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CROSS-SECTIONS FOR THE REACTIONS $Cu^{63}(n, \alpha)Co^{60}$, $Ni^{60}(n,p)Co^{60}$, $Ti^{46}(n,p)Sc^{46}$ and $Na^{23}(n,2n)Na^{22}$

by

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Abstract: Absolute activation cross-sections for the reactions $Cu^{63}(n, \alpha)Co^{60}$, $Ni^{60}(n, p)Co^{60}$, $Ti^{46}(n, p)Sc^{46}$ and $Na^{23}(n, 2n)Na^{22}$ were determined in the energy range 12.5 MeV to 16.5 MeV. Mono-energetic neutrons were obtained from the T(d, n)He^4 reaction at 1 MeV deuteron energy. The very low induced specific activities were detected by a coincidence counting technique. For comparison, statistical model calculations from 5 to 20 MeV neutron energy were performed taking into account second particle emission.

E NUCLEAR REACTIONS $Na^{23}(n, 2n)$, $Ti^{46}(n, p)$, $Ni^{60}(n, p)$, $Cu^{63}(n, \alpha)$, $E=12.5$–16.6 MeV; measured $\sigma_{n,2n}(E)$, $\sigma_{n,p}(E)$, $\sigma_{n,\alpha}(E)$. Natural targets.

1. Introduction

Measurements of activation cross-sections for reactions leading to product nuclei of long half-life are very rare and inaccurate. This is due to the low fluxes of mono-energetic neutrons available by accelerators which induce only very low activities. These low activities can hardly be distinguished from background with normal counters. On the other hand, the determination of these cross-sections by direct detection of the produced particles is in most cases associated with large uncertainties due to the plurality of the different secondary particles and their continuous energy distributions.

In all cases where two characteristic radiations per disintegration are emitted the signal-to-noise ratio can be increased considerably by application of coincidence counting technique. The reactions $Cu^{63}(n, \alpha)Co^{60}$, $Ni^{60}(n, p)Co^{60}$, $Ti^{46}(n, p)Sc^{46}$ and $Na^{23}(n, 2n)Na^{22}$ were studied by means of this technique.

2. Experimental Procedure

2.1. IRRADIATION

The general arrangement for neutron irradiation is shown in fig. 1. Neutrons between 12.6 and 16.6 MeV energy were obtained by bombarding a T–Ti target with a 25 μA beam of 1 MeV deuterons and using the angular range 20° to 155°. The samples were suspended from a graduated circle of about 82 mm radius. This circle was

adjusted with its centre above the geometrical centre of the deuteron beam spot by means of a mirror system. The geometrical size of the neutron source is defined by an aperture to a width of 3 mm and a height of 8 mm. The specimens were mounted at both sides with respect to the deuteron beam direction to determine a possible shift of the beam centre. In addition to the TD neutrons a certain number of DD neutrons (produced by self-target formation) were observed. However, the thresholds of all the examined reactions are high enough to avoid interference due to these neutrons.

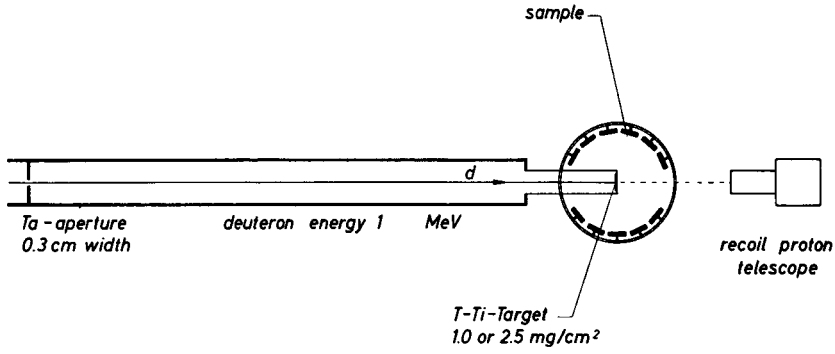

Fig. 1. Experimental arrangement for sample irradiation.

The tritium target holder and the facilities for sample mounting were kept as light as possible to keep flux attenuation low. The neutron flux was determined absolutely by means of a proton recoil telescope counter [1]) positioned in 0° direction at 25 cm

TABLE 1

Some data about irradiation and activity determination

Reaction	$Cu^{63}(n, \alpha)Co^{60}$	$Ni^{60}(n, p)Co^{60}$	$Ti^{46}(n, p)Sc^{46}$	$Na^{23}(n, 2n)Na^{22}$
Half-life of the product nucleus (y)	5.265	5.265	0.230	2.583
Tritium-titanium target used (mg/cm²)	2.5	2.5	1.0	1.0
Sample material	Cu	Ni	Ti	NaCl
Sample size (mm)	30 ∅ × 8	30 ∅ × 8	20 ∅ × 5	20 ∅ × 5
Typical specific sample activity (pCur/g)	3	3	30	14
Efficiency of the coincidence counter (%)	1.1	1.1	1.1	5.7
Background of the coincidence counter (c/h)	18	18	38	90
Typical foreground-background ratio	13	7	8	4

distance from the target. Irradiation time for each reaction was about 32 h. Information about sample material, sample dimensions and T–Ti target thickness can be obtained from table 1.

2.2. ACTIVITY DETERMINATION

Activity measurements were started about two weeks after irradiation for Cu, Ni and NaCl samples. For the Ti samples however, a waiting time of four weeks was necessary due to a 1.8 d activity from $Ti^{48}(n, p)Sc^{48}$. The induced specific activity of the samples of the order of pCur/g were determined in a γ–γ coincidence spectrometer which consists of two scintillation counters (7.6 cm × 10.2 cm ∅ NaI(Tl) crystals coupled to type 54AVP photomultipliers). Only pulses due to a photoeffect were fed into the coincidence unit (resolution time 2 μsec). The efficiency of the γ–γ coincidence spectrometer was determined with absolutely calibrated sources and was checked several times per day. To eliminate differences in geometry and γ-self-absorption between these sources and the samples, each calibrated source had the size of a normal sample and consisted of four active foils sandwiched between blocks of inactive material. These calibrated sources were delivered by the Radioactivity Group of the CBNM with an accuracy of $\pm 0.5\,\%$ for the β-activity. In the case of Na^{22}, a value of 0.898 β^+ per disintegration was used [2]).

The efficiencies and natural backgrounds of the coincidence counting equipment for the different window settings and the specific sample activities together with the resulting foreground-background ratios are listed in table 1.

3. Results

3.1. DATA EVALUATION

For activation measurements in which the irradiation time is short with respect to the half-life of the product nucleus the reaction cross-section σ is given by

$$\sigma = \frac{A_0}{N_1 N_2 \lambda},$$

where A_0 is the sample activity at the end of irradiation and λ is the decay constant of the product nucleus.

The number of neutrons per cm^2 at sample position N_1 was calculated from the proton recoil telescope measurement at 0°, taking into account the distance target-sample and the angular distribution of the TD reaction. Mean values from all available data for this angular distribution, as compared in ref. [3]), were used. Corrections for neutron absorption and scattering within the sample were applied.

The number of sample nuclei of interest N_2 is given by the sample weight, isotopic abundance and the chemical purity of the sample material.

All the final results are listed in tables 2 and 3. The mean neutron energies were calculated from the kinematics of the TD reaction taking into account the deuteron

energy, the irradiation angle and the deuteron energy loss in the target. The deuteron energy was determined with the aid of a calibrated magnetic resonance system. The given neutron energy spread is due to the finite solid angle of the samples and the target thickness. The quoted values are the half-widths of the neutron spectra seen by each sample.

TABLE 2

Experimental results for the reactions $Cu^{63}(n, \alpha)Co^{60}$ and $Ni^{60}(n, p)Co^{60}$

E_n(MeV)	$Cu^{63}(n, \alpha)Co^{60}$ σ(mb)	$Ni^{60}(n, p)Co^{60}$ σ(mb)
12.67±0.17	39.1±2.7	141±10
12.86±0.22	38.1±2.7	141±10
13.24±0.29	38.2±2.7	138±10
13.54±0.33	37.8±2.6	135± 9
14.05±0.37	39.1±2.7	122± 9
14.42±0.39	35.7±2.5	118± 8
14.99±0.39	31.6±2.2	109± 8
15.37±0.37	30.2±2.1	102± 7
15.88±0.36	27.2±1.9	90± 6
16.18±0.41	26.8±1.9	91± 6
16.52±0.46	23.3±1.6	85± 6

TABLE 3

Experimental results for the reactions $Ti^{46}(n, p)Sc^{46}$ and $Na^{23}(n, 2n)Na^{22}$

$Ti^{46}(n, p)Sc^{46}$		$Na^{23}(n, 2n)Na^{22}$	
E_n(MeV)	σ(mb)	E_n(MeV)	σ(mb)
12.60±0.11	300±21	12.63±0.11	$0.9^{+1.5}_{-0.9}$
12.76±0.14	307±21	12.81±0.15	1.1±1.1
12.98±0.17	296±21	12.98±0.17	3.3±1.7
13.10±0.18	297±21	13.24±0.20	3.4±1.2
13.38±0.20	292±20	13.46±0.22	8.0±1.2
13.54±0.22	303±21	13.79±0.23	14.2±1.4
13.88±0.24	305±21	14.05±0.25	28.0±2.1
14.05±0.25	299±21	14.42±0.26	44.0±3.1
14.42±0.26	295±21	14.71±0.27	65.8±4.6
14.61±0.26	293±21	15.09±0.26	84.8±5.9
14.99±0.27	285±20	15.37±0.25	87.3±6.1
15.18±0.26	290±20	15.72±0.23	108±8
15.55±0.24	289±20	15.99±0.21	113±8
15.71±0.23	284±20	16.25±0.20	122±9
16.03±0.21	288±20	16.42±0.19	133±9
16.31±0.19	285±20	16.61±0.20	141±10
16.52±0.19	296±20		

3.2. ACCURACY

The experimental errors on the resulting cross-sections are given in tables 2 and 3. They were calculated by compounding quadratically the uncertainties of the different factors involved.

The largest uncertainty of $\pm 5.7\,\%$ is due to the number of neutrons per cm^2 at sample position N_1. This uncertainty contains the errors of the telescope measurement ($\pm 4\,\%$), the irradiation geometry ($\pm 3\,\%$), the neutron angular distribution ($\pm 2.5\,\%$) and the neutron absorption and scattering correction ($\pm 0.5\,\%$). The uncertainty in the sample activity at the end of irradiation A_0 amounts to $\pm 2.7\,\%$ and contains statistical errors ($\pm 2.0\,\%$) and the error due to efficiency and background variations of the coincidence counter ($\pm 1.7\,\%$).

All other uncertainties are small compared with the abovementioned ones. Combining all the uncertainties one gets errors between $\pm 6\,\%$ and $\pm 7\,\%$. Only the cross-sections of the reaction $Na^{23}(n, 2n)Na^{22}$ near threshold have larger uncertainties due to the poor foreground-background ratio.

3.3. COMPARISON WITH EXISTING DATA

No previous activation measurement is known for the reaction cross-section of $Cu^{63}(n, \alpha)Co^{60}$.

A determination of the alpha particle yield at $55° \pm 55°$ resulted in a differential cross-section of 5.65 ± 0.6 mb $\cdot$ sr^{-1} at 14.8 MeV neutron energy [4]). Assumption of isotropy would lead to a reaction cross-section of 71.2 mb which is considerably higher than these results.

Furthermore there exists a measurement [5]) of the partial cross-section for $Cu^{63}(n, \alpha)Co^{60m}$ leading to the isomeric state of Co^{60} ($T_{\frac{1}{2}} = 10.5$ min). This partial cross-section was reported to be 23 ± 3 mb at 14.70 ± 0.15 MeV.

For the $Ni^{60}(n, p)Co^{60}$ reaction only one earlier activation measurement [6]) resulting in 150 ± 20 mb at 14.5 MeV neutron energy is known. However, there are some further measurements carried out by direct proton detection. Due to the plurality of different secondary particles and their continual spectra occurring in the fast neutron induced reactions, these measurements are associated with larger uncertainties. The following cross-sections have been reported for the sum of compound and direct interaction part: 155 ± 25 mb at 13.5 ± 0.1 MeV (ref. [7])), 240 ± 48 mb at 14 MeV (ref. [8])) and 158 ± 32 mb at 14.1 MeV (ref. [9])); and for the compound nucleus reaction part only: 134 ± 28 mb at 14 MeV (ref. [10])). The agreement of all results may be considered as satisfying taking into account that the cross-section of 240 ± 48 mb is surely exaggerated by observation at $34° \pm 20°$ and assumption of isotropy as stated in the original paper.

The cross-sections for the reaction $Ti^{46}(n, p)Sc^{46}$ can be compared with a rough activation measurement [11]) giving ≈ 520 mb at 14.8 ± 0.9 MeV. This result is indicated in the original paper as a tentative figure.

For the reaction $Na^{23}(n, 2n)Na^{22}$ the previous measurements of Prestwood [12]) resulted in 13.8 mb at 14.1 ± 0.2 MeV. The quoted uncertainty of ± 2.2 mb is twice the standard deviation for six measurements showing only the reproducibility. The measurement of Picard and Williamson [13]) resulted in considerably smaller cross-sections than the present work.

4. Statistical Model Calculations

For comparison statistical model calculations from 5 to 20 MeV were performed taking into account second particle emission. Cross-section formulae as given in ref. [14]) were used.

For the decay of the compound nucleus after neutron absorption emission of neutron, proton, deuteron, α-particle and γ-quanta was considered. Neutrons, protons and gammas were taken into account as second emitted particles. The reaction Q values were taken from ref. [15]).

For the dependence of level density ρ on excitation energy e the following expression was used [16]):

$$\rho(e) \approx a^{-\frac{1}{4}}(e-\delta+t(e))^{-5/4} \exp[4a(e-\delta)]^{\frac{1}{2}},$$

with the nuclear temperature given by

$$t(e) = \left(\frac{e-\delta}{a}\right)^{\frac{1}{2}} (1+[4a(e-\delta)]^{-\frac{1}{2}} + [8a(e-\delta)]^{-1}).$$

The pairing energies δ were taken from ref. [17]). The parameter a can be written as [18])

$$a = 2\alpha(j_Z+j_N+1)A^{\frac{1}{3}}$$

to include shell effects. The effective single-particle angular momentum quantum numbers j_Z and j_N were taken from ref. [18]), while for the constant α, a value [16]) of 0.0374 was used. The values of a recently derived from experimental data in ref. [20]) are in good agreement with $\alpha = 0.0374$. Other α values evaluated from experimental data are 0.031 (ref. [18])) and 0.028 (ref. [19])).

Absorption cross-sections for the formation of a compound nucleus were mainly taken from refs. [21,22]). However, since in these papers absorption cross-sections are only presented for certain Z and A values also refs. [23-25]) were consulted. All these cross-sections calculated by different authors are based on nearly the same optical potentials for one kind of incoming particles.

The results of this computation and the experiments are shown in fig. 2. Discrepancies between theory and experiment are of the order of a factor 2 to 4. It turns out that the statistical model is still not a reliable help for extrapolating experimental results. It should be noted that the theoretical cross-sections of three of the four investigated reactions are larger than the measured values.

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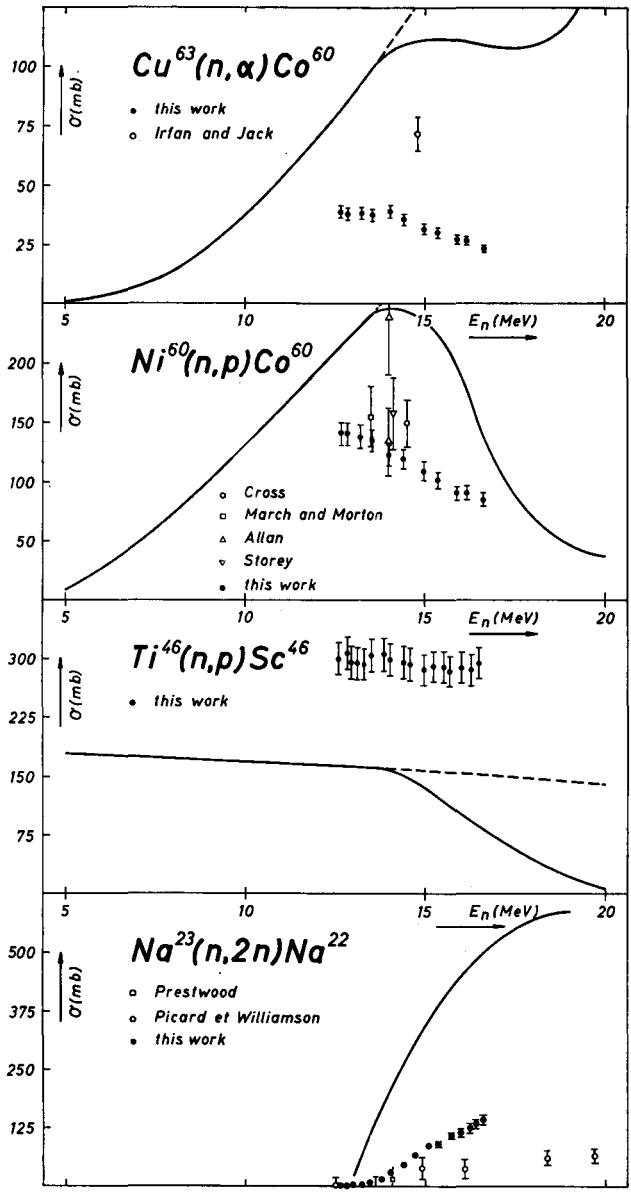

Fig. 2. Statistical model calculations of the excitation functions together with the experimental cross-sections. The dashed line represents the theoretical cross-sections without regarding second particle emission.

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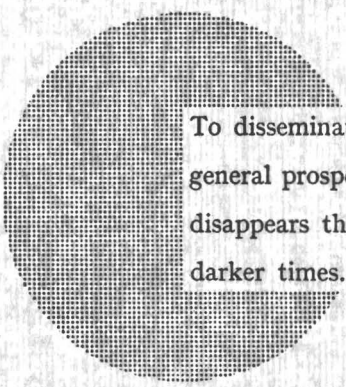

To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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