PHYSICAL REVIEW C VOLUME 6, NUMBER 3 SEPTEMBER 1972

Mass of ^{33}Si, an Example of Exotic Nucleus Production in the *s-d* Shell via Compound Reactions*

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(Received 24 April 1972)

The mass of ^{33}Si has been determined by forming this 6.3-sec activity in the ^{18}O(^{18}O, $2p+n$)-^{33}Si reaction with 50-MeV ^{18}O ions and by measuring the spectrum of β rays in coincidence with 1848-keV γ rays. An end-point energy of 3980^{+250}_{-200} keV is found for the coincident β rays which establishes the mass excess of ^{33}Si as -20509^{+250}_{-200} keV. This result differs from the previously estimated mass by 560^{+250}_{-200} keV. Log*ft* values for the decay of ^{33}Si are presented and compared with shell-model calculations. Several heavy-ion compound reactions which might be used to produce other neutron-rich nuclei in the *s-d* shell are listed.

I. INTRODUCTION

The recent predictions of the nucleon stability and masses of many exotic nuclei[1] are a natural motivation for the experimentalist to attempt to produce and measure the masses of these nuclei. Several neutron-rich nuclei have been identified via multinucleon transfer reactions by Artukh *et al.*,[2] establishing their nucleon stability. Spallation reactions induced by high-energy protons have been fruitful in producing exotic Li and Na isotopes, as reported by Klapisch *et al.*[3]

The present work is an example of a third technique for producing neutron-rich nuclei, that of heavy-ion *compound* reactions. By bombarding light, neutron-rich targets with beams of the same character is it possible to produce several exotic nuclei in the mass region from 20–40. The ^{18}O(^{18}O, $2p+n$)^{33}Si reaction[4] is one of these, and it is of sufficient cross section that it has been possible to measure the mass of ^{33}Si by delayed β-γ coincidence techniques. The same reaction should also populate ^{34}Si, although this nucleus has not yet been identified via delayed γ rays; however, it is known to be nucleon stable.[2]

II. EXPERIMENTAL WORK

The procedures for producing ^{33}Si by bombarding targets of ^{18}O with a 50-MeV beam of ^{18}O ions have been described previously.[4] The target shuttle system, which has also been described in detail,[4] was modified for β-γ coincidence measurements as shown in Fig. 1. At the counting position of the rabbit the β rays were slowed down by a 47-mg/cm^2-thick Be window on the shuttle system and by 39 mg/cm^2 of plastic tape used to hold the Ne 102 scintillator against the photomultiplier tube. The energy correction through this combination of absorbers was 175 keV, and is essentially independent of β-ray energy from 1–4 MeV. The scintillator was 2.54 cm deep and 4.6 cm in diameter, and had a density of 1.03 gm/cm^3.

γ rays were detected by a 60-cm^3 Ge(Li) detector, and standard electronics modules provided a time resolution between the γ and β detectors of 4 nsec full width at half maximum, for γ rays above 1 MeV and β rays above 0.15 MeV. A time window 9 nsec wide was used for the present work. The reals-to-randoms ratio exceeded 200.

After an irradiation of 8 sec the rabbit was transferred and the counting period was divided into two 6.3-sec bins. During each of the two counting periods γ-ray singles spectra and several coincident β-ray spectra were stored in an on-line computer. Figure 2 shows part of the γ-ray singles spectrum in the first time bin. Digital gates were set such that β rays in coincidence with the top 5 channels in the 1848-keV peak, the 21 channels in the "lower window," and the 21 channels in the "upper win-

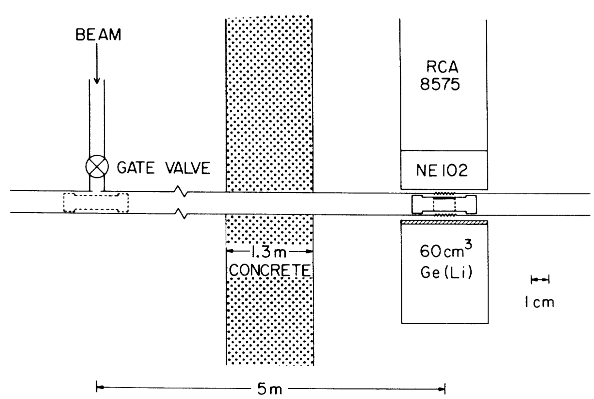

FIG. 1. Simplified diagram of the target shuttle and counting system. The rabbit is shown in the counting position (solid) and in the irradiation position (dashed).

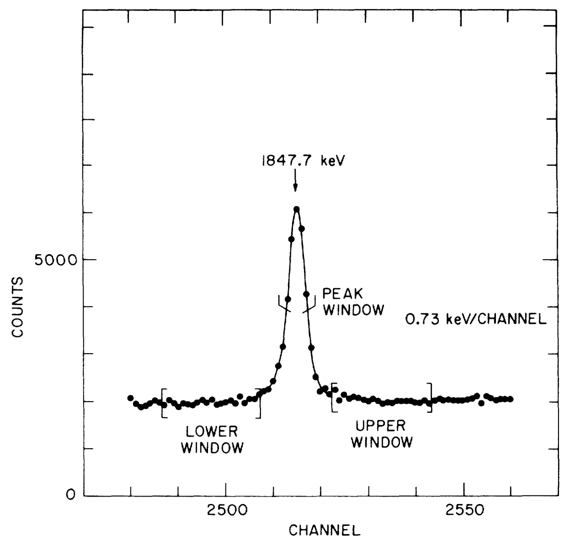

FIG. 2. Part of the γ-ray singles spectrum from the first 6.3-sec time bin. β-ray spectra in coincidence with γ rays in each of three digital windows were recorded separately.

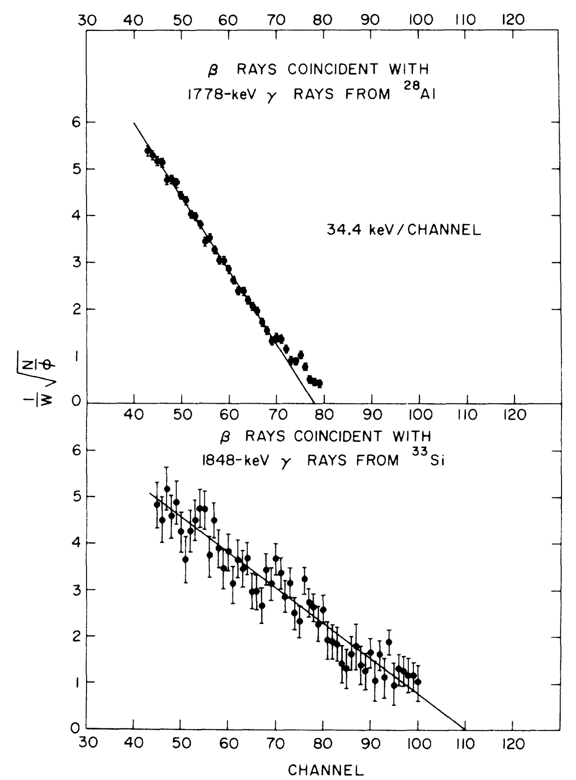

FIG. 3. Fermi-Kurie plots of the upper half of the ^{33}Si and ^{28}Al β-ray spectra. The symbol W denotes the total (kinetic + mass) energy of the β ray, N is the number of counts, and ϕ is the function defined in Ref. 6.

TABLE I. Least-squares fits to the ^{33}Si Fermi-Kurie plot.

Channels used in fitting region	Computed end-point channel	χ^2
45–85	110.6 ± 3.3	0.94
45–90	109.5 ± 2.6	0.87
50–90	109.4 ± 2.8	0.95
45–93	109.5 ± 2.3	0.85
45–95	111.3 ± 2.3	0.93
45–100	112.7 ± 1.9	0.86

dow" in Fig. 2 were stored separately. The upper- and lower-window β spectra allowed an accurate correction to be made to the photopeak-window β spectrum for the γ-ray continuum underlying the 1848-keV photopeak.

In order to calibrate the system, windows were also set on the photopeaks due to the 1779-keV γ ray from the decay of ^{28}Al formed by the ^{12}C(^{18}O, np) and ^{13}C(^{18}O, $2n+p$) reactions on carbon in the target, and the 1634-keV γ ray from the decay of ^{20}F formed by the ^{18}O(^{18}O, ^{16}O)^{20}O(β^-)^{20}F reaction. It was felt that these spectra, with end-point energies of 2863 keV[5] for ^{28}Al and 5393 keV[5] for ^{20}F, would provide convenient calibration end points, since the preliminary measurements indicated that the ^{33}Si end point was at about 4 MeV. These spectra were counted simultaneously with the β spectrum from ^{33}Si so that losses in the absorbers and possible count-rate effects were the same for all three spectra. The lower window β spectrum from Fig. 2 was also used to correct the ^{28}Al photopeak-window β spectrum for the very small γ-ray continuum underlying it. The γ-ray gain was checked periodically to assure that the digital windows were properly positioned.

The response of the β-detection system was studied by means of independent measurements on

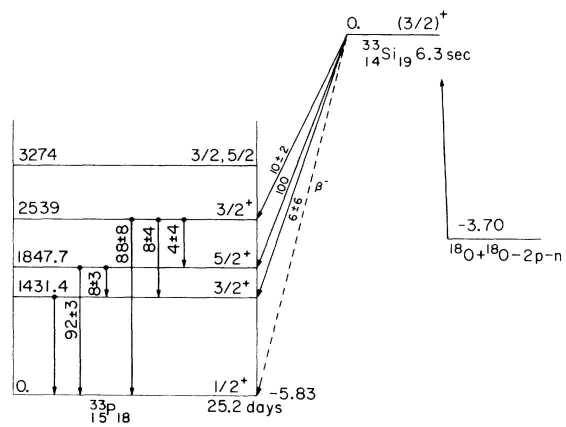

FIG. 4. ^{33}Si decay scheme. The information here is taken from Ref. 4 and from the present work.

the end points of ^{28}Al and ^{20}F, as well as from the 976-keV internal-conversion line from ^{207}Bi and the Compton edges of 2.224- and 4.439-MeV γ rays produced by a Pu-Be source surrounded with paraffin. The calibration curve was found to be linear to better than 2% up to at least 4.2 MeV, but the ^{20}F point deviated somewhat, consistent with the fact that these β rays have ranges exceeding the dimensions of the detector. Therefore, in deriving the end-point energy of ^{33}Si the ^{20}F data were not used for calibration.

For the final coincidence runs the irradiate-count procedure was continued for 30 h to obtain adequate statistics. The β spectra taken in both time bins had the same shape within statistics and were added together and corrected by the upper and lower background spectra. Fermi-Kurie plots of the resultant spectra are shown in Fig. 3. The function ϕ is that defined by Dismuke *et al.*[6] The high-energy end of the ^{28}Al plot deviates from the straight line because of the resolution of the detector, which was about 10% for pulses near channel 70. The lower half of the β spectrum is distorted owing to electron scattering and is not shown in Fig. 3. The ^{28}Al data were fitted to a straight line, and the computed intercept was independent of the fitting region as long as channel numbers above 70 were not included. Using channels 43–70, the end point is computed to be at channel 78.0 ± 0.3. Several independent tests on ^{28}Al and ^{29}Al β spectra had linear Fermi-Kurie plots for fits including this portion of the spectrum, and had computed end points which were in proportion to their accepted end-point energies. As mentioned above, this technique of determining end points agreed with Compton-edge calibration points.

The ^{33}Si β-ray plot shown in Fig. 3 was fitted to a straight line using many different fitting regions. From the results of the ^{28}Al fitting tests, we expect the proper fitting region for the ^{33}Si curve to terminate near channel 92–96. Table I lists several fitting regions and the computed end-point channel numbers, along with normalized χ^2 for each fit. We adopt an end-point channel of 110.3 ± 4, because of the uncertainty in the proper fitting region. The energy corresponding to this channel has an uncertainty of 100 keV in one direction and 175 keV in the other direction, and we combine the these results to deduce an end-point energy for the ^{33}Si β ray of 3980^{+250}_{-200} keV. Thus, as shown in the energy level diagram of Fig. 4, the total decay energy of ^{33}Si is 5.83 MeV.

TABLE II. β^- branching in the decay of ^{33}Si to ^{33}P.

Level in ^{33}P (keV)	% relative β branch (Ref. 4)	J^π	Exptl. logft (Ref. a)	Theor. logft (Ref. 8)
0	...	$\frac{1}{2}^+$	...	5.40
1431	6 ± 6	$\frac{3}{2}^+$	>5.28	5.36
1848	100	$\frac{5}{2}^+$	$4.25^{+0.13}_{-0.11}$	3.91
2539	10 ± 2	$\frac{3}{2}^+$	4.88 ± 0.17	4.50

[a] These values assume a negligible decay to the ground state.

III. DISCUSSION

The above value for the β end-point energy corresponds to a mass excess of -20509^{+250}_{-200} keV for ^{33}Si, using the scale where ^{12}C = 0. This value is 560^{+250}_{-200} keV above the Garvey estimate[1] for ^{33}Si.

Wildenthal *et al.*[7] have recently published wave functions for ^{33}P levels. There are no published wave functions for ^{33}Si, but the major component of the ^{33}Si ground state should be of the $d_{5/2}{}^{12}s_{1/2}{}^2$ $(j=0,\ t=1,\ t_z=1,\ v=0)$ $d_{5/2}{}^3$ $(j=t=\frac{3}{2},\ t_z=\frac{3}{2},\ v=1)$ configuration, coupled to a total $J=\frac{3}{2}$ with $T=\frac{5}{2}$. Here, v denotes the shell seniority, and t_z(neutron) $=+\frac{1}{2}$. Qualitative estimates of the logft values for the decay of ^{33}Si can be made from these published wave functions. The Gamow-Teller matrix element connecting ^{33}Si as described above with the published ^{33}P ground-state wave function is zero, since none of the published amplitudes for ^{33}P(0) have two nucleons in the $s_{1/2}$ shell. However, the published amplitudes for ^{33}P(0) account for only 78.6% of the wave function, and the small unpublished amplitudes in general are not negligible. One can, however, expect this ground-state β-ray branch to be weak.

Of the eight amplitudes for ^{33}P(1848) published in in Ref. 7, only the one term with the 0.337 ampli-

TABLE III. Possible reactions for studying neutron-rich isotopes in the s-d shell.

Nucleus	Reaction
^{33}Si	^{18}O(^{18}O, $2p+n$)^{33}Si
^{35}P	^{18}O(^{19}F, $2p$)^{35}P
^{34}Si	^{18}O(^{18}O, $2p$)^{34}Si
^{31}Al	^{18}O(^{15}N, $2p$)^{31}Al
	^{18}O(^{18}O, $\alpha+p$)^{31}Al
^{30}Mg	^{14}C(^{18}O, $2p$)^{30}Mg
^{29}Mg	^{13}C(^{18}O, $2p$)^{29}Mg
	^{14}C(^{18}O, $2p+n$)^{29}Mg
^{25}Ne	^{9}Be(^{18}O, $2p$)^{25}Ne
^{23}F	^{18}O(^{7}Li, $2p$)^{23}F

tude has a nonvanishing matrix element with the ^{33}Si configuration described above. We calculate a log*ft* of 4.08 for this term.

Recent calculations by Lanford and Wildenthal[8] of the β decay of ^{33}Si have been made available to the authors. Their calculations include the small amplitudes in the ^{33}P wave functions not listed in Ref. 7. Their calculations are listed in Table II, along with the results of this work and that of Ref. 4.

The theoretical log*ft* values correspond to a ground-state β branch of 18% relative to the strong branch to the 1848-keV level. We have no information on a possible ground-state β-ray branch, because of the copious high-energy β rays following the decay of ^{20}F, made by the $^{18}O(^{18}O, ^{16}O)^{20}O$ and $^{20}O \rightarrow {}^{20}F + \beta^- + \bar{\nu}$ reactions. The experimental log*ft* values presented in Table II are based upon a negligible ground-state branch, and will have to be corrected whenever this branch is measured.

Using our mass value, the theoretical log*ft* values of Lanford and Wildenthal[8] correspond to a total half-life of 2.5 ± 0.6 sec, compared with the measured[4] value of 6.3 ± 0.3 sec. This disagreement is not unreasonable, considering the distance of ^{33}Si from the valley of stability.

IV. PROSPECTS FOR EXOTIC NUCLEUS PRODUCTION IN THE *s-d* SHELL USING COMPOUND REACTIONS

Heavy-ion compound reactions with beams and projectiles ranging in mass from 10–25 have the potential capability of forming several very neutron-rich nuclei in the *s-d* shell. Table III lists some of the reactions which might be used to study these nuclei. The first two examples have already[4,9] been successful; work on some of the others is in progress. Knowledge of an approximate half-life and a proper bombarding energy are very important to the success of these reactions. Shell-model calculations[7,8] along with the mass estimates of Garvey *et al.*[1] should provide a half-life within a factor of 4, and it is hoped that future work will reveal the technique for estimating the proper bombarding energy.

ACKNOWLEDGMENTS

The authors are indebted to Dr. W. A. Lanford and Dr. B. H. Wildenthal for providing us with their log*ft* calculations prior to publication, and to Dr. J. D. Larson, for the use of his least-squares-fitting program.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

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