Persistence of Odd-Even Effect on Nuclear Level Densities at High Excitation Energy*

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(Received 19 May 1969)

Excitation functions and angular distributions for the reaction $^{54}Cr(p, \alpha)^{51}V$ have been measured between 6.5 and 20.0 MeV for the ground state and the first two excited states in ^{51}V at 0.32 and 0.92 MeV, with spins $\frac{7}{2}^-$, $\frac{5}{2}^-$, and $\frac{3}{2}^-$, respectively. From the angular distributions and the excitation functions, a compound nuclear mechanism is supported for the population of the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ levels. At higher bombarding energies there is evidence that a simple pickup mechanism dominates for producing the $\frac{7}{2}^-$ level. From the fluctuation analysis of the excitation functions for the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ levels, the decay width of the compound nucleus ^{55}Mn was obtained as a function of energy. From the differential cross sections and decay widths, the level density of ^{55}Mn was deduced at excitation energies between 15 and 23 MeV. The results were combined with low-energy level-density data previously obtained with a magnetic spectrograph. These results, when compared with similar data for even-even ^{56}Fe, show that the energy shift required to match level densities for odd and even nuclei is the same at low and high excitation energies. The energy dependence of the level density cannot be reproduced over the whole energy range with level-density expressions employing conventional odd-even corrections. The same conclusion is supported by statistical-model calculations of the excitation functions.

I. INTRODUCTION

DIRECT experimental information on nuclear level densities has, until recently, been limited to the region of excitation energy at or below the neutron binding energy. Indirect information at higher energy can be obtained from the energy spectra of emitted particles. Spectral analysis, however, only gives information on the energy derivative of the level density and not on its absolute value.

It has now been shown, however, that it is possible to extract nuclear level densities by combining measurements of the fluctuation width and the absolute cross section for a single level of the residual nucleus.[1–4] By this method the level density of the compound nucleus at excitation energies in the continuum can be determined. It is therefore possible to determine nuclear level densities over a wide range of excitation energies and compare such results with theoretical models. Less direct methods relating fluctuation widths to level-density formulations have also been reported.[5,6]

In a previous study, level-density information covering a large region of excitation energy (0–23 MeV) was obtained for even-even nuclei.[3,4] The low-energy data was obtained with a magnetic spectrograph.[7,8] The excitation-energy dependence of the data cannot be satisfactorily reproduced by a Fermi-gas model with a level-density parameter a, a moment of inertia, and a conventional "pairing-energy" correction, which are independent of excitation energy. The constant-temperature and the superconductor-level-density models are also incapable of reproducing the level densities over the extended energy region. Furthermore, one cannot reproduce with Hauser-Feshbach calculations the slopes of the excitation functions[4] and the excitation-energy dependence of the statistical decay width Γ of the compound nuclei when conventional level-density formulas are used.

In that earlier work, an empirical Fermi-gas model varying from the classical one in the pairing-energy correction, was suggested for even-even nuclei. From that analysis it could not be determined whether the modified pairing correction should be applied to both even and odd nuclei at all excitation energies, or whether the pairing-energy gap would disappear at a moderate excitation energy. In the present work we have investigated primarily the excitation-energy dependence of the level-density displacement (pairing-energy gap) between odd and even nuclei. Excitation energy is measured with respect to the ground state of each nucleus throughout this work.

* Research supported in part by U.S. Atomic Energy Commission.
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[1] A. Richter, W. Von Witsh, P. von Brentano, O. Häusser, and T. Mayer-Kuckuk, Phys. Letters 14, 121 (1965).
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[7] A. A. Katsanos, J. R. Huizenga, and H. K. Vonach, Phys. Rev. 141, 1053 (1966).
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II. EXPERIMENTAL RESULTS

Excitation functions for the reaction $^{54}Cr(p,\alpha)^{51}V$ were measured between 6.5 and 20.0 MeV with the proton beam from the University of Washington three-stage FN tandem Van de Graaff accelerator. The compound nucleus ^{55}Mn is an odd-even nucleus, one proton removed from the even-even nucleus ^{56}Fe (for which level-density data are already available).[3,4] Differential cross sections were measured for the ground and first two excited states in ^{51}V at 0.32 and 0.93 MeV, with spins $\frac{7}{2}^-$, $\frac{5}{2}^-$, and $\frac{3}{2}^-$, respectively. Enriched ^{54}Cr targets (94%) were prepared by evaporation of metallic chromium onto carbon backing. A 0.12-mg/cm^2 target was used between 6.5–12.0 MeV, and a 0.25-mg/cm^2 one between 13–20 MeV. These thicknesses correspond to approximately 5 keV for the 0.12-mg/cm^2 target at 6.5-MeV proton energy, and 6 keV for the 0.25-mg/cm^2 target at 13-MeV proton energy. The outgoing particles were detected simultaneously by six surface-barrier detectors from 170° to 40°, and in some cases at 20°. The detectors were biased to just stop the ground-state α particles. The α particles from the other Cr isotopes and carbon were all lower in energy than those going to the 0.93 level in ^{51}V.

The angle-integrated excitation functions obtained are illustrated in Fig. 1, and angular distributions at 7, 10, and 15 MeV are illustrated in Figs. 2–4, respectively. The errors in Fig. 1 below 12 MeV are mainly due to the uncertainty in the target thickness. The large errors for the two excited states above 12-MeV bombarding energy are due to poor statistics and the uncertainties associated with subtracting the tail in the pulse-height spectrum associated with the intense ground-state transition. The theoretical curves in these figures will be discussed in Sec. III. Excitation functions at the laboratory angles 40° and 170° are displayed in Fig. 5. The strong fluctuations in this figure are due to the fact that each point represents a single measurement with a thin target, whereas in Fig. 1 the cross sections have been integrated over angle.

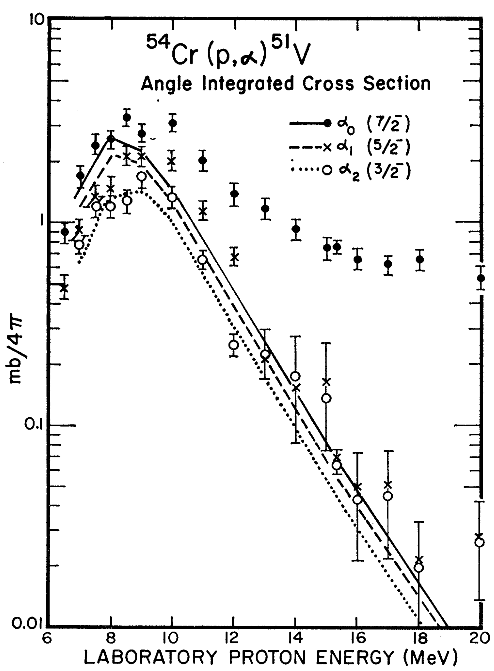

FIG. 1. Angle-integrated cross sections and results of statistical-model calculations.

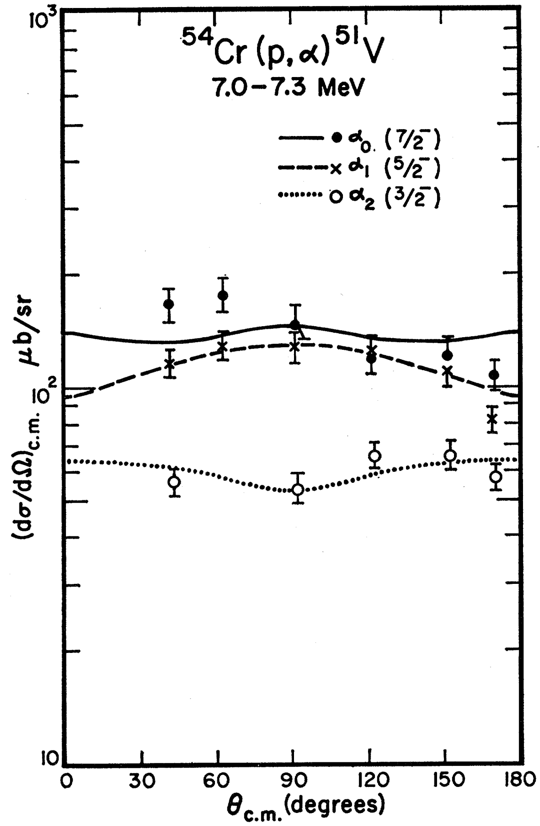

FIG. 2. Energy-integrated cross sections measured from 7.0 to 7.3 MeV with 5-keV steps, and results of statistical-model calculations normalized to the average of the first and second excited states.

Excitation functions with 5-keV steps were measured for the three levels at the laboratory angles 40°, 60°, 90°, 120°, 150°, and 170° in the energy regions 7.0–7.3 MeV and 10.0–10.3 MeV, and with 10-keV steps in the region 15.0–15.7 MeV, in order to determine the fluctuation widths Γ of the compound nucleus. Samples of these excitation functions are displayed in Figs. 6 and 7.

III. DATA ANALYSIS

A. Reaction Mechanism

The method of extracting level-density information from the cross-section and the fluctuation-width data

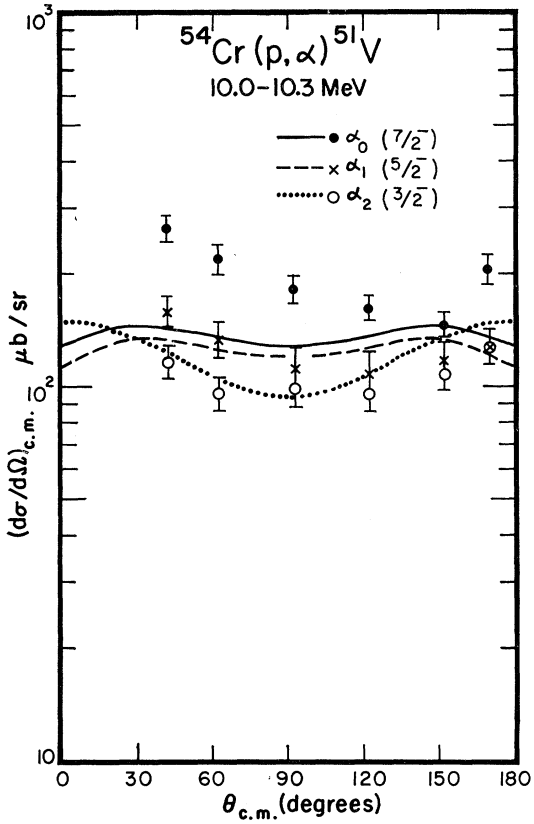

FIG. 3. Energy-integrated cross sections measured from 10.0 to 10.3 MeV with 5-keV steps, and results of statistical-model calculations normalized to the average of the first and second excited states.

requires that the reaction proceed by a compound nuclear mechanism. However, there is evidence for direct processes at certain energies and angles.

The target nucleus $_{24}{}^{54}Cr_{30}$ has four protons in the $1f_{7/2}$ shell. For the neutrons this shell is closed, and two more particles are in the $2p_{5/2}$ shell. The seniority and angular momentum, therefore, are assumed to be zero for both the neutrons and protons. If a simple pickup model is then assumed for the direct process of the (p,α) reaction, formation of a three-particle cluster from a $1f$ proton and a pair of $2p$ neutrons will leave the residual nucleus in a state with seniority 1 and angular momentum $\frac{7}{2}$. Therefore, the reaction will lead to a low-lying $\frac{7}{2}$ level but not to low-lying $\frac{5}{2}$ or $\frac{3}{2}$ levels.[9] If the two neutrons are removed from each of two pairs, the final configuration will have two unpaired neutrons, corresponding to higher excited states. Thus, this simple model predicts the low-lying $\frac{5}{2}^-$ and $\frac{3}{2}^-$ levels to be populated primarily by the compound nuclear process. From the reflection symmetry of angular distributions and the exponential falloff of the excitation functions at high energies (Figs. 1–4) a compound nuclear mechanism is supported for the population of the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ levels between 40°–170°. However, there is some evidence for contributions from direct interactions at smaller angles and higher bombarding energies, indicating some configuration mixing in the wave functions. It should also be mentioned that all three levels in ^{51}V have angular distributions with strong forward peaking in the reaction ^{50}Ti(^{3}He, d)^{51}V, even at 10 MeV.[10] Thus, at least for a stripping direct reaction, the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ states as well as the $\frac{7}{2}^-$ state are populated.

A compound nuclear process for the production of the $\frac{7}{2}^-$ level below 10 MeV is indicated by the approximate reflection symmetry of the angular distribution and by the magnitude of the cross section relative to the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states. The fraction due to direct interaction increases very rapidly above this energy (see Fig. 4). However, even at the higher energies, although the cross section of this level is a factor of 10–100 higher than the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ levels at forward angles, the cross-

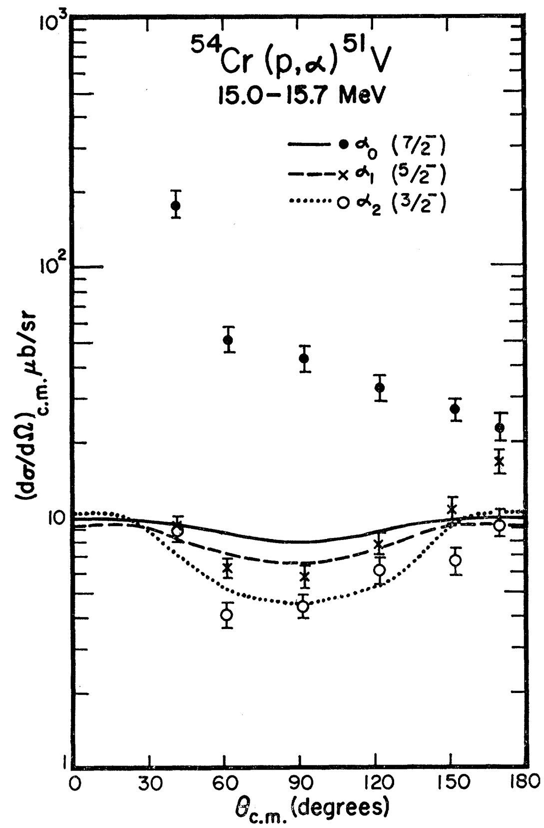

FIG. 4. Energy-integrated cross sections measured from 15.0 to 15.7 MeV with 10-keV steps, and results of statistical-model calculations normalized to the average of the first and second excited states.

[9] R. Sherr, in *Proceedings of the Conference on Direct Interactions and Nuclear Reactions Mechanisms*, edited by E. Clementel and C. Villi (Gordon and Breach Science Publishers, Inc., New York, 1963).

[10] B. J. O'Brien, W. E. Dorenbusch, T. A. Belote, and J. Rapaport, Nucl. Phys. **A104**, 609 (1968).

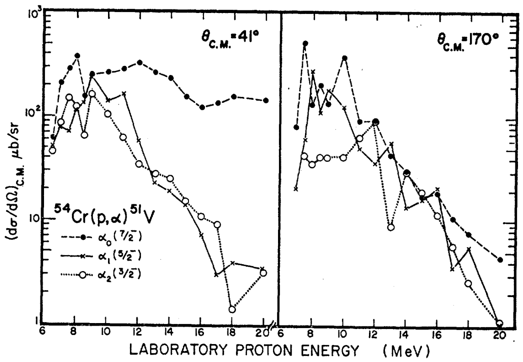

FIG. 5. Differential cross sections at 41° and 170° measured with a thin target.

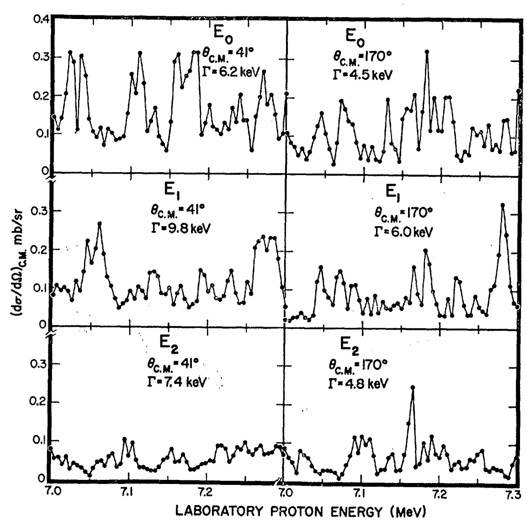

FIG. 6. Excitation functions at 41° and 170° in the energy region 7.0–7.3 MeV with 5-keV steps.

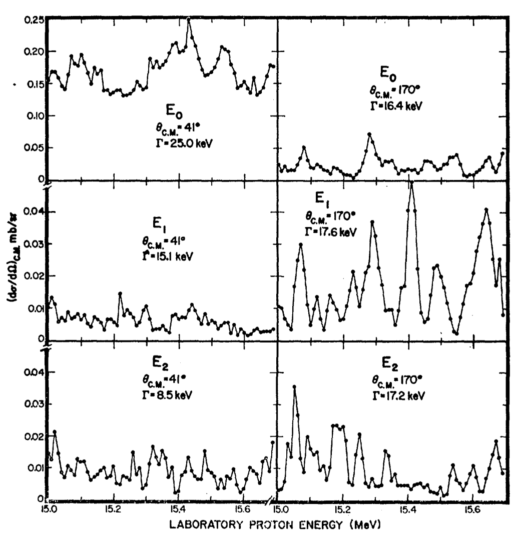

FIG. 7. Excitation functions in the energy region 15.0–15.7 MeV with 10-keV steps.

section ratios at 170° are approximately the same as predicted by Hauser-Feshbach calculations, indicating that a compound nuclear mechanism predominates at this angle. This is also indicated from the comparison of the excitation functions at 170° and 40° in Fig. 5.

On the basis of the above considerations, it was assumed that in the proton laboratory-energy range between 7 and 16 MeV only compound nuclear processes contribute to the α particles emitted at angles between 40° and 170° and populating the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ levels.

B. Analysis of the Fluctuation Spectra

The autocorrelation function $R(\Gamma,\delta)$ for each of the excitation functions was computed from

$$R(\Gamma,\delta)=\{\langle[\sigma(\epsilon_i)-\langle\sigma\rangle][\sigma(\epsilon_i+\delta)-\langle\sigma\rangle]\rangle\}/\langle\sigma\rangle^2, \quad (1)$$

where $\sigma(\epsilon_i)$ is the cross section at energy ϵ_i, and the brackets denote an average over i. The excitation functions were corrected for the energy dependence of the average cross section according to an average linear least-squares fit from all angles for each level. The widths Γ were extracted as the full width at half-maximum (FWHM) of the autocorrelation function, and are listed in Table I. The average value of Γ at 7.15 MeV E_p appearing in Table II was reduced by 35% from the directly determined value to correct for the effect of energy resolution, using the correction of Lang.[11] The average Γ widths at 10.15 and 15.35 MeV are significantly larger than the energy resolution and are reduced by less than 10%. The deviations of the individual experimental Γ widths from their averages in Table I are consistent with uncertainties associated with the finite sample size and extraction of Γ from the autocorrelation function.

C. Calculation of the Level Density of the Compound Nucleus

From the decay widths Γ, the reaction cross sections, and the optical-model transmission coefficients T_l,[12] the level densities $\rho(U)$ of ^{55}Mn were calculated from the equation[3,13]

$$d\sigma_{ab}(\theta)/d\Omega=\sum_{L\,\mathrm{even}} A_L P_L \cos\theta,$$

where

$$A_L=\frac{\sigma_c^2}{4\pi k_a^2\Gamma(\rho(U)/2)(2I_A+1)(2I_a+1)}\sum_{S_1,l_1,S_2,l_2,J}\times\frac{\delta_n{}^m(-1)^{S_2-S_1}T_{l_1}T_{l_2}Z_1Z_2}{(2J+1)\exp[-J(J+1)/2\sigma_c^2]} \quad (2)$$

[11] D. W. Lang, Nucl. Phys. **72**, 461 (1965).

[12] T_l's for protons were taken from G. S. Mani, M. A. Melkanoff, and I. Iori, CEA Report No. 2379, 1963 (unpublished); for neutrons from F. Bjorklund and S. Fernbach, Phys. Rev. **109**, 1295 (1958); for α particles from J. R. Huizenga and G. Igo, Nucl. Phys. **29**, 462 (1962).

[13] A. C. Douglas and N. MacDonald, Nucl. Phys. **13**, 382 (1959).

TABLE I. The experimental widths Γ, in keV, from the fluctuations analysis of the excitation functions.

E_p	Level	θ_L 40°	60°	90°	120°	150°	170°	av
7.15	α_0	6.2	5.9	4.0	3.4	3.5	4.5	4.5
	α_1	9.8	8.6	8.1	8.3	6.0	6.0	7.8
	α_2	7.4	...	8.2	5.0	3.8	4.8	5.8
	av							6.0
10.15	α_0	11.6	7.5	7.1	9.0	9.5	9.1	9.0
	α_1	10.9	8.6	13.2	14.5	7.2	7.0	10.2
	α_2	11.5	6.3	12.0	9.8	6.5	9.0	9.2
	av							9.5
15.35	α_0	25.0	16.5	18.3	7.9	19.6	16.4	17.3
	α_1	...	...	15.1	16.9	19.6	17.6	17.3
	α_2	8.5	10.0	15.4	25.8	13.5	17.2	15.6
	av							16.7

and $d\sigma_{ab}(\theta)/d\Omega$ is the differential cross section for the reaction $A(a,b)B$; P_L the Legendre polynomial of order L; σ_c^2 the spin-cutoff factor of the compound nucleus; k_a the wave number of the incoming particle; I_A, I_a, and J the spins of the target, the projectile, and the compound nucleus, respectively; S_1 and S_2 the entrance and exit-channel spins, and l_1 and l_2 the incoming and outgoing orbital angular momenta. The δ function δ_n^m is the parity conservation factor[3]; and the coefficients Z_1 and Z_2 are defined in terms of the Racah and Clebsch-Gordan coefficients. $\rho(U)/2$ is the density of levels of a particular parity. The principle assumption in this expression relating the average cross section and decay widths to the level density is the validity of the Hauser-Feshbach formalism and the relation $2\pi\Gamma/D=T_l$ at excitation energies in the continuum. In addition, Γ_J was assumed to be independent of J and equal to an average value of Γ. It can be seen from the curves in Fig. 8, based on calculations described in Sec. IV B, that most of the levels of the compound nucleus have

TABLE II. Density of levels of all spins and both parities for ^{55}Mn.

E_p (MeV)	U (MeV)	Level	σ_{expt} (mb)	Γ_{expt} (keV)	σ_C^2	$\rho(U)$ (MeV^{-1})
7.15	15.1	α_0	1.92	3.9	18	1.1×10^5
		α_1	1.62	3.9	18	1.0×10^5
		α_2	0.77	3.9	18	1.2×10^5
		av				1.1×10^5
10.15	18.0	α_1	1.52	8.8	20	5.1×10^5
		α_2	1.22	8.8	20	4.6×10^5
		av				4.9×10^5
15.35	23.1	α_1	0.069	15.9	22	8.0×10^6
		α_2	0.065	15.9	22	6.6×10^6
		av				7.3×10^6

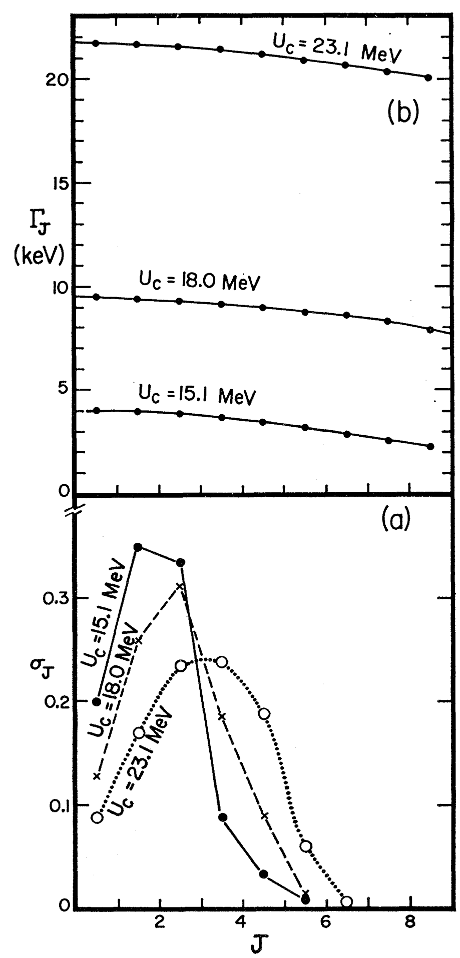

FIG. 8. Spin dependence of (a) the cross section for formation of the compound nucleus ^{55}Mn, and (b) the decay width. The cross sections are normalized to unity. The decay widths were computed using Fermi-gas level densities with $a=A/8.75$, $P(^{55}\text{Mn})=-0.5$, $P(^{54}\text{Mn})=-2.5$, $P(^{54}\text{Cr})=1.5$, and $P(^{51}\text{V})=-0.5$, and a rigid-body moment of inertia.

spins less than 5, and that the variation of Γ_J from an average value is less than 20% in this range.

The only remaining parameter which must be specified to obtain the level density is the spin-cutoff parameter $\sigma_C^2 = \mathcal{I}t/\hbar^2$. A rigid-body moment of inertia for a nucleus of radius $R = 1.2 \times A^{1/3}$ F and a temperature given by $U = at^2 - t$ were assumed.

The level densities obtained are listed in Table II and displayed in Fig. 9, along with similar data for the even-even nucleus ^{56}Fe.[3,4] The low-energy data on ^{55}Mn are from the reaction ^{55}Mn(p, p').[14] The displacement between the level-density curves for ^{56}Fe and ^{55}Mn is found to be approximately 2 MeV at excitation energies in excess of 20 MeV. The level densities at low excitation energy from magnetic spectrograph data show that the displacement persists for as low an energy as there are sufficient levels to define a "meaningful" density. The constancy of the displacement at low energies has been pointed out previously by Ericson.[15]

IV. STATISTICAL-MODEL CALCULATIONS

A. Level Densities

With level-density data for both an even-even and an odd-even nucleus over a considerably wider range of excitation energy than has been available previously, it is of interest to see how successfully conventional level-density formulations can account for observed densities. Our aim is to find the simplest formulation possible which will reproduce both the excitation-energy dependence and the odd-even dependence of the level density. Using a Fermi-gas formula modified for pairing effects, the density of levels of all spins and both parities is given by

$$\rho(U) = [ta^{1/2}/12\sqrt{2}(\mathcal{I}/\hbar^2)^{1/2}(U+t-P)^2] \times \exp[2a^{1/2}(U-P)^{1/2}], \quad (3)$$

where a is the Fermi-gas constant, P the pairing energy correction, t the thermodynamic temperature given by

$$U - P = at^2 - t, \quad (4)$$

and $\mathcal{I}$ is the nuclear moment of inertia. It is customary, when using this expression, to put $P = 0$ for odd-odd nuclei and set it equal to Δ for odd-even nuclei and equal to 2Δ for even-even nuclei. If Δ is set equal to 1.5 and a is chosen to reproduce the level densities at high excitation energies ($a = A/7.9$), the dashed curves in Fig. 9 are obtained. It can be seen that this formulation does not satisfactorily reproduce the energy dependence of the level density; the latter becoming less than unity at an excitation energy equal to the respective P values for ^{55}Mn and ^{56}Fe. On the other hand, if a is chosen to reproduce the low-energy data ($a = A/6.1$), much-too-high level densities are calculated at high energies (dotted lines). It is clear that these difficulties arise from the desire to reproduce both the absolute density and the odd-even displacement of the level densities at energies where $U - P$ approaches zero. One can alleviate the problem of reproducing the absolute densities by letting P decrease with decreasing energy, but one does this at the expense of losing the observed odd-even displacement. A much more satisfactory fit (full curves in Fig. 9) can be obtained if one instead somewhat arbitrarily sets $P = -0.5$ MeV for ^{55}Mn and $P = +1.5$ MeV for ^{56}Fe, which corresponds to an increase of the effective excitation energy of both nuclei. The uncertainty in the shift in effective excitation energy for both nuclei required to obtain a satisfactory fit is of the order 0.5–1 MeV. The energy difference between the even-even and odd-even reference surface has been increased by 0.5 MeV to a total of 2 MeV to achieve a slightly better fit to the observed displacement. An alternative mathematically equivalent approach to redefining the reference surfaces would be to allow the level-density parameter a to vary with excitation energy. However, use of this approach to account for the low-energy level densities would result in very large and physically unreasonable values of a at low excitation energies.

The best agreement with experiment using the above P values is achieved for $a = A/8.75$. This is a smaller value for a than that obtained with conventional odd-even corrections, and is in better agreement with

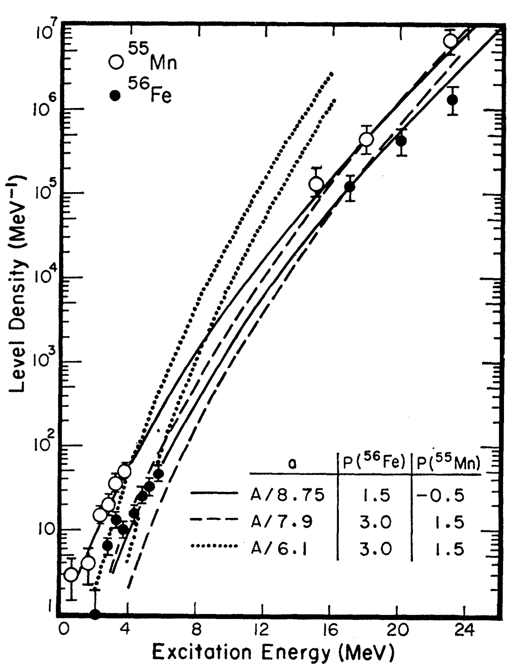

FIG. 9. Experimental level densities of ^{55}Mn and ^{56}Fe and results of Fermi-gas calculations. The excitation energy for each nucleus is measured from the ground state of that nucleus.

[14] A. A. Katsanos and J. R. Huizenga, Phys. Rev. 159, 931 (1967).
[15] T. Ericson, Nucl. Phys. 9, 697 (1959).

theoretical expectation for a Fermi gas contained in a volume of nuclear dimensions. The expected a values[16] are $a = A/8.7$ MeV^{-1} for $R = 1.5A^{1/3}$ F and $a = A/13.5$ MeV^{-1} for $R = 1.2A^{1/3}$ F.

The arbitrary pairing-energy corrections discussed above are equivalent to a shift downwards (relative to the conventional procedure) of the zero energy of all nuclei (odd or even) for the calculation of level densities. This result implies that the procedure of subtracting conventional pairing energies from the available excitation energy is an unsatisfactory compensation for the effects of the residual interactions. In analogy to the ^{55}Mn-^{56}Fe pair, the density of an odd-odd nucleus, e.g., ^{54}Mn, should be calculated using a pairing-energy correction 2 MeV less than that for ^{55}Mn, i.e., $P(^{54}\mathrm{Mn}) = -2.5$ MeV.

B. Calculation of the Excitation Functions

Statistical-model calculations for the measured excitation functions were performed using the level-density parameters deduced in the present work as well as those conventionally used. The differential cross section for each final level in a compound nuclear reaction is directly related to the level densities of the residual nuclei, which define the number of exit channels with which each final level must compete. The cross section is given by an expression similar to Eq. (2)[3,13]:

$$d\sigma_{ab}(\theta)/d\Omega = \sum_{L \text{even}} A_L P_L \cos\theta, \tag{5}$$

where

$$A_L = [4k^2(2I_A+1)(2I_a+1)]^{-1} \sum_{S_1, l_1, S_2, l_2, J} \times \frac{\delta_n{}^m (-1)^{S_2 - S_1} T_{l_1} T_{l_2} Z_1 Z_2}{G(J)} \tag{6}$$

and

$$G(J) = \sum_b \int_0^{U_{B\max}} dU_B \sum_{l_2} T_{l_2} \times \sum_{S_2 = |J - l_2|}^{J + l_2} \sum_{I_B = |S_2 - I_b|}^{S_2 + I_b} \rho_B(U_B, I_B, \pi). \tag{7}$$

In Eq. (7), b refers to all outgoing particles and B to the respective residual nuclei. The spin dependence of the level density for one parity is assumed to be given by

$$\rho(U, I, \pi) = [\rho(U)/4\sigma^2](2I+1) \exp[-I(I+1)/2\sigma^2], \tag{8}$$

and the total level density $\rho(U)$ is defined by Eq. (3).

The results of the computations are displayed in Figs. 1 and 10. α, neutron, proton, and deuteron exit channels were included. In the reaction ^{54}Cr$(p, \alpha)^{51}$V, the cross sections are primarily governed by the neutron channels and therefore by the level density of ^{54}Mn (for which the level-density parameters are not known). In the calculations of Fig. 1, the level-density parameters of the residual nuclei ^{54}Mn, ^{54}Cr, and ^{51}V were defined according to the formulation of the present work, i.e., the Fermi-gas constant $a = A/8.75$ and rigid-body moments of inertia with all the pairing-energy corrections lowered: $P(^{54}\mathrm{Mn}) = -2.5$ MeV, $P(^{51}\mathrm{V}) = -0.5$ MeV, and $P(^{54}\mathrm{Cr}) = +1.5$ MeV. The results for the two excited levels are in very good agreement with the experimental data, indicating that correct level densities are calculated with these parameters. The higher experimental values for the ground state are attributed to the contribution from a direct process. The results for the two excited states are also displayed with solid lines in Fig. 10, along with calculations based on the two extreme conventional level-density parametrizations that are represented by the dashed and dotted lines in Fig. 9. Both conventional parametrizations predict slopes for the energy dependence of the integrated cross sections which are in clear disagreement with the experimental data.

A smaller value of P in the conventional parametrization is inconsistent with the observed displacement, and an increase of P to 2 MeV in the conventional parametrization (giving a better account of the displacement) will require an even larger value of a to reproduce the absolute cross section. This arises from the fact that increasing P decreases the absolute level density and hence the number of competing channels. Increasing a increases the level density to compensate for the larger P value. A larger value of a, however, will make the calculated slopes of the excitation functions even steeper. Therefore it is clear that the experimental energy dependence of the cross section cannot be described in this statistical framework using conventional pairing-energy corrections.

Since the cross sections, compound level densities, and decay widths are interrelated through Eqs. (2)

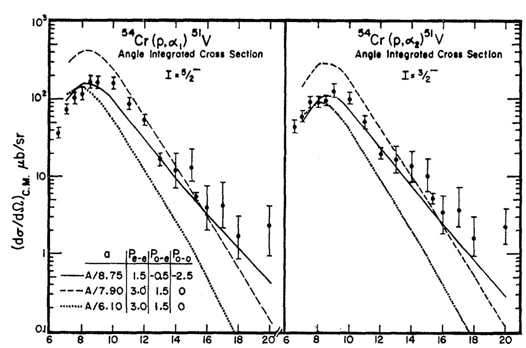

FIG. 10. Angle-integrated cross sections for the first and second excited states, and results of statistical-model calculations.

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and (5)–(7), level-density parameters that reproduce the average cross sections and the compound level densities are consistent with the observed widths. The J dependence of the width can also be calculated, and it is found that Γ_J varies only weakly with J, as indicated in Fig. 8(b).

V. SUMMARY

The odd-even shift required to match the level densities of even-even ^{56}Fe with odd-even ^{55}Mn has been found to be independent of excitation energy up to 23 MeV. The conventional procedure of subtracting pairing-energy corrections for even-even and odd-even nuclei to determine the effective excitation energy has been found to be inadequate. A more satisfactory procedure has been found to be to define the effective excitation energy from a reference surface between the even-even and odd-even ground-state mass surface rather than the odd-odd mass surface. A similar conclusion has recently been reported by Gadioli and Zetta.[17] It is interesting to note that a nuclear level-density model,[18] analogous to that used to describe superconductivity in metals, predicts a reference surface closer to the even-even than the odd-odd ground-state surface. The values of the level-density parameter a obtained using the new pairing-energy corrections are smaller than those obtained by the conventional procedure and are in better agreement with theoretical expectations.

ACKNOWLEDGMENTS

We would like to thank Professor J. S. Blair, Professor J. Bondorf, and Dr. H. Ejiri for helpful discussions and Mrs. J. Heagney for the preparation of the targets.

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PHYSICAL REVIEW C VOLUME 1, NUMBER 2 FEBRUARY 1970

Mean Lives of Some States in Si^{31} below 3.54 MeV*

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(Received 8 September 1969)

A Ge(Li) detector and the reaction $Si^{30}(d, p)Si^{31}$ with $E_d = 2$–4 MeV are used in the coincidence version of the Doppler-shift attenuation method to obtain the following information concerning the mean lives of some low-lying states in Si^{31}: $\tau(0.75\text{ MeV}) = (7.2_{-1.8}^{+2.6}) \times 10^{-13}$ sec, $\tau(1.69\text{ MeV}) = (7.4 \pm 2.3) \times 10^{-13}$ sec, $\tau(2.32\text{ MeV}) < 3 \times 10^{-13}$ sec, $\tau(3.14\text{ MeV}) = (5.0_{-2.6}^{+2.2}) \times 10^{-13}$ sec, $\tau(3.53\text{ MeV}) < 3.7 \times 10^{-14}$ sec. From these results, the reduced matrix elements for electromagnetic transitions among some of these states are obtained. A comparison is made between these reduced matrix elements and those predicted by the extreme single-particle model, the Nilsson rotational model, and the shell model with configuration mixing in the $2s_{1/2}$ and $1d_{3/2}$ shells. Our results indicate a value of $|\eta| = 2.8_{-0.4}^{+0.6}$ for the Nilsson deformation parameter for Si^{31}. A value of 752 ± 1 keV was obtained for the excitation energy of the 0.75-MeV state.

INTRODUCTION

Recently, Webb *et al.*[1] have obtained information concerning the spins, γ-ray multipole mixing ratios, and γ-ray branching ratios of the states in Si^{31} up to 3.53 MeV (see Fig. 1). Some of these γ-ray transitions seemed to exhibit large electric quadrupole amplitudes suggesting possible collective behavior in Si^{31} as in other $2s$-$1d$ shell nuclei. Indeed, Webb *et al.*[2] have made a collective model[3,4] interpretation of the low-lying structure in Si^{31} (see Fig. 1) and were reasonably successful in obtaining a consistent explanation of the multipole mixing ratios of the ground-state transitions from the states at 1.69 and 2.79 MeV.

In addition Glaudemans *et al.*[5,6] have used an inert Si^{28} core and considered configuration mixing in the $2s_{1/2}$ and $1d_{3/2}$ shells in order to determine shell-model wave functions for nuclei between Si^{29} and Ca^{40}. Wiechers and Brussaard[7] have used these wave functions to calculate $M1$ transition probabilities among the low-lying levels of some of these nuclei.

Since the electromagnetic matrix elements are relatively very sensitive to the assumed forms of the nuclear wave functions, a measurement of the mean

* Supported in part by the U.S. Atomic Energy Commission.
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