(n,γ) Cross Sections of Na^{23}, I^{127}, and Au^{197}†

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The cross sections for the $Na^{23}(n,\gamma)Na^{24}$ and the $I^{127}(n,\gamma)I^{128}$ reactions have been measured by an activation method over the neutron energy range 20 kev to 1 Mev. The neutron flux was measured with a fission detector which contained a thin layer of known weight of U^{235}. The Na^{23} cross-section variation with energy shows incompletely resolved resonance structure; an average curve through the data decreases as $1/v_n$ from 2.4 mb at 20 kev to 0.6 mb at 300 kev, and as $1/E_n$ from 0.6 mb at 300 kev to 0.2 mb at 1 Mev. The I^{127} cross section can be represented approximately by a straight line on a log-log plot, decreasing from 1.0 barn at 30 kev to 80 mb at 1 Mev. The $Au^{197}(n,\gamma)Au^{198}$ cross section, measured at a neutron energy of 180 kev, is 310±20 mb.

INTRODUCTION

NEUTRON capture cross sections in the kev to 1-Mev energy range are of considerable importance to cosmological theories of element formation[1] and to nuclear reaction theory.[2] In addition, the growing interest in intermediate and fast reactors has increased the need for capture cross-section measurements in this energy range. This increasing interest has led to a number of recent experiments[3] and to the development of a universal method[4] of measuring capture cross sections.

When a neutron is captured by a nucleus, the event causes three effects which may make possible the detection of the capture: a neutron is lost; a different nucleus is formed which may be either radioactive or stable; and prompt gamma radiation is released. The classical method of measuring a capture cross section, which is used in this experiment, relies on the detection of the radioactivity which is sometimes induced in a sample by neutrons. Detection of the prompt gamma radiation associated with capture makes possible the universal method[4] which does not depend on the formation of a radioactive nuclide. Using this method, Diven, Hemmendinger, and Terrell have begun a systematic program of measuring capture cross sections. Because there have been a number of serious disagreements in cross-section values obtained by the older method of induced radioactivity,[5] it seemed appropriate to try to resolve some of the discrepancies, in preparation for the results of the systematic studies.

Iodine, gold, and sodium are three elements which are particularly well suited for the activation technique, because they are monoisotopic, the decay schemes of the resulting nuclides are well known, and the half-lives are of convenient length. The capture cross sections of I^{127} and Au^{197} have been used as secondary standards in some experiments.[3] Because sodium is used as a coolant in some nuclear reactors, its cross section is of interest. Consequently, the capture cross sections of these nuclides have been remeasured by the method of induced radioactivity.

EXPERIMENTAL

The Na^{24} activity was induced by exposing 2-cm diameter by 1-cm thick NaI(Tl) crystals to neutron sources. In the same way the I^{128} activity was produced in 2-cm diameter by ½-cm thick crystals. The crystals served both the functions of samples and nearly 100% efficient detectors, in the manner described by Martin and Taschek.[6] The Au^{198} activity was produced in a 0.750-inch diameter by 0.010-inch thick gold disk.

The neutrons were produced by the $Li^7(p,n)Be^7$ and the $T(p,n)He^3$ reactions, initiated by a proton beam from a Van de Graaff accelerator. For neutron energies above 130 kev, the cylindrical crystals, covered with a thin sheet of rubber, were exposed at 0° to the source, because at this angle the minimum energy spread for a given neutron yield is obtained. For lower neutron energies, the crystals were exposed at backward angles to the source.

The neutron flux to which a sample was exposed was measured with a flat response long counter which had been previously calibrated with a thin-walled U^{235} fission detector placed in the position at which the samples were to be exposed. The fission detector, operated as a parallel plate ionization counter, contained a disk on which was deposited a uniform, thin layer of $U_2^{235}O_5$. The weight of U^{235} in this layer was determined very precisely by Diven[7] in an experiment performed to measure the fission cross section of U^{235}.

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

[1] Burbidge, Burbidge, Fowler, and Hoyle, Revs. Modern Phys. **29**, 547 (1957).

[2] Feshbach, Porter, and Weisskopf, Phys. Rev. **96**, 448 (1954).

[3] Macklin, Lazar, and Lyon, Phys. Rev. **107**, 504 (1957); Booth, Ball, and MacGregor, Bull. Am. Phys. Soc. Ser. II, **2**, 268 (1957); and Johnsrud, Gilbert, and Barschall, Bull. Am. Phys. Soc. Ser. II, **3**, 165 (1958).

[4] Diven, Terrell, and Hemmendinger, Phys. Rev. **109**, 144 (1958), and private communications.

[5] For references and comparisons, see D. J. Hughes and R. B. Schwartz, *Neutron Cross Sections*, Brookhaven National Laboratory Report BNL-325, (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958), second edition.

[6] H. C. Martin, Jr., and R. F. Taschek, Phys. Rev. **89**, 1302 (1953).

[7] B. C. Diven, Phys. Rev. **105**, 1350 (1957).

The number of fission counts in the detector was related to the neutron yield from the target through the fission cross section.[8] The greatest uncertainty in the experiment lies in the uncertainty of the fission cross section which is estimated to have an uncertainty of $\pm 5\%$ above 150 kev, $\pm 8\%$ between 60 and 150 kev, and $\pm 15\%$ below 60 kev.

The activities produced in the crystals were counted by placing the crystals in a mineral oil well on top of a photomultiplier tube. Excellent discrimination was obtained between the Na^{24} activity which has a 15-hour half-life[9] and the I^{128} activity which has a 25-minute half-life.[10] The sodium activations were generally one hour long, with an interval of six to eight hours before counting the activity. The iodine activity was produced in three-minute irradiations, and then the activity was immediately counted for five minutes. Both activities were followed through several half-lives in a few cases to make sure that a negligible number of contamination counts were being recorded. The pulse-height distributions of the two activities were obtained after very intense irradiations of two crystals. The distributions had the appearance expected from the decay schemes[9,10] and are shown in Fig. 1.

I^{128} decays to Xe^{128} by emitting β particles in about 94% of the disintegrations. The other 6% of disintegrations results in the formation of Te^{128} by electron capture. Figure 1 shows that the 26-kev Te^{128} K x-ray, which should be counted with almost 100% efficiency, was detected. The pulse-height distribution was obtained down to a pulse-height equivalent to an energy of 10 kev, at which point the photomultiplier tube noise set in. It was assumed that the distribution extrapolated smoothly into zero pulse height below 10 kev, and the integrated number of counts in the pulse-height distribution was taken to be the total number of I^{128} disintegrations in the counting period. Standard radioactive decay theory was used to relate the number of disintegrations back to the original number of I^{128} atoms formed in the sample.

In a similar fashion, Na^{24} decays to Mg^{24} by emitting β particles in 100% of the disintegrations, followed by two gamma rays. As in the case of counting the I^{128} activity, the pulse-height spectrum was obtained down to an equivalent 10 kev, and extrapolated smoothly to zero pulse height.

A single gold activation was made by attaching the sample to the thin hemispherical cap of the fission detector which faced the neutron source. The irradiation was carried out at 0° from the source; fission counts were recorded simultaneously. The 2.7-day Au^{198} activity was detected in a very carefully calibrated NaI(Tl) scintillation counter gamma-ray detector.[11] The original number of Au^{198} atoms formed in the sample was determined with a standard error of $\pm 3\%$.

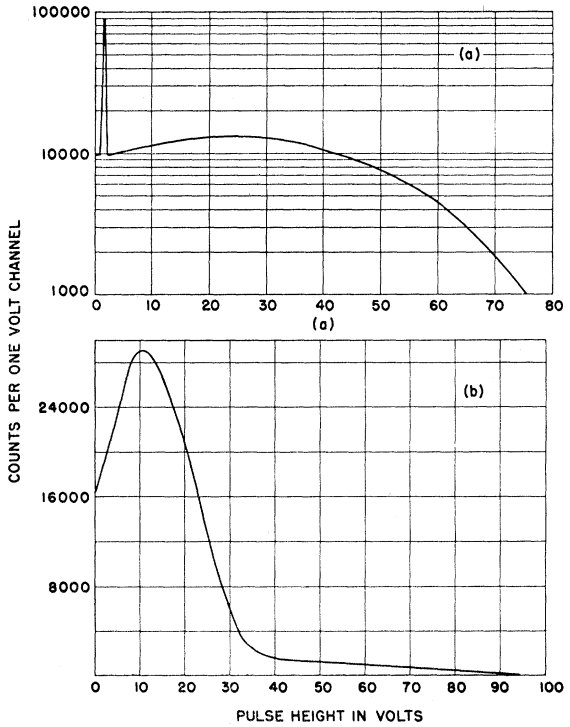

FIG. 1. (a) Pulse-height distribution of I^{128} activity in a NaI(Tl) crystal. 94% of the disintegrations result in beta emission, with a beta end-point energy of 2.1 Mev. In 6% of the disintegrations electron capture in I^{128} leads to Te^{128} resulting in the sharp x-ray line observed at low pulse heights. (b) Pulse-height distribution of Na^{24} activity in a NaI(Tl) crystal. Approximately 100% of the disintegrations lead to emission of beta-particles with an end point energy of 1.4 Mev. Gamma rays with higher energies result in the long tail on the high-energy side of the beta spectrum.

The experimental room in which the irradiations were made is about 20 feet above the ground, and is surrounded by a sheet metal building, so the background of thermal neutrons should have been relatively low. A number of experimental checks confirmed that this background was negligibly low. There was no observable difference in the activities induced in samples wrapped in cadmium sheet and in uncovered samples. Checks were also carried out by counting first with the fission detector bare and then with the counter covered with thin cadmium sheet; there was no difference within counting statistics.

In order to determine the effect of neutron scattering in the crystal samples, cross sections for $I^{127}(n,\gamma)I^{128}$ were measured with both $\frac{1}{2}$- and 1-cm thick crystals. No difference was observed in the two cross sections. This is the expected result, since the calculated influence of scattering is approximately the same for both crystal sizes. The effect of neutron scattering in a sample is to

[8] Fission cross sections were taken from a recent compilation by W. D. Allen and R. H. Henkel which appears in *Progress in Nuclear Energy* (Pergamon Press, Ltd., London, 1958), Ser. I, Vol. II, p. 31.

[9] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).

[10] Bencser, Farrelly, Koerts, and Wu, Phys. Rev. **101**, 1027 (1956).

[11] C. H. Reed and D. R. F. Cochran (to be published).

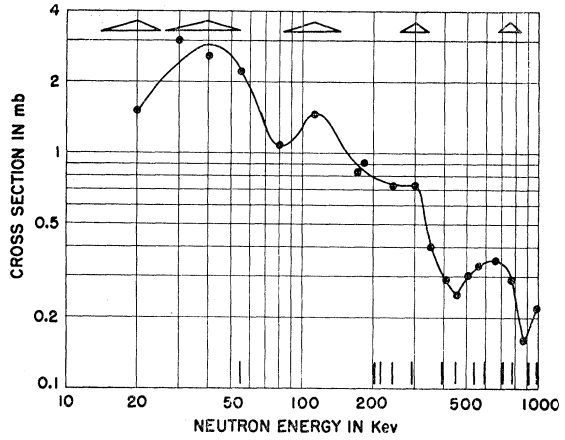

FIG. 2. $Na^{23}(n,\gamma)Na^{24}$ cross-section curve. The triangles at the top of the graph represent the neutron energy spread of the points. The vertical lines at the bottom represent the neutron energies at which resonances are known to occur in the total cross section.[5]

increase the average path length; corrections of about 3% have been made to the data for scattering.

Various other errors in the experiment were considered and corrections made. These errors include scattering of neutrons by the samples into or out of the neutron detectors used in the experiment, scattering of neutrons by the wall of the fission detector, finite length of the neutron source in the case of the $T(p,n)He^3$ gas targets, and the finite size of the sample. Exact corrections were possible for some of these effects. In others, an exact determination was not possible; approximate corrections were made, introducing errors of a few percent. Standard compounding of the various errors in the experiment yielded a standard deviation of $\pm 18\%$ for (n,γ) cross sections below 60 kev, $\pm 12\%$ for cross sections between 60 and 150 kev, and $\pm 8\%$ for cross sections above 150 kev.

RESULTS

The $Na^{23}(n,\gamma)Na^{24}$ reaction cross section as a function of energy is shown in Fig. 2. An average curve through the points, ignoring the peaks and valleys, decreases as the reciprocal of neutron velocity at low energies, changing to a $1/E_n$ dependence at higher energies. There is an obvious resonance type structure in the curve, but the poor energy resolution makes impossible more than a rough comparison between the known resonances in the total cross section[5] of Na^{23} and the peaks in the excitation curve. It seems probable that there may be one or more levels in Na^{24}, not detected in the total cross section work, which are excited when Na^{23} captures neutrons with energies of about 35 and 110 kev. The cross sections of this experiment are in reasonable agreement with previous results in the 200-kev to 1-Mev energy range.[5] The low-energy result can be compared with the 1 ± 0.2 mb at 24-kev cross section of Macklin, Lazar, and Lyon[3] which was obtained with an Sb-Be source Considering the standard errors of the two experiments and the energy resolution of the present result, the agreement between the two experiments seems satisfactory.

The $I^{127}(n,\gamma)I^{128}$ cross-section curve is shown in Fig. 3. As would be expected because of the close energy level spacing in a medium weight nuclide at the excitation energy resulting from capture, there is no apparent resonance structure in the excitation curve. The present results can be compared to the results of a number of independent experiments compiled in reference 5. The agreement with an average curve drawn by the compiler is within 10%. A recent measurement by Diven, Hemmendinger, and Terrell[4] at 400 kev agrees within experimental errors with the result of this experiment.

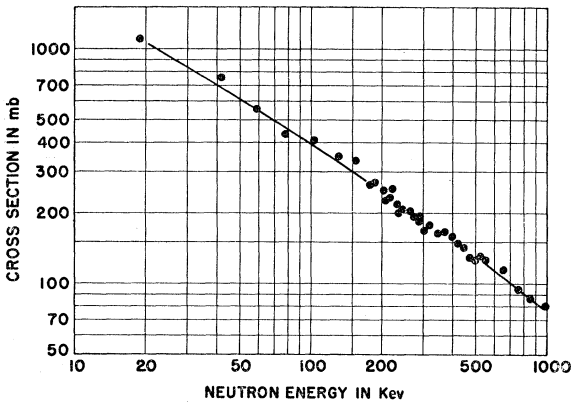

FIG. 3. $I^{127}(n,\gamma)I^{128}$ cross-section curve. The neutron energy spreads are about 15–25 kev up to 550 kev; above, the spreads are about 100 kev.

The $Au^{197}(n,\gamma)Au^{198}$ cross section at a neutron energy of 180 ± 30 kev is 310 ± 20 mb. This value is in good agreement with recent results obtained by Diven *et al.*,[4] as well as the more recent values given in reference 5.

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