# Gamma-Rays from $Mg^{26}$†*

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The energies of the gamma-rays found in coincidence with the protons of the $Na^{23}(\alpha,p)Mg^{26}$ reaction have been measured with a NaI(Tl) scintillation counter. The experiments revealed doubt as to the existence of an excited state at 0.4 Mev. A direct transition to ground was found from the 1.83-Mev excited state. Competition between a cascade transition to the 1.83-Mev excited state and a weaker crossover transition to ground was observed for the 2.97-Mev excited state. With the 3.97-Mev excited state were identified a cascade transition to the 1.83-Mev excited state and a probable crossover transition to the ground state. For the decay of the 4.35-Mev excited state, a 1.38-Mev transition to the 2.97-Mev excited state was established. There is also a discussion of possible spin and parity assignments and a few decay schemes proposed by the use of the Weisskopf lifetime formulas.

## I. INTRODUCTION

THE modes of decay of the lower excited states of $Mg^{26}$ have been investigated by combining NaI(Tl) scintillation spectrometer gamma-ray energy measurements with a proton gamma-ray coincidence study of the $Na^{23}(\alpha,p)Mg^{26}$ reaction. The experimental method was the same as that used by Allen, May, and Rall[1] in the investigation of the $Al^{27}(\alpha,p)$ reaction. Further development of the spectrometer has resulted in better resolution and larger solid angle for gamma-ray detection. Improvements in the electronic circuits include nonoverloading characteristics and increased stability.

## II. EXCITED STATES OF $Mg^{26}$

Of the excited states of $Mg^{26}$ listed by Alburger and Hafner,[2] those at 1.91, 2.85, 4.0, and 5.0 Mev were found by several workers using the $Na^{23}(\alpha,p)Mg^{26}$ reaction. The most recent of these investigators, Motz and Humphreys,[3] also identified a level at 0.44 Mev on the basis of the double peaked structure of the long-range proton group. Since these were the best values for the energy levels available at the time, the experimental conditions for this coincidence study were based on these values. After the experimental work was completed, results of the magnetic analysis of the proton groups from the $Mg^{25}(d,p)Mg^{26}$ reaction published by Endt, Haffner, and Van Patter[4] established the energy levels more precisely at 1.83, 2.97, 3.97, 4.35 Mev, and higher values. The 0.44-Mev level was not observed, and the 4.0-Mev level was found to be a doublet of 0.38-Mev spacing.

By using a "peaked" proportional counter and aluminum foils for range measurements, the proton spectrum of Fig. 1 was obtained for the coincidence study. In order to obtain higher coincidence counting rates, resolution was sacrificed both by employing a large window proportional counter and by reducing the "peaking" bias.

## III. COINCIDENCE TECHNIQUE

The detection geometry is shown in Fig. 2. A 10-mg/cm² NaBr target evaporated on tantalum was placed at 45° to the incident 7.8-Mev alpha-particle beam of the Yale cyclotron. Protons were observed at 90° and the $1\frac{1}{2}$ in. diameter by 1 in. thick NaI(Tl) crystal was placed directly behind the target for large solid angle gamma-ray detection. Energy resolution of 11 percent for the $Cs^{137}$ gamma-ray was obtained with the diffuse reflector of MgO and with a selected crystal and 5819 photomultiplier. A block diagram of the counting circuits is shown in Fig. 3. With an amount of absorbing foil such that only protons corresponding to a desired excited state were counted, the gamma-ray pulses for this state were selected for display on the synchroscope screen by triggering the sweep with the coincidence pulse. The pulse heights were photographed on continuously moving film and later analyzed to form a pulse-height distribution. An energy scale was established on each film by taking time exposures of the pulse-height distributions from $Cs^{137}$, $Na^{22}$, and ThC″, providing calibration energies of 0.661, 0.511 and 1.28, and 2.62 Mev, respectively.

## IV. PULSE-HEIGHT DISTRIBUTIONS

### A. The 0.44-Mev Excited State

With the absorber set at 60 cm to detect the long-range proton group, considerable difficulty was experienced in obtaining a coincidence counting rate greater than the accidental coincidence rate. To compensate for the low proton yield, a larger solid angle proton counter was employed in the form of a $1\frac{1}{2}$-in.

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‡ Now at Bell Telephone Laboratories, Murray Hill, New Jersey.

1 Allen, May, and Rall, Phys. Rev. 84, 1203 (1951).
2 D. E. Alburger and E. M. Hafner, Revs. Modern Phys. 22, 373 (1950).
3 H. J. Motz and R. F. Humphreys, Phys. Rev. 74, 1232 (1948).
4 Endt, Haffner, and Van Patter, Phys. Rev. 86, 518 (1952).

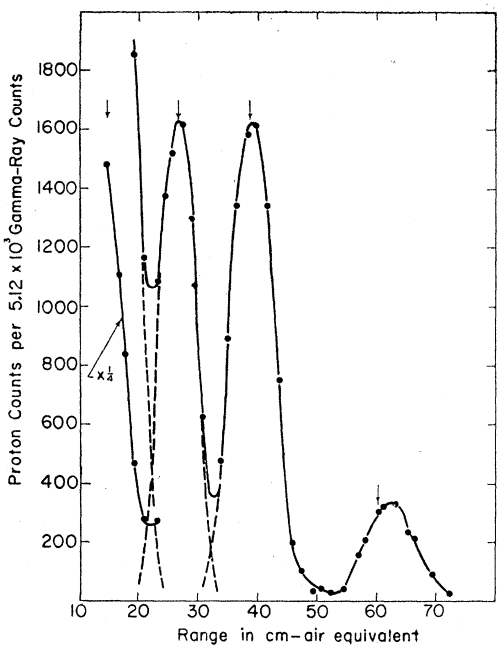


FIG. 1. Proton groups of $Na^{23}(\alpha,p)Mg^{26}$ reaction for observation at 90°. Arrows indicate absorber used for various excited states.

diameter stilbene scintillation counter. As is shown in the coincidence data of Table I, 714 coincidences were observed. Of these 583 were calculated to be accidental coincidences from the relation for the accidental rate, $A=2\tau N_1N_2$, where $\tau$ is the coincidence circuit resolving time ($2.5\times10^{-7}$ sec), and $N_1$ and $N_2$ are the singles counting rates in the separate channels. A large fraction of the 131 true coincidences would contribute to a photoelectric peak for a 0.4-Mev gamma-ray, since the photoelectric effect accounts for a large fraction of the total cross section at this energy. The analyzed data presented in the upper curve of Fig. 4 showed such a peak superimposed on the accidental background.

A spectrum of the gamma-ray background which is reproduced in the lower curve of Fig. 4 showed a peak at about the same energy. This curve was taken with a single-channel analyzer and with no coincidence technique. If this peak in the background curve is due to a 0.4-Mev excited state, then the intensity of this peak relative to the background would indicate that a much larger number of true coincidences should have been observed. Thus, the similarity of these two curves suggests that the upper one might consist entirely of accidental coincidences. This is quite possible because the average accidental rate calculated here will be smaller than the true accidental rate since the latter varies as the square of the cyclotron beam intensity. Although this error in the number of accidental coincidences is difficult to estimate, it is in the right direction to allow consideration of all the observed coincidences as accidentals.

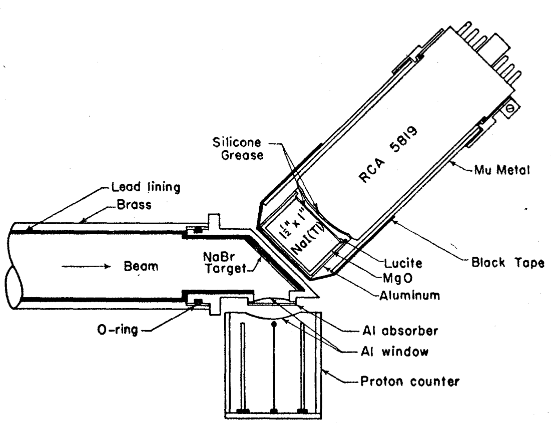


FIG. 2. Diagram of proton and gamma-ray counters.

If then no true coincidences were observed for this state, considerable doubt arises as to the existence of this state. This is further supported by the facts that (1) the number of protons per coincidence listed in Table I is much larger than for the other states, and

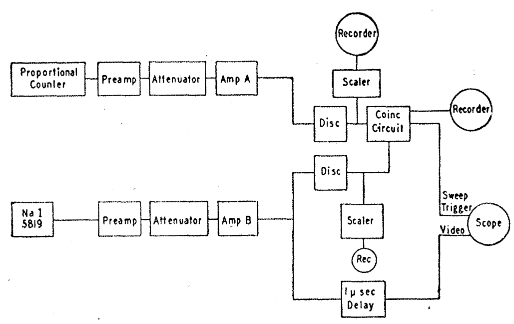


FIG. 3. Block diagram of counting circuits.

(2) Endt *et al.*[4] did not observe a proton group for this state.

### B. The 1.83-Mev Excited State

Figure 5 shows the pulse-height distribution obtained with an absorbing foil of 38.5-cm air equivalent in the proton channel. The 1.83-Mev transition to the ground state is indicated by a photopeak at 1.83 Mev, a Compton edge at 1.6 Mev, and pair peaks at 1.3 and 0.81 Mev. The peak at 1.14 Mev is attributed to the strong gamma-ray of the cascade transition from the 2.97-Mev state to the 1.83-Mev state (see Sec. IV, C and Fig. 6). This shows that some protons from the next lower energy group were counted and that more absorber should have been used. This curve was taken early in the experimental work when the scintillation counter resolution was 16 percent. Data taken later with better resolution was made useless by a pulse-height shift during the cyclotron run.

### C. The 2.97-Mev Excited State

The pulse-height distribution of Fig. 6 was taken with 26.5 cm of absorber in the path of the protons. Two gamma-rays are clearly indicated by their photopeaks at 1.14 and 1.83 Mev, showing the cascade transition to be the prominent mode of decay. For the 1.83-Mev gamma-ray, the Compton edge is shown at 1.6 Mev and the pair peak at about 0.81 Mev superimposed on the Compton distribution of the 1.14-Mev gamma-ray. The large number of counts above 1.83 Mev are associated with a weak 2.97-Mev crossover transition, although the number of counts is too small to establish any definite peaks. By comparing the areas under the curves, the cascade transition was estimated to be six times as strong as the crossover transition.

### D. The 3.97-Mev and 4.35-Mev Excited States

In Fig. 7 is shown the pulse-height distribution observed with 14.5 cm absorber (owing to air and proton windows) in an effort to identify the gamma-rays of a state at 4.0 Mev before it was known that there are two states here separated by 0.38 Mev. Although this separation resulted in both states being counted simultaneously, some useful information was obtained.

Four prominent peaks were observed, two of which can be identified as photo peaks of the 1.14- and 1.83-Mev gamma-rays indicating cascade transitions from the higher states. The peak at 1.4 Mev has been identified with the photopeak of a 1.38-Mev transition from the 4.35-Mev state to the 2.97-Mev state. The fourth prominent peak, that at 1.6 Mev, is too sharp to be entirely due to the 1.83-Mev Compton distribution and has been assigned as the pair peak with escape of one annihilation quantum corresponding to a 2.14-Mev transition from the 3.97-Mev state to the 1.83-Mev state. The lower pair peak of the 2.14-Mev gamma-ray almost coincides in energy with the 1.14-Mev photopeak and the 2.14-Mev photopeak may contribute to the change in slope at about 2.15 Mev.

TABLE I. Coincidence data.

| Excited state | Coincidences | Observed accidental | Protons per coincidence | Coincidences per hour |
|---|---|---|---|---|
| 0.44 | 714 | 1.2 | 4300 | 68 |
| 1.83 | 6387 | 15.3 | 52 | 426 |
| 2.97 | 8630 | 39.6 | 44 | 445 |
| 3.97 and 4.35 | 16357 | 64.4 | 34 | 1636 |

The large number of pulses above 2 Mev as compared with Fig. 6 shows that there is probably at least one higher energy gamma-ray in addition to the 2.97-Mev crossover transition which is expected because of the transition to the 2.97-Mev excited state. Although the statistics are too poor to make identification certain, the changes in slope at 2.9 and 3.45 Mev favor the identification of the 3.97-Mev transition rather than the 4.35-Mev transition.

## V. DISCUSSION

In Sec. IV, A it was shown that there is considerable doubt as to the existence of the 0.44-Mev excited state. No transitions to this state were found among the gamma-rays from the higher states.

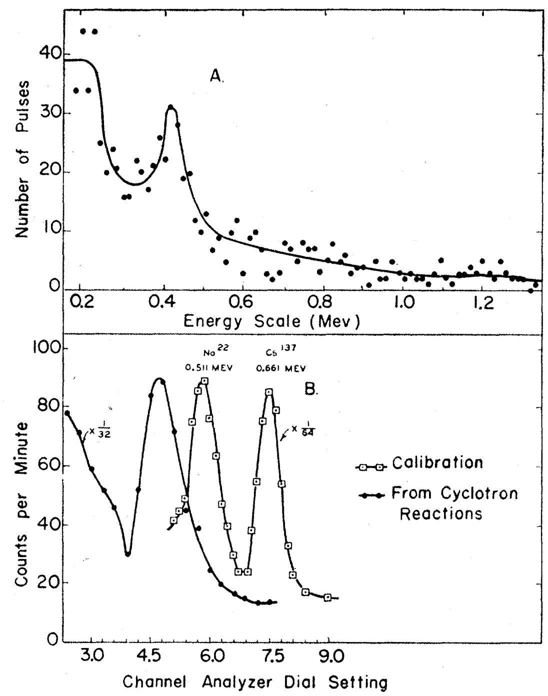


FIG. 4. A. Gamma-rays from 0.44-Mev excited state of $Mg^{26}$ (coincidence data); B. gamma-ray background (no coincidences)—same energy scale as above.

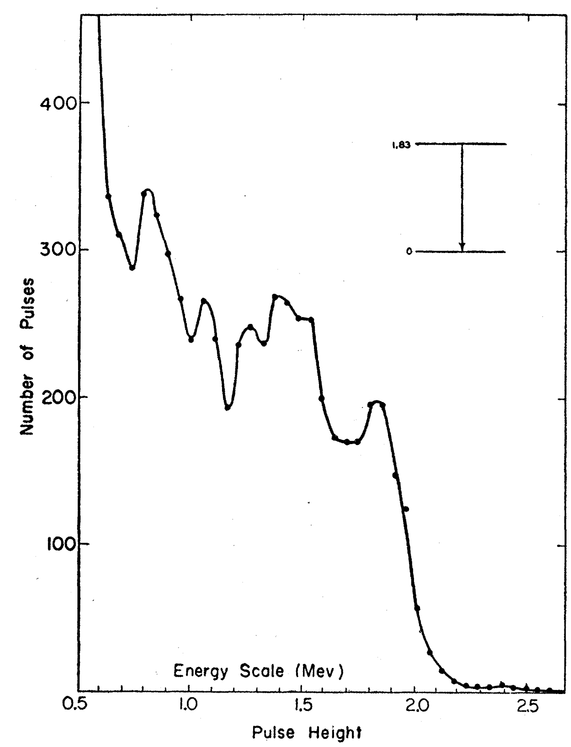


FIG. 5. Gamma-rays from 1.83-Mev excited state of $Mg^{26}$.

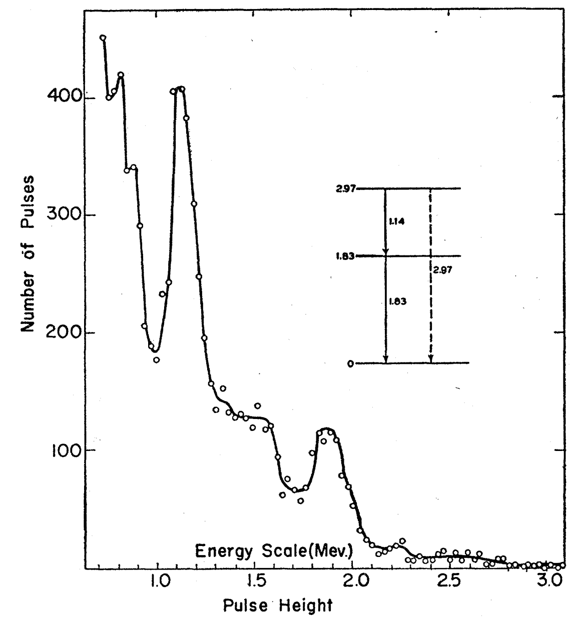


FIG. 6. Gamma-rays from 2.97-Mev excited state of $Mg^{26}$.

For discussion of possible spin and parity assignments it seems reasonable to consider the 1.83-Mev state as the first excited state. On the basis of the studies of even-even nuclei by Goldhaber and Sunyar[5] and by Scharff-Goldhaber,[6] the ground state can be considered to have spin zero, even parity and the $n$th excited state to have spin $I \leq 2n$ with two even favored for the first excited state. It was shown that in the decay of the 2.97-Mev excited state, there exists competition between the 1.14-Mev cascade transition and the weaker 2.97-Mev crossover transition with an intensity ratio of about six. Although the Weisskopf[7] lifetime formulas are not generally considered sufficiently accurate for this application, for lack of better relations, these were used to calculate intensity ratios for various types of transitions of these energies. The three possibilities shown in Fig. 8 were the only ones which gave order of magnitude agreement with the observed ratio. The next lower ratio 0.05 was for both transitions either $E2$ or $M2$, and the next higher ratio 150 was for either $E2/E3$ or $M2/M3$.

After comparison with the limited experimental data available, it has been estimated[5,8] that the lifetimes of electric transitions calculated from the Weisskopf relations may be too long by a factor of 100, whereas the magnetic transitions give approximate agreement. If the ratios of Fig. 8 are corrected accordingly, none give order of magnitude agreement with the observed ratio. Of the three possibilities, case (a) with spin two even for the first excited state agrees best with evidence[6] for other even-even nuclei. However, if both the first and second excited states have spin two even, any spin assignment for the fourth excited state results in a 2.52-Mev transition to the 1.83-Mev state which is at least six times as strong as the 1.38-Mev transition to the 2.97-Mev state which was observed.

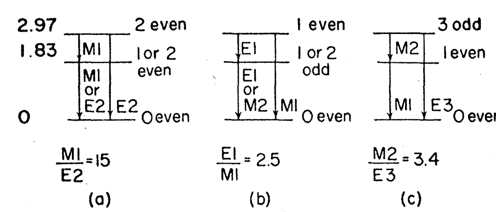


FIG. 8. Possible transitions, spins, and parities for the 1.83- and 2.97-Mev excited states.

Spin and parity assignments for the third and fourth excited states cannot be reduced to a small number of possibilities since the large number of gamma-rays present in Fig. 7 makes the relative intensity estimates difficult. Although many other schemes cannot be excluded, two schemes which best account for all the observed gamma-rays are (starting with the ground state) 0 even, 1 even, 2 even, 2 even, 3 or 4; and 0 even, 1 or 2 odd, 1 even, 1 even, 2 odd.

Recently published angular distribution studies of the

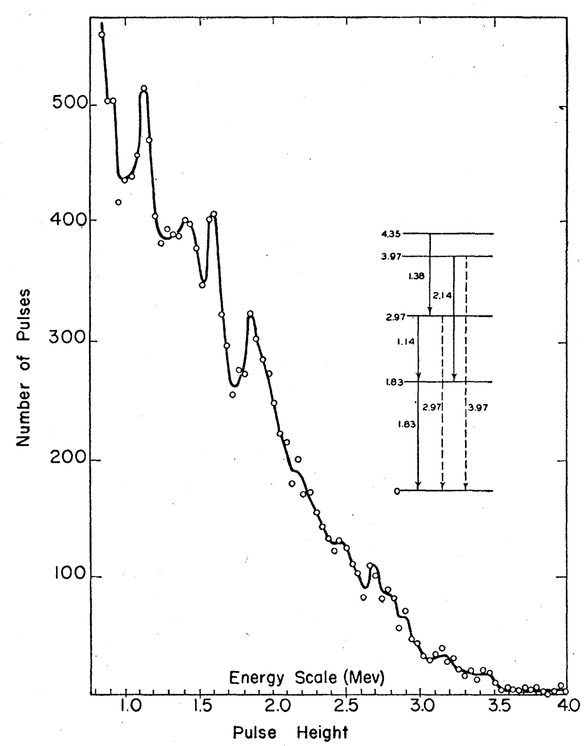


FIG. 7. Gamma-rays from 3.97- and 4.35-Mev excited states of $Mg^{26}$.

[5] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

[6] G. Scharff-Goldhaber, Phys. Rev. **87**, 218 (1952).

[7] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).

[8] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 633.

$Mg^{25}(d,p)Mg^{26}$ reaction by Holt and Marsham[9] have shown that the second, third, and fourth excited states are spin 2 or 3, even parity, and the first excited state may have a spin between 0 and 5, with even parity. These data are in good agreement with the first scheme of the preceding paragraph if the following spin and parity assignments are made: 0, 1, 2, 2, 3, all even parity.

The authors wish to express their appreciation for the helpful counsel and encouragement of Professor Waldo Rall who suggested this problem and under whom the work was completed. They also thank Professor E. C. Pollard and Professor H. A. Schultz for many helpful discussions.

[9] J. R. Holt and T. N. Marsham, Technical Report ONRL-121-52, Office of Naval Research, London (unpublished).

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# A Search for $Si^{32}$ in Natural Silicon

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Two samples of quartz that had been exposed to an intense neutron flux have been examined radiochemically for the presence of 25-day $P^{33}$. Only $P^{32}$, formed presumably from impurities, has been found. Using the limits of detectability and analysis conditions and assuming 0.05 barn for the neutron capture cross section of $Si^{32}$, an upper limit of $4\times10^{-6}$ percent results for the abundance of $Si^{32}$ in natural silicon.

NUCLEAR systematics[1] indicate that $Si^{32}$ might be a beta-stable nuclide and occur in natural silicon in small, as yet undetected, amounts. The upper limit to its abundance from mass-spectrographic analysis[2] is one part in 50 000. A much lower limit can be inferred from some negative results of neutron activation experiments that are reported here.

Two different samples of quartz that had been exposed to a rather intense neutron flux were examined radiochemically for $P^{33}$. This nuclide has a half-life of 25 days and a beta-energy of 0.26 Mev. If there is any $Si^{32}$ in natural silicon, exposure to neutrons should produce $Si^{33}$ by the $(n,\gamma)$ reaction. Since $Si^{33}$ is expected to be short lived, the presence of $Si^{32}$ in natural silicon should be reflected by the presence of 25-day $P^{33}$ in neutron irradiated silicon.

Phosphorus was isolated radiochemically from about 30 g of each sample of quartz by evaporating away $SiF_4$ in the presence of phosphorus carrier, and then alternating ammonia phosphomolybdate and magnesium ammonium phosphate precipitations. The final precipitate showed a small amount of radioactivity that was proven by chemical recycling to be phosphorus and by absorption and decay curves to be $P^{32}$. This, presumably, was the product of the interaction of neutrons on sulfur or phosphorus impurities in the quartz. It is estimated that if the beta-radioactivity isolated had contained as much as 10 percent $P^{33}$ it would have been detected in either decay or absorption curves.

This limit of detectability and the irradiation and analysis conditions, yield a limit for the product of the natural abundance of $Si^{32}$ multiplied by the activation cross section of $Si^{32}$ to form $Si^{33}$. The limits from the two samples are listed in Table I.

TABLE I. Results of search for $P^{33}$ in neutron-activated silicon.

| Sample | 1 | 2 |
|---|---|---|
| Upper limit to cross section in barns×abundance | $3.2\times10^{-9}$ | $1.6\times10^{-9}$ |
| Upper limit to abundance of $Si^{32}$ (assuming a cross section of 0.05 barn for $Si^{32}$) | $6.4\times10^{-8}$ | $3.2\times10^{-8}$ |

Sample 1 exposed in the thimble of the Argonne Heavy Water Pile for about 12 hours
Sample 2 exposed in the "goat hole" of the Argonne Heavy Water Pile for about 5 days

An upper limit of $2\times10^{-9}$ for the product of the abundance of $Si^{32}$ in natural silicon multiplied by the cross section of $Si^{32}$ in barns, results from this work. Although thermal neutron absorption cross sections do not follow too regular a pattern anywhere in the Periodic Table, we estimate the cross section of $Si^{32}$ to be $5\times10^{-2}$ barn with an uncertainty of a factor of 10 by comparison with other light even-even nuclei. The abundance of $Si^{32}$ in natural silicon can then be calculated to be less than $4\times10^{-6}$ percent.

[1] This has been emphasized, for example, by H. Suess in private discussions at the University of Chicago.
[2] Edward P. Ney and John H. McQueen, Phys. Rev. 69, 41 (1946).