$Ni^{58}(n,p)Co^{58m,g}$ Cross Section and Isomer Ratio from 1.04 to 2.67 MeV*

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The cross sections and isomer ratios for the $Ni^{58}(n,p)Co^{58m,g}$ reaction have been measured relative to the $U^{235}(n,f)$ reaction for neutron energies of 1.04 to 2.67 MeV. The absolute yield of Co^{58} was determined by counting coincidences between the 0.800-MeV γ ray and the annihilation radiation of the positrons from the decay of the Co^{58} ground state. The observed cross sections and isomer ratios are compared with calculated values obtained by assuming compound nucleus formation and proton emission only to the 5+ and 2+ states of Co^{58}.

INTRODUCTION

THE primary purpose of the experiment described here was to make an accurate measurement of the $Ni^{58}(n,p)Co^{58}$ excitation function. Although this reaction is very useful as a fast neutron flux monitor,[1] little information is available as to its excitation function. A number of investigators have measured the reaction cross section for pile neutrons[1–4] and a few have reported measurements at 14 MeV.[5,6] In at least two cases,[1,3] measurements have been made of the relative yields of the two Co^{58} isomers for pile neutrons. Gonzales *et al.*[7] have reported measurements over the neutron energy range of 2.2 to 3.6 MeV with an absolute error in the cross sections of $\pm 15\%$. The absolute cross sections were obtained by comparing the Co^{58} activity with the amount of Si^{31} formed in the $P^{31}(n,p)Si^{31}$ reaction at 3.55 MeV.

We have measured the $Ni^{58}(n,p)Co^{58}$ cross section and the relative yields of the two isomeric states of Co^{58} for neutrons of energies between 1.04 and 2.67 MeV. The neutron flux was monitored by the $U^{235}(n,f)$ reaction while the absolute yield of Co^{58} was determined by counting coincidences between the 0.800-MeV γ ray and the annihilation radiation of the positrons from the decay of the Co^{58} ground state.

EXPERIMENTAL

Neutrons were produced by the $Li^7(p,n)Be^7$ reaction using the analyzed proton beam from a Van de Graaff accelerator. The thickness of the lithium targets combined with the angular resolution gave a spread in neutron energy which varied from $\sim$100 keV at 1.04 MeV to $\sim$75 keV at 2.67 MeV. The nickel targets were metal disks 2.54 cm in diameter and 0.475 cm thick. They were placed 3.5 cm from the neutron source and were irradiated for times ranging from 4 to 7 h at the lower neutron energies to about 1 h at the highest.

Immediately after irradiation the nickel targets were counted in a NaI(Tl) scintillation spectrometer with a window set over the 0.800-MeV γ-ray photopeak from the decay of the Co^{58} ground state. The decay was followed over a period of several days. Only three activities were observed in the targets. These were the 9-h Co^{58} metastable state which decays into the 71-day ground state and the 2.56-h Ni^{65} formed by the $Ni^{64}(n,\gamma)Ni^{65}$ reaction. The relative yields of the metastable and ground states of Co^{58} were obtained from an analysis of the decay curves. Consistent results were readily obtained at the higher neutron energies where the relative yield of Ni^{65} was low. At the lower neutron energies (<1.2 MeV) the low yields of Co^{58} combined with the high relative yields of Ni^{65} made the analysis of the decay curves increasingly uncertain. For this reason, two additional irradiations were made at neutron energies of 1.25 and 1.15 MeV with the nickel targets placed only 2.3 cm from the source while the bombardment time was increased from 4 to 7 h. The closer spacing combined with the increase in irradiation time increased the yield of Co^{58} by a factor of 4 and halved the relative amount of Ni^{65}.

The total yield of Co^{58} was determined from counts taken after the shorter lived activities had decayed. The absolute disintegration rate was determined by comparing the target with a Co^{58} standard. The standard was a nickel disk of the same material and dimensions as the targets. It was activated by irradiating it with neutrons from a Po-Be source for several weeks until its total activity was $\sim 10^5$ disintegrations per minute. After waiting several days for all short lived activities to decay, the absolute disintegration rate was determined by coincidence counting using the 0.800-MeV γ ray and the annihilation radiation of the associated positrons. The standard was counted at frequent intervals while the radioactive decay of the target was being followed in order to detect any shift in gain or efficiency of the counting equipment. The γ-ray spectrum of the standard showed no indication of any activity other than the 71-day Co^{58}. The estimated error in the determination of

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TABLE I. Cross sections and isomer ratios for the $Ni^{58}(n,p)Co^{58m,g}$ reaction.

Neutron energy (MeV)	σ_f U^{235} (b)	σ_r $Ni^{58}(n,p)Co^{58}$ (mb)	$\sigma(Co^{58m})/\sigma(Co^{58g})$
1.04	1.26	1.2± 0.1	0.48±0.32
1.15	1.27	3.8± 0.3	0.43±0.09
1.25	1.27	5.6± 0.5	0.18±0.03
1.36	1.28	5.2± 0.4	0.40±0.30
1.46	1.29	10.5± 0.9	0.24±0.02
1.57	1.30	12.4± 1.0	0.32±0.03
1.67	1.31	18.4± 1.5	0.29±0.01
1.87	1.32	31.1± 2.6	0.34±0.03
2.07	1.33	52 ± 4	0.36±0.01
2.37	1.31	97 ± 8	0.35±0.03
2.67	1.28	139 ±12	0.31±0.01

the absolute disintegration rate of the standard was ±3%.

The U^{235} fission cross section was chosen as the most suitable for monitoring the neutron flux as it is known to ±5% over the energy range covered.[8,9] The actual values used are listed in Table I. The uranium used had the following composition:

$$U^{234}, \quad (0.910\pm0.009)\%;$$
$$U^{235}, \quad (93.24\ \pm0.05)\%;$$
$$U^{236}, \quad (0.445\pm0.004)\%;$$
$$U^{238}, \quad (5.41\ \pm0.05)\%.$$

About 0.2 mg of uranium was deposited on a platinum foil as a thin film covering an area 1.88 cm in diameter. This foil formed one wall of an ionization chamber and was placed behind and in contact with the nickel target. The amount of U^{235} present was determined by α counting the foil in a 2π counter and from the mass spectroscopic analysis. The estimated error was ±3%. The result of the α count was confirmed by chemical analysis with an estimated error of ±3%. The ratio of the results of the two methods was 0.995.

The following corrections were made to the data:

1. At these energies the $Li^7(p,n)Be^7$ reaction yielded two monoenergetic neutron groups. A correction was made using the data of Bevington *et al.*[10]

2. At neutron energies above 1.4 MeV an appreciable fraction of the counts recorded by the monitor counter were made from the fission of U^{238}. A correction was made using the fission cross sections compiled by Allen and Henkel.[8]

3. The nickel targets were relatively thick and afforded some shielding for the monitor counter causing it to read low. This effect was measured by target in, target out measurements. The correction was about 4%.

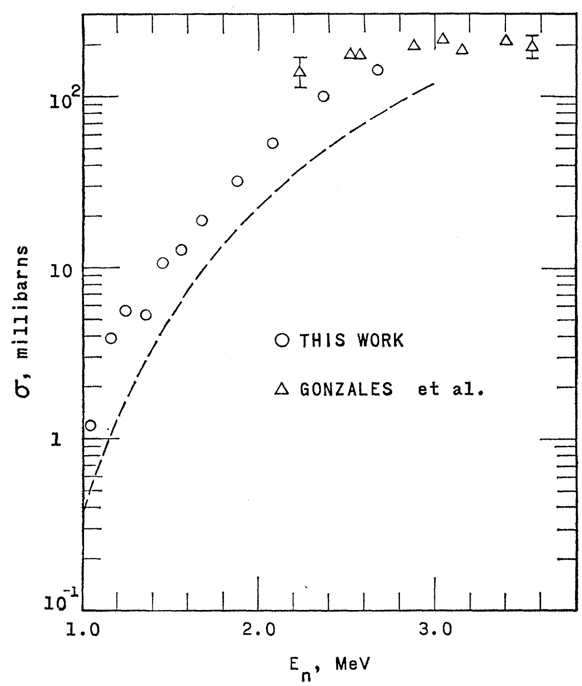

FIG. 1. Excitation function for the reaction $Ni^{58}(n,p)Co^{58}$. The error bars indicate the total error. The points designated by △ are the results of Gonzales *et al.* (reference 7). The dashed curve was calculated assuming that the reaction proceeds through proton emission directly to the two final states.

4. The effective thickness of the nickel targets was larger than the geometric thickness due to neutron scattering within the target. A correction for this effect was made according to the method of Schmitt.[11] The correction amounted to about 5%.

5. Since the nickel targets were larger than the U^{235} monitor foil and were placed nearer the neutron source a geometric correction was necessary. The estimated error in the geometry factor was ±2%.

6. Since the angular distribution of the neutrons from the source was peaked at 0° and since the nickel targets subtended a larger solid angle than the monitor foil, the total number of neutrons incident on the nickel targets were less than the number indicated by the monitor counts. The correction for this effect was made using the data of Bevington *et al.*[10] A typical correction was ±2%.

RESULTS

The results of the cross section measurements are given in Table I and Fig. 1. The relative error in the results is largely due to the statistical counting errors and to small variations in the relative positions of the target disks and the monitor foil. These are believed to be of the order of 1 or 2% for most of the data points. The indicated errors include estimates of all known sources of error. The recognized sources of error and

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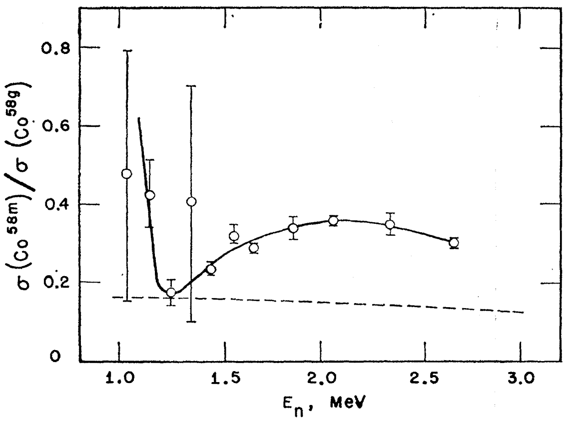

FIG. 2. The isomer ratio, $\sigma(Co^{58m})/\sigma(Co^{58g})$, for the reaction $Ni^{58}(n,p)Co^{58}$. The dashed curve was calculated assuming that the reaction proceeds by proton emission directly to the two final states.

typical values are

1. U^{235} fission cross section, $\pm 5\%$.
2. Relative yield of the first neutron group from the $Li^7(p,n)Be^7$ reaction, $\pm 1\%$.
3. Uncertainty in the total mass of the U^{235} in the monitor counter, $\pm 3\%$.
4. Uncertainty in the absolute disintegration rate of the Co^{58} standard, $\pm 3\%$.
5. Uncertainty in the target transmission correction, $\pm 1\%$.
6. Statistical errors in counting, $\pm 1\%$. The lowest energy point had an error of $\pm 3\%$.
7. Uncertainty in the relative geometric factor, $\pm 4\%$.

Combining all these errors gave an uncertainty of $\sim 8\%$ to all the data points above 1.14-MeV neutron energy.

The agreement of these data with the measurements of Gonzales *et al.*[7] is not very good (Fig. 1). The region of overlap is small (2.2 to 2.7 MeV) and involves measurements at only two energies in each experiment. However, it is obvious that in this region the cross sections obtained from this experiment are 30 to 60% lower and are increasing much more rapidly with energy.

The relative yields of the two Co^{58} isomers, $\sigma(Co^{58m})/\sigma(Co^{58g})$ are given in Table I and Fig. 2. Previous measurements with pile neutrons have given values of ~ 0.4 for the isomer ratio. While these values are higher than the one observed in this experiment, they are not inconsistent since the metastable state has the higher spin and is expected to show an over-all increase with increasing energy. However, the appearance of an initial decrease in the relative yield of the metastable state followed by a minimum at 1.25 MeV is surprising. The existence of this minimum depends on the validity of the two lowest energy points where accurate relative yields were difficult to obtain. The measurement at 1.04 MeV is the result of three measurements but the results were widely scattered due to the high relative yield of Ni^{65}. However, the points at 1.15 and 1.25 MeV are the results of six and four determinations, respectively, with standard deviations of $\pm 20\%$.

At the energies covered in this experiment only a few levels should be involved in the reaction. The target nucleus, Ni^{58}, is an even-even nucleus whose first excited level is a $2+$ rotational state at 1.452 MeV.[12] Although Co^{58} is an odd-odd nucleus and should have a number of low-lying levels, it seems probable that a large fraction of the n, p reaction will involve proton emission directly to the $2+$ ground state and the $5+$ metastable state since the proton can have maximum energies of only 1.5 to 3 MeV. Other low-lying levels will also contribute to the reaction but unless they are less than 0.5 MeV above the ground state their contribution will be negligible due to the Coulomb barrier. Altogether, it appears that the assumption of particle emission only to the above levels is a good first approximation.

Cross sections were calculated for the $Ni^{58}(n,p)Co^{58}$ reaction on the basis of the above approximation and assuming compound nucleus formation. The neutron and proton transmission coefficients used were those calculated by Moldauer[13] for a diffuse potential well with a spin-orbit term and surface absorption. The potential is given by

$$V = V_0\rho(r) - V_{LS}\left(\frac{\hbar}{\mu c}\right)^2 \boldsymbol{\sigma}\cdot\mathbf{l}\frac{1}{r}\frac{d}{dr}\,\mathrm{Re}\rho(r)$$

$$\rho(r) = \frac{1}{1+\exp[(r-R_0)/d]} - i\zeta\exp[-(r-R')^2/\omega],$$

where $V_0(\text{neutrons}) = 56.0$ MeV, $V_0(\text{protons}) = 46.0$ MeV, $\zeta(\text{neutrons}) = 0.143$, $\zeta(\text{protons}) = 0.109$, $V_{LS} = 7.0$ MeV, $\omega = 0.5$ F, $d = 0.4$ F, $R_0 = 5.032$ F, and $R' = R_0 + 1.0$ F. Angular momentum and parity were conserved and neutrons and protons with angular momenta ≤ 3 were included. The results are shown by the dashed curves in Fig. 1 and Fig. 2. While the shape of the calculated excitation function is very similar to the observed one, it is too low by a factor of ~ 2. The isomer ratio, $\sigma(Co^{58m})/\sigma(Co^{58g})$, is also low by a similar factor and shows a slight decrease over the energy range covered. It is very probable that other levels in Co^{58} are involved in the reaction. For example, the existence of a $4+$ level at about 0.2 MeV would almost double the isomer ratio and cause it to show an increase with energy.

The minimum observed in $\sigma(Co^{58m})/\sigma(Co^{58g})$ at 1.25 MeV may be due to fluctuations in the distribution of spin states in the compound nucleus. It is known from

[12] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Offices, National Academy of Sciences–National Research Council, Washington 25, D. C.).
[13] P. A. Moldauer (private communication).

neutron total cross-section measurements that the level spacings are large.[14] Thus, the energy resolution of this experiment may cover only a few levels. A low density of the higher spin states in the compound nucleus at an excitation energy of $\sim$10.9 MeV could very easily explain the minimum observed there.

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Neutron-Proton Scattering below 20 MeV*

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Critical examination and analysis of existing *n-p* scattering data below 20 MeV reveal that they provide quantitative information only about the *S*-wave scattering lengths and effective ranges, which are found to be $a_t=5.396\pm0.011$ F; $a_s=-23.678\pm0.028$ F; $r_t=1.726\pm0.014$ F; $r_s=2.51\pm0.11\pm0.043$ F; where the second error quoted for r_s is a conservative estimate of the uncertainty due to departures from the shape-independent approximation. The correlations in error are $\langle\delta a_t\delta a_s\rangle=-0.7828\delta a_t\delta a_s$; $\langle\delta a_t\delta r_s\rangle=-0.8547\delta a_t\delta r_s$; $\langle\delta a_s\delta r_s\rangle=0.7029\delta a_s\delta r_s$. An estimate of the contribution to the total cross section from scattering in higher angular momentum states, based on model calculations, *p-p* phases, and the $\cos\theta$ term in the differential cross section, allows the deviation from the shape-independent approximation to be computed at 14.1 and 19.665 MeV from total cross-section measurements. It is shown on theoretical grounds that this must come almost entirely from the $^1S_0$ state, and extreme limits to this variation are established. The value found is close to zero at both energies, in accord with theoretical expectations, but the uncertainty is so large that it barely excludes the extreme limits. Some qualitative evidence for or against the existence of the long-range one pion exchange interaction in this state could be obtained by improving the experiments below 5 MeV, but the uncertainty arising from the non-*S* wave scattering precludes any but qualitative results. It is shown that this uncertainty cannot be removed by improved measurement of the differential cross section because 8 independent pieces of experimental information are required. We conclude that the energy variation of the *S* waves below 20 MeV cannot be measured without recourse to experiments which separate the spin states of the particles, such as spin-correlation, triple scattering, polarized-beam polarized-target, etc. If some information is taken from *p-p* scattering and some from theory, a single such measurement in each system might suffice; this minimal program is briefly discussed.

I. INTRODUCTION

ALTHOUGH the neutron-proton interaction has been the subject of intensive experimental and theoretical study since the discovery of the neutron in 1932, and was correctly interpreted by Yukawa as due to the exchange of quanta of finite mass in 1935, until very recently there has been no basic theoretical model capable of accounting for all the qualitative features revealed by the experimental investigations. The discovery of two- and three-pion resonances showed immediately[1,2] that at least an important part of the problem could be understood, and connected with earlier speculations about "vector mesons."[3–5] It had already been conclusively demonstrated[6] that the long-range part of the interaction in high-angular momentum states is quantitatively described by the exchange of single pions. The ω, and to a lesser extent the ρ, account for the strong short-range repulsion in the nucleon-nucleon system, the spin-orbit interaction, and the strong short-range attraction in the nucleon-antinucleon system. If the $^1S_0$ scattering length is fitted, single-pion exchange is too weak to account for the effective range[7,8] even in the absence of a short-range repulsion, so something must give a strong attraction

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