Level density of ^{57}Co

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(Received 2 August 1993)

Levels in ^{57}Co have been studied in the region of resolved levels ($E < 5.5$ MeV) with measurements of the ^{57}Fe$(p,n)^{57}$Co neutron spectrum with resolution $\Delta E \sim 5$ keV. Seventeen previously unknown levels are located. Level density parameters in the continuum region are deduced from thick target measurements of the same reaction and additional level density information is deduced from Ericson fluctuation studies of the reaction ^{56}Fe$(p,n)^{56}$Co. A set of level density parameters is found which describes the level density of ^{57}Co at energies up to 14 MeV. Efforts to obtain level density information from the ^{56}Fe$(d,n)^{57}$Co reaction were unsuccessful, but estimates of the fraction of the deuteron absorption cross section corresponding to compound nucleus formation are obtained.

PACS number(s): 21.10.Ma, 24.60.Dr, 24.60.Ky, 27.40.+z

I. INTRODUCTION

Level densities are important in many areas of nuclear physics. They represent an important input ingredient in Hauser-Feshbach calculations and are, therefore, relevant to astrophysical nucleosynthesis calculations as well as fission and fusion reactor design. Knowledge of the total density of levels is also needed to answer questions in basic nuclear physics, including the bulk behavior of the nucleus and the determination of whether the nucleus represents a chaotic system.

A number of techniques have been used to study nuclear level densities. In the low energy region, levels can be resolved and counted. High resolution ($\Delta E \approx 10$ keV) can be achieved with magnetic spectrographs and many studies have utilized charged-particle reactions. Somewhat better resolution can be obtained for gamma rays, and detection of the gamma rays produced in capture or other reactions can give useful level density information. The fact that cascades often occur is both an advantage and a disadvantage. Levels not populated in the primary reaction may be seen as secondary or tertiary products of gamma cascades, reducing the likelihood that levels are missed. This same multiplicity of paths does complicate the interpretation of the results, however, since many more gamma ray energies than levels will occur and in some cases misassignments can result. Very good resolution can also be obtained for the bombarding energy in resonance reactions (p,p) or (p,γ), and so if the level is slightly unbound, it can be located with high precision as a compound nuclear resonance.

Despite the variety of techniques available, most level schemes are incomplete even in the region of the lowest 100 levels. Reactions which are largely direct are very selective and even compound nuclear reactions have limitations imposed by angular momentum conservation and barrier penetrability. Finally, restrictions on gamma ray branching and the complicated form of the spectrum can cause levels to be missed in gamma ray studies.

Level densities in the continuum ($\Gamma > D$) must be measured using other techniques. One of the most common has been the study of evaporation spectra. Early measurements of this type were often plagued with backgrounds and were sometimes analyzed with oversimplified theoretical expressions, but more recent results have led to reliable information. At energies above 10–15 MeV, the study of Ericson fluctuations has yielded important level density information. In this case the information is obtained for the compound nucleus rather than the final nuclei and the level density is at the compound nuclear excitation energy.

The present measurements were undertaken to compare the results from these techniques for one nucleus over a wide range of energy. A pair of reactions, ^{56}Fe$(d,n)^{57}$Co and ^{57}Fe$(p,n)^{57}$Co, was chosen for comparison of the resolved level and the evaporation spectrum techniques, and the Ericson fluctuations in the reaction ^{56}Fe$(p,n)^{56}$Co were also studied.

II. EXPERIMENTAL PROCEDURE

A. Resolved level measurements

Data for the ^{56}Fe$(d,n)^{57}$Co and ^{57}Fe$(p,n)^{57}$Co reactions were obtained at the tandem electrostatic accelerator of Ohio University. High resolution data were obtained with the use of thin targets ($\Delta E \lesssim 3$ keV) and the 30 m flight path of this facility. To obtain absolute energies for the neutrons, the time of flight of the neutron was measured over a 29.6 m flight path. The time calibration of the spectrometer electronics was carried out in two steps. The relative width of each time channel was determined with the use of a radioactive source. This gave pulses which were uncorrelated in time with the pulsing

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system timing pulses. The relative time width per channel is then proportional to the number of counts in each channel with the time width per channel found to be very nearly constant over most of the time range. The absolute time calibration was accomplished by measuring the channel differences of peaks produced at regular intervals by an oscillator. Neutrons were detected in an array of NE213 scintillation detectors, which allowed the suppression of gamma background through the use of pulse shape discrimination.

The resolution of a time-of-flight spectrometer is a rapid function of neutron energy for fixed time resolution, with the best resolution obtained at low energies. A bias level slightly below 1 MeV was set on the detectors. This set a lower limit on the neutron energies detected and resulted in a window of best resolution from about 1.1 MeV to 1.7 MeV. Thus, a range of bombarding energies was utilized in order to move different regions of excitation in ^{57}Co into the zone of best neutron energy resolution.

Measurement of the neutron energy and determination of the bombarding energy result in a direct determination of the Q value and hence the excitation energy for each observed level. Observation of a given peak at multiple angles or bombarding energies is required to establish that the peak is not due to a contaminant. Evidence of carbon and oxygen contamination of the targets could be seen in the (d,n) measurements, but the (p,n) Q values for ^{12}C and ^{16}O are so negative that the (p,n) spectra did not show contaminant peaks.

High resolution spectra were measured at angles from 0° to 150° in 25° steps. Bombarding energies were from 3 to 5 MeV in 0.5 MeV steps for deuterons and 5, 6, 7, 7.5, 8, and 8.7 MeV for protons.

Results from the (d,n) reaction were very disappointing. The positive Q of this reaction would allow higher energy levels to be populated than in the (p,n) reaction at a given bombarding energy. Unfortunately, large fractions of the observed neutron spectra were due to direct reactions. These, in turn, are highly selective, populating some states very strongly and hardly populating neighboring states at all. This meant that many states were missed and no information on new levels could be deduced.

Spectra from the (p,n) reaction were quite useful in testing current level schemes. Virtually all previously known levels were observed and 17 new levels were also found. Inspection of the current level scheme [1] of ^{57}Co indicates that significant numbers of levels are missing above 5 MeV, based on the fact that the slope of the level density does not increase above this point. It is also evident from the Nuclear Data Sheets that no one measurement has yielded evidence for all of the known levels. Many of the energy levels between 4 and 5 MeV have been located as a result of a study [2] of the ^{60}Ni$(p,\alpha)^{57}$Co reaction. This cross section has large compound nuclear contributions and was investigated with good resolution ($\Delta E \lesssim 15$ keV). Because of the large Coulomb barrier for alphas, however, the outgoing alpha energy is limited to energies above about 4 MeV, limiting the excitation energy range which can be studied. Also, the high stopping power of alpha particles limits the energy resolution obtainable. The present measurements were carried out with a spectrometer which could achieve resolution better than 2 keV for 1 MeV neutrons, but the resolution actually obtained was limited to about 5 keV. The additional contributions to the energy width were due to the charged-particle energy loss in the target and small modulations in charged-particle energy caused by the pulsing and bunching electronics.

A check on the accuracy of the flight path was obtained by measuring the total neutron cross section of carbon. A number of sharp peaks in the carbon cross section allows a very precise determination of the flight path by checking the location of these structures. The adjustment needed was 3 mm, consistent with the uncertainty in this parameter. Similarly, tests of the accuracy of the reaction angle and bombarding energy could be made by allowing small variations about the nominal values and checking the energy of the first few states in the spectrum. No changes in angle were required, but bombarding energy adjustments of up to 2.5 keV were needed for various runs. This is consistent with the uncertainty in the nominal value of this parameter. As a result of these checks, it is felt that the centroid values for the peaks are accurate to about 1.5 keV, even though the resolution was typically 5 keV. Figures 1 and 2 show a typical spectrum.

Table I lists the energies of 17 levels which were identified in multiple runs but not previously observed. The previous level scheme also lists some levels for which the uncertainty in energy is large ($\gtrsim 5$ keV). This is likely to lead to uncertainty in the level scheme, since this often leaves an ambiguity as to whether two levels seen in two separate experiments are really separate levels. In Table II we present determinations of energies for levels which were previously observed but for which our level energies are more precise. Other levels which have large or unspecified errors [1] include those at 5.057, 5.103, and 5.167 MeV; these were not seen in the present measurements. All previously proposed levels below 5 MeV were seen in the present measurement, though in the case of the 2.133 and 2.133 08 doublet, the two states were not resolved.

It should not be concluded from the completeness of

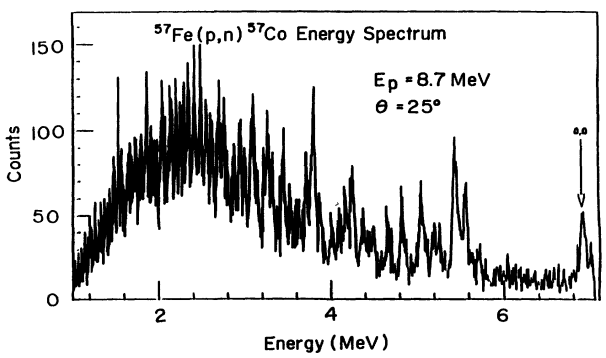

FIG. 1. Neutron spectrum from the ^{57}Fe$(p,n)^{57}$Co reaction at a bombarding energy of 8.7 MeV and an angle of 25°.

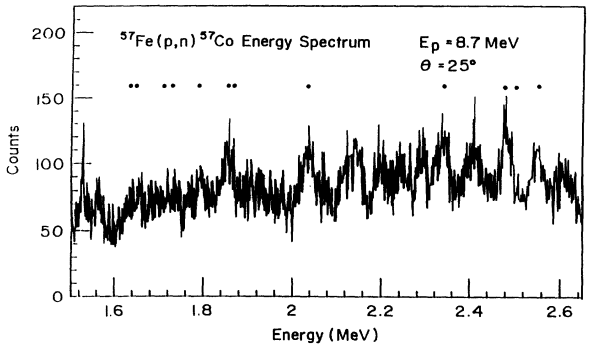

FIG. 2. Enlargement of the spectrum shown in Fig. 1, showing in greater detail the region between 1.6 MeV and 2.6 MeV. Peaks corresponding to newly identified levels are shown with closed circles.

the spectrum below 5 MeV that we have also seen all levels up to 5.7 MeV. The rapidly increasing level density makes observing weak states much more difficult above 5 MeV. Further study of this excitation energy region using gamma rays would be useful in determining spins and parities of these levels.

B. Continuum measurements

Similar techniques were used for obtaining continuum spectra for the ^{56}Fe$(d,n)^{57}$Co and ^{57}Fe$(p,n)^{57}$Co spectra. In this case, thick targets ($\Delta E \sim 150$ keV) and a shorter flight path (10.4 m) were used. For the evaporation spectra, absolute cross sections are required. The neutron detector efficiencies were determined by measuring neutron yields from the ^{7}Li$(p,n)^{7}$Be, ^{11}B$(p,n)^{11}$C, T$(p,n)^{3}$He, and D$(d,n)^{3}$He reactions. This technique allows a determination of the level density spanning both the region of resolved levels as well as the region where the levels overlap. The basic characteristics of such spectra produced by compound nuclear reactions are a Maxwellian shape as a function of outgoing energy and

TABLE I. Energy assignments to new levels in ^{57}Co.

Excitation energy (MeV) ± (keV)
4.426 ± 1.6
4.472 ± 1.7
4.486 ± 2.0
4.638 ± 1.6
4.945 ± 1.8
5.114 ± 1.7
5.124 ± 1.4
5.186 ± 1.4
5.245 ± 1.2
5.260 ± 1.8
5.324 ± 1.7
5.338 ± 1.8
5.499 ± 1.9
5.543 ± 1.4
5.613 ± 1.6
5.631 ± 1.5
5.699 ± 1.6

TABLE II. Level energies determined with improved precision.

Previous value [1]		Present value	
E (MeV)	ΔE (keV)	E (MeV)	ΔE (keV)
3.973	a	3.971	1.5
5.138	a	5.136	1.5
5.638	±5	5.644	1.6

[a]Error not given in Ref. [1].

an angular distribution which is symmetric about 90°. Based on these two criteria, the (p,n) reaction was largely due to compound nuclear processes. In contrast, the indications from the thin target measurements that the (d,n) reaction was primarily direct were confirmed by the thick target results. The angular distribution was forward peaked, and the emission spectrum was substantially harder than the corresponding (p,n) spectrum. Typical evaporation spectra are shown in Figs. 3 and 4.

C. Ericson fluctuations

Ericson fluctuations [3] may be studied by measuring an excitation function with very good resolution. Since fluctuation measurements provide information on the level density of the compound nucleus, the ^{56}Fe$(p,n)^{56}$Co reaction was studied with the 29.6 m flight path at Ohio University. In most cases, this has been done for charged-particle reactions by using very thin targets and measuring the excitation function step by step. This is quite challenging and would be even more difficult for a reaction like (p,n). Fortunately, there is a much more efficient method for obtaining a high resolution excitation function. The low-lying levels in ^{56}Co are separated by energies of 100 keV or more. If a target of thickness less

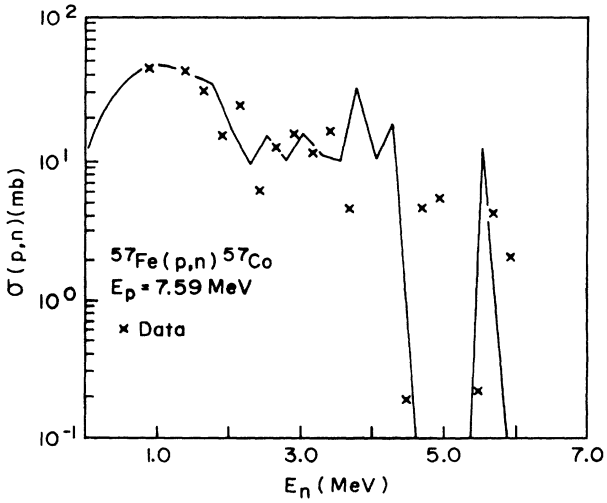

FIG. 3. Neutron spectrum from ^{57}Fe$(p,n)^{57}$Co integrated over angle. The bombarding energy is 7.59 MeV. Experimental points are denoted with (×) and are the cross section integrated over a 250 keV bin. The calculation is the Hauser-Feshbach calculation discussed in the text.

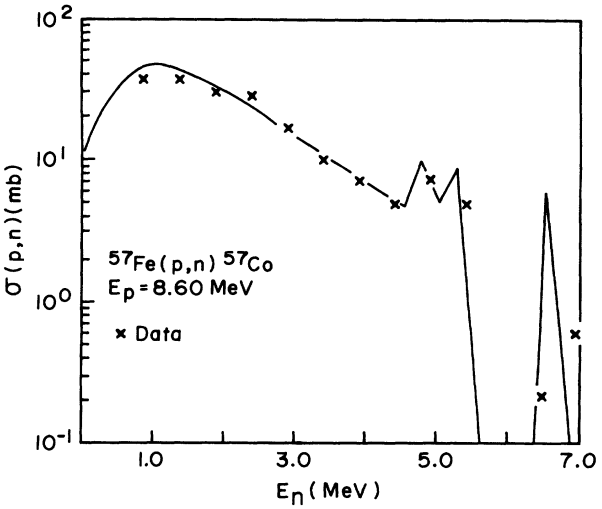

FIG. 4. Same as Fig. 3, except that the bombarding energy is 8.6 MeV.

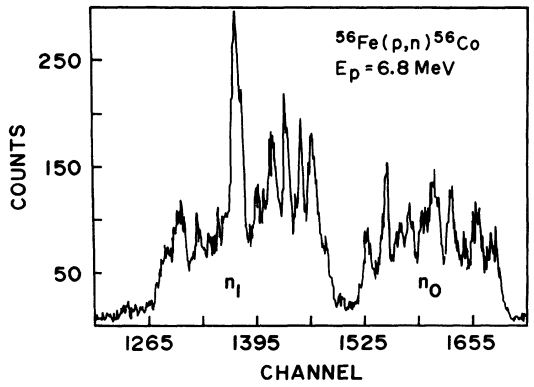

FIG. 5. Excitation function for the ^{56}Fe$(p, n_0)^{56}$Co and ^{56}Fe$(p, n_1)^{56}$Co reaction at a bombarding energy of 6.8 MeV, where the target thickness allows an excitation energy range of more than 100 keV to be studied in one measurement.

than the thickness producing this proton energy loss is used, the final state peaks will be broadened but still resolved. By using the full flight path for neutrons, very good resolution for the neutron energy can be obtained if the neutron energy is about 1–1.5 MeV. Thus, for each final level in ^{56}Co, a proton energy can be found which produces a neutron peak in this energy region, and the energy of the proton which induced the reaction can be inferred to a precision of about 2 keV, even though the target thickness is about 100 keV. In other words, the neutron energy resolution allows us to obtain an excitation function for the reaction over the range $E_p - \Delta$ to E_p, where E_p is the incident energy and Δ is the proton energy loss in the target. The bombarding energy was then increased by $2\Delta/3$, yielding an excitation function over the range $E - \Delta/3$ to $E + 2\Delta/3$. This provided for some amount of overlap and allowed successive excitation functions to be merged. Note that for this technique no contribution to the "resolution" from target thickness occurs, allowing a resolution of 2–3 keV in the neutron spectrum. Spectra were obtained at angles from 0° to 150° at intervals of 25°. A typical spectrum is shown in Fig. 5. At slightly higher energies, the second excited state was also seen.

III. ANALYSIS AND RESULTS

The analysis of the high resolution data was based on very precise determination of the neutron energy for each peak and use of kinematics to relate this energy to a Q value and hence an excitation energy in ^{57}Co. As was mentioned in Sec. II, the ^{56}Fe$(d, n)^{57}$Co spectra were found to be useless in locating new levels, since it was obvious that a substantial fraction of the previously known levels was missed. This was presumably due to the fact that direct reaction contributions appeared to dominate the spectrum in the region of low-lying levels. The Q values for ^{12}C(d, n) and ^{16}O(d, n) were such as to allow large contaminant peaks to appear in the spectrum.

For the ^{57}Fe$(p, n)^{57}$Co spectrum, contributions from ^{12}C and ^{16}O were ruled out because of large negative Q values. The small abundance of ^{56}Fe in the target produced very few peaks because of the very negative Q for the ^{56}Fe$(p, n)^{56}$Co reaction. The peaks which were seen were for levels at low excitation in ^{56}Co; these have well-known energies and the reaction kinematics for these peaks were only consistent with the assumption of a mass 56 target. The nominal value for the flight path was adjusted slightly to make the peaks in the ^{12}C total neutron cross section line up with known values. Similarly, small adjustments in the reaction angle and bombarding energy were made to bring peaks corresponding to levels at low excitation energy into agreement with known values.

Results from the high resolution (p, n) measurements are encouraging but do suggest some additional work. It would be desirable to make coincidence measurements (either particle-gamma or gamma-gamma) to try to determine the spins and parities of the new levels. Finally, the present results could be extended at laboratories where higher energy proton beams are available.

Continuum spectra were integrated in 250 keV bins at each angle; these cross sections were then fit with a Legendre polynomial expansion including $\ell = 0$ and $\ell = 2$ terms to obtain the total cross section in each energy bin. Evaporation spectra were analyzed using the Hauser-Feshbach formalism [4] with the computer code HF [5]. Transmission coefficients were calculated using the computer code FOP [6] and optical potentials for protons, neutrons, and alpha particles from Refs. [7–9], respectively. The deuteron channel was not included as an exit channel but was used as an entrance channel; the potential parameters were due to [10].

Additional input to the Hauser-Feshbach code included known level schemes for the lowest 20 levels for the final nuclei reached by emission of protons, neutrons, and alpha particles. Level density parameters are also needed for these same nuclei. A microscopic Fermi gas level density code RHOTHERM [5] was used with the single particle levels of Seeger and Perisho [11] to calculate level densities using the formalism of statistical mechanics and including a BCS Hamiltonian. This approach yields nu-

merical values of the level density as a function of energy, which are then fit with the function

$$\rho(E) = \frac{e^{2\sqrt{a(E-\delta)}}}{12\sqrt{2}\,\sigma\, a^{1/4}(E-\delta)^{5/4}} \quad (1)$$

to obtain best-fit values of a and δ for each nucleus. Values of σ as a function of energy were taken from the level density calculated from Seeger-Perisho single particle levels.

The calculated spectra were then compared with the measurements and adjustments made in the input parameters to bring the two into agreement. Relatively small sensitivity to the particular optical model parameters is found, and the level density parameters in the alpha and proton channels are found to influence the magnitude of the neutron spectrum but not its shape. Parameters for ^{57}Co could be determined without significant interference from the other channels. Best-fit values were $a = 6.5$ and $\delta = 0.7$. Individual spectra could be fit somewhat better by varying these parameters slightly, but the values quoted provide the most consistent results for the entire body of data.

Level density values at higher energies were deduced from Ericson fluctuation measurements of the ^{56}Fe$(p,n)^{56}$Co reaction to three final states. In studying the fluctuations, information is deduced about the level density of the compound nucleus, and so these studies also give information about the level density of ^{57}Co. As has been shown by Ericson [3], excitation functions for compound nuclear processes continue to fluctuate even when the energy is high enough that the compound levels overlap. In this limit, the fluctuations can be analyzed to yield an average width, Γ. This width, in turn, can be related to the compound nuclear level density as follows:

$$\rho(E) = \frac{1}{2\pi\Gamma}\sum_J \frac{P_J}{H(J)}\sum_i T_i^J. \quad (2)$$

Here J is the compound nuclear spin, $H(J)$ is the relative probability a compound level has spin J, P_J is the fraction of the cross section σ_{ab} which proceeds through spin J, and $\sum_i T_i^J$ is the sum of the transmission coefficients to all decay channels from compound states of spin J. Transmission coefficients were obtained for protons, neutrons, alpha particles, and deuterons from Refs. [7], [8], [9], and [10], respectively. The function $H(J)$ has the form

$$H(J) = \frac{2J+1}{2\sigma^2}\, e^{-(J+\frac{1}{2})^2/2\sigma^2}, \quad (3)$$

and so it is specified by the parameter σ, which is $\langle J_z^2\rangle^{1/2}$, where this quantity may depend on energy.

Three techniques have frequently been used to determine Γ. The first involves calculation of the autocorrelation function

$$C(\epsilon) = \frac{\langle[\sigma(E+\epsilon)-\langle\sigma\rangle][\sigma(E)-\langle\sigma\rangle]\rangle}{(\langle\sigma^2\rangle-\langle\sigma\rangle^2)} = \frac{1}{1+(\epsilon/\Gamma)^2}, \quad (4)$$

where the last equality allows Γ to be deduced from the dependence of $C(\epsilon)$ on ϵ. A second technique involves counting the peaks in the excitation function over a given energy range. The value for Γ [12] is then

$$\Gamma = 0.55/N, \quad (5)$$

where N is the number of peaks per unit energy. Finally, the value for Γ can be determined from a Fourier series analysis [13] of the excitation function. If

$$\sigma(E) = \sum_k \left\{ a_k \cos\frac{2\pi kE}{I} + b_k \sin\frac{2\pi kE}{I}\right\}, \quad (6)$$

then

$$S_k = a_k^2 + b_k^2 = 4\pi\frac{\Gamma}{I}(\mathrm{var}\,\sigma)e^{-2\pi k\Gamma/I}. \quad (7)$$

In this expression, I is the total energy interval and varσ is the variance of the cross section.

The present analysis has relied on techniques 2 and 3 to deduce Γ. A comparison of the results of the three techniques by Dallimore and Hall [14] indicates consistency between them.

Values for Γ deduced from these two techniques were averaged to obtain an experimental value for the width. Finally, Γ values deduced from each of the three neutron groups were averaged. This value was then converted to a level density and is shown on Fig. 6.

Earlier fluctuation studies of the ^{57}Co compound nucleus were made by Ernst *et al.* [15]. Results from the analysis of these authors are shown on Fig. 7. The results of Ref. [15] are at a somewhat higher energy but agree with the predictions based on the lower energy fluctuation data and the evaporation spectra analysis. This result is interesting since under some circumstances the fluctuations in proton elastic or inelastic cross sections will be dominated by the amplitude proceeding through

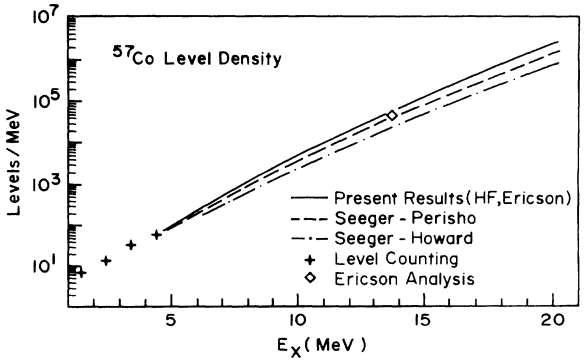

FIG. 6. Level density of ^{57}Co. Shown are present results (solid line) which represent a combination of information from evaporation spectra and Ericson fluctuations, a calculation based on Seeger-Perisho single particle levels (dashed line), and one based on Seeger-Howard levels (dot-dashed line). Crosses mark the values obtained from level counting at low energies (including new levels proposed in this work) and the diamond marks the level density point found from the present Ericson fluctuation results.

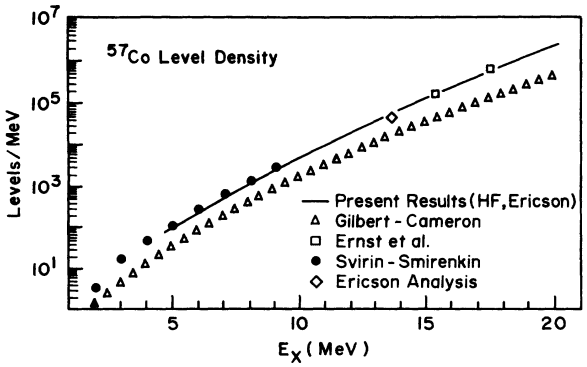

FIG. 7. Level density of ^{57}Co. Triangles denote the predictions of the parameters of Gilbert and Cameron, squares the results of Ernst *et al.*, and solid circles the results of Svirin and Smirenkin. The solid line and diamond have the same meaning as in Fig. 6.

analog compound states, while the fluctuations in a (p,n) cross section should be due to those in the nonanalog $(T = T_z)$ states [16]. The dominance of the analog states in proton scattering would be especially strong for systems which have small (p,n) Q values, i.e., have most of the decays for $T = T_z$ states leading to neutron emission. In the present case, (p,n) Q is quite negative for ^{56}Fe, and so the consistency of the (p,p) and (p,n) results is not surprising. The large Q value for (p,n) results in substantial contributions to the proton scattering cross section from the $(T = T_z)$ nonanalog states.

Additional studies of the level density of ^{57}Co have been completed by Svirin and Smirenkin [17]. These authors also analyzed evaporation spectra from the ^{57}Fe$(p,n)^{57}$Co reaction and obtained the energy dependence shown in Fig. 7. As can be seen, it is in good agreement with the present results.

The calculations based on Seeger-Perisho and Seeger-Howard [18] levels give reasonable agreement with the data. Both give an energy dependence which is slightly too slow and underpredict the level density. Results for the Seeger-Perisho levels are slightly superior to those of Seeger-Howard as seen in Fig. 6.

Comparison of these results with those from other studies is complicated by the fact that the level density form Eq. (1) depends on a, δ, and σ. Normally, values of σ are not the primary cause of differences between level density compilations, because σ does not enter the exponential and because values of σ are believed to be established to about 20%.

The coupling between a and δ can result in fits which match at a particular energy but disagree at all others. From Eq. (1) we obtain the results

$$\frac{d\rho}{\rho} = \sqrt{a(U-\delta)}\,\frac{da}{a} \tag{8}$$

and

$$\frac{d\rho}{\rho} = -\sqrt{a(U-\delta)}\,\frac{d\delta}{U-\delta} + \frac{3}{2}\,\frac{d\delta}{U-\delta}. \tag{9}$$

Comparing Eqs. (8) and (9), we see that for a about 6 and $U-\delta$ about 6, the change of one unit in a is approximately compensated by a change in δ of the same magnitude and direction. As the energy increases, the two effects do not compensate, and for U large, the dependence on a is dominant. Thus, determinations of the level density at energies above 10 MeV are particularly effective at determining a and are not so sensitive to δ.

Three major compilations which have been based on neutron resonances are those of Gilbert and Cameron [19], Dilg *et al.* [20], and Rohr [21]. Of these, Refs. [19] and [21] used only neutron resonances while Ref. [20] used low-lying levels as well and also included proton resonance level counts. Thus, neither Gilbert and Cameron nor Rohr included any information from ^{57}Co in developing their systematics. Gilbert and Cameron and Rohr did use similar energy shifts, however, and so the higher a value for Rohr means that his values are higher for the level density than Gilbert and Cameron at all energies. The difference between the two values is as much as an order of magnitude about 15 MeV. The present results correspond to an a value which is between those of Refs. [19] and [21] and the energy shift is smaller but not by much. Thus, the present results are between these predictions in this energy range. Dilg *et al.* use a back-shifted parameterisation. This gives a larger value for the level density at low energy and a smaller value at high energies than a conventional formulation if the two are matched at 7 MeV. One set of Dilg *et al.* is based on the assumption that the moment of inertia is that of a rigid body while the other assumes it is half of that value. Under either of these assumptions, the level density is less rapidly varying than the present results, although the agreement is good in the region of the nucleon binding energy.

Level density parameters for ^{57}Co have been proposed by Vonach *et al.* [22] and Braga-Marcazzan and Milazzo-Colli [23]. The latter authors propose an a value for ^{57}Co of 6.46, which is in excellent agreement with the present results. It is also based on fluctuation measurements with the ^{56}Fe(p,p_0) reaction. The work of Ref. [22] is based on proton resonance counting in ^{56}Fe + p but not higher energy results, while the Braga-Marcarzzan–Milazzo-Colli study did not include low energy ($E < 12$ MeV) results. Vonach *et al.* derive parameters for both a conventional Fermi gas and also one with variable a, as proposed by Ignatyuk *et al.* [24]. The two forms give very similar level densities about 7 MeV, but at higher energies the conventional Fermi gas results of [22] were closer to the present results. Table III shows the comparison of the present results with those of Refs. [19–22]. The values predicted by Ernst *et al.* [15] and Braga-Marcazzan and

TABLE III. Comparison of level density predictions for ^{57}Co.

Energy (MeV) U	Present level density $\rho(U)$	Ratios of previous results to present results [19]	[22]	[21]	[20]
5	85	0.4	0.6	1.1	1.2
10	4.2×10^3	0.4	0.7	1.9	0.9
15	8.3×10^4	0.4	0.9	3.2	0.8
20	1.2×10^6	0.3	1.0	4.5	0.7

Milazzo-Colli are very close to the present results and are not tabulated. Of the tabulations compared, those of [20] and [21] are in best agreement with the present data at 5 MeV, while at 15 MeV the value of [22] is closest.

The conclusion to be drawn is that having information available over a wide range of energies is valuable. Although the four sets of values are within a factor of 2.5 of one another at 5 MeV, they differ by more than an order of magnitude about 15 MeV. The values which were derived from fits to ^{57}Co data [15,17,22,23] are superior to those based on the systematics of neighboring nuclei [19].

Since the energy dependence of the conventional Fermi gas form is unphysical for energies close to the pairing and shell shift, a fit to the resolved-level region was made with the form

$$\rho(E) = A\, e^{BE}, \tag{10}$$

where $A = 2.89$ and $B = 0.688$. This represents the level density very well from 2 to 5 MeV. This agrees well with the conventional Fermi gas parametrization at 5 MeV, but is closer to the actual level density between 2 and 5 MeV than is the Fermi gas form.

As a by-product of the effort to get level density information from the ^{56}Fe(d,n) reaction, calculations were made of the compound nuclear spectrum from this reaction with the level density parameters deduced from the (p,n) reaction study. The comparison shows more high energy and fewer low energy neutrons in the measurement than in the calculation. By multiplying the calculation by the appropriate reduction factor, one can achieve a reasonable fit to the spectrum below an outgoing energy of 3 MeV, which is primarily due to compound nuclear processes; this factor gives an approximate indication of the fraction of the absorption cross section which corresponds to compound nuclear processes. We have attempted to estimate this fraction using some simple assumptions. Noncompound mechanisms do not result in a large peak in the 1 MeV region as do compound processes; thus, it was assumed that the peak in this region was due to compound reactions. At each bombarding energy, the peak height observed experimentally was lower than that calculated with the Hauser-Feshbach formalism using level density parameters which fit the (p,n) spectra.

At this point, it was necessary to make an assumption about the direct reaction processes. One extreme is to assume that any direct reaction is not followed by a compound nuclear process. This would be the case if a (d,p) or (d,n) stripping reaction occurred to a bound final state. Another possibility of such a reaction would be one which resulted in a one-step direct reaction which broke up the deuteron into a free neutron and a free proton, using the target to absorb some momentum. A second limit would be one in which each direct reaction is followed by absorption of the remaining particle and subsequent compound nuclear decay. Since at the present bombarding energies for deuterons the typical compound nuclear reaction results in the emission of two particles, this assumption (that a direct reaction is followed by a compound nuclear decay) would still reduce the compound nuclear particle yield. For each of these two limits, a fraction of compound nuclear events was calculated and the two values averaged. The uncertainty was assigned as the difference between the average and the extreme values. We note that this error estimate does not include any uncertainty due to an incorrect reaction cross section prediction from the optical parameters used. A recent study of proton optical potentials in this region [25] found that predictions based on global systematics overestimated the absorption below 6 MeV. If this result also holds for deuterons, it would increase the fraction of compound nuclear events.

TABLE IV. Fraction of the reaction cross section corresponding to compound nuclear processes for ^{56}Fe+d.

E_d (MeV)	f
3.8	0.51 ± 0.18
4.8	0.58 ± 0.15
5.8	0.7 ± 0.1
6.9	0.78 ± 0.07
7.9	0.77 ± 0.07

An alternative procedure would have been to calculate the fraction of the observed neutron spectrum which did not have a shape as a function of outgoing energy consistent with compound predictions. This technique was felt to be less reliable because the proton spectrum was not measured, requiring an assumption as to whether (d,n) and (d,p) direct cross sections are the same. Although no specific calculations were made, the values obtained using this approach would have been in rough agreement with those listed in Table IV.

Other studies of deuteron-induced reactions [26,27] have also examined this question. The focus in these experiments was on energies above 8 MeV, where the fraction of compound reactions is apparently decreasing with energy. Our results show an opposite slope but do not contradict the earlier results because they are in a lower energy region. For similar mass targets, the earlier results indicate fractions near 0.8 at 10 MeV, which is consistent with our value at 8 MeV. Improvement in our understanding of this problem will require measurement of both proton and neutron spectra for a target for which an optical model parameter set is available in the energy range of interest.

IV. SUMMARY AND CONCLUSIONS

A comprehensive study of the level density of ^{57}Co has utilized resolved level counting, evaporation spectra, and Ericson fluctuations. The result of this study is a level density parametrization which gives a good representation of the level density from 2 to 14 MeV. Of particular importance is the fact that the results of the evaporation spectra analysis agree with the Ericson fluctuation results. Tests of the level density generated from theoretical calculations utilizing noninteracting fermions show relatively good agreement with the data, as do the results of some recent level density compilations. The (p,n) reaction in this mass region is found to be superior to the (d,n) reaction for level density studies.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Grant No. DE-FG02-88-ER40387.

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