to add one point. De Broglie assumes that not only electrons, but also light quanta, are associated with particles. A consistent application of the interpretation suggested here requires, however, as shown in Appendix A, that light quanta be described as electromagnetic wave packets. The only precisely definable quantities in such a packet are the Fourier components, $q_{\mathbf{k},\mu}$, of the vector potential and the corresponding canonically conjugate momenta, $\Pi_{\mathbf{k},\mu}$. Such packets have many particle-like properties, including the ability to transfer rapidly a full quantum of energy at great distances. Nevertheless, it would not be consistent to assume the existence of a "photon" particle, associated with each light quantum.

We shall now discuss Rosen's paper briefly.[10] Rosen gave up his suggested interpretation of the quantum theory, because of difficulties arising in connection with the interpretation of standing waves. In the case of the stationary states of a free particle in a box, which we have already discussed in Sec. 8, our interpretation leads to the conclusion that the particle is standing still. Rosen did not wish to accept this conclusion, because it seemed to disagree with the statement of the usual interpretation that in such a state the electron is moving with equal probability that the motion is in either direction. To answer Rosen's objections, we need merely point out again that the usual interpretation can give no meaning to the motion of particles in a stationary state; at best, it can only predict the probability that a given result will be obtained, if the velocity is measured. As we saw in Sec. 8, however, our interpretation leads to precisely the same predictions as are obtained from the usual interpretation, for any process which could actually provide us with a measurement of the velocity of the electron. One must remember, however, that the value of the momentum "observable" as it is now "measured" is not necessarily equal to the particle momentum existing before interaction with the measuring apparatus took place.

We conclude that the objections raised by Pauli, de Broglie, and Rosen, to interpretations of the quantum theory similar to that suggested here, can all be answered by carrying every aspect of our suggested interpretation to its logical conclusion.

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Neutrons from the Disintegration of the Separated Isotopes of Silicon by Deuterons*

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The neutron spectra from deuterons on silicon have been studied by the method of recoil protons and photographic plates. Thick isotopic targets of the three separated isotopes of silicon were irradiated by deuterons of energy 1.4 Mev, supplied by the Bartol Van de Graaff statitron, observations being carried out at angles of zero and ninety degrees with the incident deuterons. Q-values, from which energy levels in the residual nuclei of phosphorous may be calculated, are as follows:

Reaction	Q-values (Mev)
$Si^{28}(d,n)P^{29}$	0.29
$Si^{29}(d,n)P^{30}$	3.27, 2.52, 1.81, 1.27
$Si^{30}(d,n)P^{31}$	4.92, 4.59, 3.73, 2.70, 1.51

The estimated probable error in the Q-values is 40 kev.

THERE are three stable isotopes of silicon, Si^{28}, Si^{29}, and Si^{30}, having respectively relative abundances of 92.28 percent, 4.67 percent, and 3.05 percent. When these elements are irradiated by deuterons, neutrons are emitted in the following three reactions.

$$(1)\ Si^{28}+d\rightarrow P^{29}+n^1+Q_1,$$

$$(2)\ Si^{29}+d\rightarrow P^{30}+n^1+Q_2,$$

$$(3)\ Si^{30}+d\rightarrow P^{31}+n^1+Q_3.$$

Naturally occurring silicon has been previously bombarded with deuterons to observe the neutron spectra.[1] However, because of the element of ambiguity introduced by the presence of the mixture of isotopes, the data are difficult of interpretation. To reinvestigate the above three reactions, quantities of the separated isotopes, in the form of silicon dioxide, were obtained from the Y-12 plant, Carbide and Carbon Chemicals Division, Union Carbide and Carbon Corporation, Oak Ridge, Tennessee. The mass analyses of the various targets are shown in Table I.

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† Calcutta, India. Guest physicist, Bartol Research Foundation, 1951.

‡ The contribution of D. M. Van Patter to this article consists of the preparation of the Appendix.

[1] R. A. Peck, Jr., Phys. Rev. 73, 947 (1948).

TABLE I. Isotopic analysis of target materials.

Si^{28}		Si^{29}		Si^{30}	
Isotope	Percent	Isotope	Percent	Isotope	Percent
28	99.4	28	29.1	28	40.97
29	0.4	29	68.6	29	2.44
30	0.2	30	2.2	30	56.59

Thick isotopic targets of the separated isotopes of silicon were irradiated by deuterons of energy 1.40 Mev, supplied by the Bartol Van de Graaff statitron. The neutrons emitted in the three reactions above were recorded in Eastman NTA plates located at zero and ninety degrees with the incident deuterons.

In evaluating the energies of the neutron groups of all of the three reactions above, two procedures have been employed. One has been to apply the range-energy relation of Lattes, Fowler, and Cuer[2] to NTA plates, increasing the observed energy by two percent to allow for an acceptance angle of twelve degrees in the forward direction; the other has consisted in decreasing the result of the first method by an amount indicated by a recently obtained calibration curve[3] for NTA plates, and increasing it to take into account the use of a thick target.[4] The latter procedure has been considered to give the preferable result. The procedures of evaluation described above will be referred to respectively as Method I and Method II.

$Si^{28}(d,n)P^{29}$

The energy spectrum of the acceptable recoil protons of the neutrons emitted in the reaction $Si^{28}(d,n)P^{29}$ is shown in Fig. 1. Observations were carried out at zero degrees and ninety degrees in the laboratory system of coordinate axes. As indicated in the figure, two groups of neutrons appear at both angles of observation. The group of lower energy is assigned to the reaction $C^{12}(d,n)N^{13}$. The more energetic is thought to be related to the formation of P^{29} in its ground state. In the forward direction, high energy neutrons of low intensity

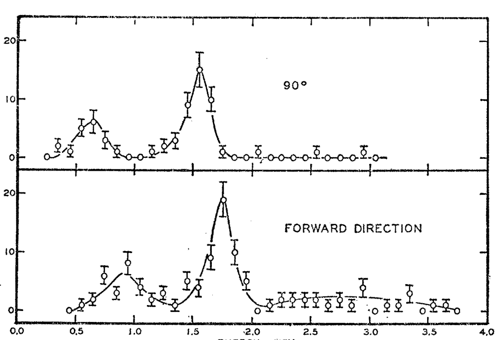

FIG. 1. Recoil protons knocked on in the forward direction by the neutrons from $Si^{28}(d,n)P^{29}$.

[2] Lattes, Fowler, and Cuer, Proc. Phys. Soc. (London) **59**, 883 (1947).
[3] Richards, Johnson, Ajzenberg, and Laubenstein, Phys. Rev. **83**, 994 (1951).
[4] S. C. Snowdon (to be published).

TABLE II. Ground-state Q-values for $Si^{28}(d,n)P^{29}$.

	Method I	Method II
Q-value (Mev)	0.36 ± 0.04	0.29 ± 0.04

are present. These are thought to result from the bombardment of "low Z" contaminants on the walls of the vacuum tube and of the magnet box between the poles of the beam focusing magnet of the Van de Graaff statitron. Plates in the forward direction are sensitive to neutrons emanating from these points, whereas the plates at ninety degrees to the beam are perpendicular to their direction of emission and hence do not record their recoil protons in the acceptable sense. This point is born out by the fact that no appreciable evidence of the presence of neutrons beyond those of the ground state is apparent in the data obtained at ninety degrees. The data of Fig. 1 are summarized in Table II.

The Q-values of Table II are means of those calculated at each of the two angles of observation. It is to be noted that they are in disagreement with the previously reported Q-value of -0.80 ± 0.10 Mev,[1] and with those values calculated from other reactions and from mass values (see Appendix).

$Si^{29}(d,n)P^{30}$

The spectra of acceptable recoil protons of the neutrons emanating from $Si^{29}(d,n)P^{30}$ are shown in Fig. 2. The most energetic group[5] is assigned to $N^{14}(d,n)O^{15}$,

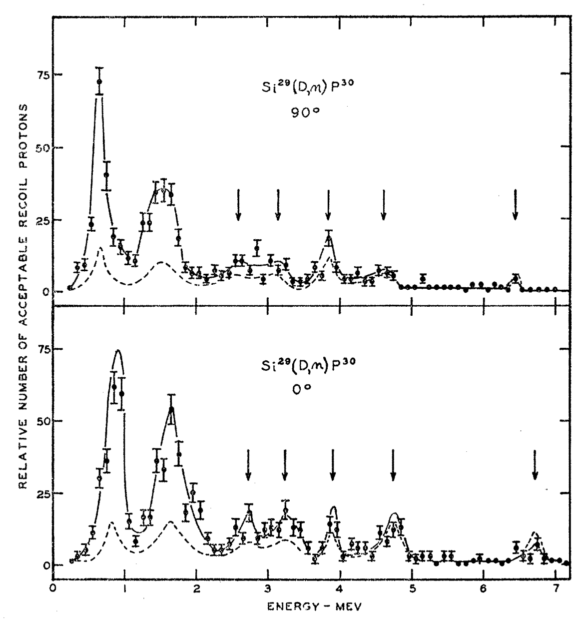

FIG. 2. Energy spectrum of the acceptable recoil protons of the neutrons from the reaction $Si^{29}(d,n)P^{30}$.

[5] The neutron group of the nitrogen reaction appears at zero degrees and ninety degrees in the data relating to $Si^{29}(d,n)P^{30}$ and in the forward direction alone in measurements on $Si^{30}(d,n)P^{31}$. The absence of this group at ninety degrees in the latter reaction

the least energetic one to $C^{12}(d,n)N^{13}$. The ground-state group of the reaction $Si^{28}(d,n)P^{29}$, the reaction of the preceding discussion, is also clearly present. The intermediate groups are assigned to the reaction $Si^{29}(d,n)P^{30}$. The data of Fig. 2 are summarized in Table III.

The energy levels of P^{30} in Table III are calculated from the preferred values of Method II.

$Si^{30}(d,n)P^{31}$

The acceptable recoil proton groups of the neutrons from $Si^{30}(d,n)P^{31}$ are shown in Fig. 3.[6] Here again, the most energetic group, appearing at 6.75 Mev in the forward direction, is assigned to $N^{14}(d,n)O^{15}$; the least energetic one to $C^{12}(d,n)N^{13}$. Again, the ground-state group of $Si^{28}(d,n)P^{29}$ is present. The remaining groups are assigned to $Si^{30}(d,n)P^{31}$. The data of Fig. 3 are summarized in Table IV.§

The nuclear energy levels of P^{31} have been calculated from the preferred Q-values of Method II.

TABLE III. Q-Values of $Si^{29}(d,n)P^{30}$ and energy levels of P^{30}.

Q-values (Mev) Method I	Q-values (Mev) Method II	Excitation levels of P^{30}
1.41±0.04	1.27±0.04	2.00±0.06
1.97±0.04	1.81±0.04	1.46±0.06
2.68±0.04	2.52±0.04	0.75±0.06
3.51±0.04	3.27±0.04	0.00

CONCLUSIONS

The energies of the neutron groups from deuterons on the separated isotopes of silicon have been measured. In many instances the calculated energy levels of the residual nuclei of phosphorous agree with those already obtained (see reference 1, Table II). The bearing of the measurements upon the masses and reaction energies of the silicon region are discussed in the appendix.

The writers wish to acknowledge the continued interest of Dr. W. F. G. Swann, Director of the Bartol Research Foundation.

is not considered significant, because statistical difficulties are encountered in accumulating acceptable long tracks. From the several spectra, an average Q-value of 5.11±0.04 Mev is calculated for $N^{14}(d,n)O^{15}$, using Method II of the text. This result is in good agreement with the previously reported energy release of 5.15±0.05 Mev [W. M. Gibson and D. L. Livesey, Proc. Phys. Soc. (London) **60**, 523 (1948)].

[6] The broken line of Figs. 2 and 3 represents the actual distribution of neutron energies corrected for variation with energy of the *n-p* scattering cross section and acceptance probability.

§ *Note added in proof:* In each of the three figures, the data at zero and ninety degrees have not been normalized to take into account plate area scanned. No information is thus presented concerning the angular distributions of the neutron groups. The fluctuation of the intensity of the carbon group relative to those of the other neutron groups is thought to be related to statitron performance. Excessive sparking and breakdown in the vacuum tube appear to increase the carbon contamination.

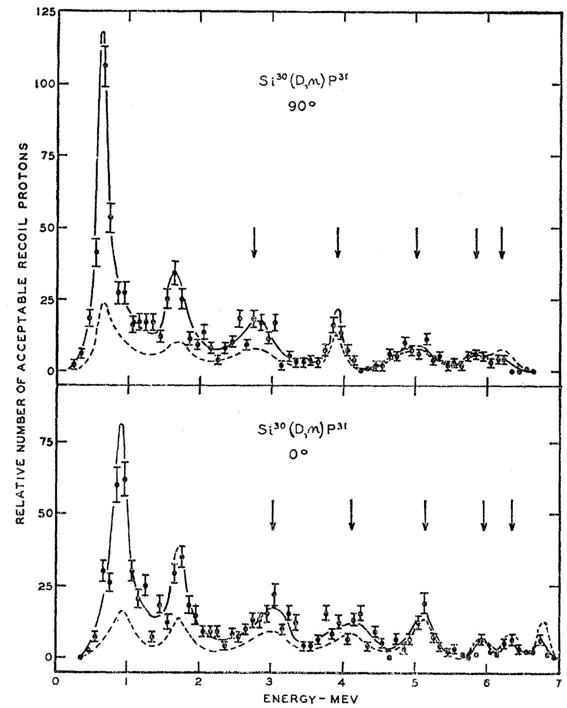

FIG. 3. Recoil protons of the neutrons emitted in the reaction $Si^{30}(d,n)P^{31}$.

APPENDIX: DISCUSSION OF RESULTS

Recent precise measurements[7,8] of nuclear Q-values involving nuclei with $Z=10$ to 16 have led to a revision of masses in that region.[9,10] However, in many cases, the most accurate method of estimating a given reaction energy involves the use of mass differences rather than a table of masses. It is of interest to compare the Q-values of the ground states measured by Mandeville, Swann, and Chatterjee with the reaction energies which can be predicted from the measurements of other workers.

The Reaction $Si^{28}(d,n)P^{29}$.—The end point of the beta-transition $P^{29} \xrightarrow{\beta^+} Si^{29}$ has been measured as 3.63±0.07 Mev[11] by means of cloud chamber and magnetic field. Except for the results of the present paper relating to reaction $Si^{28}(d,n)P^{29}$, the beta-transition above is the only link connecting the nucleus of P^{29} with other nuclei. Combining the total disintegration energy of the beta transition, 4.65±0.07 Mev, with the reaction energy of the

TABLE IV. Q-values of $Si^{30}(d,n)P^{31}$ and energy levels of P^{31}.

Q-values (Mev) Method I	Q-values (Mev) Method II	Excitation levels of P^{31} (Mev)
1.64±0.04	1.51±0.04	3.41±0.06
2.28±0.04	2.70±0.04	2.22±0.06
3.95±0.04	3.73±0.04	1.19±0.06
4.79±0.04	4.59±0.04	0.33±0.06
5.16±0.04	4.92±0.04	0.00

[7] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

[8] W. W. Buechner, *et al.*, M.I.T. report, Laboratory for Nuclear Science and Engineering (May 31, 1951).

[9] H. T. Motz, Phys. Rev. **81**, 1061 (1951).

[10] A. H. Wapstra, to be published.

[11] White, Creutz, Delsasso, and Wilson, Phys. Rev. **59**, 63 (1941).

TABLE AI. Q-values in Mev.

Reaction	Observed	Calculated from nuclear reactions	Calculated from masses
$Si^{28}(d,n)P^{29}$	0.29 ± 0.04	0.81 ± 0.07	0.81 ± 0.09
$Si^{29}(d,n)P^{30}$	3.27 ± 0.04	3.25 ± 0.18	3.24 ± 0.11
$Si^{30}(d,n)P^{31}$	4.92 ± 0.04	5.08 ± 0.02	5.03 ± 0.06

reaction $Si^{28}(d,p)Si^{29}$, 6.246 ± 0.007 Mev,[7] and with the neutron-proton mass difference of 0.782 ± 0.001 Mev,[12] a reaction energy 0.81 ± 0.07 Mev may be calculated for the reaction $Si^{28}(d,n)P^{29}$.

The Reaction $Si^{29}(d,n)P^{30}$.—The Q-value for the formation of P^{30} in the ground state in the reaction $Si^{29}(d,n)P^{30}$ may be calculated from each of two independent cycles of nuclear reactions.

I. (a) $P^{31}+\gamma\rightarrow P^{30}+n-(12.37\pm0.2)$ Mev[13,14]
(b) $P^{31}+p\rightarrow Si^{28}+He^4+(1.909\pm0.015)$ Mev[15]
(c) $Si^{28}+d\rightarrow Si^{29}+p+(6.246\pm0.007)$ Mev[7]
(d) $2d\rightarrow He^4+(23.834\pm0.007)$ Mev[12]

$$Q=(2d-He^4)-1.909\text{ Mev}-6.246\text{ Mev}-12.37\text{ Mev}=3.31\pm0.20\text{ Mev}$$

II. (a) $Si^{29}+d\rightarrow Si^{30}+p+(8.388\pm0.013)$ Mev[8]
(b) $P^{30}\xrightarrow{\beta^+}Si^{30}+(4.52\pm0.35)$ Mev[16]
(c) $n\xrightarrow{\beta^-}p+(0.782\pm0.001)$ Mev[12]

$$Q=(p-n)-4.52\text{ Mev}+8.388\text{ Mev}=3.09\pm0.35\text{ Mev}$$

A weighted average of results I and II is 3.25 ± 0.18 Mev.

[12] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).
[13] McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).
[14] A. Katz and L. Penfold, Phys. Rev. **81**, 815 (1951).
[15] D. M. Van Patter and P. M. Endt, preliminary value.
[16] C. Magnan, Ann. phys. **15**, 5 (1941).

The Reaction $Si^{30}(d,n)P^{31}$.—In the case of the reaction $Si^{30}(d,n)P^{31}$, precise estimates of the energy release can be made by two independent methods.

I. (a) $Si^{30}+d\rightarrow Si^{31}+p+(4.367\pm0.010)$ Mev[7]
(b) $Si^{31}\xrightarrow{\beta^-}P^{31}+(1.51\pm0.01)$ Mev[17]
(c) $n\xrightarrow{\beta^-}p+(0.782\pm0.001)$ Mev[12]

$$Q=(p-n)+4.367\text{ Mev}+1.51\text{ Mev}=5.095\pm0.015\text{ Mev}$$

II. (a) $Si^{29}+d\rightarrow Si^{30}+p+(8.388\pm0.013)$ Mev[8]
(b) $Si^{28}+d\rightarrow Si^{29}+p+(6.246\pm0.007)$ Mev[7]
(c) $P^{31}+p\rightarrow Si^{28}+He^4+(1.909\pm0.015)$ Mev[15]
(d) $d\rightarrow p+n-(2.225\pm0.002)$ Mev[12]
(e) $2d\rightarrow He^4+(23.834\pm0.007)$ Mev[12]

$$Q=(2d-He^4)+(d-n-p)-6.246\text{ Mev}-8.388\text{ Mev}-1.909\text{ Mev}=5.066\pm0.022\text{ Mev}$$

An arithmetical average of the results of I and II is 5.08 ± 0.02 Mev.

The foregoing calculated values are listed in Table AI of this Appendix together with values estimated from a table of binding energies recently computed by Wapstra.[10] The agreement between these values is not surprising, because Wapstra's binding energies are based to a large extent upon nuclear Q-values.

It may be seen from this table that the observed Q-value for the reaction $Si^{29}(d,n)P^{30}$ is in agreement with other measurements, and, in fact, establishes the mass of P^{30} with greater precision than was previously possible. The observed energy release, 4.92 ± 0.04 Mev, for the reaction $Si^{30}(d,n)P^{31}$ is somewhat lower than the more accurate predicted value of 5.08 ± 0.02 Mev; however, it seems probable that the ground-state group of the reaction has been observed. In the case of $Si^{28}(d,n)P^{29}$, the observed energy release of 0.29 ± 0.04 Mev is in distinct disagreement with the estimated value of 0.81 ± 0.07 Mev. This discrepancy can be attributed to either an inaccuracy in the early measurement[11] of the end point of the transition $P^{29}\xrightarrow{\beta^+}Si^{29}$ or to the fact that the ground state of the reaction $Si^{28}(d,n)P^{29}$ has not been observed in the measurements of the present paper.

[17] H. W. Newson, Phys. Rev. **51**, 624 (1937).