Activation Cross Sections of Calcium, Potassium, and Aluminum for 14.2-MeV Neutrons

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(Received 23 June 1967; revised manuscript received 26 September 1967)

The cross sections for some (n,t), (n,d), (n,p), (n,α), and $(n,2n)$ reactions have been measured on the various enriched isotopes of calcium and spectroscopically pure potassium and aluminum. Powdered samples, wrapped in thin aluminum foils to act as neutron monitors, were irradiated with 14.2±0.2 MeV neutrons. The induced absolute activities were measured by a calibrated and specially shielded well-type NaI(Tl) crystal. The following results (in millibarns) for the cross sections have been obtained: $Al^{27}(n,p)Mg^{27}$, 71±9; $Ca^{40}(n,t)K^{38}$ (ground state), 0.18±.02; $Ca^{42}(n,p)K^{42}$, 190±24; $Ca^{43}(n,p)K^{43}$, 93±12; $Ca^{43}(n,d)K^{42}$, 1.3; $Ca^{44}(n,p)K^{44}$, 20±8; $Ca^{44}(n,\alpha)Ar^{41}$, 35±3; $Ca^{44}(n,d)K^{43}$, 2.6±.4; $Ca^{48}(n,2n)Ca^{47}$, 900±108; $K^{39}(n,2n)K^{38}$ (ground state),2.6±.4; $K^{41}(n,p)Ar^{41}$, 50±6; $K^{41}(n,\alpha)Cl^{38}$, 46±6. The cross sections for the $Ca^{43}(n,d)K^{42}$ and $Ca^{44}(n,d)K^{43}$ reactions are reported for the first time. Other cross sections measured in this work are compared with their earlier values.

I. INTRODUCTION

ALTHOUGH a large amount of work has been devoted to measurements of fast-neutron-induced reaction cross sections,[1] the field is far from complete, because the cross sections for most of the rare reactions have not yet been measured; and in addition the cross sections for many (n,p), (n,α), and $(n,2n)$ reactions reported by different authors differ from each other by a factor of about 2 or more[2] for the same reaction.

A majority of the cross sections for the fast-neutron-induced reactions have been measured by the activation technique. But this technique has not been so extensively used for the measurements of the small cross sections, because the activities produced in such reactions are small and therefore difficult to measure. However, this method can be used to measure small cross sections if one uses large samples for irradiation, γ counting, high efficiency of detection, and a counting setup with low background, as well as a higher flux and a longer period of irradiation and counting. In γ counting, the corrections for the source absorption and scattering are not as serious as in β counting, and, further, it offers a double check (peak position and half-life) on the activity under measurement.

Although the cross sections for the (n,d) reactions are not expected to be very small[3] (about a few mb), yet many of these cross sections have not been measured; this is because the product nucleus of the (n,d) reaction is the same as that of the (n,p) reaction on the next lower isotope. From the knowledge of the cross section of the (n,p) reaction, one can subtract its contribution from the combined activity and get the contribution of the (n,d) reaction alone. But such a subtraction is meaningful only when the two contributions are comparable. This will not be so unless the abundance of the next lower isotope is much smaller than the isotope on which the (n,d) cross section is to be measured, because the cross sections of the (n,p) reactions are usually much larger than those of the (n,d) reactions. Therefore, in order to make such subtraction meaningful, one may have to use enriched isotopes. The use of enriched isotopes may become essential even for the measurement of other cross sections on the isotopes whose natural abundance is extremely small. In this work, the cross sections for some of the (n,t), (n,d), (n,p), (n,α), and $(n,2n)$ reactions have been measured at $E_n=14.2\pm0.2$ MeV on the enriched $Ca^{42-44,48}$ isotopes and spectroscopically pure Ca, K, and Al by the activation technique incorporating the ideas stated above.

II. EXPERIMENTAL DETAILS

In order to use large samples for counting with higher efficiency, cylindrical sources must be used in well-type crystals. We have built[4] a specially shielded γ-counting setup, employing a well-type NaI(Tl) crystal and a 1024-channel analyzer. The total and the photopeak efficiencies of this crystal for cylindrical sources of various heights, made up of the absorbers covering the entire periodic table, have been measured[4] for gamma rays of energies from 0.14 to 2.75 MeV. The sensitivity of this setup is such that with a neutron flux of the order of 10^7 to 10^8 n/cm^2 sec, cross sections of the order of a few $\mu b/g$ of the irradiated sample can be determined. The cross sections reported here have been measured by taking $Al^{27}(n,\alpha)Na^{24}$ as the standard reaction with $\sigma=115\pm5$ mb [5] at $E_n=14.2\pm0.2$ MeV. Most of the targets used in this work were in powdered form. They were shaped into cylinders by enclosing them in polyethylene tubes. These tubes were found not to give any γ activity when counting was started 1 min after the end of irradiation. The cylindrical

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samples wrapped in thin aluminum foils were irradiated with 14.2±0.2-MeV neutrons. The 300-keV deuteron beam from the Cockcroft-Walton accelerator of the Tata Institute of Fundamental Research was used to induce the reaction $H^3(d,n)He^4$ to generate these neutrons. The irradiations were performed by putting the cylindrical samples in the plane perpendicular to the direction of the deuteron beam passing through the tritium target. In each case, the duration of irradiation was adjusted to produce the activity of interest in optimum amount as compared to the interfering activities. The decay curve and the γ-ray spectrum of the activities produced in each irradiation was recorded by the measuring setup reported earlier.[4] The γ-ray spectrum of Na^{24} produced in the (n,α) reaction on Al was also recorded after each irradiation. Only those runs were analyzed in which the neutron flux could be kept constant within a few percent. Suitable photopeaks were used to determine the cross sections. The number of photopeak counts of the selected γ ray emitted by the active nucleus produced in the reaction is related to its cross section by

$$A=P\theta C/(1+\alpha)(\sigma\phi N/\lambda)(1-e^{-\lambda t})(e^{-\lambda t_a}-e^{-\lambda t_b}), \quad (1)$$

where A is the number of photopeak counts collected in time (t_b-t_a), P is the effective photopeak efficiency for the selected γ ray, θ is its branching ratio, C is the source absorption correction factor, α is the internal conversion coefficient of the selected gamma ray, σ is the cross section for the reaction, ϕ is the flux, N is the number of nuclei irradiated, λ is the decay constant of the active nucleus, t is the duration of the irradiation, t_a is the time from the end of irradiation when counting was started, and t_b is the time from the end of irradiation when counting was stopped. The source absorption has already been taken into account in the measured efficiencies. Therefore $C=1$ in the present case. The flux has been eliminated by comparing the activities produced in the standard reaction and the reaction under study. The values of θ, λ, and α have been taken from the literature.[6,7] The effective photopeak efficiency was calculated using the formulas given in Ref. 4.

The error in the cross sections reported here is composed of the errors in the various quantities entering into Eq. (1). The errors in the efficiency, the number of photopeak counts, and the cross section for the standard reaction are about 5% each. The errors in θ, λ, and α may vary from nucleus to nucleus, but they have been taken to be 2% each. N, t, t_a, and t_b have been measured with an accuracy better than 1% in this work. It may be noted that all these quantities except the cross section for the standard reaction will enter twice in the cross-section determination. Therefore, the total error in the cross section reported here is about 12%.

III. EXPERIMENTAL RESULTS AND COMPARISON

The results of the cross-section measurements in this work are presented in Table I, along with the material used, the percentage enrichment of the isotopes, and the experimental cross section given in the literature.[8] Many consistent measurements exist for the $Al^{27}(n,p)Mg^{27}$ cross section.[9] This was measured in this work to give an over-all check to our measuring system. Our value for this cross section is in agreement with the values reported earlier.[9] Our value for the cross section of the $Ca^{40}(n,t)K^{38}$ (ground state) reaction is in good agreement with the value obtained by Menetti and Pasquarelli,[10] but it is less by a factor of about 100 than the value reported by Khurana and Govil.[11] It may be noted from Table I that the values of the other cross sections reported by these authors[11] are usually higher by a factor of about 4 than the other reported values. There are two earlier measurements (110±13 mb [12] and 501±24 mb [10]) for the (n,p) cross section on Ca^{43}, differing from each other by a factor of 5. Our value agrees with one of them.[12] A value (1.3 mb) has been obtained for the first time for the cross section of (n,d) reaction on Ca^{43}. It has not been possible to give any realistic error for this value, because with the present enrichment of Ca^{43}, most (75%) of the activity of the K^{42} was found to be due to (n,p) reaction on Ca^{42}, present in the sample. The values of the (n,p) and (n,α) cross sections on Ca^{44} obtained by us are in general agreement with the literature values,[10,13,14] except for the values given in Ref. 11. The error in the cross section for the $Ca^{44}(n,p)K^{44}$ reaction is large, because the decay scheme of K^{44} is not well known. A value of 2.6±0.4 mb has been obtained for the first time for the (n,d) reaction on Ca^{44}. The cross sections for the other reactions obtained by us are in general agreement with the values reported in the literature. It may be noticed that the measured cross sections for the (n,p) reactions on the three successive isotopes of calcium (Ca^{42},Ca^{43},Ca^{44}) are in general agreement with the Levkovskii trend.[15]

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TABLE I. Measured cross sections at $E_n = 14.2 \pm 0.2$ MeV.

Reaction studied	Material used	% enrichment of isotopes	σ obtained by us in mb	σ expt. given in literature in mb
$Al^{27}(n,p)Mg^{27}$	Al foil, 0.0512[g]	Natural	71 ± 9	(50 to 115) 80 ± 10[a]
$Ca^{40}(n,t)K^{38}$ (ground state)	$CaCo_3$, 0.9362[g]	Natural	0.18± 0.02	20 ± 4[b] ≤0.10[c] 0.15± 0.05[d]
$Ca^{42}(n,p)K^{42}$	$CaCo_3$, 0.0215[g]	Ca^{42}—93.7	190 ± 24	182 ± 27[e] 160 ± 30[f] 181 ± 9[d]
$Ca^{43}(n,p)K^{43}$	$CaCo_3$, 0.0336[g]	Ca^{43}—70.54 Ca^{44}—17.59 Ca^{42}— 1.5	93 ± 12	110 ± 13[e] 501 ± 24[d]
$Ca^{43}(n,d)K^{42}$	$CaCo_3$, 0.0336[g]	Ca^{43}—70.54 Ca^{44}—17.59 Ca^{42}— 1.5	1.3	...
$Ca^{44}(n,p)K^{44}$	$CaCo_3$, 0.1225[g]	Ca^{44}—98.6 Ca^{43}— 0.06	20 ± 8	37 ± 7[f] 91 ± 20[b] 25 ± 12[g] 39 ± 7[d]
$Ca^{44}(n,\alpha)Ar^{41}$	$CaCo_3$, 1.1225[g]	Ca^{44}—98.6 Ca^{43}— 0.06	35 ± 3	35 ± 10[g] 113 ± 20[b]
$Ca^{44}(n,d)K^{43}$	$CaCo_3$, 0.1225[g]	Ca^{44}—98.6 Ca^{43}— 0.06	2.6 ± 0.4	...
$Ca^{48}(n,2n)Ca^{47}$	$CaCo_3$, 0.0442[g]	Ca^{48}—95.64	900 ±108	1070 ±360[h] 920 ±184[i]
$K^{39}(n,2n)K^{38}$ (ground state)	K_2Co_3, 0.9272[g]	Natural	2.6 ± 0.4	2.7 ± 0.15[j]
$K^{41}(n,p)Ar^{41}$	K_2Co_3, 0.9272[g]	Natural	50 ± 6	81 ± 33[k]
$K^{41}(n,\alpha)Cl^{38}$	K_2Co_3, 0.9272[g]	Natural	46 ± 6	50 ± 25[l] 31.4 ± 11[m]

[a] Reference 9.
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IV. CONCLUSION

The cross sections for many (n,d) reactions around 14-MeV neutron energy have not yet been measured because of the large interference due to the characteristic activity from the (n,p) reaction on the next lower isotope. This work suggests that it is possible to measure these cross section by using about 10 mg of highly enriched isotopes and the low-level counting set up described in Ref. 4.

ACKNOWLEDGMENT

We wish to thank S. C. Vaidya for assistance with the 300-kV accelerator.