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GAMMA RAYS FROM THE $^{31}P(n, \gamma)^{32}P$ REACTION

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Abstract: The $^{31}P(n, \gamma)^{32}P$ reaction is studied with a 5 cm^3 Ge(Li) counter. Altogether, 54 γ-rays are detected with experimental energy errors between 0.4 and 3.0 keV. The Q-value of the reaction is determined as $Q = 7936.8 \pm 0.8$ keV.

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NUCLEAR REACTIONS $^{31}P(n, \gamma)$, E = thermal; measured E_γ, I_γ; deduced Q. ^{32}P deduced levels, branching. Natural target.

1. Introduction

This investigation is a continuation of work reported earlier ^{1}). It was thought worthwhile to measure the γ-radiation from the $^{31}P(n, \gamma)^{32}P$ reaction with a Ge(Li) counter, to clear up a number of ambiguities in the results of ref. ^{1}), as e.g. the sequence of γ-rays in some of the cascades.

2. Experimental arrangement

A thin-walled teflon cylinder, 4.3 cm long and 1.0 cm diam., containing 4.3 g of red phosphorus, was placed in a horizontal beam ^{2}) emerging from the Dutch High Flux Reactor in Petten. The thermal neutron flux is about 10^7 $cm^{-2} \cdot sec^{-1}$.

The neutron capture γ-radiation was detected at 10 cm from the target with a 5 cm^3 RCA-Victor Ge(Li) counter, having a depletion layer of 7 mm thickness. The signal is fed through an Ortec 109 preamplifier and a Nuclear Enterprises NE 5259 amplifier to an Intertechnique 4096-channel analyser, having a 2048-channel analogue-to-digital converter. The system has an energy resolution of 5 keV at 1 MeV and 12 keV at 6 MeV. The spectrum was measured in three separate irradiations in which the E_γ = 0-2.3, 0-3 and 3-7 MeV regions were covered. For the latter region a biassed amplifier, amplifier and stretcher, Ortec 408, 410 and 411 were used, respectively.

The background radiation was measured with the thermal neutron beam removed by means of a ^{6}LiF shutter. Beam-on and beam-off measurements, each for 1 h, were alternated. The total spectrum and background spectrum were accumulated in the first and the second half of the 4096-channel memory, respectively. A typical measurement lasted 20 h.

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3. Analysis of the measurements

Before and after each measurement, a calibration run was made with a precision pulse generator †, having a non-linearity, i.e. the relative deviation of the pulse height from the setting, of $\leqq 4\times 10^{-5}$. These measurements determine the relation between channel number and pulse height. It was found that the response function, which is constructed from 25 calibration points, is of the third order. Higher orders were tried, but were found to give no significant improvement.

Pulse height is converted into γ-ray energy by using γ-rays in the spectrum of well-known energy. Suitable are the annihilation radiation, and the pair and full-energy peaks of the 2224.5±0.2 keV γ-ray [3]) from the ^{1}H(n, γ)^{2}H reaction. Phosphorus is sufficiently hygroscopic to provide strong hydrogen peaks.

One strong triple cascade which contains only low-energy γ-rays ($E_\gamma < 4$ MeV) serves to calculate the Q-value of the ^{31}P(n, γ)^{32}P reaction with a precision of 0.8 keV from the 0-3 MeV spectrum. This Q-value, together with the energy of some accurately measured low-energy γ-rays, makes it possible to calculate the energy of a number of high-energy γ-rays, which serve in turn for the energy calibration of the 3-7 MeV spectrum.

The internal consistency is quite good. The standard deviation in the reaction energy, as found by adding energies of cascading γ-rays in 27 different ways is 1.0 keV. Here the error is solely calculated from the experimental γ-ray energies, without using the estimated errors, assuming that the sums are Gaussian distributed.

The intensities of the measured γ-rays were obtained by computing the areas of full-energy peaks for E_γ = 0-1.5 MeV and the areas of the pair peaks for E_γ = 2.5-8 MeV. In the E_γ = 1.5-2.5 MeV region, both the full-energy peaks and pair peaks were used, if possible.

The efficiency curves for full-energy, single-escape and pair peaks were obtained by using a set of calibrated radioactive sources and the ^{32}S(n, γ)^{33}S reaction [4]) for $E_\gamma \leqq 5.42$ MeV, and the ^{35}Cl(n, γ)^{36}Cl reaction [5]) for $6.11 \leqq E_\gamma \leqq 8.58$ MeV. In order to normalize the calibration points obtained from the chlorine spectrum to the other calibration points, the 5.42 and 7.64 MeV γ-rays following neutron capture in a mixed sulphur-iron target were measured, after this source was calibrated with a 12.7 cm × 12.7 cm NaI crystal [1]). A mixed sulphur-chlorine target is not attractive because the capture cross sections of these elements differ by about two orders of magnitude. Thus it is difficult to produce a homogeneously mixed target.

It was found that the intensity of the single-escape peaks is 7 % of the pair-peak intensity, independent of energy.

Due to the uncertainties of the scintillation-spectrometer measurements, the intensity calibration has an estimated error of 10 %.

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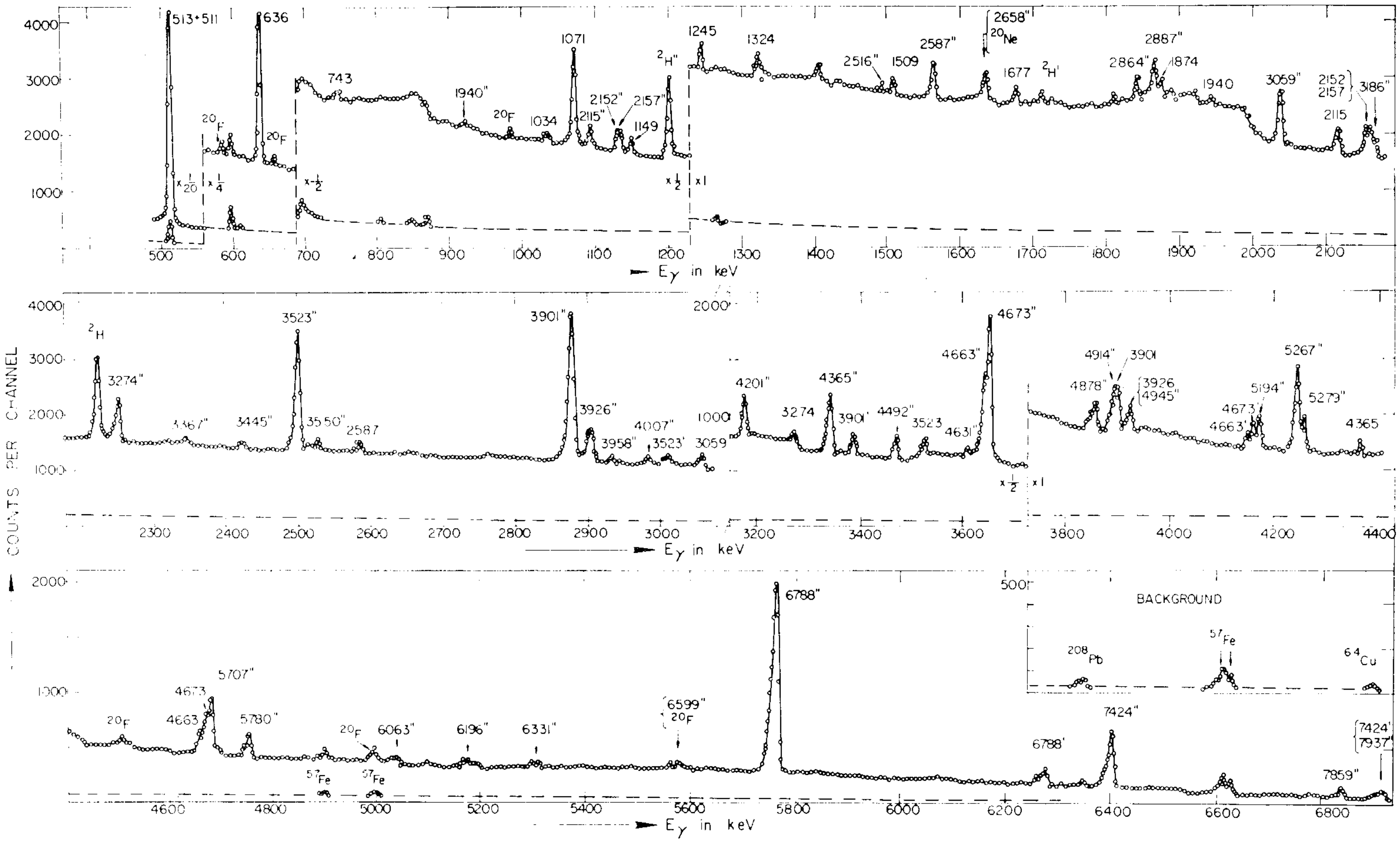

Fig. 1. Single spectrum of the $^{31}P(n, \gamma)^{32}P$ reaction and background spectrum, counting time 10 h. All peaks which belong to ^{32}P are labelled with their energy in keV. The full-energy, single-escape and pair peaks are indicated by unprimed, single-primed and double-primed energies, respectively. A few lines, assigned to other nuclei are indicated also. The energy scale is not corrected for recoil losses.

4. Results and discussion

The spectrum in fig. 1 shows the E_γ = 0-3 and E_γ = 3-7 MeV measurements. All γ-rays which are believed to belong to ^{32}P are labelled with the energy in keV. The full-energy, single-escape and pair peaks are indicated by unprimed, single-primed and double-primed energies, respectively. Gamma rays following neutron capture in a number of other nuclei are also indicated.

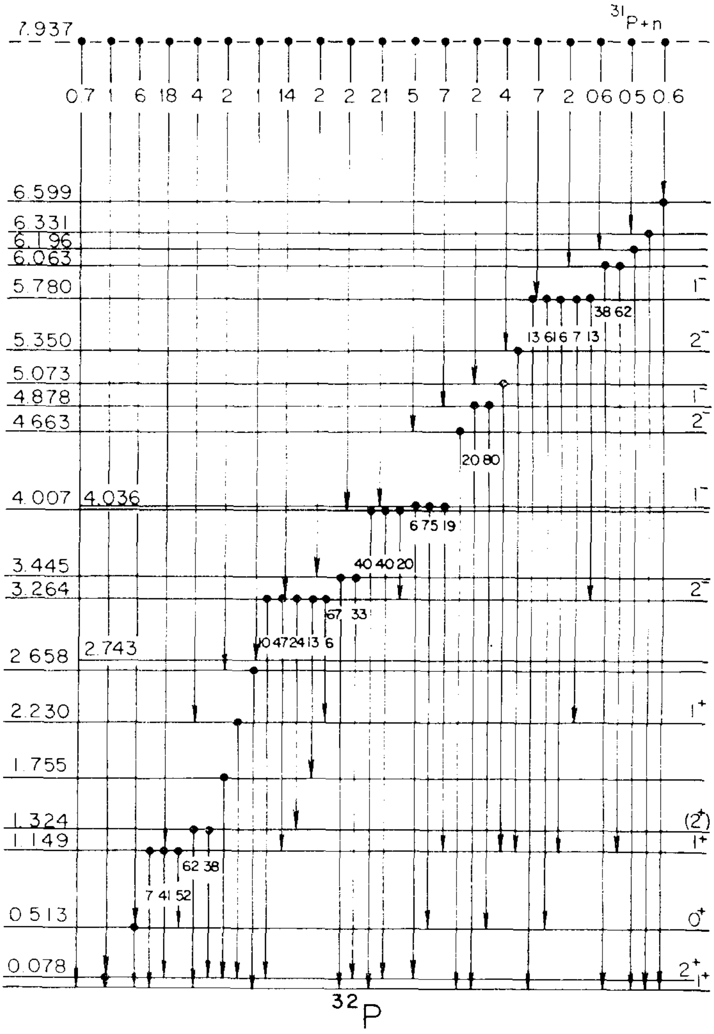

Fig. 2. Decay scheme of ^{32}P. The intensities of primary γ-rays are in numbers per 100 captures. For the bound levels the branching ratios are given.

Table 1 lists the results of ^{32}P. The errors in the energies are compounded from the error in reading the channel number or from the error in the calibration function. The

TABLE 1

Gamma rays observed in the $^{31}P(n, \gamma)^{32}P$ reaction

	E_γ [a] (keV)	Intensity (number of γ-rays per 100 captures)	Interpretation [b]
1	7935.3±2.0	0.8±0.2	C → 0
2	7858.5±1.0	1.1±0.2	C → 0.078
3	7424.2±1.0	5.6±0.6	C → 0.513
4	6786.8±1.0	18.0±1.8	C → 1.149
5	6599.4±3.0	0.6±0.2	6.599 → 0
6	6330.6±3.0	0.5±0.2	6.331 → 0
7	6196.2±3.0	0.6±0.3	6.196 → 0
8	6063.1±3.0	1.1±0.3	6.063 → 0
9	5780.1±1.5	0.9±0.2	5.780 → 0
10	5707.4±1.5	4.5±0.5	C → 2.230
11	5278.9±1.0	1.7±0.3	C → 2.658
12	5266.2±1.0	3.9±0.5	5.780 → 0.513
13	5194.0±1.5	1.4±0.3	C → 2.743
14	4944.8±2.0	0.6±0.3	(4.945 → 0)
15	4914.9±3.0	1.2±0.3	6.063 → 1.149
16	4877.6±1.0	1.4±0.3	4.878 → 0
17	4673.0±1.5	17.1±1.7	C → 3.264
18	4664.9±1.5		4.663 → 0
19	4630.7±2.0	0.5±0.2	5.780 → 1.149
20	4492.1±1.0	1.8±0.2	C → 3.445
21	4363.7±1.0	5.9±0.6	4.878 → 0.513
22	4199.9±1.0	3.5±0.4	5.350 → 1.149
23	4006.9±1.0	0.9±0.2	4.007 → 0
24	3957.0±0.8	1.1±0.2	4.036 → 0.078
25	3926.0±0.5 [c]	5.3±0.5	5.073 → 1.149; C → 4.007; 4.007 → 0.078
26	3900.4±0.4	21.3±2.1	C → 4.036
27	3550.0±1.0	0.6±0.2	5.780 → 2.230
28	3523.0±0.4	15.0±1.5	4.036 → 0.513
29	3444.1±1.5	1.2±0.3	3.445 → 0
30	3368.2±1.0	0.5±0.2	3.445 → 0.078
31	3274.1±0.3	5.4±0.5	C → 4.663
32	3187.0±1.5	2.1±0.3	3.264 → 0.078
33	3058.7±0.6	6.6±0.7	C → 4.878
34	2886.8±0.8	3.5±0.4	4.036 → 1.149
35	2863.9±1.0	2.0±0.3	C → 5.073
36	2656.9±2.0	[d]	2.658 → 0
37	2586.6±0.6	4.7±0.5	C → 5.350
38	2515.8±1.0	0.9±0.5	5.780 → 3.264
39	2157.5±1.0	6.5±0.7	C → 5.780
40	2152.0±1.0	6.4±0.6	2.230 → 0.078
41	2114.5±0.8	7.7±0.8	3.264 → 1.149
42	1939.4±1.0	3.5±0.8	3.264 → 1.324
43	1874.4±1.5	2.0±0.6	C → 6.063
44	1676.8±1.0	1.5±0.4	1.755 → 0.078
45	1509.0±1.0	2.5±0.3	3.264 → 1.755
46	1323.2±1.0	2.9±0.3	1.324 → 0
47	1244.6±1.0	1.9±0.3	1.324 → 0.078
48	1148.8±0.8	3.2±0.3	1.149 → 0
49	1071.4±0.6	16.7±1.7	1.149 → 0.078
50	1033.7±1.0	1.2±0.2	3.264 → 2.230
51	744.3±1.0	0.5±0.2	4.007 → 3.264
52	636.8±0.5	21.8±2.2	1.149 → 0.513
53	513.4±0.5	[d]	0.513 → 0
54	78.0±0.5 [e]	[d]	0.078 → 0

[a] Corrected for recoil losses.

[b] C denotes the capturing state. The level energies are given in MeV.

[c] At least double.

[d] Intensity not determined. Peak is obscured by another one.

[e] Calculated energy.

intensities are normalized such that the sum for all primary γ-rays is 100. The level energies, given in table 2, are calculated from a least-squares program which fits the energies adding up to the binding energy found as $Q = 7936.8 \pm 0.8$ keV. This value, which is determined from adding the energies of the lines 26, 28 and 53, is in excellent agreement with the value $Q = 7936.6 \pm 2.4$ keV from the known masses [6]. The interpretation (table 1) of most of the γ-rays is based on the coincidence measurements reported earlier [1]. The interpretation of the remaining γ-rays is discussed below.

The decay scheme, shown in fig. 2, is in fair agreement with the former decay scheme [1]. New transitions and new interpretation of γ-rays are the following.

TABLE 2

Energy levels of ^{32}P deduced from the measured γ-ray energies

E_x(keV)	E_x(keV)	E_x(keV)
78.1 ± 0.3	2742.8 ± 2.0	5072.9 ± 1.5
513.1 ± 0.3	3264.2 ± 0.6	5349.8 ± 0.6
1149.4 ± 0.5	3445.3 ± 1.0	5779.5 ± 0.6
1323.6 ± 0.5	4006.9 ± 1.0	6062.8 ± 1.5
1754.9 ± 0.8	4036.2 ± 0.5	6196.2 ± 3.0
2229.8 ± 0.6	4662.8 ± 0.4	6330.6 ± 3.0
2657.7 ± 0.7	4877.6 ± 0.5	6599.4 ± 3.0

(i) *The decay of the* $E_x = 5.780$ MeV *state.* The ground-state decay follows unambiguously from the presence of γ-ray 9. Gamma ray 19 is interpreted as the decay to the third excited state. Gamma rays 27 and 38 are the transitions to the $E_x = 2.230$ and 3.264 MeV states, respectively, as was suggested already from coincidence experiments [1].

(ii) *The* C → 2.743 MeV *transition.* It is quite probable that γ-ray 13 is a primary, although the present experiment does not exclude the existence of a transition from the $E_x = 5.707$ MeV state [7] to the second excited state.

(iii) *The* 6.063 → 1.149 MeV *transition.* Formerly [1] γ-ray 15 was interpreted as the primary to the $E_x = 3.007$ MeV state [7]. Since the presently measured γ-ray energy makes this interpretation very unlikely and because the population of the $E_x = 6.063$ MeV state is much stronger than the ground-state decay of this state, this γ-ray is interpreted as the 6.063 → 1.149 MeV transition.

(iv) *The* C → 4.663 → 0 MeV *cascade.* Its existence follows unambiguously from the observed γ-rays 18 and 31. No evidence is found for a C → 3.264 → 0 MeV cascade [1].

(v) *The* C → 4.007 → 0 *and* C → 4.007 → 0.078 MeV *cascades.* From ref. [1], it is known that there exists a 3.93 ± 0.02 MeV peak which is coincident "with itself", interpreted as the C → 4.04 → 0.08 MeV cascade. The intensity of this cascade is considerably stronger than found for the C → 4.036 → 0.078 MeV cascade in the present experiment. The peak found at 3926 keV, which is at least double, is partly explained now by interpreting it as the C → 4.007 and 4.007 → 0.078 MeV transitions. Furthermore γ-ray 23 is interpreted as the ground-state decay of the 4.007 MeV level.

(vi) *The* C → 5.073 → 1.149 MeV *cascade.* This follows from the presence of γ-ray 35 together with the remaining part of the peak at 3926 MeV, the latter being interpreted as the 5.073 → 1.149 MeV transition.

(vii) *The* 3.445 → 0.078 MeV *transition.* This transition explains γ-ray 30.

(viii) *The* 3.264 → 2.230 *and* 4.007 → 3.264 MeV *transitions.* These transitions are implied by γ-rays 50 and 51, respectively. Although this interpretation is quite probable, also other interpretations are possible.

TABLE 3

Gamma rays observed in some other (n, γ) reactions

E_γ [a] (keV)	Intensity [b]	Interpretation [c]
7916.5±2.0		^{64}Cu: C → 0
7645.9±3.0		^{57}Fe: C → 0
7633.3±1.5		^{57}Fe: C → 0.014
7369.7±3.0		^{208}Pb: C → 0
6599.8±3.0	[d]	^{20}F: C → 0
6019.4±2.0	0.8±0.2	^{20}F: 6.019 → 0
		^{57}Fe: C → 1.625
5924.3±3.0		^{57}Fe: C → 1.723
5534.9±2.0	0.5±0.2	^{20}F: C → 1.06
1634.8±0.6	3.0±0.8	^{20}Ne: 1.635 → 0
983.6±1.0	0.9±0.2	(^{20}F: 0.99 → 0)
655.3±1.0	0.5±0.2	(^{20}F: 0.66 → 0)
583.6±0.5	1.5±0.3	^{20}F: C → 6.019

[a] Corrected for recoil losses.

[b] Only for ^{20}F, in the same intensity scale as for the ^{32}P γ-rays.

[c] C denotes the capturing state.

[d] Intensity not determined, because this peak also belongs to ^{32}P.

No evidence is found for a C → 3.32 → 0.52 MeV cascade [1]. Moreover it should be noticed that the existence of a possible C → 4.414 → 0.513 MeV cascade, which involves 3523 and 3901 keV γ-rays, cannot be excluded from the present investigation.

Finally, from the measured angular correlation 1 in table 4 of ref. [1], it follows that $J(4.663) = 2$. Since $l_n(4.663) = 1$ (ref. [7]) it is reasonable to assume pure E1 radiation in both γ-rays. The angular correlation is weakened by the admixture of the C → 3.264 → 0.078 MeV cascade (1^+(E1)2^-(E1)2^+).

Besides γ-rays in ^{32}P and the ^{2}H γ-ray, a number of lines assigned to transitions in ^{20}F, ^{20}Ne, ^{57}Fe, ^{64}Cu and ^{208}Pb are observed; see fig. 1 and table 3.

The ^{20}F lines and the ^{20}Ne line result from radiative neutron capture in ^{19}F, present in the teflon target holder and the beam tube [1]). From ref. [8]) it follows that the intensity of the ^{20}Ne line (3.0 ± 0.8 %) equals the total contribution of ^{20}F to this measurement.

From ref. [9]) it is known that the 6599, 6019 and 5534 keV γ-rays belong to ^{20}F. The first γ-ray is also assigned to ^{32}P, on basis of earlier work [1]), where it is shown that a level at $E_x = 6.60$ MeV is excited, decaying to either the ground state or the first excited state. A possible $6.60 \rightarrow 0.078$ MeV transition in ^{32}P could not be detected in the present work. The 583.6 keV γ-ray is assumed to excite the 6.019 MeV level in ^{20}F. From this assumption a reaction energy of $Q = 6603.0 \pm 2.0$ keV is found, in good agreement with $Q = 6597.3 \pm 4.7$ keV, given in ref. [6]). The 983.6 and 655.3 keV γ-rays are interpreted as the transitions from the third and first excited state to the ground state in ^{20}F, respectively.

Neutron capture in the iron and lead containing shielding of neighbouring neutron-diffraction experiments cause the ^{57}Fe and ^{208}Pb γ-lines, whereas the ^{64}Cu line results from neutron capture in the copper monochromator of a diffraction set-up. It may be noted that, on the average, the Q-values found here for the neutron capture in these nuclei agree well with those given in ref. [6]).

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