*Work supported by the U. S. Atomic Energy Commission.

†Submitted in partial fulfillment of the requirements for the Ph.D. degree in the Department of Chemistry, Purdue University. Present address: The Enrico Fermi Institute, University of Chicago, Chicago, Illinois.

[1]G. B. Saha and N. T. Porile, Phys. Rev. 151, 907 (1966).

[2]N. T. Porile, I. Fujiwara, and R. Hahn, Phys. Rev. 170, 958 (1968).

[3]S. K. Chang and N. T. Porile, to be published.

[4]J. M. Alexander, J. Gilat, and D. H. Sisson, Phys. Rev. 136, B1289 (1964).

[5]J. M. Alexander and G. N. Simonoff, Phys. Rev. 162, 952 (1967).

[6]N. T. Porile and I. Fujiwara, Phys. Rev. 176, 1166 (1968).

[7]J. Lindhard, M. Scharff, and H. E. Schiøtt, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 33, No. 14 (1963).

[8]I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. 116, 683 (1959).

[9]N. T. Porile and S. Tanaka, Phys. Rev. 135, B122 (1964).

[10]A. O. Hanson, R. F. Taschek, and J. H. Williams, Rev. Mod. Phys. 21, 635 (1949).

[11]D. E. Rundquist, M. K. Brussel, and A. I. Yavin, Phys. Rev. 168, 1296 (1968).

[12]C. M. Fou and R. W. Zurmühle, Phys. Rev. 176, 1339 (1968).

[13]M. K. Brussel, D. E. Rundquist, and A. I. Yavin, Phys. Rev. 140, B838 (1965).

[14]C. M. Fou and R. W. Zurmühle, Phys. Rev. 140, B1283 (1965).

PHYSICAL REVIEW C VOLUME 5, NUMBER 4 APRIL 1972

New Isotope of Silicon: 6.3-sec ^{33}Si[†]

D. R. Goosman and D. E. Alburger

Brookhaven National Laboratory, Upton, New York 11973

(Received 3 December 1971)

^{33}Si has been produced via the $^{18}O+^{18}O \rightarrow ^{33}Si+2p+n$ reaction using 23–40-MeV ^{18}O ions. Identification is made from the observed γ rays of 1431.3 ± 0.5, 1847.69 ± 0.25, and 2538 ± 2 keV which agree with the first three excited states of ^{33}P. By means of the reaction $^{31}P(t,p)$-^{33}P, γ rays from the first two excited states of ^{33}P have been measured as 1431.4 ± 0.3 and 1847.60 ± 0.15 keV. The three ^{33}Si γ rays decay together and a value of $T_{1/2}=6.3\pm0.3$ sec is obtained from the 1848-keV line. Relative γ intensities correspond to ^{33}Si β branches to the 1431-, 1848-, and 2539-keV states of ^{33}P in the ratios $0.06\pm0.06:1:0.10\pm0.02$. No information was obtained on a possible ^{33}Si ground-state β branch. The results are consistent with the expected mass and spin-parity ($J^{\pi}=\frac{3}{2}^{+}$) of the ^{33}Si ground state.

I. INTRODUCTION

Predictions of the nucleon stability of many highly neutron-rich isotopes in the light nuclei have been made by Garvey *et al.*[1] It is an exciting and challenging goal for the experimentalist to produce these isotopes and to measure their masses, lifetimes, and decay properties.

Artukh *et al.*[2] have reported cross sections for making many neutron-rich nuclei with $Z \leq 10$, via studying multinucleon-transfer reactions occurring with a beam of 137-MeV ^{16}O ions on very heavy targets. The same group has also bombarded ^{232}Th targets with 290-MeV ^{40}Ar ions, and has recently reported[3] the existence of 17 new isotopes with Z between 12 and 17. In particular, they were able to report that ^{33}Si has a lifetime longer than 10^{-7} sec, which was the time of flight of product nuclei from their target to a ΔE-E telescope. To date this is the only experimental information known to us concerning ^{33}Si.

The present work describes the first known measurements of the decay properties of ^{33}Si. In attempting to make more refined measurements on the γ-ray spectrum following the β decay of ^{20}O as produced in the reaction $^{18}O(^{18}O,^{16}O)^{20}O$, γ rays were seen which could not be attributed to the decay of any known nucleus. We show in this work that these γ rays are due to ^{33}Si, produced by the reaction $^{18}O(^{18}O,2pn)^{33}Si$. This result shows that heavy-ion *compound* reactions, as well as transfer reactions,[3] may be a fruitful method of studying neutron-rich nuclei in the $2s$-$1d$ shell.

II. APPARATUS AND PROCEDURES

^{18}O ions used in this work were provided by the second accelerator of the Brookhaven National Laboratory tandem Van de Graaff facility. Beam currents used were typically about 0.2 μA (electrical) of the 5^{+} charge state. This value was set by counting-rate considerations.

The ^{18}O targets were made by heating 0.03-mm-thick Ta metal sheets in an environment of oxygen enriched to 99.3% in ^{18}O. By weighing the sheets before and after oxidation, target thicknesses could be determined to about 30% and were typically 630 μg/cm^2 thick on each side of the tantalum. This represents an energy loss of about 4 MeV for 40-MeV ^{18}O ions. Targets of natural oxygen were made in the same way for use in background runs.

In order to eliminate neutron damage to the Ge-Li γ-ray detector and activities induced in apparatus near the target, the delayed γ rays from the ^{18}O+^{18}O reaction were counted in an adjacent target room. The targets were cut into plates 1.5 cm square and clamped into "rabbits" made of Delrin (acetal resins). This material is excellent for rabbits because of its light weight, machinability, and because it is free of nitrogen, a common source of γ-ray background. The target was irradiated *in vacuo* in one room, the beam was intercepted, and then the target was transferred with a stream of helium through a 1.3-m-thick concrete shielding wall into the counting room. The irradiation was done *in vacuo* to avoid the use of entrance foils, which are easily destroyed by the beam and cause radioactive recoil atoms to be collected by the target and contaminate the γ-ray spectrum. A solenoid valve isolated the vacuum lines of the accelerator during the transfer time. Following the transfer of the rabbit back from the counting room to the irradiation room, the solenoid valve was opened again to pass the beam after a brief pumpdown time. The pumping time was utilized also to allow the activity of ^{20}O, which has a 13.6-sec half-life,[4] to diminish to a negligible value before the beginning of the next cycle.

The delayed γ rays were detected by a 50-cm^3 Ge-Li detector separated from the counting position of the rabbit by 8.5 mm of graphite and 3 mm of Pb. The vacuum of the rabbit transfer tubing at the counting position was separated from the room atmosphere by a 0.25-mm-thick Be window used to minimize β bremsstrahlung. After waiting typically 0.5 half-lives from the end of the irradiation period for short-lived activities to decrease, delayed γ rays were counted and routed into either halves or quarters of a 4096-channel pulse-height analyzer.

Timing for operating the valves and the beam chopper in the rabbit system and for the routing into sections of the analyzer memory was provided by a 10-channel crystal-controlled programmer.[4a] This digital timer consists of two scalers for each of the 10 devices it can control, and a frequency divider for reducing the frequency of a 10-kHz oscillator with an accuracy of one part in 10^5 to a basic clock frequency. By means of a front-panel pin-board configuration, 10 independent time intervals for driving external devices can be set. Accuracies of one part in 10^4 were typical for the time intervals used in this work. A typical time sequence for one complete irradiate-count cycle is shown in Table I. Many different timing sequences were used during this work.

III. RESULTS

Initial spectra, taken using ^{18}O ions at 30-MeV incident lab energy and with a timing cycle appropriate for ^{20}O decay, showed the presence of a γ ray near 1848 keV with a half-life shorter than 13 sec. Mak, Spinka, and Winkler,[4] in their study of ^{18}O(^{18}O, ^{16}O)^{20}O at 26 MeV, reported seeing an unidentified γ ray near this energy which decayed faster than the ^{20}O lines. Both their spectra and ours contained many γ rays due to compound and transfer reactions on ^{18}O and ^{12}C in the targets. However, all of the lines in our initial spectra were positively identified as belonging to known activities except the one near 1848 keV. This is probably the same γ ray as one of the two unidentified lines reported by Mak, Spinka, and Winkler.[4] Runs on natural oxygen targets and both thin and thick carbon targets did not reveal this γ ray.

TABLE I. A typical timing sequence, suitable for a 6-sec activity.

Function	Start time (sec)	Stop time (sec)
Pumpdown	0.0	37.5
Open beam valve	30.0	37.0
Irradiate target	30.5	36.5
Transfer target	37.5	39.5
Count in first quarter	39.6	45.5
Count in second quarter	45.5	51.5
Count in third quarter	51.5	57.5
Count in fourth quarter	57.5	63.5
Transfer target	63.6	65.6
Reset to zero	65.7	

In order to increase the yield of this line, the beam energy was raised to 40 MeV and spectra were routed into four quarters of the analyzer in 6.8-sec intervals. The net yield of the 1848-keV γ ray, corrected for dead time (2%), is shown for each time period in Fig. 1. This gave a preliminary result of 6.4 ± 0.5 sec for the half-life of this line.

The timing cycle was then reset to maximize the yield of the 6.4-sec activity in the presence of the 13.6-sec ^{20}O activity. In particular, the irradiate time was shortened from 14 to 6.4 sec. Weak sources of $^{40}K(1460.75\pm 0.06$ keV [5]) and $^{88}Y(1836.13\pm 0.04$ keV [5]) were situated near the Ge-Li counter to calibrate the energy scale simultaneously with the counting of the new activity. Part of the spectrum from the first timing period is shown in Fig. 2. In addition to the 1848-keV line, 1431- and 2538-keV lines of about the same half-life were observed. Another run at 40 MeV with much higher dispersion (663 eV/channel) was taken to determine more precisely the energies of these three lines, and part of this spectrum is shown in Fig. 3. After considering effects due to

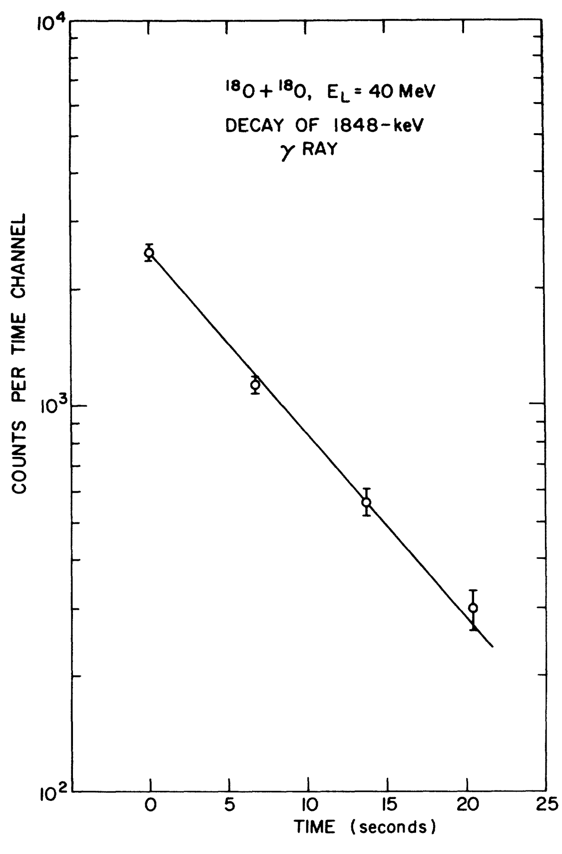

FIG. 1. The yield of the 1848-keV γ ray in each of the four time bins.

the nonlinearity of the system, statistics, and slight gain differences between the first and second counting periods (only partially compensated for by the ^{88}Y calibration), the energy of this line was determined to be 1847.69 ± 0.25 keV. Two methods were used to determine the energy of the 1848-keV line. Although the peaks are slightly asymmetric, a least-squares fit using Gaussians and an estimate of the centroid positions shown in Fig. 3 gave results which agreed well within the 0.25-keV quoted uncertainty. Spectra similar to Fig. 3 determined the energies of the other two lines as 1431.3 ± 0.5 and 2538 ± 2 keV. No other unidentified γ rays below 5 MeV were seen in these spectra.

The half-lives of the three lines were determined by averaging the results of the low- and high-dispersion runs at 40 MeV, and Fig. 4 shows the results for the three lines at all measured beam energies. A value of 6.3 ± 0.3 sec is adopted from several runs on the 1848-keV line at 40 MeV, after correction for dead time as measured by the ^{88}Y yield in each time bin.

By averaging several runs, the 1431-, 1848-, and 2538-keV γ-ray intensities were determined to occur in the ratios $0.16\pm 0.05:1:0.10\pm 0.02$. Table II shows the production cross section for the 1848-keV γ ray at three energies.

IV. IDENTIFICATION OF THE DAUGHTER NUCLEUS

A search of the recent literature revealed a very likely candidate for the nucleus in which these γ-ray transitions occur: ^{33}P. Measurements by Harris, Nagatani, and Olness[6] and others[7] had indicated that the energies of the first three excited levels of ^{33}P were at 1432 ± 3, 1848 ± 3, and 2540 ± 3 keV, respectively. In order to decrease the uncertainties in the energies of the first two excited states, a Zn_2P_3 target 500 $\mu g/cm^2$ thick on a thick Ta backing was bombarded with 3.0-MeV tritons from the 3.5-MeV Van de Graaff to produce these γ rays via the reaction $^{31}P(t,p)^{33}P$. The same Ge-Li counter as that used in the $^{18}O + ^{18}O$ work was placed at 90° to the triton beam, and ^{40}K and ^{88}Y calibration sources were counted simultaneously with the γ rays from ^{33}P. Because of the relatively long lifetimes[6] of the first two excited states of ^{33}P, the γ-ray lines in the (t,p) reaction had essentially the instrumental line shape and the errors due to the setting of the 90° detector angle were negligible. Runs at two different gains were taken, and spectra very similar to that shown in Fig. 3 were obtained. In this way the energies of the γ rays from the first two excicited states in ^{33}P were determined to be 1431.4

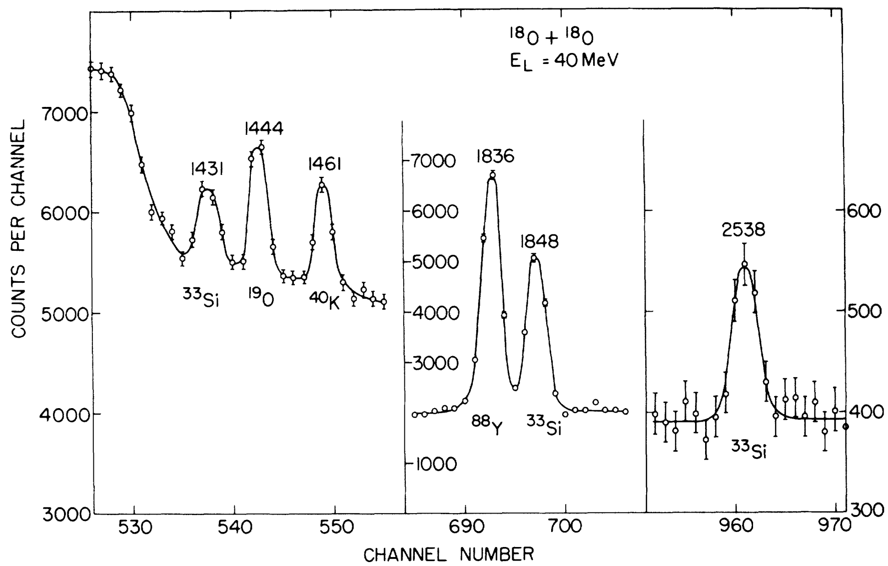

FIG. 2. Part of the delayed γ-ray spectrum obtained with a 6.4-sec irradiation time. The numbers above the peaks are energies in keV and the parent nucleus is indicated under each peak.

± 0.3 and 1847.60 ± 0.15 keV. The results of these measurements and those of the $^{18}O + ^{18}O$ work are summarized in Table III. The fact that no known nucleus with a half-life near 6 sec emits γ rays of these energies and the close correspondence between the energies seen in Table III definitely establishes the daughter nucleus as ^{33}P. Averaging the present and previous results, we adopt an energy value of 2539 ± 2 keV for the third excited state of ^{33}P.

V. IDENTIFICATION OF THE PARENT NUCLEUS

The question arises as to which parent nucleus is responsible for the 6.3-sec half-life. Since the 1848-keV line is not made by bombarding targets of natural oxygen on tantalum or carbon on tantalum, it is unlikely that the target responsible is heavier than ^{18}O. The compound nucleus for $^{18}O + ^{18}O$ is ^{36}S, and contaminants much heavier than ^{18}O would make it very unlikely to produce delayed γ rays in ^{33}P. Also, no activity was seen arising from any parent nucleus heavier than mass 34. There are thus only five possibilities for the parent: ^{35}P, ^{34}Si, ^{33}Si, ^{33}Al, or an isomer of ^{33}P.

TABLE II. The measured cross section, integrated over a 630 ± 200-$\mu g/cm^2$-thick ^{18}O target, for the production of the delayed 1848-keV γ ray at three ^{18}O beam energies.

^{18}O beam energy (MeV)	Production cross section for 1848-keV γ ray (μb)	Target thickness (MeV)
23	14 ± 7	5.7
30	113 ± 57	5.1
40	510 ± 200	4.2

A. Isomer of ^{33}P

The γ-ray branching of the low excited states in ^{33}P is shown in Fig. 5, as reported by Harris, Nagatani, and Olness.[6] Although there are no known very high-spin states in ^{33}P, it is always

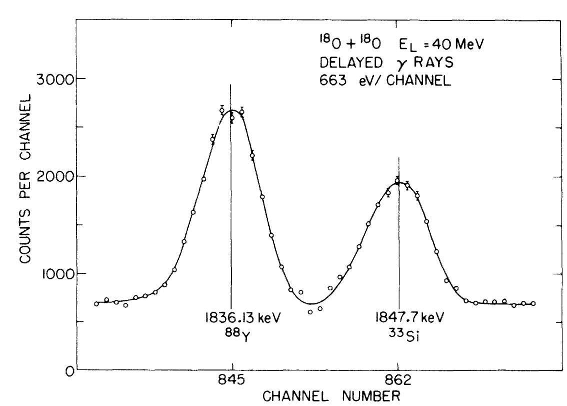

FIG. 3. Part of the high-dispersion run, showing the energy calibration of the 1847.7-keV line. The vertical lines show the channel numbers used to compute the energies.

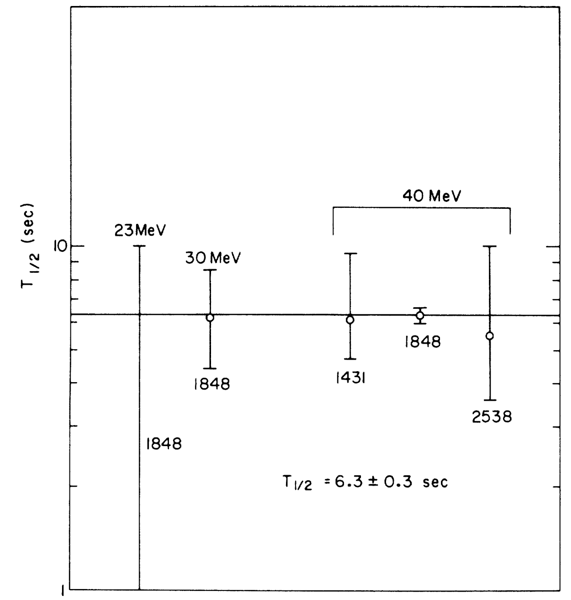

FIG. 4. The measured half-lives for the three new γ rays at different beam energies. At 23 MeV the half-life of the 1848-keV γ ray was only determined as being less than 10 sec.

possible that heavy-ion reactions such as $^{18}O+^{18}O$, which can carry many units of angular momentum into the compound nucleus, could populate a very high-spin isomer, which is unknown because it cannot be populated by ordinary reactions such as $^{31}P(t,p)^{33}P$.

Since the yield of the 1848-keV line is 10 times that of the 2539-keV line, the hypothetical isomer in ^{33}P would have to decay to both the 2539- and 1848-keV levels. If the isomer were the parent, the γ ray from the isomer to the 1848-keV level would appear above 690 keV in the observed γ-ray spectra. Including effects of attenuation and efficiency, the observed spectra show no γ ray of sufficient intensity above 500 keV. Thus we exclude this possibility.

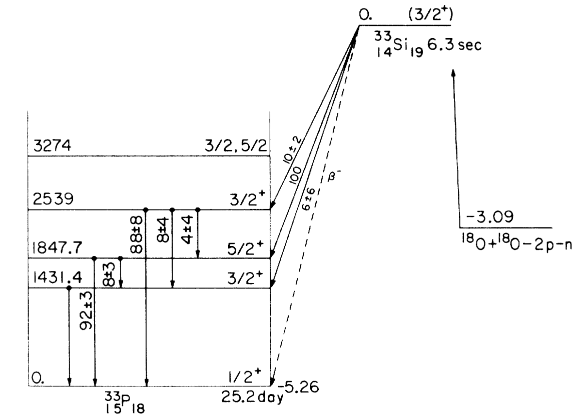

FIG. 5. Part of the mass-33 level scheme. The mass of ^{33}Si is the estimate of Ref. 1. The γ-ray branching ratios in ^{33}P are from Ref. 6. Small recoil terms for the energies of the first two excited ^{33}P levels have been included.

B. ^{33}Al, ^{34}Si, and ^{35}P

Using the masses of Garvey *et al.*,[1] the threshold lab energy for making ^{33}Al is 24.4 MeV, yet the 1848-keV line is observed as low as 23 MeV. The recent compilation by Cerny[8] shows that these mass estimates are usually within 150 keV of the measured masses in this region. Even if the mass estimate were in error by a few MeV, the reaction $^{18}O(^{18}O, 3p)^{33}Al$ would still have a cross section unobservably low at 23 MeV in the present experiment. Also, the expected half-life of ^{33}Al is of the order of 50 msec for a slightly retarded but allowed Gamow-Teller decay. These two arguments exclude the possibility that the 6.3-sec activity is ^{33}Al, followed by sequential β decays through ^{33}Si to ^{33}P.

The reaction $^{18}O(^{18}O, 2p)^{34}Si$, followed by β decay to an excited state in $^{34}P \rightarrow ^{33}P^* + n$, is excluded because the mass estimate for ^{34}Si would have to be in error by 6 MeV for it to be a delayed neutron emitter to the 2539-keV level in ^{33}P. Similarly,

TABLE III. The results of γ-ray energies seen by previous and present $^{31}P(t,p)^{33}P$ work and delayed γ-ray energies from $^{18}O+^{18}O$.

$^{31}P(t,p)^{33}P$ Previous results (keV)	$^{31}P(t,p)^{33}P$ Present results (keV)	$^{18}O+^{18}O$ delayed γ rays Present results (keV)
1432 ± 3 [a]	1431.4 ± 0.3	1431.3 ± 0.5
1848 ± 3 [a]	1847.60 ± 0.15	1847.69 ± 0.25
2540 ± 3 [b]		2538 ± 2 [c]

[a] Reference 6.
[b] Mean of the values 2538 ± 4 keV from Ref. 6 and 2542 ± 3 keV from the summary of previous work given in Ref. 7.
[c] From columns 1 and 3 a mean value of 2539 ± 2 keV is adopted for the third excited state of ^{33}P.

the reaction $^{18}O(^{18}O, p)^{35}P(\beta^-)^{35}S^* \rightarrow {}^{33}P^* + d$ is excluded because the mass estimate for ^{35}P would have to be in error by 13 MeV.

C. ^{33}Si

The remaining possibility for the parent is ^{33}Si, produced by $^{18}O(^{18}O, 2pn)^{33}Si$, as shown in Fig. 5. The numbers for the proposed β branches are derived from the observed intensities and the reported[6] γ-ray branching in ^{33}P. More than half of the 1431-keV γ rays seen in this work are due to the $(8\pm3)\%$ branch[6] to this state from the 1848-keV level.

The ground-state β-branching strength is unknown, and is dashed in Fig. 5, but using the mass for ^{33}Si shown in this figure, the values of $\log ft$ to the 2539-, 1848-, and 1431-keV states are greater than 4.4, 4.0, and 5, respectively. These values are consistent with allowed Gamow-Teller β decays from the ground state of ^{33}Si (expected spin-parity $J^\pi = \frac{3}{2}^+$) to the first three excited states of ^{33}P. The presence of the numerous other activities in the target precluded any attempts to measure the ^{33}Si β branching to the ground state of ^{33}P.

^{33}Si could also be made by the reaction $^{17}O(^{18}O, 2p)^{33}Si$, but the targets used contained only 0.14% ^{17}O. From the runs on natural oxygen targets (0.037% ^{17}O) at 40 MeV, less than 15% of the 1848-keV γ rays are made by $^{18}O + {}^{17}O$.

VI. SUMMARY

Delayed transitions in ^{33}P have been identified from the $^{18}O + {}^{18}O$ reaction, and these are almost certainly due to the 6.3-sec ^{33}Si nucleus. It is expected that heavy-ion compound reactions will reveal more neutron-rich isotopes in the future.

---

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

[1]G. T. Garvey, W. J. Gerace, R. L. Jaffe, I. Talmi, and I. Kelson, Rev. Mod. Phys. Suppl. 41, S1 (1969).

[2]A. G. Artukh, V. V. Avdeichikov, J. Erö, G. F. Gridnev, V. L. Mikheev, V. V. Volkov, and J. Wilczynski, Nucl. Phys. A160, 511 (1971).

[3]A. G. Artukh, V. V. Avdeichikov, G. F. Gridnev, V. L. Mikheev, V. V. Volkov, and J. Wilczynski, Nucl. Phys. A176, 284 (1971).

[4]H. B. Mak, H. Spinka, and H. Winkler, Phys. Rev. C 2, 1729 (1970).

[4a]G. E. Schwender, D. R. Goosman, and K. W. Jones, to be published.

[5]J. B. Marion, University of Maryland Technical Report No. 656, 1968 (unpublished).

[6]W. R. Harris, K. Nagatani, and J. W. Olness, Phys. Rev. C 2, 1412 (1970).

[7]W. G. Davies, J. C. Harvey, and W. J. Darcey, Nucl. Phys. A128, 465 (1969).

[8]J. Cerny, in Proceedings of the Fourth International Conference on Atomic Masses and Fundamental Constants, The National Physical Laboratory, Teddington, England, September 1971 (unpublished).

PHYSICAL REVIEW C VOLUME 5, NUMBER 4 APRIL 1972

Search for Nondirect Effects in the $^{28}Si(p, p_{0,1,2})^{28}Si$ Excitation Function from 16–18.2 MeV*

K. W. Kemper, J. D. Fox, and D. W. Oliver

Department of Physics, Florida State University, Tallahassee, Florida 32306

(Received 12 November 1971)

Excitation functions have been measured at laboratory angles of 60, 80, and 120° in 50–100-keV steps for proton scattering from the 0^+, 2^+, and 4^+ members of the ground-state rotational band in ^{28}Si. Prominent structure of width 300 keV is seen in both the 2^+ and 4^+ cross sections at all three angles and throughout the entire energy range from 16 to 18.2 MeV. At 60°, there is a 30% change in the 2^+ and 4^+ cross sections over the resonance at 17.7 MeV. The presence of this structure makes very dubious the quadrupole and hexadecapole deformations extracted from direct-reaction analyses of proton scattering below 18 MeV.

I. INTRODUCTION

Several scattering experiments have indicated that ^{28}Si possesses a hexadecapole deformation, but the values obtained from high-energy α-particle and electron inelastic scattering experiments are a factor of 3 smaller than the values derived from low-energy proton scattering. The value ob-