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Isospin and the Bohr Independence Hypothesis

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The influence of isospin on statistical nuclear decay at approximately 20 MeV is investigated for two composite systems ^{66}Zn and ^{64}Zn by measurement of the cross sections and the energy spectra of protons and α particles emitted from the two composite systems. The composite system ^{66}Zn was formed at an excitation energy of 19.7 MeV in the ^{65}Cu + p and ^{62}Ni + α reactions, while the composite system ^{64}Zn was formed at an excitation energy of 19.5 MeV in the ^{63}Cu + p and ^{60}Ni + α reactions. In both systems the experimental cross-section ratio $\sigma(\alpha,\alpha')\sigma(p,p')/\sigma(\alpha,p)\sigma(p,\alpha)$ exceeded the value of approximately unity predicted by the Bohr independence hypothesis and the statistical theory of compound-nuclear decay including angular momentum. The cross-section ratios were 2.2 ± 0.2 and 1.3 ± 0.1 for the ^{66}Zn and ^{64}Zn composite systems, respectively. The major part of the deviation of these ratios from unity in both the composite systems is ascribed to an isospin selection rule acting in the $T_>$ states of both composite systems which causes these states to decay preferentially by proton emission. Other factors which might enhance these ratios, such as direct reactions and reduced moments of inertia, are considered and are found to change the above ratios by a relatively small amount.

I. INTRODUCTION

In nuclear reactions with slow neutrons, a typical experimental result is the long lifetime of nuclear states observed as closely spaced narrow resonances following the capture of a neutron. To account for the long lifetime of these resonances Bohr[1] put forth in 1936 his famous compound-nucleus postulate. According to this postulate, a nuclear reaction takes place in two stages. First, the projectile is absorbed by the target nucleus leading to the formation of a compound system whose lifetime is much longer than the time of transit of a nuclear particle through a nucleus. In the second stage, the intermediate system breaks up by the emission of a nucleon or a complex particle. Due to the long lifetime of the compound system, the disintegration stage is completely independent of the mode of formation of the compound system. The only "memory" that the compound nucleus retains is that with regard to the conservation laws.

This concept was later extended by several authors[2] to the region of overlapping levels, and the experimental results are interpreted using a statistical model for nuclear decay. The statistical aspects of nuclear reactions have been discussed in detail by Bodansky.[3] The basic approximation of the statistical theory of nuclear reactions is that the transition amplitudes have random phases and therefore cause no interference effects. This makes it possible to apply the Bohr independence hypothesis in the region of overlapping levels. Thus, the decay mode of the compound nucleus is independent of its mode of formation except that it depends on the quantum numbers of the system, energy, angular momentum, parity, etc. Therefore, the reaction cross section can be separated into two quantities, one dependent only on the entrance channels and the other dependent only on the exit channels.

In a recent article[4] evidence was presented to show that isospin is another quantum number that is conserved (at least partially) in the region of overlapping levels in addition to energy, angular momentum, parity, etc. This paper continues earlier work[4] on the effects of isospin on the statistical decay of composite systems ^{64}Zn and ^{66}Zn. We will use the phrases "composite system" and "compound system" in the spirit of our previous paper.[4] A composite system characterizes an excited system consisting of a strongly interacting group of nucleons. A composite system embodies such reactions as semidirect, precompound, and compound-nuclear reactions. A compound nucleus lives long enough to completely forget all the memory of the incident channels. Except for the quantum numbers, energy, angular momentum, parity, and isospin, the decay mode is completely independent of the mode of formation.

It was Ghoshal[5] who tested first the validity of the Bohr assumption in the medium-energy region. Ghoshal[5] studied the decay of the composite system ^{64}Zn formed by the $^{60}\mathrm{Ni}+\alpha$ and $^{63}\mathrm{Cu}+p$ reactions at several bombarding energies. The validity of the Bohr assumption was tested via the approximate equality of the $\sigma(\alpha,pn)/\sigma(\alpha,2n)$ and $\sigma(p,pn)/\sigma(p,2p)$ cross-section ratios. Other investigations[6] of the same system qualitatively reproduced Ghoshal's results. However, shifts in excitation functions and an apparent violation of the independence hypothesis were noted. Grover and Nagle[7] studied the decay of the composite system ^{210}Po formed by bombarding ^{206}Pb with α particles and ^{209}Bi with protons at certain energies. Differences noted in the measured cross-section ratios $\sigma(p,n)/[\sigma(p,n)+\sigma(p,2n)]$ and $\sigma(\alpha,n)/[(\alpha,n)+\sigma(\alpha,2n)]$ indicated conclusively the role played by angular momentum conservation in the apparent violation of the independence hypothesis. This apparent violation is interpreted as being due to the different angular momentum brought in by the two different entrance channels. Therefore, the independence hypothesis will be valid only if the angular momentum distributions in the composite systems formed by the two entrance channels are identical.

Integral experiments of Ghoshal's type do not lend themselves to a study of the contribution to the compound process by the noncompound processes and, hence, their influence on the independence hypothesis. In recent years,[4,8] such a study is afforded by measurement of spectra of particles evaporated from a composite system.

Experimental results based on the measurement of cross-section ratios from our spectra indicate that the independence hypothesis is violated in the systems investigated in this work. As observed previously,[4] there is a tendency for proton emission to have a larger probability when the bombarding particle is a proton. There is, no doubt, some contribution, in addition to the compound-nuclear processes, from the direct and the precompound[9] processes, especially at the more-forward angles and in the high-energy side of the spectra. To minimize such effects, the beam energies in our experiments were kept low. The energy and the angular distributions of the (α,α'), (α,p), and (p,α) spectra were found to be consistent with a compound-nuclear type of process. The (p,p') spectra have small contributions of noncompound protons. However, the apparent violation of the independence hypothesis observed in this work must be attributed to some cause other than direct protons.

To ascertain whether the enhancement in our experimental ratio $\sigma(\alpha,\alpha')\sigma(p,p')/\sigma(\alpha,p)\sigma(p,\alpha)$ was due to any uncertainties in the spin cutoff factors,[10] we performed theoretical calculations of the above ratio varying the moments of inertia of the residual nuclei in each composite system. The results of such calculations, discussed in detail later in this paper, ruled out such a possibility. We feel that the deviation of the ratio $\sigma(\alpha,\alpha')\sigma(p,p')/\sigma(\alpha,p)\sigma(p,\alpha)$ from that required by the independence hypothesis is due to the isospin selection rule acting in the $T_>$ channels of the composite system. The $T_>$ state of the composite system is formed with a fractional intensity of $1/(2T+1)$, whereas the $T_<$ state takes $2T/(2T+1)$ of the initial intensity, where T is the isospin of the target nucleus. Even though the $T_<$ states take more of the initial strength than the $T_>$ states, it is from the latter that there is a preferential enhancement of proton emission. This enhancement is largest when the $T_<$ state decays mainly by neutron emission.

It is well known that the isospin is expected to be a good quantum number in two energy ranges.[11-13] At low excitation energy, individual levels of the same spin and parity are well isolated and have good isospin purity. In this range, the static criterion for the validity of the isospin rule is that $\langle H_C \rangle \ll \langle D_{J,\pi} \rangle$, where $\langle H_C \rangle$ is the average Coulomb matrix element that causes isospin mixing, and $\langle D_{J,\pi} \rangle$ is the average spacing between levels of the same spin and parity. At high energy, individual states no longer have a well-defined isospin. Nevertheless, the selection rules are expected to be obeyed because many overlapping levels of the composite system are simultaneously excited in a total state of initially well-defined isospin. This state decays before the Coulomb force causes much isospin mixing.

The dynamic criterion for the validity of the isospin selection rule in the high-energy range is that $\langle \Gamma_{J,\pi} \rangle \gg \langle H_C \rangle$. Therefore, if $\langle \Gamma_{J,\pi} \rangle \gg \langle H_C \rangle$ the system breaks up before Coulomb forces have had time to cause considerable mixing of the isospins of the composite system. The composite systems studied in this work fall in the energy range of about 20 MeV, and we expect the isospin selection rule to be at least partially obeyed. Bloom[14] has shown for low excitation energy that $\langle H_C \rangle$ is between 1 and 40 keV. It is, therefore, not possible to make a good theoretical estimate of the validity of the isospin selection rules for our two highly excited nuclei, ^{66}Zn and ^{64}Zn. Neither have any fluctuation experiments been done on these two systems from which experimental values of the decay widths of these nuclei can be obtained. However, from measured widths of neighboring nuclei[15] we estimate that the widths are approximately 5 keV.

II. EXPERIMENTAL PROCEDURE

In these experiments we studied two composite systems, ^{64}Zn and ^{66}Zn, at excitation energies of 19.5 and 19.7 MeV, respectively. The composite system ^{64}Zn was formed in the reactions ^{63}Cu$(p,p')^{63}$Cu, ^{63}Cu$(p,\alpha)^{60}$Ni, ^{60}Ni$(\alpha,p)^{63}$Cu, and ^{60}Ni$(\alpha,\alpha')^{60}$Ni with 12.0-MeV protons and 16.6-MeV α particles, respectively. The composite system ^{66}Zn was formed in the reactions ^{65}Cu$(p,p')^{65}$Cu, ^{65}Cu$(p,\alpha)^{62}$Ni, ^{62}Ni$(\alpha,p)^{65}$Cu, and ^{62}Ni$(\alpha,\alpha')^{62}$Ni with 11.0-MeV protons and 16.2-MeV α particles, respectively. The projectiles used in these bombardments were accelerated to the desired energy in the Emperor tandem Van de Graaff at the Nuclear Structure Research Laboratory of the University of Rochester.

The targets used in these experiments were self-supporting foils[16] having the following thicknesses and isotopic compositions: ^{63}Cu, 0.515 mg/cm^2 and 99.67 at.%; ^{60}Ni, 0.485 mg/cm^2 and 99.79 at.%; ^{65}Cu, 0.517 mg/cm^2 and 99.70 at.%; ^{62}Ni, 0.465 mg/cm^2 and 98.70 at.%. In each experiment, the target foil was rotated 30° from the position normal to the beam. Particle detectors were placed behind a collimator of 0.32-cm diam and 15 cm from the target. Beam intensities ranged from 0.06 to 0.46 μA and a typical run lasted about 2 h.

For the targets, bombarding particles, and energies under investigation, the Q values for the emission of deuterons, tritons, and ^{3}He restrict the energies of these particles to less than 3.5 MeV. The α particles were detected by thin-surface-barrier detectors with thicknesses just sufficient to stop the most energetic α particles. The maximum energy deposited in these detectors by protons is about 4.7 MeV. A gate was set to reject the low-energy signals. This made it possible to determine the α-particle spectra accurately to energies as low as 5.0 MeV without a particle-identifying telescope. The α particles from (α,α') and (p,α) reactions were detected under identical settings with the same geometry, gain settings, electronics, etc., in order to obtain very accurate cross-section ratios. A ΔE-E solid-state charged-particle detection telescope was used to detect protons. The two different ΔE counters used in these experiments are 45 and 55 μ thick. A computer program CONTLX was used to generate the identification spectrum and to establish gate settings for each particle type. The proton data were acquired in an on-line mode with a PDP-8 and a PDP-6 computer system. Like the α-particle spectra, the proton data for the (p,p') and (α,p) reactions were collected under identical conditions in the consecutive experiments. The background before and after each run was found to be small by remotely rotating a blank target holder into the target position. The proton and α-particle spectra were studied at 75, 90, 140, 145, and 165°.

III. EXPERIMENTAL RESULTS

Raw data for protons from the reactions ^{63}Cu$(p,p')^{63}$Cu and ^{60}Ni$(\alpha,p)^{63}$Cu are shown in Fig. 1 while that for the reactions ^{65}Cu$(p,p')^{65}$Cu and ^{62}Ni$(\alpha,p)^{65}$Cu are shown in Fig. 2. The α-particle spectra from the reactions ^{60}Ni$(\alpha,\alpha')^{60}$Ni and ^{63}Cu$(p,\alpha)^{60}$Ni are shown in Fig. 3. In Fig. 4 are shown the α-particle spectra from the reactions ^{62}Ni$(\alpha,\alpha')^{62}$Ni and ^{65}Cu$(p,\alpha)^{62}$Ni.

The differential cross sections for all the reactions studied were computed using the computer code CSECT. Impurity peaks resulting from the interaction of projectiles with ^{12}C and ^{16}O absorbed on the targets were subtracted prior to the compu-

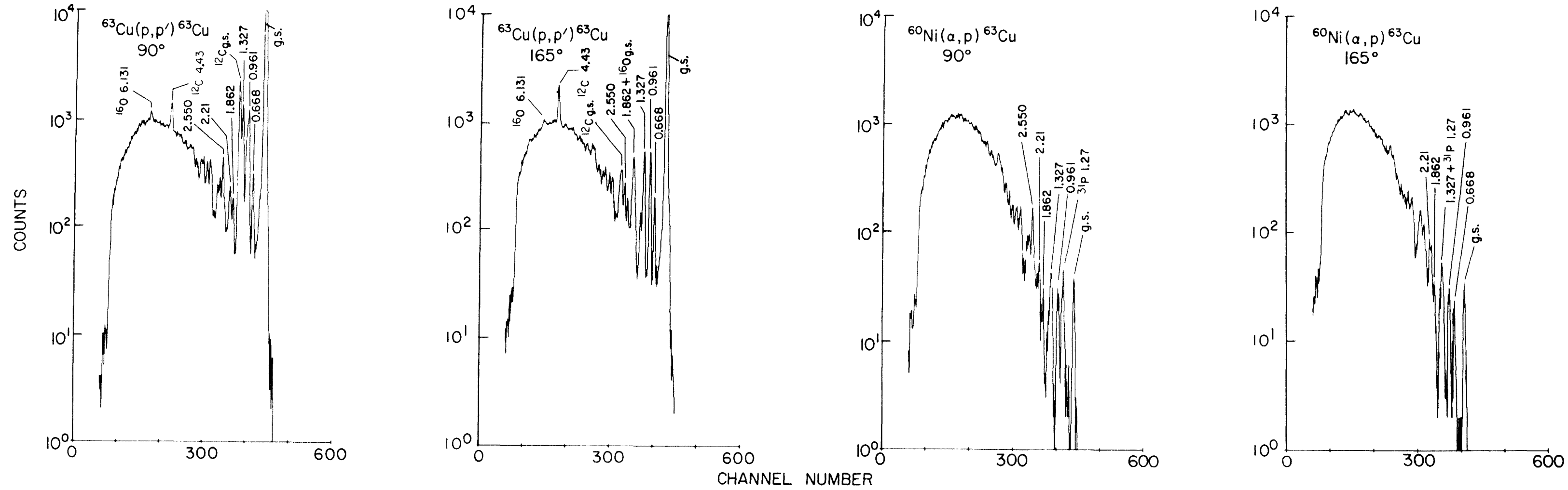

FIG. 1. Energy spectra of protons resulting from the reactions $^{63}Cu(p,p')^{63}Cu$ and $^{60}Ni(\alpha,p)^{63}Cu$ at scattering angles of 90° (lab) and 165° (lab). The bombarding energies of protons and α particles were 12.0 and 16.6 MeV, respectively. Some of the lines in the spectra have been identified.

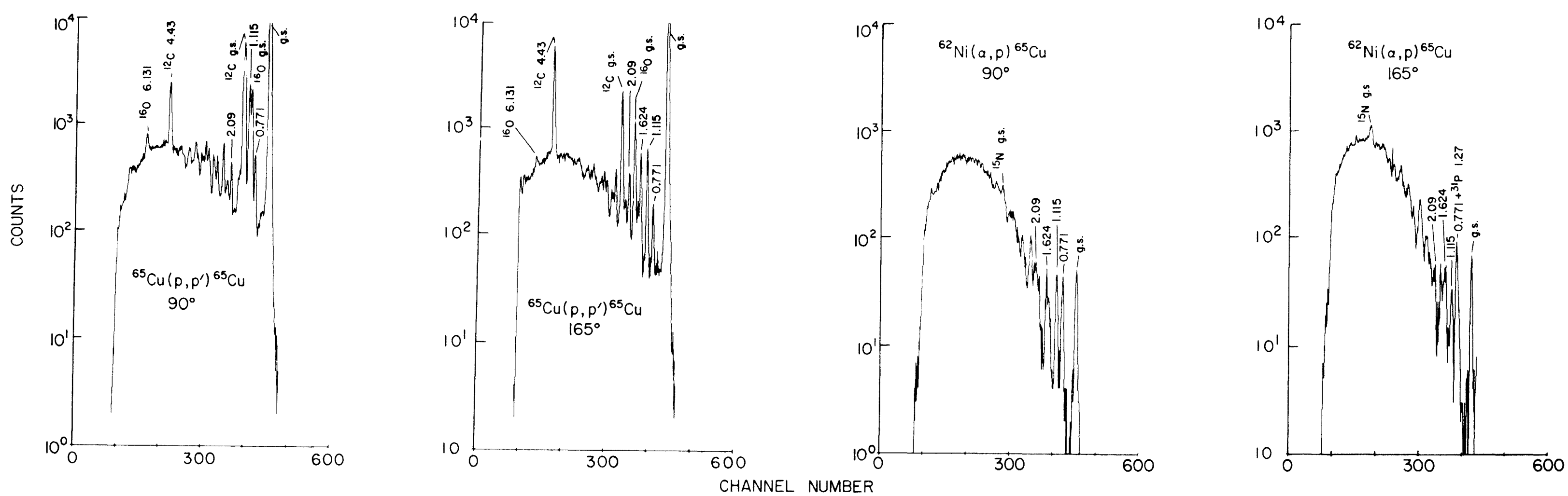

FIG. 2. Energy spectra of protons from the reaction $^{65}Cu(p,p')^{65}Cu$ with 11.0-MeV protons and the reaction $^{62}Ni(\alpha,p)^{65}Cu$ with 16.2-MeV α particles at scattering angles of 90° (lab) and 165° (lab). Some of the lines in the spectra have been identified.

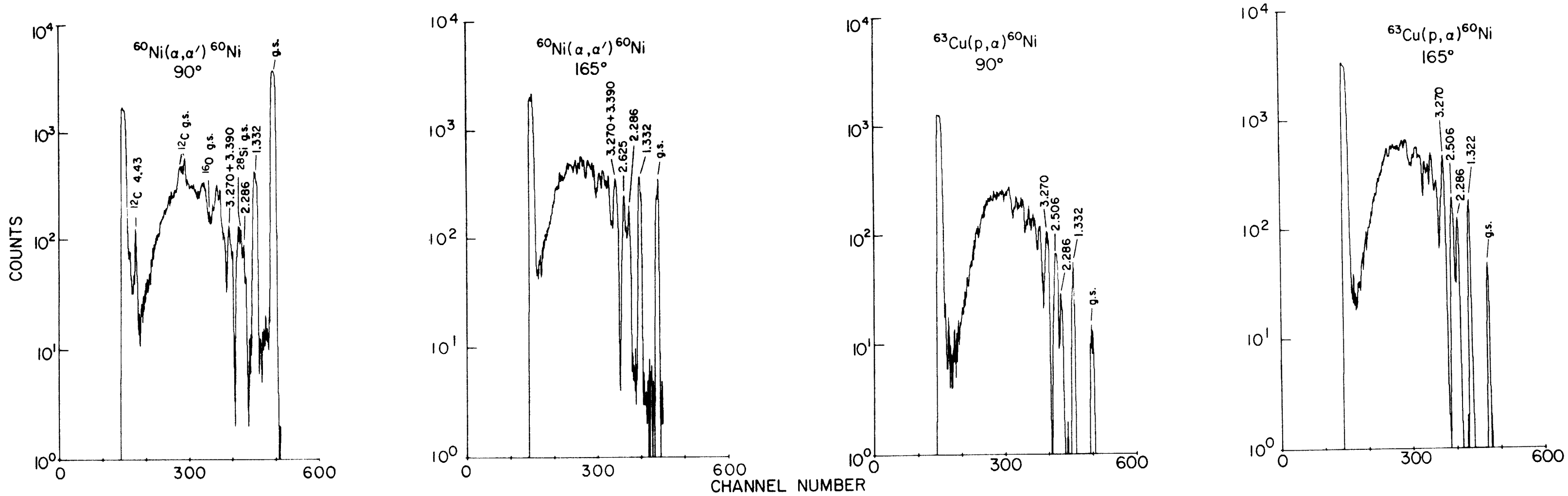

FIG. 3. Energy spectra of αparticles from the reaction ^{60}Ni$(\alpha,\alpha')^{60}$Ni with 16.6-MeV α projectiles and the reaction ^{63}Cu$(p,\alpha)^{60}$Ni with 12.0-MeV protons at scattering angles of 90° (lab) and 165° (lab). Some of the lines in the spectra have been identified.

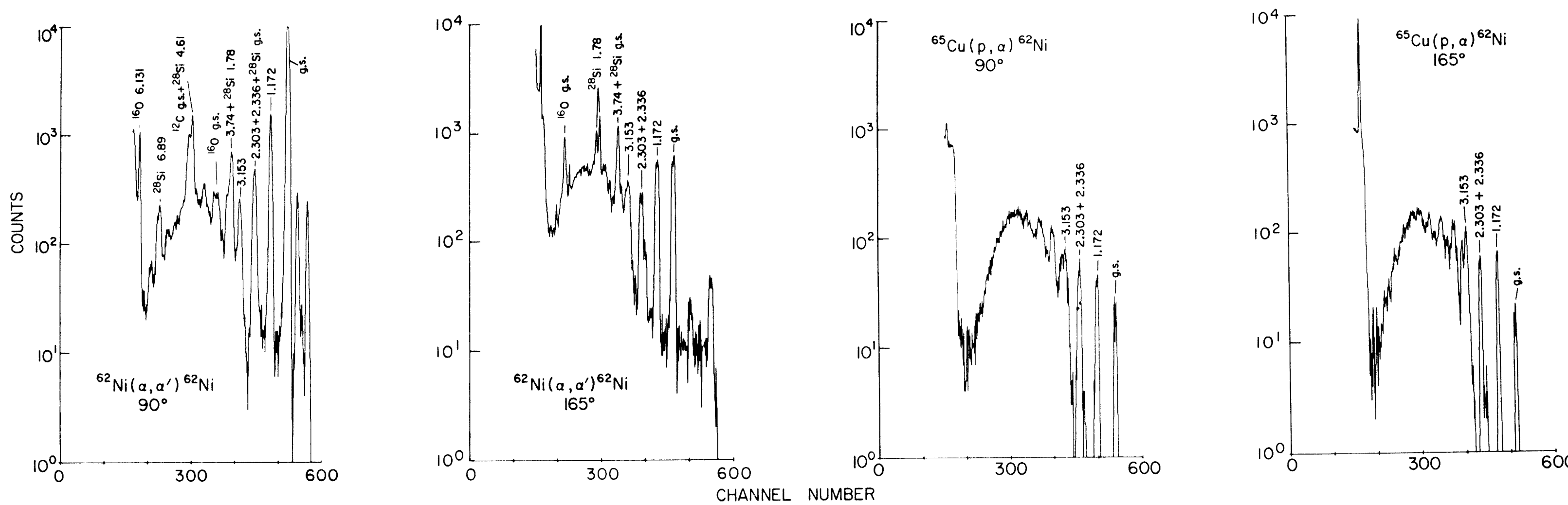

FIG. 4. Energy spectra of α particles from the reaction ^{62}Ni$(\alpha,\alpha')^{62}$Ni with 16.2-MeV α projectiles and the reaction ^{65}Cu$(p,\alpha)^{62}$Ni with 11.0-MeV protons at scattering angles of 90° (lab) and 165° (lab). Some of the lines in the spectra have been identified.

tation of the differential cross sections. The resulting spectra without the discrete lines due to the most energetic emitted particles are shown in the Figs. 5 and 6.

Due to the small angular momentum brought in by the incoming protons, the angular distributions of the reactions $^{63}Cu(p,p')^{63}Cu$ and $^{65}Cu(p,p')^{65}Cu$ are essentially isotropic. However, the cross sections for these reactions are slightly higher at 90° than those at more backward angles. We interpret this discrepancy as arising from a small contribution to these cross sections from noncompound processes. Since the α particles transfer larger angular momenta, the reactions $^{60}Ni(\alpha,p)^{63}Cu$, $^{62}Ni(\alpha,p)^{65}Cu$, $^{63}Cu(p,\alpha)^{60}Ni$, $^{65}Cu(p,\alpha)^{62}Ni$, $^{60}Ni(\alpha,\alpha')^{60}Ni$, and $^{62}Ni(\alpha,\alpha')^{62}Ni$ have larger anisotropies. For instance, the reactions $^{63}Cu(p,\alpha)^{60}Ni$, $^{65}Cu(p,\alpha)^{62}Ni$, $^{60}Ni(\alpha,p)^{63}Cu$, and $^{62}Ni(\alpha,p)^{65}Cu$ have experimental anisotropies of 8 to 12%. The $^{60}Ni(\alpha,\alpha')^{60}Ni$ and $^{62}Ni(\alpha,\alpha')^{62}Ni$ reactions have measured anisotropies of 55 and 33%, respectively.

In Table I are listed the measured values of the cross sections for the various reactions studied. These values are obtained by integrating the differential cross sections over angle and energy within the energy limits listed in Table I. The cross-section ratios $\sigma(\alpha,\alpha')\sigma(p,p')/\sigma(\alpha,p)\sigma(p,\alpha)$ are listed also in Table I. These ratios are independent of the target thicknesses, absolute calibration of the Faraday cup, and most other systematic errors.

IV. DISCUSSION

There are always two processes that compete in the interpretation of nuclear-reaction mechanisms; namely, a direct-reaction process and a compound-nucleus process. The test of the validity of Bohr's independence hypothesis requires that the reactions proceed via the compound-nucleus formalism. Characteristic aspects of a compound-

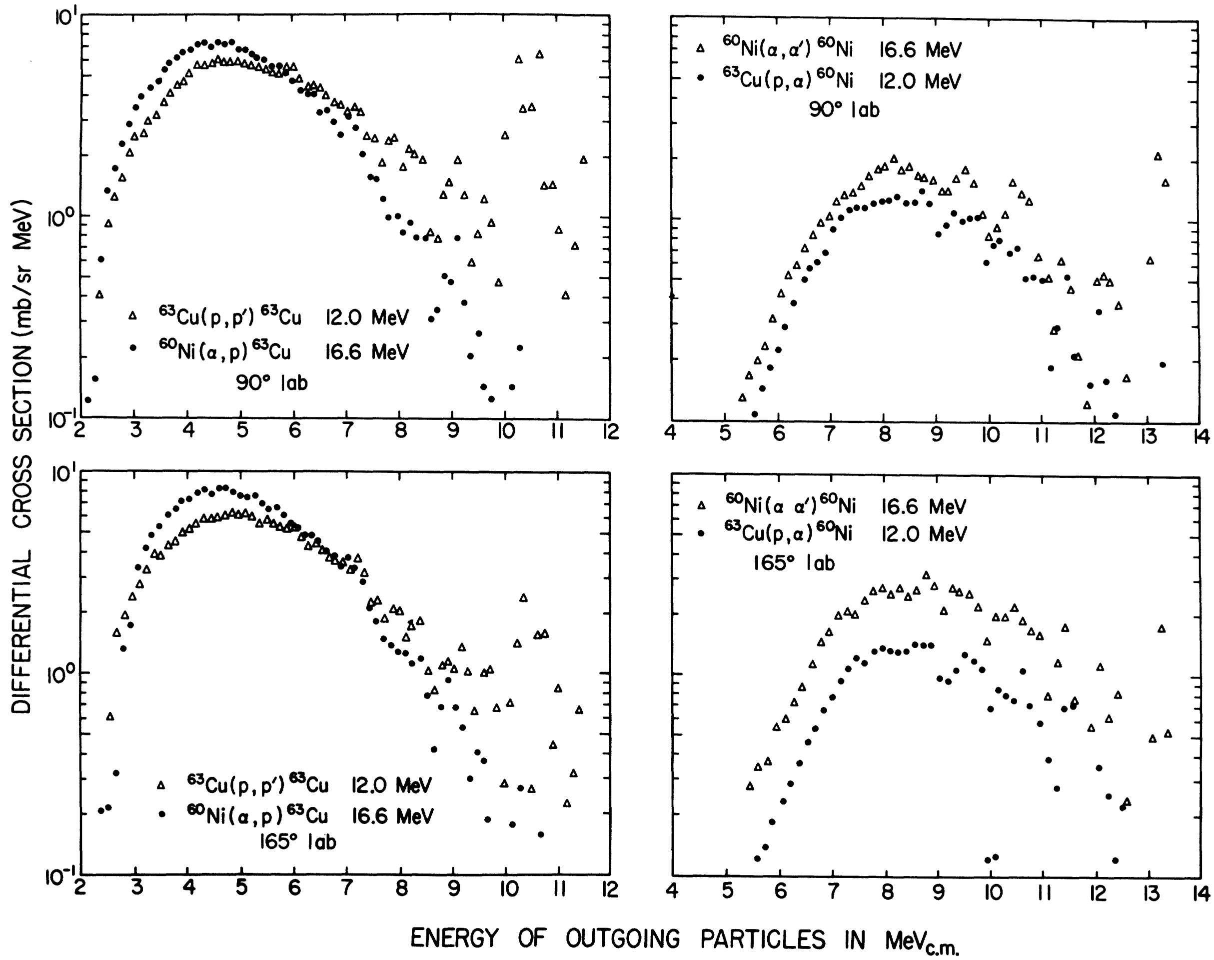

FIG. 5. Experimental differential cross sections calculated with the computer code CSECT for the reactions with 12.0-MeV protons on a ^{63}Cu target and 16.6-MeV α particles on a ^{60}Ni target at scattering angles of 90° (lab) and 165° (lab).

nucleus process are that the angular distributions of the various emitted particles are symmetric about 90° and that each of the emitted particles has a Maxwellian character. However, due to Coulomb effects, the charged-particle spectra are distorted on the low-energy side. The noncompound processes like the direct and precompound processes tend to distort the spectral shape on the high-energy side. The experimental results of the spectra studied in this paper indicate that within the energy range studied, the bulk of the particles are evaporated via the compound-nucleus process. The small discrepancies from the predicted compound-nucleus spectra observed in the reactions $^{63}Cu(p,p')^{63}Cu$ and $^{65}Cu(p,p')^{65}Cu$ at 90° are interpreted in terms of noncompound contributions (~15%). The experimental anisotropies of the (α,p), (p,α), and (α,α') reactions are in good agreement with the theoretical anisotropies for these reactions computed on the basis of the statistical model of compound-nuclear reactions with a rigid-body moment of inertia.

Computations of theoretical spectra based on the statistical model require a knowledge of the level-density parameters including the Fermi-gas constant a, the energy shift Δ, and the spin cutoff parameter σ. The energy shift Δ is an adjustable parameter to correct the level density for pairing and shell energies and defines the energy of a fictive ground state with respect to the actual ground state. Since the knowledge of these parameters for the nuclei in our experiment is scant, we arbitrarily varied a and Δ so as to give the best fit to the experimental spectra. Two such fits to the experimental spectra are shown in Fig. 7.

The aim of our experiment is to find a suitable explanation for the apparent violation of the Bohr independence hypothesis. According to the Bohr

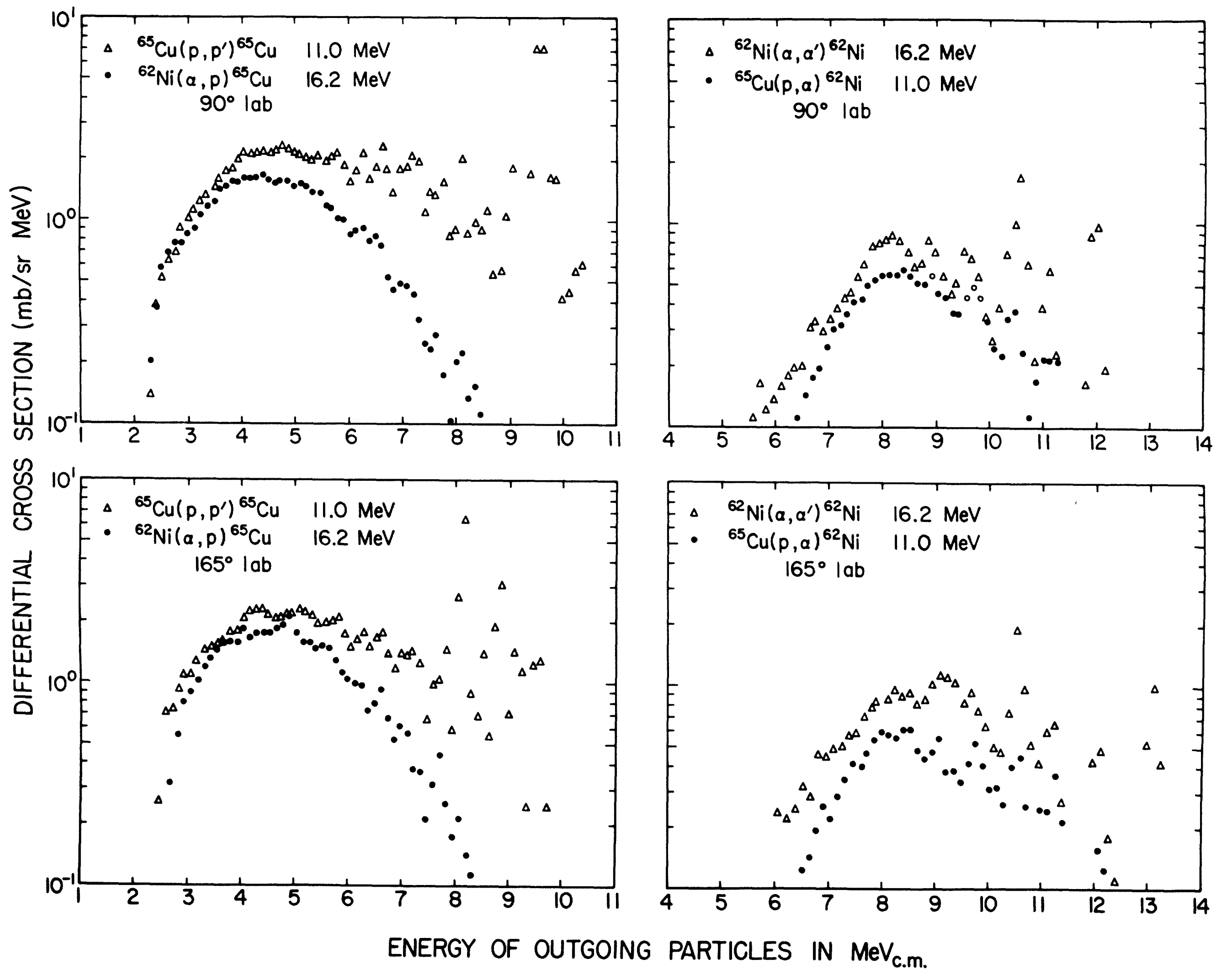

FIG. 6. Experimental differential cross sections calculated with the computer code CSECT from the reactions with 11.0-MeV protons on a ^{65}Cu target and 16.2-MeV α particles on a ^{62}Ni target at scattering angles of 90° (lab) and 165° (lab).

independence hypothesis, if the only memory that the composite system retains is that of energy, angular momentum, and parity, then the ratios

$$\frac{\sigma(^{62}\mathrm{Ni}(\alpha,\alpha')^{62}\mathrm{Ni})}{\sigma(^{62}\mathrm{Ni}(\alpha,p)^{65}\mathrm{Cu})}\times\frac{\sigma(^{65}\mathrm{Cu}(p,p')^{65}\mathrm{Cu})}{\sigma(^{65}\mathrm{Cu}(p,\alpha)^{62}\mathrm{Ni})}=R_1,$$

$$\frac{\sigma(^{60}\mathrm{Ni}(\alpha,\alpha')^{60}\mathrm{Ni})}{\sigma(^{60}\mathrm{Ni}(\alpha,p)^{63}\mathrm{Cu})}\times\frac{\sigma(^{63}\mathrm{Cu}(p,p')^{63}\mathrm{Cu})}{\sigma(^{63}\mathrm{Cu}(p,\alpha)^{60}\mathrm{Ni})}=R_2,$$

should each be approximately equal to unity. Soon after Ghoshal's work,[17] apparent violations of the independence hypothesis were observed[6,7] and the deviations were explained in terms of the different angular momenta brought in by the different projectiles used to make the same composite system.

A composite system formed by bombardment with α-particle projectiles has an angular momentum distribution that is peaked at a higher value of angular momentum than the same composite system formed with protons (see Fig. 8).

Theoretical calculations of the ratios R_1 and R_2 were performed including the angular momentum in the statistical theory and showed that the two ratios R_1 and R_2 change very little from unity. For instance, in these theoretical calculations, we found that R_1 and R_2 were 1.10 and 1.06, respectively. Hence, the large experimental deviations of the ratios R_1 and R_2 cannot be explained by inclusion of the angular momentum in the statistical theory.

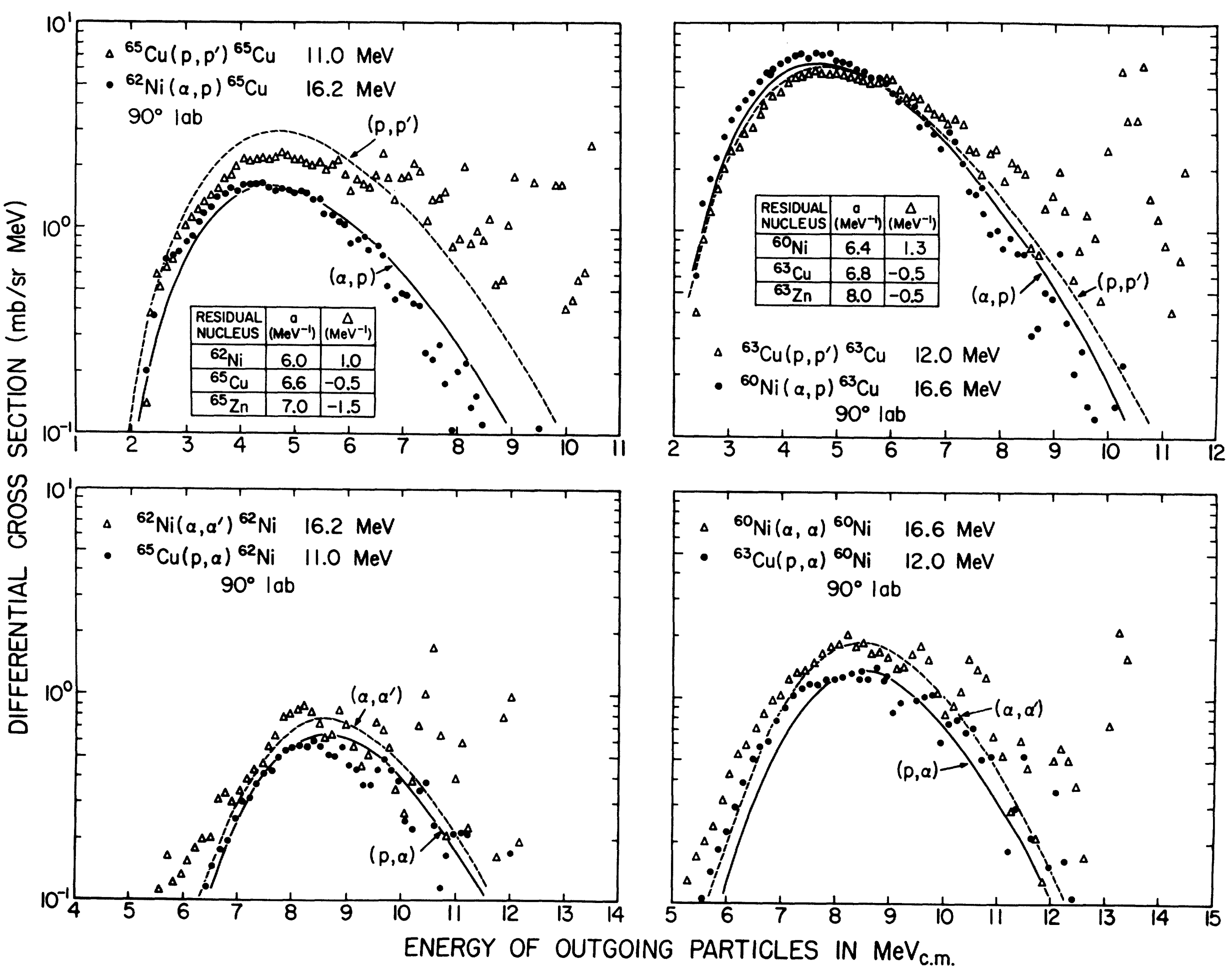

FIG. 7. Theoretical fits to experimental spectra at 90° for the two composite systems ^{64}Zn and ^{66}Zn. The theoretical spectra are generated including the isospin in the statistical theory as outlined in the Appendix. A Fermi-gas level density is used in the theory. The level-density parameter a_y and energy shift Δ_y for the residual nucleus obtained by emission of particle y from the compound nucleus are shown in the figure. A rigid-body moment of inertia is employed for the various residual nuclei. These calculations serve to illustrate that the statistical model reproduces the magnitude and the general shape of spectra. A slight variation in the shapes of spectra such as (p,p') and (α,p) or (α,α') and (p,α) is due to different angular momentum distributions in the composite systems brought in by the different bombarding particles.

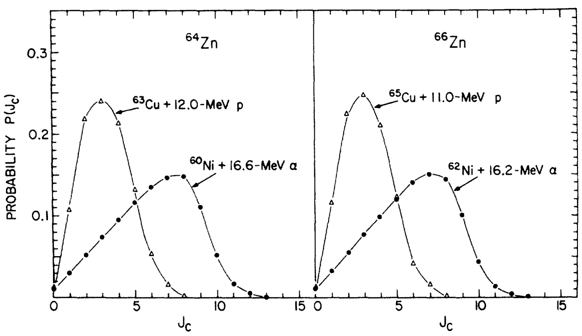

FIG. 8. Angular momentum distributions in the composite system ^{64}Zn and ^{66}Zn at excitation energies 19.5 and 19.7 MeV, respectively. The incident particle bombarding the appropriate target nuclei is shown in the figure. The calculations are done using the computer code ABACUS II. The angular momentum J_c is in units of $\hbar$.

Since there is some uncertainty as regards the exact values of the level-density parameters, we performed theoretical calculations by varying the level-density parameters a, Δ, and the spin cutoff factor σ. By varying the parameter a of one of the residual nuclei by 30% the ratio R_1 changes by an amount up to 14%, depending on the particular channel and the direction of the change in a. The ratio R_1 changes by only 6% when the energy shift Δ is changed from ($\Delta_\alpha = 1.0$, $\Delta_p = -0.5$, $\Delta_n = -1.5$ MeV) to ($\Delta_\alpha = 3.0$, $\Delta_p = 1.0$, $\Delta_n = 1.5$ MeV). We conclude from these calculations that the large deviations in the experimental ratios R_1 and R_2 cannot be explained by changes in the level-density parameters a and Δ.

Theoretical calculations of the ratios R_1 and R_2 were performed also for different values of the moments of inertia of the residual nuclei. The results are shown in Fig. 9, where the ratio R_2 is plotted as a function of the moments of inertia of the residual nuclei, where the moments of inertia are given in terms of the percent of the rigid-body values. The latter figure serves to illustrate also the variation of each of the cross sections (p,p'), (p,α), (α,α'), and (p,α) with reduction of the moments of inertia. It is readily seen that the (α,α') reaction is the most sensitive to changes in the moments of inertia of the residual nuclei.

Reduction in the moments of inertia of all of the residual nuclei in the exit channels to 75% of their rigid-body values increases the ratio R_2 to 1.1. From experimental angular-distribution measurements for (α,α') reactions[18] one obtains values of the moments of inertia for this mass region which are essentially rigid-body values. Hence, we attribute the large deviations in the ratios R_1 and R_2 from unity to one or more other factors than the moments of inertia.

A quantitative experimental measure of the fraction of particles emitted in a particular reaction from noncompound processes is impossible to obtain in a simple and direct way. Hence, we have made estimates of the cross sections of the precompound and direct processes by detailed comparison of the experimental spectra and angular distributions with statistical theory of compound-nuclear decay including angular momentum.[18] These cross-section estimates are based only on measurements at angles between 90 and 180° to emphasize the compound-nuclear reaction. The various analyses indicate that the experimental (α,p), (p,α), and (α,α') energy spectra and angular distributions are consistent with a compound-nuclear process. However, the (p,p') spectra (after subtracting the contributions of the elastic and low-lying isolated levels) may contain a few percent of noncompound protons. Estimates of the contributions from noncompound processes were obtained from comparisons of the nuclear temperature determined for the (p,p') reaction

TABLE I. Experimental cross sections for the reactions studied and the cross-section ratio $\sigma(\alpha,\alpha')\sigma(p,p')/\sigma(\alpha,p)\sigma(p,\alpha)$.

Reaction	Energy of projectile (MeV in lab)	Integration limits of spectrum (MeV c.m.)	Experimental cross section [σ(mb)]
^{65}Cu$(p,p')^{65}$Cu	11.0	2.45–8.0	$113^a \pm 17$
^{62}Ni$(\alpha,p)^{65}$Cu	16.2	2.45–8.0	69 ± 10
^{65}Cu$(p,\alpha)^{62}$Ni	11.0	6.0–10.5	21 ± 3
^{62}Ni$(\alpha,\alpha')^{62}$Ni	16.2	6.0–10.5	33 ± 5
^{63}Cu$(p,p')^{63}$Cu	12.0	2.5–9.0	$298^a \pm 45$
^{60}Ni$(\alpha,p)^{63}$Cu	16.6	2.5–9.0	332 ± 50
^{63}Cu$(p,\alpha)^{60}$Ni	12.0	5.5–12.0	62 ± 9
^{60}Ni$(\alpha,\alpha')^{60}$Ni	16.6	5.5–12.0	101 ± 15

[a] Contains contribution of precompound protons.

with temperatures determined for the (α, p) and (α, α') reactions populating levels in the same residual nucleus.[18] By this method we estimate that the contributions of noncompound protons are between 11 and 16% for the reactions $^{63}Cu(p, p')^{63}Cu$ and $^{65}Cu(p, p')^{65}Cu$. Although these estimates are subject to some error, the large deviations in R_1 and R_2 from unity are not explainable in terms of noncompound-nuclear reactions.

We have pointed out in the Introduction that at sufficiently high excitation energies isospin may be a good quantum number.[11-13] In the following discussion we assume that our composite systems are formed with good isospin. With protons as projectiles, we assume that two isospins $T_<$ and $T_>$ are formed with relative intensities of $2T/(2T+1)$ and $1/(2T+1)$, respectively, where T is the isospin of the target nucleus. With α-particle projectiles, only one isospin, $T_<$, is formed. Isospin level schemes for ^{64}Zn and ^{66}Zn are shown in Fig. 10.

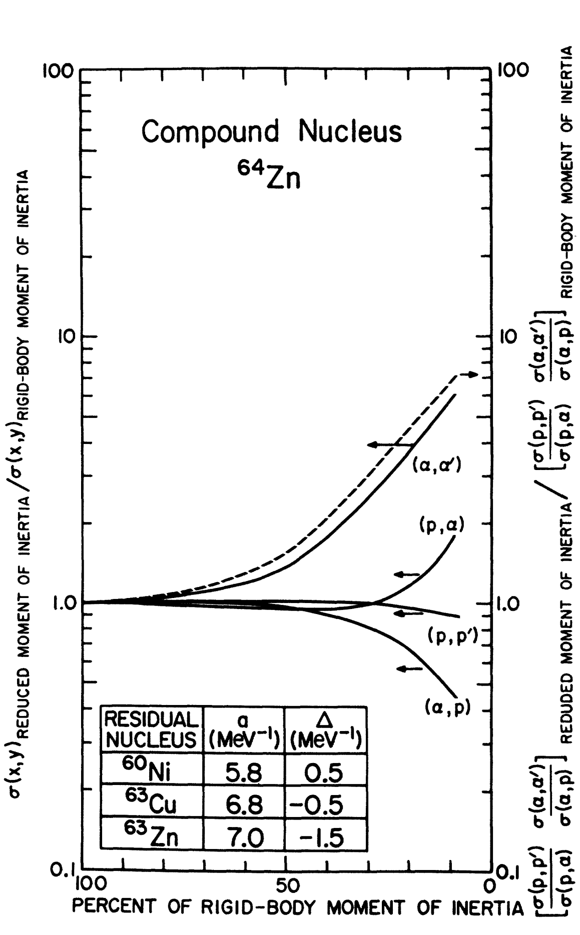

FIG. 9. Effects of reduced moments of inertia on the various theoretical cross sections and the cross-section ratio for the composite system ^{64}Zn. On the left ordinate is plotted the ratio of the cross sections (α,α'), (p,p'), (α,p), and (p,α) calculated using a reduced moment of inertia for the residual nuclei to the corresponding cross sections calculated using a rigid-body moment of inertia. On the right ordinate is plotted the ratio $\sigma(\alpha,\alpha')\sigma(p,p')/\sigma(\alpha,p)\sigma(p,\alpha)$ at varying moments of inertia.

The theoretical ratio R_1 for the composite system ^{66}Zn is given by[4]

$$R_1 = \frac{\sigma_\alpha F_<(\alpha, \alpha')\sigma_p(C_<{}^2 F_<(p,p') + C_>{}^2 F_>(p,p'))}{\sigma_\alpha F_<(\alpha, p)\sigma_p(C_<{}^2 F_<(p,\alpha) + C_>{}^2 F_>(p,\alpha))}, \tag{1}$$

where σ_α and σ_p are the reaction cross sections for the α and proton projectiles, respectively, at the appropriate energies. The quantities $F_<(x, y)$ and $F_>(x, y)$ are the fractions of the lower and upper isospin states, respectively, of the composite system ^{66}Zn formed by projectiles x which decay by emission of particles y. Equation (1) is valid only for a particlular excitation energy of the composite system. With α particles as projectiles, only the $T_<$ lower state is formed; whereas, with protons as projectiles both states $T_<$ and $T_>$ are formed. The square of the Clebsch-Gordan coefficients give the relative weights of each of the two states of the composite system. For the composite system ^{66}Zn, $C_<{}^2 = \frac{7}{8}$ and $C_>{}^2 = \frac{1}{8}$ because for the target ^{65}Cu, $T = T_z = \frac{7}{2}$. For the composite system ^{64}Zn, $C_<{}^2 = \frac{5}{6}$ and $C_>{}^2 = \frac{1}{6}$ with $T = T_z = \frac{5}{2}$ for the ^{63}Cu target. For the ^{66}Zn composite system, substituting the appropriate coefficients into Eq. (1) gives

$$R_1 = \frac{F_<(\alpha, \alpha')[\frac{7}{8}F_<(p,p') + \frac{1}{8}F_>(p,p')]}{F_<(\alpha, p)[\frac{7}{8}F_<(p,\alpha) + \frac{1}{8}F_>(p,\alpha)]}. \tag{2}$$

We simplify Eq. (2) by assuming that $F_>(p, \alpha) = 0$. This assumption is valid if isospin is a good quantum number, since the decay of $T_>$ state of the composite system ^{66}Zn by α emission is strongly hindered due to the Coulomb barrier and the paucity of $T = 4$ states in the residual nucleus, ^{62}Ni (see Fig. 10).

Using the assumption $F_>(p, \alpha) = 0$, Eq. (2) reduces to

$$R_1 = \frac{F_<(\alpha, \alpha')F_<(p,p')}{F_<(p, \alpha)F_<(\alpha,p)}\left[1 + \frac{1}{7}\frac{F_>(p,p')}{F_<(p,p')}\right]. \tag{3}$$

The effects of angular momentum and the spin cutoff factors of the residual nuclei are contained in the quantity in front of the square bracket of Eq. (3). The quantity inside the bracket controls the dependence of the ratio R_1 on the isospin.

Not only the decay of α particles from the $T_>$ states is hindered but also the decay from the same states by neutron emission is hindered because the $T_>$ states in the residual nucleus ^{65}Zn are shifted to higher energy and consequently their density is small. Hence, one expects the $T_>$ states to decay predominantly by proton emission. In the limit the branching ratio $F_>(p,p')$ should approach unity. A theoretical calculation for the decay of the $T_>$ states by protons, α particles, and neutron emission with the assumption that isospin is a good quantum number predicts a value of 0.99 for the branching ratio $F_>(p,p')$. Substituting the experimental value of 2.2 ± 0.2 for R_1 and the theoretical value of 1.10 for the quantity $F_<(\alpha,\alpha')F_<(p,p')/F_<(p,\alpha)F_<(\alpha,p)$ into Eq. (3), the experimental value

$$\frac{F_>(p,p')}{F_<(p,p')} = 7.0 \pm 1.3 \tag{4}$$

is obtained.

The experimental value of the branching ratio $F_>(p,p')$ gives an indication of the extent of isospin purity in the composite system. There is no way of distinguishing experimentally the protons emitted by the $T_<$ states from those emitted by the $T_>$ states. Hence, an experimental estimate of $F_<(p,p')$ is not possible. Nevertheless, a good estimate of the magnitude of $F_<(p,p')$ may be made by assuming that $F_<(p,p') \simeq F_<(\alpha,p)$.

For the composite system ^{66}Zn,

$$F_<(\alpha,p) = \frac{\sigma(^{62}\text{Ni}(\alpha,p)^{65}\text{Cu})}{\sigma(^{62}\text{Ni}(\alpha,p)^{65}\text{Cu}) + \sigma(^{62}\text{Ni}(\alpha,\alpha')^{62}\text{Ni}) + \sigma(^{62}\text{Ni}(\alpha,n)^{65}\text{Zn})}\,. \tag{5}$$

The experimental values of $\sigma(^{62}\text{Ni}(\alpha,p)^{65}\text{Cu})$, $\sigma(^{62}\text{Ni}(\alpha,\alpha')^{62}\text{Ni})$, and $\sigma(^{62}\text{Ni}(\alpha,n)^{65}\text{Zn})$ for 16.2-MeV α particles are 69, 33, and 880 mb,[19] respectively. After substituting these values into Eq. (5), the value of $F_<(\alpha,p)$ is 0.07 ± 0.01 Using the results of a statistical calculation for the decay of $T_<$ state by protons, α particles, and neutrons the value of the ratio $F_<(p,p')/F_<(\alpha,p)$ is 1.13. The experimental value of the branching ratio $F_<(p,p')$ is then 0.08 ± 0.01. Substituting this value into Eq. (4) gives an experimental value of the branching ratio $F_>(p,p')$ of 0.6 ± 0.1. This result indicates that a large fraction of the $T_>$ states of the composite system ^{66}Zn at 19.7-MeV excitation energy decay before $T_>$ ceases to be a good quantum number.

For the composite system ^{64}Zn formed at 19.5-MeV excitation energy, the ratio R_2 is 1.3 ± 0.1 and the theoretical value of the quantity $F_<(\alpha,\alpha') \times F_<(p,p')/F_<(p,\alpha)F_<(\alpha,p)$ is 1.06. The experimental values of the cross sections $\sigma(^{60}\text{Ni}(\alpha,p)^{63}\text{Cu})$, $\sigma(^{60}\text{Ni}(\alpha,\alpha')^{60}\text{Ni})$, and $\sigma(^{60}\text{Ni}(\alpha,n)^{63}\text{Zn})$ for 16.6-MeV α particles are 332, 101, and 440 mb,[19] respectively. Inserting the values of these cross sections into Eq. (5) gives a value for $F_>(\alpha,p)$ of 0.38 ± 0.04. The experimental value of the ratio $F_>(p,p')/F_<(p,p')$ is 1.2 ± 0.2. Using the theoretical value of 0.96 for the quantity $F_<(p,p')/F_<(\alpha,p)$, the experimental value of the branching ratio $F_>(p,p')$ is 0.4 ± 0.1. This result indicates little, if any, enhancement in the proton decay from the $T_>$ states of the composite system ^{64}Zn.

In Table II we list the experimental values of the quantities $\sigma(\alpha,\alpha')\sigma(p,p')/\sigma(p,\alpha)\sigma(\alpha,p)$, $F_>(p,p')/F_<(p,p')$, $F_<(\alpha,p)$, and $F_>(p,p')$, and the theoretical values of the quantities $F_<(p,p')/F_<(\alpha,p)$ and $F_<(\alpha,\alpha')F_<(p,p')/F_<(p,\alpha)F_<(\alpha,p)$ for the two composite systems studied in this work and those for the composite systems ^{63}Cu and ^{60}Ni reported in an earlier work.[4] The ^{66}Zn composite system affords a good example for an experimental observation of the role played by isospin in the statistical decay. On the other hand, in the ^{64}Zn system the enhancement from the $T_>$ state due to proton emission is relatively small and therefore this system is a less desirable case for the study of isospin effects on the statistical decay. This difference in the two nuclei is due to the smaller proton-to-neutron emission ratio from the $T_<$ states in the ^{66}Zn composite system.

If one assumes there is a certain amount of mixing[20] of the $T_>$ with the $T_<$ states, and that the decay of the $T_<$ states is independent of whether they were formed directly or from $T_>$, then Eq. (3) may be rewritten in the form

$$R = \frac{F_<(\alpha,\alpha')F_<(p,p')}{F_<(p,\alpha)F_<(\alpha,p)}\left[1 + \frac{1-\mu}{2T+\mu}\,\frac{F_>(p,p')}{F_<(p,p')}\right], \tag{6}$$

where μ is the fraction of the width of $T_>$ states which is mixed with $T_<$ and T is the isospin of the target nucleus bombarded with protons. If $F_>(p,p')$ is assumed equal to unity, then it is possible to calculate μ from Eq. (6). The quantity $1-\mu$ listed in Table II represents the unmixed fraction of $T_>$ states which decay by proton emission.

Nuclei in the medium-to-high-mass region decay mainly by neutron emission and in this respect are favorable for the study of isospin effects on the statistical decay. However, these nuclei have large values of isospin in their ground states and proton capture leads to only a small fractional strength of $T_>$ states in the composite system. Even so, the (p,p') cross section from the $T_>$

TABLE II. Determination of the values of $F_>(p,p')$ for various nuclei.

Composite system	Excitation energy (MeV)	$\left(\frac{\sigma(\alpha,\alpha')\sigma(p,p')}{\sigma(p,\alpha)\sigma(\alpha,p)}\right)_{\text{exp}}$	$\left(\frac{F_<(\alpha,\alpha')F_<(p,p')}{F_<(p,\alpha)F_<(\alpha,p)}\right)_{\text{theory}}$	$\left(\frac{F_>(p,p')}{F_<(p,p')}\right)_{\text{exp}}$	$[F_<(\alpha,p)]_{\text{exp}}$	$\left(\frac{F_<(p,p')}{F_<(\alpha,p)}\right)_{\text{theory}}$	$[F_>(p,p')]_{\text{exp}}$	$(1-\mu)_{\text{exp}}$
^{66}Zn	19.7	2.2 ± 0.2	1.10	7.0 ± 1.3	0.07 ± 0.01	1.13	0.6 ± 0.1	0.6 ± 0.1
^{63}Cu	18.9	2.0 ± 0.2	1.09	5.0 ± 1.0	0.13 ± 0.02	1.04	0.7 ± 0.1	0.7 ± 0.1
^{60}Ni	22.3	1.4 ± 0.1	1.09	1.4 ± 0.2	0.26[a] ± 0.03	1.02	0.4 ± 0.1	0.4 ± 0.1
^{64}Zn	19.5	1.3 ± 0.1	1.06	1.2 ± 0.2	0.38 ± 0.04	0.96	0.5 ± 0.1	0.5 ± 0.1

[a] Semitheoretical calculations.

states may make a sizable contribution to the total (p,p') cross section if the (p,p') cross section from the $T_<$ states is very small.

V. CONCLUSION

Experimental results for the ratios R_1 and R_2 indicate a considerable deviation from the results predicted by the Bohr independence hypothesis. The large observed deviation cannot be explained by including the conservation of angular momentum in the statistical theory of nuclear reactions. In addition, it does not seem possible to account for the large measured deviations of the ratios R_1 and R_2 from unity by either the experimentally allowable reductions of the moments of inertia of the residual nuclei from the rigid-body values (≥75% rigid) or contributions from direct reactions. However, the large observed deviation of the ratios R_1 and R_2 can be readily explained in terms of an isospin selection rule acting in the $T_>$ states of the two composite systems studied. This selection rule tends to enhance the (p,p') cross section. The $T_>$ states in the two composite system decay preferentially by proton emission. The measured values of the ratios R_1 and R_2 depend on the magnitude of the branching ratio $F_<(p,p')$. If $F_<(p,p')$ is small, a large enhancement in the ratio R is expected as we observe in R_1.

VI. APPENDIX

The energy and the angular distributions of particles emitted in a compound-nucleus reaction are given by Eq. (A1) of Ref. 4.

The transmission coefficients for the entrance and the exit channels required in the theoretical calculations were computed using the computer code ABACUS II . Optical-model parameters used were those of Bjorklund and Ferbach[21] for neutrons, Perey[22] for protons, and Huizenga and Igo[23] for α particles.

Statistical-model calculations incorporating the conservation of isospin were accomplished as follows: With α particles as projectiles only one isospin, $T_<$, is formed in the composite system; with protons as projectiles, two isospins, $T_<$ and $T_>$, are formed in the composite system. Since the two isobaric spins $T_<$ and $T_>$ are assumed to be formed with good isospin purity, the decay of each of these spin states is treated separately. Conventional transmission coefficients are used in the entrance and the exit channels weighted with the appropriate Clebsch-Gordan coefficients (see Fig. 10). In the calculation of the level density of the residual nuclei, account is taken of the isospin as well as the excitation energy and the angular momentum. Thus, in the statistical calculation

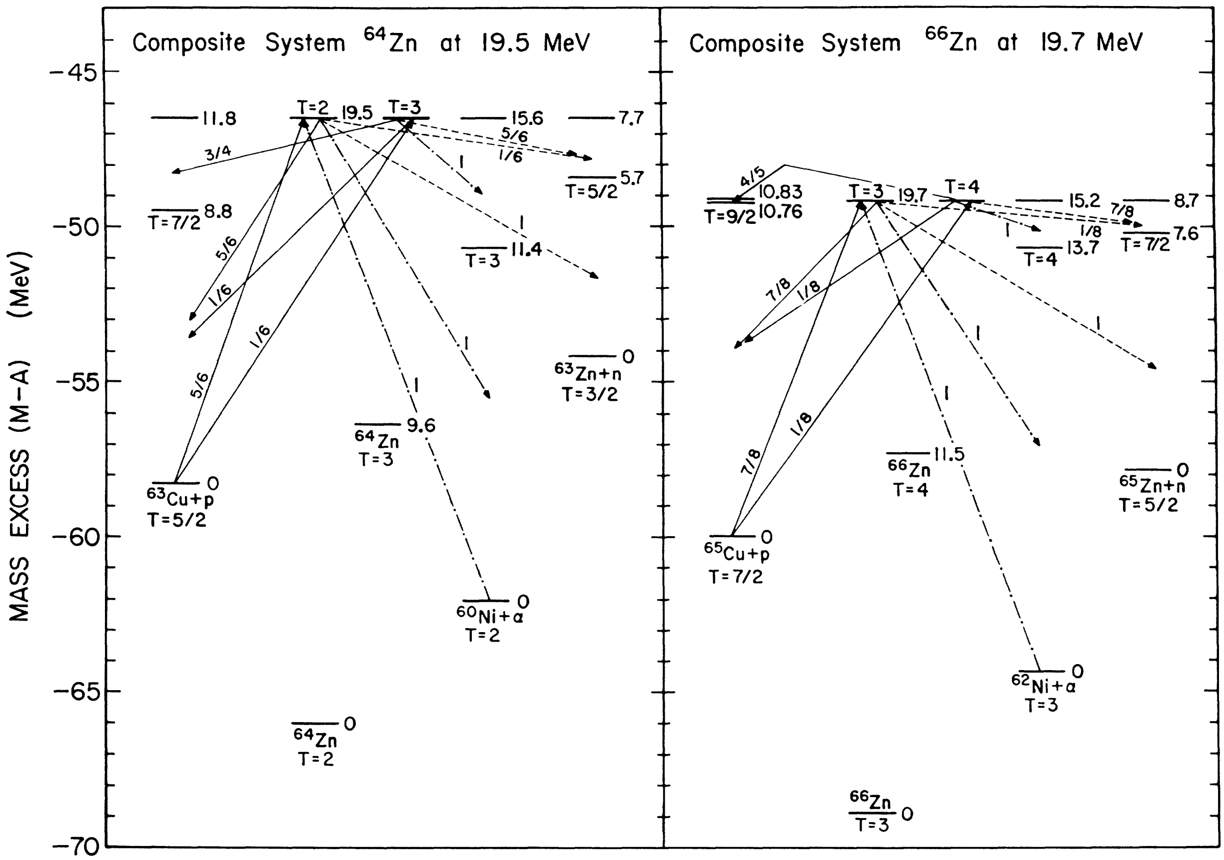

FIG. 10. Isospin level schemes for the composite systems ^{64}Zn and ^{66}Zn and the corresponding residual nuclei investigated. Each horizontal line represents a level. The number beside the level gives the energy of a level in MeV relative to the lowest energy of a particular configuration. The lines with the arrow pointing upwards indicate the isospin states of the composite systems. The arrows pointing downwards show the decay of these states. The number along each of these lines is the square of the Clebsch-Gordan coefficient for the coupling of (T, T_z) of the target (or residual nucleus) and (t, t_z) of the incident particle (or emitted particle) to that of the states of the composite system.

of particle evaporation from the $T_>$ states of the composite system we assume that the density of levels of the second isospin is the same as that for the isobaric analog nucleus at the corresponding excitation energy.

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Angular-Correlation Study of ^{27}Si Between $E_x = 2.5$ and $E_x = 5$ MeV Using the Reaction ^{28}Si(^{3}He, $\alpha\gamma$)^{27}Si†

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Angular correlations and branching ratios have been measured for the 2.65-, 2.86-, 2.91-, 4.14-, and 4.30-MeV states in ^{27}Si. When combined with the known lifetimes, the results exclude spins $\frac{7}{2}$ and $\frac{9}{2}$ for the 2.86-MeV state and spin $\frac{3}{2}$ for the 2.91-MeV state; the branching ratios suggest that the 2.86- and 2.91-MeV states are the mirrors of states at 2.98 and 3.00 MeV in ^{27}Al. The 4.30-MeV state is assigned $J^\pi = \frac{5}{2}^+$; its decay scheme is very similar to that of the 4.41-MeV state in ^{27}Al. Multipole mixing ratios are presented and compared with the predictions for mirror nuclei recently reported for *sd*-shell nuclei.

I. INTRODUCTION

The mirror nuclei ^{27}Al and ^{27}Si have been extensively studied. The electromagnetic transitions in ^{27}Al have been thoroughly investigated up to 5-MeV excitation.[1-6] The electromagnetic decays of several low-lying states in ^{27}Si have been studied by Lewis, Roberson, and Tilley[7]; the present work was undertaken to investigate the remaining levels in ^{27}Si below 5-MeV excitation. The recent independent discovery by two groups[8,9] of a new state in ^{27}Si very near the state previously known at 4.46 MeV should allow a one- to-one correspondence of all known[10] levels in these two mirror nuclei up to 5 MeV.

Among the states in ^{27}Si the doublet at 2.86 and 2.91 MeV is of particular interest. It seems likely that these states are the mirrors of states in ^{27}Al at 2.98 and 3.00 MeV which have been assigned[4] $J^\pi = \frac{3}{2}^+$ and $\frac{9}{2}^+$, respectively. Recently a group at Triangle Universities Nuclear Laboratory has resolved the two states in ^{27}Si in a study of the reaction ^{28}Si(^{3}He, α)^{27}Si. They found that the lower member is well fitted by an $l_n = 2$ distorted-wave Born-approximation (DWBA) calculation which is consistent with a spin assignment $J^\pi = \frac{3}{2}^+$ for this level.[11]

Additional motivation for the present study lies in the fact that electromagnetic decays in mirror nuclei are of particular interest; specifically, a recent survey[12] of the available data by Glaudemans and Van der Leun has revealed remarkable regularities in the signs and magnitudes of $E2/M1$ multipole mixing ratios for mirror transitions. It is clearly useful to test these ideas in as many cases as possible.