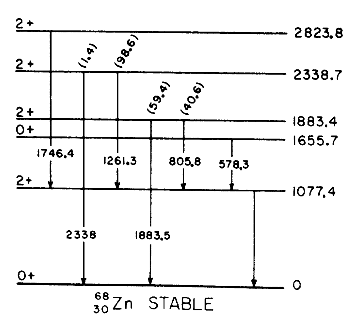

FIG. 5. Excited-level scheme of ^{68}Zn populated by the decay of 68.3-min ^{68}Ga ($I\pi=1+$).

[7] L. W. Nordheim, Phys. Rev. **23**, 322 (1951).

Such a ground-to-ground β transition of ^{68}Cu to ^{68}Zn would imply that the most probable spin of 30-sec ^{68g}Cu is 1. Bakhru and Mukherjee[3] tenuously assigned a spin of 2 to 30-sec ^{68g}Cu since they did not observe a 4.6-MeV ground-to-ground β-ray transition.

ACKNOWLEDGMENTS

We would like to thank Professor P. K. Kuroda for his valuable comments and suggestions. We would also like to thank P. H. Pile for operation of the accelerator and technical assistance.

PHYSICAL REVIEW VOLUME 188, NUMBER 4 20 DECEMBER 1969

Mean Lifetimes and Branching Ratios of Low-Lying Levels in ^{33}S†

C. E. Ragan, III,* C. E. Moss,‡ R. V. Poore, and N. R. Roberson

Duke University and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706

AND

G. E. Mitchell and D. R. Tilley

North Carolina State University, Raleigh, North Carolina 27607 and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27706

(Received 20 August 1969)

The mean lifetimes of the levels of ^{33}S below 3.3-MeV excitation energy have been measured by the Doppler shift attenuation method. The ^{30}Si(α, n)^{33}S reaction was used to populate these states. SiO_2 targets (enriched to 95% in ^{30}Si) evaporated onto Ni backings were bombarded with α-particles ranging in energy 5.5–9.0 MeV. γ-ray spectra were recorded with a 20-cc Ge(Li) detector at 0°, 90°, and 510° to the beam. The following mean lifetimes were found: τ(0.842-MeV level) = 1.66±0.34 psec, τ(1.968) = 182±22 fsec, τ(2.313) = 183±25 fsec, τ(2.869) < 15 fsec, τ(2.937) > 4 psec, τ(2.970) = 82±12 fsec, τ(3.221) < 65 fsec. The branching ratios of the 2.970-MeV level were determined to be (90±5)% to the ground state and (10±5)% to the second excited state.

I. INTRODUCTION

THE low-lying levels of ^{33}S have been the subject of a number of investigations; the available information up to 1967 is summarized by Endt and Van der Leun.[1] The energy levels have been located primarily by the ^{32}S(d, $p\gamma$)^{33}S and ^{32}S(n, γ)^{33}S reactions.[2–4] However, relatively little is known about the absolute strengths of the γ-ray transitions. Recently, certain collective aspects of ^{33}S have been studied via the ^{31}P(^{3}He, p)^{33}S reaction,[5] and Dubois[6] has used the ^{34}S(^{3}He, α)^{33}S reaction to study the lowest $T=\frac{3}{2}$ states as well as some of the low-lying $T=\frac{1}{2}$ states.

Theoretical calculations have been carried out by Bishop,[7] Glaudemans *et al.*,[8] and Glaudemans, Wildenthal, and McGrory.[9] The calculations for the ($2s_{1/2}$, $1d_{3/2}$) shell performed by Glaudemans, Wildenthal, and McGrory[9] using a surface δ interaction give good agreement with experiment. Wiechers and Brussaard[10] have calculated the $M1$-transition probability for the 0.842→0 transition in ^{33}S using the wave functions of Glaudemans *et al.*[8]

The present paper[11] describes a study of the low-lying levels of ^{33}S up to an excitation energy of 3.3 MeV. The mean lifetimes of the first seven excited states of ^{33}S were measured using the Doppler-shift attenuation method (DSAM). States of interest were populated by the ^{30}Si(α, n)^{33}S reaction. The γ-ray decay modes of the 2.97-MeV state were determined, and limits on the branching of other states were obtained.

II. PROCEDURE

A. General

The Triangle Universities Nuclear Laboratory FN tandem Van de Graaff accelerator was used to accelerate

† Work supported in part by the U.S. Atomic Energy Commission.
* National Defense Education Act Fellow.
‡ Present address: University of Colorado, Boulder, Colo.
[1] P. M. Endt and C. Van der Leun, Nucl. Phys. **A105**, 1 (1967).
[2] J. A. Becker, L. F. Chase, Jr., D. B. Fossan, and R. E. McDonald, Phys. Rev. **146**, 761 (1966).
[3] J. M. O'Dell, R. W. Krone, and F. W. Prosser, Jr., Nucl. Phys. **82**, 574 (1966).
[4] G. Van Middelkoop and H. Gruppelaar, Nucl. Phys. **80**, 321 (1966).
[5] R. S. Cox, R. W. West, and R. J. Ascuitto, Phys. Rev. **175**, 1419 (1968).
[6] J. Dubois, Nucl. Phys. **A117**, 533 (1968).
[7] G. R. Bishop, Nucl. Phys. **14**, 376 (1959).
[8] P. W. M. Glaudemans, G. Wiechers, and P. J. Brussaard, Nucl. Phys. **56**, 529 (1964); **56**, 548 (1964).
[9] P. W. M. Glaudemans, B. H. Wildenthal, and J. B. McGrory, Phys. Letters **21**, 427 (1966).
[10] G. Wiechers and P. J. Brussaard, Nucl. Phys. **73**, 604 (1965).
[11] A preliminary version of this work was presented at a recent American Physical Society meeting: N. R. Roberson, C. E. Ragan, III, C. E. Moss, R. V. Poore, G. P. Lamaze, G. E. Mitchell, and D. R. Tilley, Bull. Am. Phys. Soc. **14**, 629 (1969).