Excitation function of the ^{58}Ni(n,d)^{57}Co reaction near its threshold

S. M. Qaim and R. Wölfle
Institut für Chemie 1 (Nuklearchemie), Kernforschungsanlage Jülich GmbH, D-5170 Jülich, Federal Republic of Germany
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Cross sections were measured by the radiochemical method for the formation of ^{57}Co in the interactions of 6.4 to 9.5 MeV neutrons with nickel. The only contributing process up to 8.3 MeV is the ^{58}Ni(n,d)^{57}Co reaction; between 8.4 and 9.5 MeV, however, small contributions (< 10%) from (n,n′p) and (n,pn) processes are also expected. The excitation function shows a rapid increase beyond 8 MeV, reaching almost the maximum at about 15 MeV. Hauser-Feshbach calculations on the first-chance emission of a deuteron show that beyond 11 MeV the relative contribution of the statistical processes decreases and at about 15 MeV it is < 30% of the total (n,d) cross section. Calculations involving precompound effects (reported in the literature) seem to agree with the experimental trend over the energy range of 9–15 MeV within a factor of 2.

The emission of deuterons in fast-neutron-induced reactions occurs generally in the light mass region (cf. Ref. 1). For nuclei with $A \leqslant 10$ the emitted deuteron spectra have been studied at several incident neutron energies up to 20 MeV (cf. Ref. 2). For nuclei with $A = 10$–100, however, due to much smaller cross sections such investigations have been carried out only at 14 MeV (cf. Refs. 1–7). The spectra are generally forward peaked and are described by a proton pickup process.

Similar to spectral measurements, systematic radiochemical studies on medium and heavy mass nuclei have been carried out mainly at 14 MeV (for a review cf. Ref. 8), and only in a few cases in the energy range of 14–20 MeV (cf. Refs. 2, 9, 10). Those data do not describe the excitation function of an (n,d) reaction, since the measured cross sections give a sum of (n,d), (n,n′p), and (n,pn) processes, all of which are energetically possible and lead to the same product nucleus. The validation of various nuclear models on the basis of integral (n,d) cross-section data for medium and heavy mass nuclei is thus generally based on integrated spectral data obtained only at one energy (~ 14 MeV).

This work describes the first systematic study of the energy dependence of an (n,d) reaction cross section for a medium mass target nucleus.

The quasimonoenergetic neutrons in the energy range of 6–10 MeV were produced via the ^{2}H(d,n)^{3}He reaction using a deuterium gas target at our variable energy compact cyclotron (cf. Ref. 11). Sample preparation for irradiations consisted of sintering together about 20 g Ni powder (99.999% pure) to a solid mass of cylindrical form with a length of 1.2 cm and a diameter of 1.6 cm. Irradiations were done for 6–8 h at a distance of 0.5 cm (in some cases at 1.5 cm) from the back of the beam stop of the deuterium gas target. The angle subtended by the sample relative to the deuteron beam ranged from 7° to 48°, depending on which part of the gas cell was considered as the reference point for neutron production. The primary deuteron energy was varied between 4.0 and 7.0 MeV. The mean neutron energy (as well as energy spread) effective for each irradiated sample was calculated as described earlier.[11] The mean neutron flux density effective for each sample was determined using the internal monitor reaction ^{58}Ni(n,p)^{58}Co, the cross sections of which at different neutron energies were taken from the ENDF/B-V file[12] and are given in Table I. The mean neutron flux densities were found to lie between 1.50×10^7 and 7.35×10^7 cm^{-2}sec^{-1}.

TABLE I. Cross sections for the ^{58}Ni(n,d)^{57}Co reaction.

Mean neutron energy[a] (keV)	$\frac{\sigma(^{58}\mathrm{Ni(n,d)}^{57}\mathrm{Co})}{\sigma(^{58}\mathrm{Ni(n,p)}^{58}\mathrm{Co})^{b}}$	$\sigma(^{58}$Ni(n,p)^{58}Co)[b,c] (mb)	$\sigma(^{58}$Ni(n,d)^{57}Co)[d] (mb)
6410 ± 223	$(1.21\pm0.27)\times10^{-4}$	580 ± 41	0.07 ± 0.02
6953 ± 236	$(1.35\pm0.37)\times10^{-4}$	593 ± 42	0.08 ± 0.02
7532 ± 195	$(1.17\pm0.51)\times10^{-4}$	598 ± 42	0.07 ± 0.03
8020 ± 230	$(2.84\pm0.85)\times10^{-4}$	599 ± 42	0.17 ± 0.05
8539 ± 224	$(2.00\pm0.68)\times10^{-4}$	600 ± 43	0.12 ± 0.04[e]
9154 ± 100	$(4.85\pm1.89)\times10^{-4}$	598 ± 42	0.29 ± 0.12[e]
9518 ± 257	$(1.66\pm0.22)\times10^{-3}$	595 ± 42	0.99 ± 0.15[e]

[a]The deviations do not give errors; they show energy spreads due to angle of emission and deuteron energy loss in the gas target.
[b]This is the internal monitor reaction used for neutron flux measurements.
[c]Monitor reaction cross-section data were taken from ENDF/B-V (Ref. 12).
[d]The errors describe the overall errors which were obtained by combining the statistical and systematic errors in quadrature. For details see text.
[e]These values may contain small contributions (< 10%) from the (n,n′p) and (n,pn) processes. For discussion see text.

Each irradiated nickel sample was dissolved in 10 M HCl, 15 mg each of Co and Fe were added as carriers, and cobalt (^{58}Co/^{57}Co) was separated via anion-exchange chromatography (cf. Ref. 13). Thereafter, a thin source of cobalt (incorporating ^{58}Co/^{57}Co), suitable for counting soft γ rays of ^{57}Co, was prepared by electrodeposition on a Cu backing.

The radioactivity of each sample was measured using a large sized Ge(Li) detector. Initially ^{58}Co[$T_{1/2}$=70.8 d, E_γ=811 keV (99.45%)], formed via the ^{58}Ni(n,p)^{58}Co reaction, was the dominating activity and ^{57}Co[$T_{1/2}$=271 d, E_γ=122 keV (85.6%)], the activity under investigation, was hardly detectable. After about one year the contribution of ^{58}Co was significantly reduced, and the presence of the weak ^{57}Co activity became evident. Measurements were then performed for about a year and the ^{57}Co activity was determined. The smallest ^{57}Co activity encountered was about 0.1 cpm (count per min) and the highest about 9 cpm. In the case of ^{58}Co, on the other hand, the count rates were quite high.

From the count rates of the activation products obtained the contributions due to background neutrons, which were produced via the interaction of deuterons with structural materials of the gas target as well as via the breakup of deuterons on D_2 gas, were subtracted. For the former contribution our own gas in/gas out results were used (cf. Ref. 11), whereas for the breakup contribution the results of Meadows and Smith[14] were applied [the latter only for the monitor reaction ^{58}Ni(n,p)^{58}Co]. From the thus corrected count rates, the decay rates at the end of irradiations were obtained by applying the usual corrections like those for decay, chemical yield, absorption of γ rays, γ-ray intensity (I_γ), efficiency of the detector for the counting geometry used, coincidence losses, pileup of γ rays, etc. (cf. Refs. 8, 11, and 15). The cross sections were then calculated using the known activation equation.

The major error in the present measurements originated from the weak count rates of ^{57}Co (counting statistics and difficulty in the determination of the photopeak area) and amounted to between 11 and 44%. Other significant sources of error were the uncertainties in the excitation function of the monitor reaction (7%) and the efficiency of the detector (3%). Several other less significant sources of error were similar to those described earlier.[11] The overall error was obtained by combining all the individual errors in quadrature and amounted to between 15 and 45%.

Measurements were done at seven neutron energies between 6.4 and 9.5 MeV. The data are presented in Table I both as a ratio of ^{58}Ni(n,d)^{57}Co to ^{58}Ni(n,p)^{58}Co cross sections, as well as in the form of absolute cross sections. All the data relevant to the formation of ^{57}Co have been measured for the first time in this energy range. The threshold energy for the ^{58}Ni(n,d)^{57}Co reaction lies at 6.05 MeV and that for the ^{58}Ni(n,n$'$p+pn)^{57}Co process at 8.31 MeV. The first four cross-section values therefore give the pure (n,d) reaction data, and the latter three values entail a sum of the (n,d), (n,n$'$p), and (n,pn) processes. The combined contribution of the (n,n$'$p) and (n,pn) processes, however, is expected to be small for $E_n \leq 10$ MeV. Model calculations suggest (cf. Refs. 9,10) that the contribution of the (n,n$'$p) and (n,pn) processes to the formation of ^{57}Co at E_n=9.5 MeV should be $<10\%$ of the (n,d) contribution. The three cross-section values reported for neutron energies between 8.5 and 9.5 MeV therefore also give primarily (n,d) data.

The ^{58}Ni(n,d)^{57}Co reaction cross-section data are plotted in Fig. 1 as a function of the neutron energy. The value at 14.8 $\pm$0.3 MeV was obtained by an integration of the emitted deuteron spectra.[6] The cross section increases slowly at first but fairly rapidly above 8 MeV, reaching almost the maximum at about 15 MeV.

In order to shed some light on the reaction mechanism we performed Hauser-Feshbach calculations on the first-chance emission of a deuteron using the code HELGA (for details cf. Refs. 8, 16, and 17). The results (not averaged over the experimental energy widths) are also given in Fig. 1. Over the neutron energy range of 8.5–10 MeV the agreement between experiment and theory is fairly good. Beyond 11 MeV the relative contribution of the statistical processes decreases and at about 15 MeV it is $<30\%$ of the total (n,d) cross section. This conclusion is similar to that deduced from angular distribution measurements: the strongly forward peak deuteron spectrum suggests the occurrence of direct processes (cf. Ref. 6).

Detailed calculations involving compound nucleus and precompound effects [and correcting for depletion by direct (n,n$'$) processes] have been performed at Vienna for fast-neutron-induced reactions on ^{58}Ni (cf. Refs. 9 and 10). The preequilibrium emission was considered for first-chance processes in the frame of the exciton model. The emission rates for nucleons account for the type of the projectile, those for α particles for cluster preformation. Calculations were done using the code STAPRE. The results for the ^{58}Ni(n,d)^{57}Co reaction are shown in Fig. 1. Those calculations seem to agree with the experimental trend over the energy range of 9–15 MeV within a factor of 2.

Model calculations described above cannot reproduce the excitation function over the energy range of 6–8 MeV. This is the region where the reaction is energetically possible but

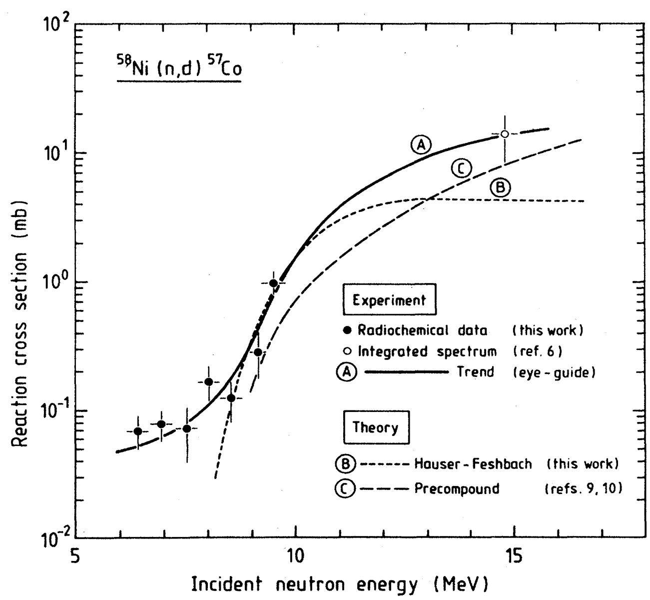

FIG. 1. Excitation function of the ^{58}Ni(n,d)^{57}Co reaction. Points and the solid line describe the experimental data and trend. The experimental data points between 8.5 and 9.5 MeV may contain small contributions ($<10\%$) from (n,n$'$p) and (n,pn) processes (see text). The dashed lines give results of Hauser-Feshbach and precompound calculations.

the Coulomb barrier is not overcome. Presumably some tunneling effect is involved.

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