Evaporation of Coincident Protons in $\alpha+Ni^{58}$ Reactions*

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(Received December 21, 1961)

A study has been made of nuclear reactions in which two or more protons are emitted, in the bombardment of nickel isotopes by alpha particles. The most extensive data were obtained for 32-Mev alpha particles, with a Ni^{58} target. A smaller amount of data were obtained at 27 and 42 Mev, and with Ni^{60} and Ni^{62} targets. The two protons were observed in a coincidence arrangement, using scintillation counter dE/dx—E detectors. The energy correlations and distributions, the angular correlations and distributions and the yields were compared with predictions based on the statistical theory. There was extensive agreement, and therefore it is concluded that most of the observed events arise from evaporation from an excited compound nucleus. For Ni^{58} at 32 Mev, the cross section for compound nuclear events in which two or more protons are evaporated was found to be 560 ± 50 mb which is over one third the total reaction cross section. This large cross section can be quantitatively understood in terms of the proton richness of the emitting compound nucleus. This conclusion follows from an analysis in which it is shown that the relative proton and neutron emission probabilities in other experiments (especially with 14-Mev incident neutrons) are strongly correlated with proton richness.

I. INTRODUCTION

THE experiment reported here is concerned with the nature of particle emission in nuclear reactions at moderate energies (a few tens of Mev).[1] This general problem has been the subject of numerous previous experimental studies in which measurements are made either of the excitation functions for specific reactions or of the energy and angular distributions of emitted particles. In the present experiment the latter approach was used, and energy and angular distributions were investigated for pairs of coincident protons emitted in the bombardment of nickel isotopes by alpha particles with energies ranging from 27 to 42 Mev. The observation of pairs of particles offers varied opportunities for comparison with predictions of theoretical models, and in particular comparisons were made with the predictions of the statistical theory of nuclear reactions.[2]

In this theory it is assumed that the projectile and target nucleus form a compound system in which the conserved quantities, such as energy and angular momentum, become randomly shared among the various possible degrees of freedom before particle emission occurs. In a wide variety of recent studies, involving medium energy incident nucleons, alpha particles, and heavy ions, the distributions and yields of the emitted particles have been found to be consistent with the belief that the bulk of the reaction cross section at moderate energies does involve events of this character.[3–18] However, significant problems remain in the detailed analysis of the experimental results and as yet no truly quantitative statistical theory has been formulated. In addition, it has been found in many of these studies, as well as in earlier work,[19–21] that an appreciable part of the cross section involves processes which are not compatible with statistical ideas. Briefly, there are among the emitted particles too many forward-directed particles, too many high energy particles, and too many charged particles. These particles are attributed to so-called direct interactions, in which particle

* This work was supported in part by the U. S. Atomic Energy Commission.

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[1] Much of this work is described more completely by R. K. Cole, Ph.D. thesis, University of Washington, 1959 (unpublished) and C. R. Gruhn, Ph.D. thesis, University of Washington, 1961 (unpublished). A preliminary report was presented by D. Bodansky, R. K. Cole, W. G. Cross, C. R. Gruhn, and I. Halpern, *Proceedings of the International Conference on Nuclear Structure, Kingston* (University of Toronto Press, Toronto, 1960), p. 749.

[2] For a recent review of this theory see, for instance, T. Ericson, *Advances in Physics*, edited by N. F. Mott (Taylor and Francis, Ltd., London, 1960), Vol. 9, p. 425. An earlier discussion of the theory is presented in J. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).

[3] The references cited below (4–18) represent a sampling of recent work. For citation of other papers and especially earlier ones, see the bibliographies in these articles, and in reference 2.

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emission occurs before very many nuclear degrees of freedom become involved in the reaction. The observation of direct interaction processes has at times stimulated questioning of the basic validity of the compound nuclear viewpoint, but it is now generally accepted that both of these processes occur. It remains an open question whether intermediate processes also play a significant role.

It is of obvious interest to understand detailed aspects of these processes and to determine their relative importance in different situations. However, it is at present an uncertain matter to unfold an observed distribution of emitted particles into its direct and statistical components, especially as one does not know exactly what form each of the two distributions should take. The unfolding is further complicated by the fact that the statistical part of the distribution can itself be a superposition of contributions from several stages in an evaporation sequence. These superposition problems tend to make the assignment of values to nuclear statistical model parameters, on the basis of spectrum observations, difficult and ambiguous.

The experimental choices in the present work reduce the complications due to the superposition of direct interaction contributions by establishing a situation in which the observed events should be dominated by evaporation, i.e., by statistical emission. They also offer varied means of verifying that this domination actually occurs. These choices will now be discussed:

(*1*) *Projectile:* Alpha particles were used. They are particularly good "compound nuclear" projectiles in that they have small mean free paths for absorption in nuclei and are not as likely as other projectiles to strip or pick up.

(*2*) *Coincidence:* The use of coincidence provides information about correlations in energy and angle of particles emitted in a single event. No correlations should exist if the particles represent successive emissions from a compound system, other than correlations imposed by conservation laws. The coincidence method provides an opportunity to verify that such independent emission occurs. Through the study of angular correlations, it also permits an exploration of the processes by which the excited system gives up the rather appreciable angular momentum brought in by the incident alpha particle. (The measurement and interpretation of angular correlations in these reactions will be discussed in more detail in a later paper. In the present paper the angular distributions will be discussed only in terms of their implications concerning the validity of the statistical model.)

(*3*) *Emitted particles studied:* Protons are studied rather than neutrons because they are easier to detect. Alpha particles also could be detected, despite greater difficulties due to their smaller typical range, but there are generally fewer alpha particles emitted than protons. Furthermore, if one is trying to establish a situation favorable for the study of compound nuclear features, it is probably best to study emitted particles which differ from the incident particles.

(*4*) *Target:* Ni^{58} was chosen as the main target for study because there was considerable evidence that in Ni^{58} bombardments the ratio of protons to neutrons emitted is unusually high.[22] This is now understood to follow naturally from the fact that Ni^{58} is unusually proton-rich. Other nickel isotopes, namely Ni^{60} and Ni^{62}, were also used for purposes of comparison.[23]

(*5*) *Bombarding energy:* At the time the experiment was first undertaken, the bombarding energy of 32 Mev represented the lowest energy which could be achieved with adequate intensity by degradation of the 42-Mev beam of the University of Washington cyclotron. A bombarding energy greater than 32 Mev is undesirable because it increases the likelihood of $2p$ coincidence events which really involve the emission of more than two particles and the observed proton distributions then become superpositions involving first, second, third, etc. protons. To avoid the complications of "third proton" contamination entirely, a bombarding energy of 27 Mev is desirable, and this was achieved in a later stage of the experiment.

(*6*) *Energy threshold:* An effort was made to achieve a low threshold energy for the detection of the emitted protons, as protons evaporated from a compound nucleus are expected to have lower energies than directly ejected protons. The requirement for a low threshold is in some conflict with simultaneous requirements for a system which rejects alpha particles and which provides fast coincidence information.

The remaining sections of the present paper deal with the experimental arrangements and methods (Sec. II), the observed proton energy spectra (Sec. III), the observed angular distributions and correlations (Sec. IV), the total yields for proton emission (Sec. VI), and a summary of these results (Sec. VII). As an aid to the understanding of the total proton yield, the general problem of the relative neutron and proton emission probabilities is discussed in Sec. V.

II. EXPERIMENTAL ARRANGEMENT

The data of the present experiment were obtained in two experimental arrangements, referred to below as arrangements A and B. The arrangements are similar in their over-all aspects, but differ in details. Arrangement A was used in the earlier stages when the experiment was mainly concerned with the study of the nature of the reaction. For this purpose detailed information on individual events was more important than the accumulation of good statistics. Arrangement B was used in later stages where the emphasis changed to a study of angular correlations, and statistical precision

[22] See, e.g., B. L. Cohen, E. Newman, and T. H. Handley, Phys. Rev. **99**, 723 (1955).

[23] We are indebted to the Electromagnetic Separation Group of the Atomic Energy Research Establishment, Harwell, England for supplying us with the nickel targets used in this experiment.

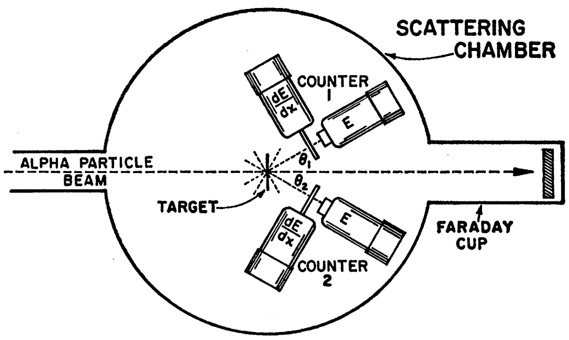

FIG. 1. Experimental arrangement. Each detector consists of two scintillation phosphors and two photomultiplier tubes. The detectors rest on trays which can be independently rotated about an axis through the center of the target. The target can be rotated about the same axis. (The defining aperatures used for the incident beam and for the counters are not shown.)

became more important. The information obtained in the two different arrangements is complementary, and therefore both sets of data are retained. We begin with a description of arrangement A. Most of the comments made here are also valid for arrangement B. The changes, which distinguish B from A, are described in the closing paragraphs of this section.

The charged reaction products studied here were detected in coincidence by two scintillation counter telescopes. A simplified sketch of these telescopes, and of their placement in the scattering chamber, is shown in Fig. 1. Each telescope consisted of two scintillators in a conventional "$dE/dx-E$" arrangement. The dE/dx scintillator was made of plastic, 0.0025-in. thick; the E scintillator was a CsI(Tl) crystal, thick enough to stop 20-Mev protons. In each telescope the defining aperture was $\frac{1}{2}$-in. in diameter and was normally located about $3\frac{3}{8}$-in. from the target. These relatively large solid angles were required to provide adequate coincidence counting rates. As the counting rates varied smoothly with angle, the angular width ($8\frac{1}{2}°$) was not excessive.

Signals from the four counters were used to establish an over-all quadruple coincidence, produced by two charged particles, and to determine the identity and energy of these particles. The coincidence was established by demanding a moderately fast coincidence ($\sim 2\times 10^{-8}$ sec) between the two dE/dx counters and a slower ($\sim 10^{-6}$ sec) coincidence between this double coincidence and the outputs of the two E counters. The particle identification and energy determination were accomplished by examining the pulses from the four counters. These pulses were amplified and displayed, with suitable delays, on the trace of a Tektronix 517 oscilloscope whose sweep was triggered by the quadruple coincidence signal. Each event was separately photographed and scanned.

To complement the photographic record, and to provide information during the run, two twenty-channel pulse-height analyzers were used to record the pulses from the E counters for each quadruple coincidence. This electronically recorded data did not distinguish between protons and alpha particles, nor was it able to provide information about energy correlations.

The first part of each run was devoted to the alignment of the entire system with the help of the 10.5-Mev proton beam of the cyclotron. This beam, when bombarding a thin polystyrene target, provided a copious source of coincident protons, 90° apart, from proton-proton scattering. By varying the angles of the counters with respect to the beam, protons of different energies could be selected. (In order to obtain monoenergetic groups, a special narrow collimator was used in these alignment runs.) These coincidence events were used in selecting suitable voltages and gains, in establishing proper timing, in determining the energy calibration, and in checking the efficiency of the counters for proton detection.

A calibration curve, relating incident proton energy to pulse height in the E counter, was obtained from 3.0 to 7.5 Mev using these coincident protons. A point at 10.5 Mev was obtained using elastic scattering of protons from nickel or gold. The calibration was found to be linear from 4.0 to 10.5 Mev and it was assumed to remain linear at slightly higher energies. (This linearity was later confirmed, in arrangement B, by observing protons up to 15 Mev from the elastic scattering of alpha particles in hydrogen.)

To determine the efficiency of a particular counter, the quadruple coincidence rate was compared to the triple coincidence rate omitting that counter. It was found that the efficiency of each E counter was at least 98% for protons emitted from the target with energies of 3.0 Mev or greater. It was about 90% at 2.8 Mev, and fell rapidly for lower energies. Biases and voltages were chosen for the dE/dx counters such that the efficiency was 100% for pulses $\frac{1}{3}$ as large as those from 5.2-Mev protons. This insured that the dE/dx counters remained fully efficient for proton energies up to 20 Mev.

The photographs of dE/dx and E pulses for protons of known energy were used in setting up criteria for particle identification. For each passage of a particle through the two counters the pair of pulse heights obtained can be regarded as coordinates in a two dimensional plot of dE/dx vs E. The aggregate of points obtained in this way for particles known to be protons lay in a broad band that was displaced from a corresponding band for alpha particles (obtained from alpha-particle bombardment of C^{12}). The two bands were contiguous but their overlap was very small, thereby making an unambiguous particle identification usually possible. More quantitatively, it is estimated that the alpha-particle contamination in the data for Ni^{58}, which was the most intensively studied nuclide, was less than 3%. The broadness of the bands was due to the poor resolution in the dE/dx counters which in turn arose from the use of thin scintillators. As explained above, it was important to maintain a low threshold for incident protons, and therefore the small possible alpha-particle contamination was accepted. Under the circumstances it was of course impossible to distinguish deuterons from protons, but it is expected that deuteron events are relatively rare, both because deuterons are an unlikely evaporation product and because of the moderately high threshold for the (α,pd) events.

When the foregoing preparations and calibrations had been completed, the actual experimental run began. During the experimental runs, the beam was stopped in a Faraday cup and the charge was measured with a ballistic galvanometer. A typical current was about 0.2 mμamp and one run would last for about 1 μcoul, i.e., about one or two hours. This low intensity was a consequence of the large loss in beam due to multiple scattering in the degrader. However, it had an associated advantage in that it gave a negligibly low accidental rate, as verified by taking "accidental data" with the signal to one fast coincident input delayed by a time equal to one cyclotron rf period. (The normal rate was restored when the signals to both inputs were delayed.)

Although most of the data were taken for Ni^{58}, a moderate amount of data was also obtained for Ni^{60} and Ni^{62}. The thicknesses of these targets all lay between 2.5- and 3.5-mg/cm^2. (The Ni^{58} target was enriched to 93.5%. The yields calculated below for Ni^{58} include the necessary allowance for a 6% Ni^{60} impurity. The Ni^{60} and Ni^{62} targets were free from significant isotopic impurities.) The target angles, relative to the beam, were chosen so that the targets would not appear too thick to either telescope; even for the most unfavorable orientations, and lowest observable proton energies, the energy loss in the target was less than $\frac{1}{4}$ Mev. Small oxygen, hydrogen, and carbon impurities may have contaminated all targets but, as the common impurities do not tend to break up into pairs of protons, the impurities were less of a concern here than they might have been in a noncoincidence experiment. (The impurity problem is considered briefly in Sec. VI.)

Most of the runs were made at 32 Mev because this energy represented a reasonable compromise between adequate beam intensity and the low excitation energy needed to reduce contributions from events in which more than two nucleons are emitted. A number of runs were also made at 35 Mev and at 42 Mev in order to obtain a rough indication of the dependence on energy of the observed distributions. The lower energies were obtained by degrading the normal 42-Mev cyclotron beam in water-cooled copper foils placed between the cyclotron and the magnetic external beam-analysis system. The energy was determined from the measured foil thickness; this determination was confirmed by comparing the energies of degraded alpha particles scattered from gold with the energies of undegraded particles scattered from carbon.

Measurements were made at only a limited number of pairs of angles because the coincidence counting rates were fairly low. Furthermore, preliminary runs indicated that the distributions varied smoothly with angle. Attention was mainly devoted to measurements with both counters at the same angle (especially 30°, 90°, and 150°) on opposite sides of the beam.

As discussed at the beginning of this section, the preceding description refers specifically to arrangement A, but applies also in large measure to arrangement B. The differences between these arrangements will now be discussed.

Several modifications were made in the physical configuration, which were largely associated with the transfer of the apparatus from the original scattering chamber (23-in. diameter) to a newly available larger chamber (60-in. diameter and 24-in. height at center). With the added space it became possible to view the dE/dx phosphor with two photomultiplier tubes, instead of one, leading to an improvement in pulse height resolution by a factor of about two. This improvement was in part exploited by reducing the thickness of the phosphor to 0.002 in. Together with a reduction in the thickness of an aluminum light shield between the phosphors, this lowered the proton energy threshold, for 90% efficient detection, from about 2.8 Mev to about 2.5 Mev.

It was then also found possible to obtain adequate beam intensity, with tolerable background and accidental rates, at an incident alpha-particle energy of 27 Mev. This was accomplished by placing an aluminum degrader at a point near the target, rather than a copper degrader near the cyclotron exit channel. The larger scattering chamber provided space for adequate shielding between the degrader and detectors.

The other major change involved a modification of the particle identification system. As discussed below, it was found using arrangement A that there are apparently no significant correlations in the energies of the two protons. Therefore, it appeared reasonable to study only the uncorrelated energy spectra. This removed a major motivation for the tedious photographic pulse-height-analysis technique, and instead protons were distinguished from alpha particles by electronic analysis of the signals from the dE/dx and E detectors. The analysis was based on an addition of the E and dE/dx signals. With a proper ratio of the amplification for these signals, their sum was essentially constant over a wide range of proton energies. The present adder system for particle identification thus served the same function as the more conventional multiplier systems. (Addition is more suitable than multiplication in this situation due to the nonlinear response of the plastic dE/dx scintillator to heavily ionizing particles.) Pulses corresponding to protons were selected by differential analyzers. The outputs of the two differential analyzers were placed in coincidence with the quadruple coincidence signal described above

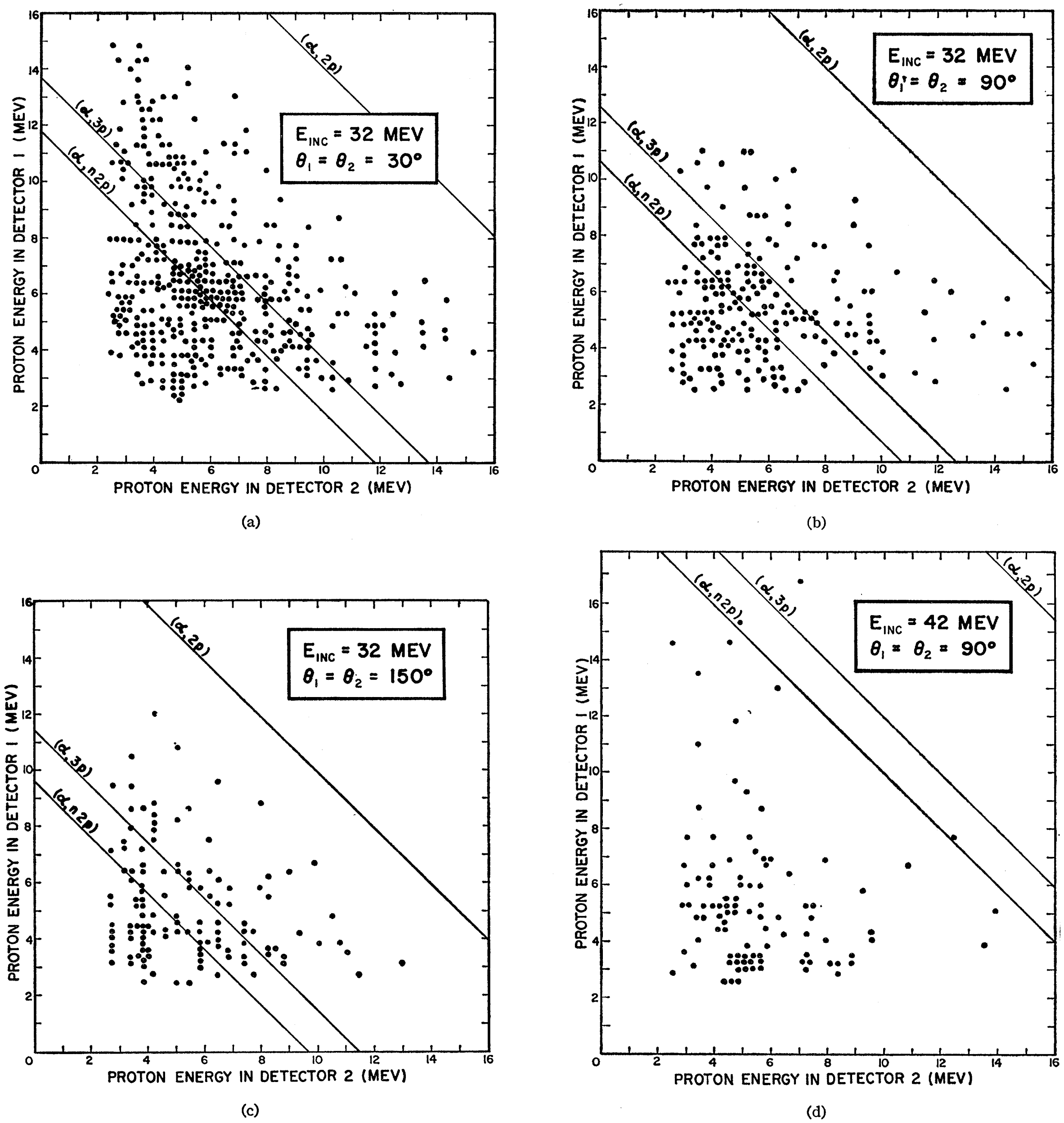

FIG. 2. Examples of two-dimensional energy distributions (with arbitrary relative normalization) for coincident protons from a Ni^{58} target bombarded by alpha particles. Each dot corresponds to a single event. Its position specifies the laboratory energies of the protons entering the detectors. The solid diagonal lines show the kinematic limits for the indicated reactions, as discussed in the text.

for arrangement A. This final signal, representing a coincidence between two particles identified to be protons, was used to gate two twenty-channel analyzers. The proton energy spectra, from the two E detectors, were displayed in these analyzers.

II. ENERGY SPECTRA OF THE EMITTED PROTONS

The raw data for a given run in arrangement A are most conveniently presented in terms of a two-dimensional plot of laboratory energy distributions as illustrated in Fig. 2. A qualitative examination of these plots, for all of the data obtained, shows that:

(1) The spectra are qualitatively similar for all angles, targets and incident energies.

(2) The protons tend to have low energies. There are very few pairs of protons in which the total energy is near the maximum possible energy. In fact, a large fraction of the observed proton pairs were emitted with energies low enough to permit the emission of a third particle.

(3) There are no striking correlations between the energies of the two coincident protons.

Before discussing the proton spectra in more detail we will consider the extent to which the third particles, mentioned in point (2), occur. Limits on the total kinetic energy available to the observed protons in various reactions can be calculated from the relevant Q values. Such limits are shown as solid diagonal lines in Fig. 2. Referring to Fig. 2, one finds that the Ni^{58} with 32-Mev incident alpha particles, only about 34% of the observed events involve proton energies so high as to preclude the emission of additional particles. Another 22% of the events lie in a band where the only additional emitted nucleon can be a proton whose energy is less than 2 Mev. Such low-energy protons can only appear, if they appear at all, as the last step in the evaporation sequence, in competition with gamma rays. They would be below the energy threshold of the detectors and hence would not themselves contribute to the observed proton rate. (Similarly a low-energy alpha particle is energetically possible but would also escape detection.) Thus, at least 56% of the observed events begin with the emission of the two observed protons. The remaining 44% of the events are more difficult to characterize. They probably involve neutrons, protons, or alpha particles as an additional emission product. Consideration of the competition between these particles, indicates that the neutron is the most likely additional particle. As low-energy protons do not compete favorably with neutrons unless neutron emission is energetically impossible, it is likely that in these three-particle events one of the protons will appear at the end of the evaporation sequence (favored by the low proton binding energies in this region). Thus, these events are more often of the type *p-n-p* or *n-p-p*, rather than *p-p-n*. On the basis of very approximate calculations of the relative importance of these different types of events,[24] it is estimated that altogether about 60% of the observed coincident proton events start with the emission of two protons, for an incident alpha-particle energy of 32 Mev. This result will be used below in comparing observed and predicted proton yields.

An inspection of the plots of Fig. 2 shows no strong correlations between the proton energies in the two counters. The correlation question can also be investigated by plotting the spectra in one counter for various energy intervals in the other counter. This is done in Fig. 3 for data taken at a bombarding energy of 32 Mev with both counters at 90°. It is found that the spectrum in one counter is almost independent of the energy in the other counter. Even in the statistical model a weak correlation is expected, due to limitations on total

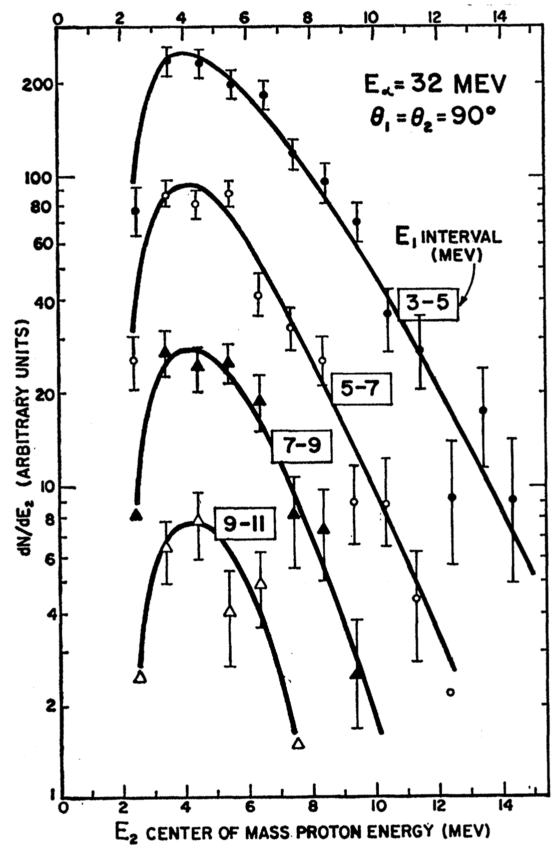

FIG. 3. Spectra for examination of energy correlations. Each curve shows the relative number of protons per unit energy in counter 2 when there is also a proton, within a specified energy interval, in counter 1. For clarity of display, the curves are drawn with arbitrary vertical positions.

available energy and the dependence of nuclear temperature on excitation energy. On the other hand no strong correlations would be expected. The results appear consistent with statistical evaporation, as the only observed correlation is a slight tendency for more high energy protons when one considers the lowest energy interval in the other counter.

In the absence of energy correlations between the two protons, it is reasonable to study the spectra in a single counter (still for coincidence events). Such spectra are shown in Figs. 4 and 5, where results obtained with arrangement B, at different energies and angles, are compared. In general, all the spectra have a broad peak, at energies in the neighborhood of 4 to 5 Mev, followed at higher energies by an approximately exponential fall-off.

A comparison of spectra obtained at incident alpha-particle energies of 27, 32, and 42 Mev, with both counters at 90°, is made in Fig. 4. The peak position shifts from about 4.5 Mev at 27 and 32 Mev to about 5.0 Mev at 42 Mev. Furthermore, the slope of the exponential fall-off becomes slightly less steep as one

[24] For these and similar calculations we have used spectra kindly provided by Dr. Z. Fraenkel, on the basis of the program described in reference 7. We have slightly modified these spectra to consider emission of protons down to energies as low as 2 Mev.

goes from 27 to 42 Mev, corresponding very roughly to an increase in "average temperature" of about 20%.

It would be desirable to use these spectra to determine the nuclear level density, and, also, to explain their dependence on incident energy in terms of the level density and the Coulomb barrier. However, such an attempt, in this and similar experiments, encounters serious difficulties:

(1) The spectrum is a composite one, involving protons emitted as the first, second, or even third particle in the evaporation sequence.

(2) The functional form of the dependence of the level density on excitation energy is not well established although the level density is universally believed to increase rapidly with excitation energy.

(3) The level densities are different for even-even, even-odd, and odd-odd nuclei, and near magic numbers, due to the depression of the ground state by pairing or shell effects.[2] These ground-state effects presumably disappear as one goes to higher excitation energies.

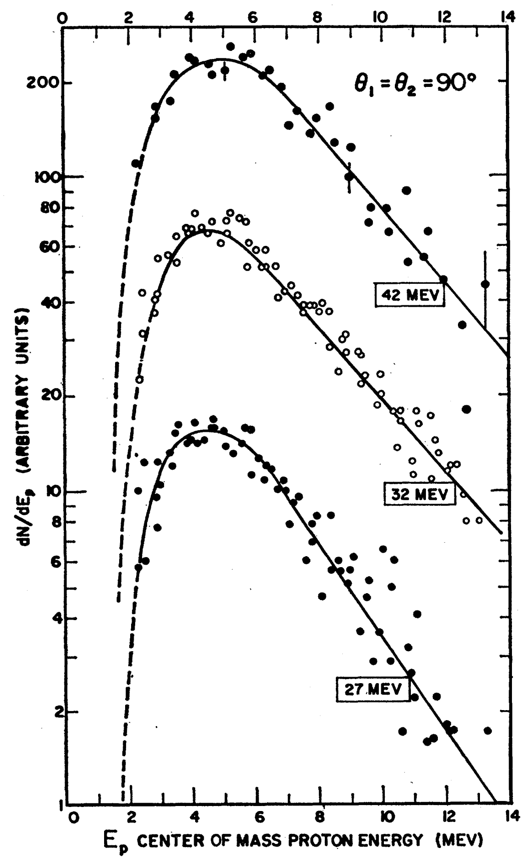

FIG. 4. Comparison of proton energy spectra at different incident alpha-particle energies. The target was Ni^{58}. Each curve shows the (c.m.) energy distribution for one of the counters for protons which are in coincidence with protons of any energy in the second counter. For clarity of display, the curves are drawn with arbitrary vertical positions. Typical statistical errors are shown for some of the points.

However, it is not known how high in excitation energy one must go before the ground state configuration is entirely forgotten; i.e., one does not know the rate at which the nucleus assumes a "normal" level density.

(4) There is uncertainty concerning the inverse cross section used in determining the level density from the spectrum. Cross sections calculated neglecting the diffuseness of the nuclear potential should not in principle be correct.[25] It is not yet clear how satisfactory present optical-model calculations are in predicting total cross sections, nor how appropriate they are for excited nuclei, which may have lesser transparency.

In principle, studies of spectra can be used to help shed light on the problems enumerated above. However, the data obtained in this coincidence situation do not have the statistical precision to warrant so ambitious an analysis. Instead, we are interested in a preliminary question: Granting the uncertainties in quantitative predictions of an evaporation model, are the observed spectra consistent with qualitative expectations? In other words, does it appear hopeful to look for the explanation of these spectra within the framework of a compound nuclear statistical analysis?

Returning, then, to the energy dependence of the spectral shape, it is concluded that these results are qualitatively consistent with the statistical model. The residual excitation energy, after the emission of one proton, almost doubles in going from 27 to 42 Mev. Some increase in the "average temperature" is therefore anticipated in most versions of the statistical model, and the observed 20% increase is not unreasonable. In fact, it is smaller than some estimates would suggest. The shift of the spectral peak to higher energies, with increasing incident energy, can be understood in terms of the higher temperature, and the relatively lesser importance of protons emitted at the end of the cascade. It is to be noted that the energy at the peak of the spectrum is lower than the height of the square-well Coulomb barrier (7 Mev, if one chooses a fairly large radius, $R=1.5A^{\frac{1}{3}}$ f). This is consistent with proton spectra observed in other work with incident alpha particles,[14] neutrons,[26] and protons.[6] Similar results have also been found for evaporated alpha particles.[9] These observations illustrate the present difficulties in the quantitative understanding of the effect of the Coulomb barrier on particle emission. They do not, however, appear to imply any departure from statistical behavior.

A comparison of spectra obtained at different angles, for an incident energy of 32 Mev, is made in Fig. 5. The exponential fall-off is slightly less steep at 30° than at 90° and 150°. Such differences between forward and backward angles are commonly attributed to direct interactions. If, with this viewpoint, the direct inter-

[25] J. M. C. Scott, Phil. Mag. 45, 441 (1954).

[26] See, e.g., L. Colli, U. Facchini, I. Iori, M. G. Marcazzan, and A. M. Sona, Nuovo cimento 13, 730 (1959).

action component is assumed to be given by the difference in the curves, in the region of exponential fall-off, it is concluded that the direct protons constitute less than 5% of the observed protons at 30°. The detailed angular distributions necessary to estimate the contribution of direct interactions to the total cross section are not known. An extrapolation based on the results of Swenson and Cindro[27] for (α,p) reactions at 30.5 Mev suggests that the fractional direct interaction contribution to the total cross section is less than the fractional contribution to the 30° point.

It is possible to compare the present results with those of similar experiments by comparing the "temperatures" derived from the spectra. For the reasons outlined above, we do not feel that this "temperature" provides very helpful information about the nuclear level density. However, independent of questions of level density, one would expect similar spectra in compound nuclear processes involving nuclei of similar mass number and excitation energy. For purposes of comparison, a conventional temperature was extracted from the energy distributions observed at 32 Mev with both counters at 90° (see Fig. 4 or 5). This experimental temperature was found in the usual way from the slope of a plot (not shown) of $\ln[dN/E\sigma(E)dE]$ vs E, where E is the proton energy and $\sigma(E)$ is the inverse total proton cross section as interpolated from a tabulation of Blatt and Weisskopf,[2] ($r_0=1.5$ f). Applying this prescription to the 32-Mev data obtained with both counters at 90°, gives an average temperature of about 1.4 Mev for protons with kinetic energies between 5 and 11 Mev.

This temperature can be compared to other temperatures found in the same region of the periodic table ($A\sim$40–65). Most of the relevant data refer to slightly lower average residual excitation energies. In 14-Mev (n,p) measurements, for instance, Glover and Purser[28] find $T=1.35$ Mev for first protons. Other authors have reported both higher[17] and lower[5] temperatures for (n,p) spectra in this mass region. The (α,p) measurements of Lassen and Sidorov at[14] 19.3 Mev give temperatures ranging from 1.05 to 1.35 Mev, again for first protons. As summarized by Sherr and Brady,[16] reactions leading to the residual nucleus Fe^{56} give temperatures ranging from 0.95 Mev in 7-Mev (n,n') studies[18] to 1.5 Mev in 17-Mev (p,α) studies.[16]

It is seen that the temperature found in the present experiment lies near the top of the range of those cited above, as might be expected with the higher excitation energy. But in view of the problems discussed earlier and of the large, and as yet unexplained, scatter in the reported temperatures, this provides only qualitative support for the conclusion that the protons in the present experiment are evaporated from a compound nucleus.

[27] W. Swenson and N. Cindro, Phys. Rev. **123**, 910 (1961).

[28] R. N. Glover and K. H. Purser, Nuclear Phys. **24**, 431 (1961).

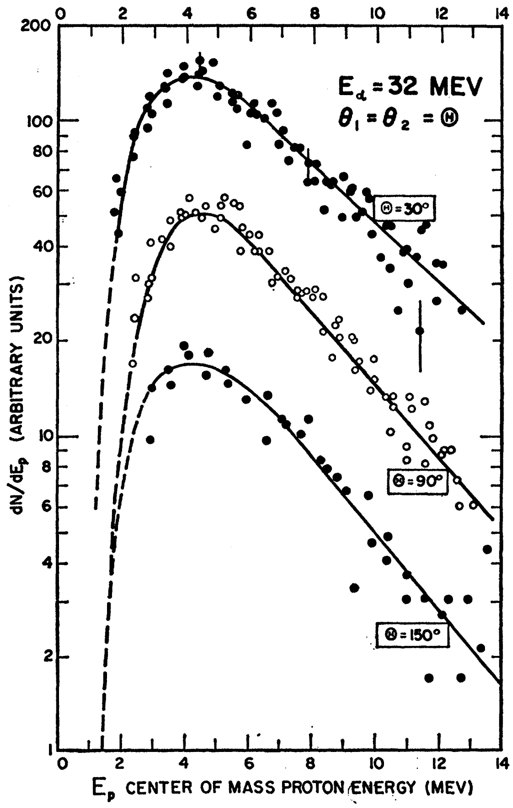

FIG. 5. Comparison of proton energy spectra at different counter angles. The target was Ni^{58}. Each curve shows the (c.m.) energy distribution for one of the counters for protons which are in coincidence with protons of any energy in the second counter. (The dashed portions of each curve represent extrapolations below the counter energy threshold; see beginning of Sec. IV.) For clarity of display, the curves are drawn with arbitrary vertical positions. Typical statistical errors are shown for some of the points.

IV. ANGULAR DISTRIBUTIONS AND CORRELATIONS OF PROTON PAIRS FROM Ni^{58}

Differential cross sections for two-proton yields were determined with the counters at several pairs of angles. The results obtained in the bombardment of Ni^{58} are shown in Fig. 6.

In determining the yield at each angle, it was necessary to include a correction for those events involving protons too low in energy to be detected. This was done by extrapolating the center-of-mass energy distributions to low energy (see Fig. 5), and including the estimated low-energy yield in the total number of events. The extrapolation was somewhat arbitrary, but at forward angles and at 90° the observed points extend to energies well below the peak of the spectrum and hence the uncertainty in the extrapolation introduces little error in the cross section. The uncertainties are greater at backward angles, where the laboratory energies are lower. It was assumed that the shape of the low energy part of the c.m. spectrum is symmetric about 90°, and hence, for instance, the 30° distribution was used to determine the 150° extrapolation. With this procedure it was estimated for a counter at 150°, in arrangement *B*, that the subthreshold contribution is (10±3)%. For two counters at 150°, the over-all uncertainty in this correction is therefore 6%. The probable errors of Fig. 6 include the uncertainties in the low energy extrapolation.

The main qualitative features of the distributions of Fig. 6 are the large anisotropy and, for incident energies of 27 and 32 Mev, the approximate symmetry about 90°. The large anisotropies can be qualitatively understood in terms of evaporation from a nucleus of high angular momentum,[29] or, equivalently, from a rapidly-rotating nucleus.[30] The curves of Fig. 6 are calculated using the latter model, in which the nucleus is represented by a rotating Maxwellian gas. It is found on this basis, ignoring Coulomb effects, that the emission probability is proportional to $\exp(\lambda \sin^2\Psi)$, where Ψ is the angle between the particle emission direction and the nuclear spin direction (which must be averaged over the possible orientations of the spin axis). The parameter λ is related to the nuclear moment of inertia and temperature, and to the average angular momentum deposited by the incident alpha particle. It was

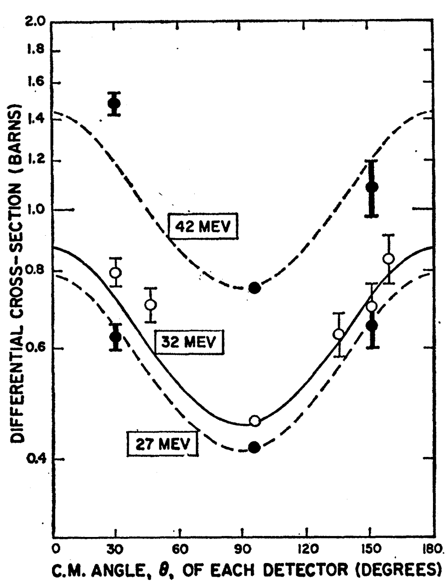

FIG. 6. Differential cross sections for coincident proton events, when the two counters are symmetrically situated at angles θ on opposite sides of the beam, in alpha-particle bombardment of Ni^{58}. The ordinate (log scale) is expressed in terms of $(4\pi)^2\Sigma$, where Σ is the measured differential cross section in barns per square steradian. (For an isotropic angular distribution, Σ would be the total cross section for the production of pairs of coincident protons.) The solid curve represents the best fit to the 32-Mev data of the angular distribution function derived from a classical model. The dashed curves are this same curve, displaced to pass through the data taken at the other energies. The error bars represent errors relative to 90°. The absolute cross section at 90° has a probable error of ten percent.

here determined empirically to be 0.79 from a best fit to the observed distribution at backward angles for 32-Mev incident alpha particles. A more detailed discussion, including implications of these and other results on angular distributions and correlations, will be presented in a forthcoming paper.

The departure from symmetry about 90° is interpreted, in conventional terms, as arising from direct interaction processes. At 27 Mev the angular distributions are seen to be completely symmetric, within experimental uncertainty, and there is thus no evidence that direct processes contribute to the coincident proton yield. At 32 Mev the yield at 30° is found to be (10±6)% higher than at the corresponding c.m. backward angle, and the departure from symmetry becomes still greater at 42 Mev. Using the estimated extrapolation mentioned in Sec. III, it is inferred that the direct processes contribute less than (10±6)% to the total $2p$ yield at 32 Mev, which is not very different from the upper limit of 5% estimated earlier from the spectra (Sec. III).

An angular-correlation test of one of the symmetries expected in the statistical theory was made in which one counter was held fixed at 90°, and the other counter placed alternatively at 150° on the same side of the beam or at 150° on the opposite side of the beam. The ratio of the coincident yield in the former case to the coincident yield in the latter case was 0.98±0.07. This absence of correlation is to be expected if the protons are evaporated from a compound nucleus, as the second emitted proton would appear with equal chance on either side of the beam, no matter on which side the first proton had been emitted. In a direct interaction on the other hand, it would be entirely possible that the probability of a coincidence would depend on the angle between the protons.

V. RELATIVE PROTON AND NEUTRON EMISSION PROBABILITIES

Section VI will be concerned with a comparison between the proton yields observed in this experiment and predictions assuming statistical emission. For this comparison, and as a matter of general interest, this section is concerned with the extraction of the best values of the relative proton and neutron emission widths, Γ_p/Γ_n, from the data of other experiments.

The main factors in the proton-neutron competition are the Coulomb barrier, which inhibits proton emission, and the relative level densities of the residual nuclei, which often favors proton emission. The relative level densities depend upon the relative excitation energies of the residual nuclei, and hence on the nucleon separation energies in the emitting nucleus. As pointed out some time ago by Hurwitz and Bethe,[31] nuclear level densities at moderate excitation energies should not be estimated from the actual nuclear excitation energies,

[29] T. Ericson and V. Strutinski, Nuclear Phys. 8, 284 (1958).
[30] I. Halpern, Bull. Am. Phys. Soc. 5, 510 (1960).
[31] H. Hurwitz and H. Bethe, Phys. Rev. 81, 898 (1951).

since these are sensitive to the odd-even fluctuations of ground state masses. These densities should be computed instead from an excitation energy based on a fictitious ground state, whose mass varies smoothly with mass number. Such a procedure takes into account the fact that fluctuations due to pairing forces do not persist to higher excitation energies. A similar argument can probably also be made for the absence of shell effects on level densities at these higher excitation energies. Various prescriptions for appropriate pairing and shell corrections to the excitation energy have been given by Newton,[32] Cameron,[33] and Dostrovsky, Fraenkel and Friedlander.[7] The latter group have shown that a wide variety of excitation functions could be accounted for in a unified way if such correction terms were included. It has been similarly shown that the proton yield in 14-Mev (n,p) reactions are closely correlated to the neutron-proton binding energy differences, if the latter are calculated with the inclusion of corrections of the same sort.[5,8,17]

The goal of the pairing and shell corrections is to provide a means of ignoring special ground-state properties and hence, in effect, of considering only gross nuclear properties. Extending this view, the question of determining corrected binding energies can be entirely bypassed in the expectation that the relative neutron and proton emission probabilities will depend smoothly on just the mass number, A, and charge, Z, of the emitting nucleus or, more particularly, on the proton richness of the emitting nucleus.

The relation between yields and proton richness can be analyzed quantitatively in terms of properties of the nuclear mass surface. Omitting the usual odd-even terms, the mass of an atom of charge Z and mass number A is, to a very good approximation,

$$M(Z,A)=M(Z_0,A)+\tfrac{1}{2}B(Z-Z_0)^2,$$

where Z_0 represents the charge (usually not integral) at the center of the stable valley, and B is a measure of the width of the stable valley. B is independent of Z, but in general varies with A. In terms of these parameters, the difference between the neutron and proton separation energies, S_n and S_p, is

$$S_n-S_p=(M_n-M_H)+B[(Z-Z_0)-(\tfrac{1}{2}-dZ_0/dA)], \quad (1)$$

where M_n and M_H are the masses of the neutron and H atom, and where the variation of B with A is ignored. Z and Z_0 refer to the emitting nucleus. [The expression $(\frac{1}{2}-dZ_0/dA)$ in Eq. (1) arises from a neutron-proton asymmetry in the mass surface. In the mass region under consideration it is essentially constant at a value of 0.05, and hence is of minor importance.]

The magnitude of B can be determined empirically from the relation $B=(d/dZ)(S_n-S_p)$, using tabulated

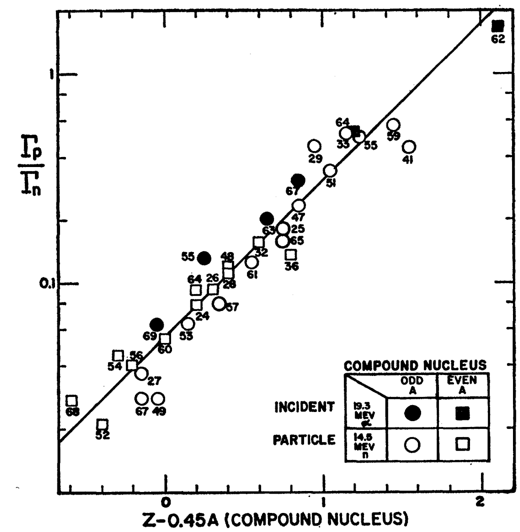

FIG. 7. Dependence of the ratio of proton to neutron evaporation probabilities upon the distance of the emitting nucleus from the center of the stable valley. The abscissa, $Z-0.45A$, is a measure of this distance for intermediate mass nuclei (see text). The solid line represents an approximate empirical fit to points obtained mostly from data for incident neutrons and in part from data for incident alpha particles. (The mass number of the compound nucleus is given adjacent to each point.)

values of the separation energies.[34] It is found that B is rather independent of A between $A=45$ and $A=70$, except for odd-even fluctuations. Averaging over these fluctuations gives $B=2.9$ Mev, in the region $A=45-70$.

The magnitude of Z_0 can also be determined, with the aid of Eq. (1), from an examination of the empirical dependence of S_n-S_p on Z, again using the tabulated separation energies.[34] It was found that Z_0 remains very nearly proportional to A between $A=42$ and 62. The mean value of Z_0/A is 0.450, with an rms deviation of only 0.004. At nearby lower values of A, Z_0/A slightly exceeds 0.45, and at nearby higher values of A it is somewhat less than 0.45.

These considerations suggest that Γ_p/Γ_n should depend smoothly on $Z-Z_0$ or, more specifically, on $Z-0.45A$. In Fig. 7 a number of experimental values of Γ_p/Γ_n have been plotted against this simple function. The experimental points refer to 14-Mev (n,p) data for target nuclei from $A=23$ to $A=67$, and to 19.3-Mev (α,p) data for targets from $A=51$ to $A=65$. These laboratory energies, for the incident neutrons and alpha particles, lead on the average to compound nuclei of the same excitation energy, about 22 Mev, thus avoiding possible small complications due to temperature differences.

The proton yields for 14-Mev incident neutrons were taken from the comprehensive survey made by Allan[5] of "first proton" cross sections. These measurements were made with photographic plates, and in principle

[32] T. D. Newton, Can. J. Phys. 34, 804 (1956).
[33] A. G. W. Cameron, Can. J. Phys. 36, 1040 (1958).
[34] V. J. Ashby and H. C. Catron, University of California Radiation Laboratory Report UCRL-5419, 1959 (unpublished).

include (n,pn) events and exclude direct (n,p) events, as desired for the present analysis. The neutron yields were determined by subtracting the proton yields and estimated yields for additional events from the total reaction cross sections measured by MacGregor, Booth, and Ball.[35] No very complete information is available concerning the additional events, but it appears reasonable to estimate, as an average for the target nuclei considered, an over-all cross section of about 250 mb for these events. Typically this includes about 50 mb for direct protons,[36] 100 mb for direct neutrons,[37] 30 mb for deuterons,[28,38] and 70 mb for alpha particles.[39]

The 19-Mev (α,p) points shown in Fig. 7 are taken from the measurements of Lassen and Sidorov[14] of (α,p) cross sections for six target nuclei. "Second" protons from (α,np) reactions were excluded by the authors through an analysis of the energy spectrum, and the results again refer only to "first" protons. The cross section for neutron emission is taken to be the difference between the total cross section and the (α,p) cross section, with an additional subtraction of 100 mb to account very approximately for (α,α') reactions[9] and possible direct interactions. The total reaction cross sections were determined by interpolation of results of optical-model calculations of Huizenga and Igo[40] and range from 1310 mb for V^{51} to 1230 mb for Cu^{65}.

It is seen in Fig. 7 that the data for Γ_p/Γ_n correlate well with $Z-Z_0$. The scatter of the points about an empirical straight line drawn through them is not large. Deviations from the straight line for the neutron data are typically about 15%, and in general do not appear to exceed the probable experimental uncertainties. There is agreement between the trend of the alpha particle and neutron points extending over a range of more than a factor of 25 in Γ_p/Γ_n. The alpha-particle points lie in general slightly higher than the neutron points, with a typical discrepancy of about 25%, but at present it is not clear if this discrepancy is experimentally significant.

Points for targets of odd A show no appreciable displacement from those for targets of even A, confirming the expectation that the complications of odd-even corrections can be avoided by considering the charge and mass of the nucleus, rather than the actual binding energies. Similarly there is no evidence for dependence upon shell structure, with the possible exception of the point for the closed shell nucleus, Ca^{40}. [This point is unusually far below the straight line of Fig. 7. However, the (n,p) cross section upon which this point was based was particularly sensitive to the analysis procedure.[5] The only other reported measurement[8] for Ca^{40} leads to a value of Γ_p/Γ_n which is above, rather than below, the straight line. It would be of interest to resolve the experimental disagreement.] Of course, the possibility is not excluded that more precise data will reveal small effects in which it becomes necessary to consider detailed ground state properties. But, at present, it appears that the ground state properties are "forgotten" at typical residual excitation energies reached in these reactions ($\sim$11 Mev).

It is somewhat surprising that the agreement between the experimental points and the empirical straight line remains good over a region in Z which is much wider than the region in which the significant parameters in the analysis remain constant. The explanation probably lies in a cancellation between several effects. For instance, at low values of A the approximation $Z_0=0.45A$ leads to an overestimate of the difference $Z-Z_0$, and the experimental points in Fig. 7 are plotted too far to the right. However, at low A the Coulomb barrier is lower and B is larger than at intermediate A, and for the same difference, $Z-Z_0$, the proton yield is therefore greater. Thus, in effect, the low-A points are plotted too far to the right and too high. An approximate estimate of the magnitude of these effects shows that it is not impossible for them to bring most of the low-A points close to the straight line which is defined by the data at intermediate A.

It is also of interest to compare the proton-neutron ratios predicted by Fig. 7 with the results of measurements with other incident particles. The most relevant remaining data, for this region of excitation, appears to be that of Cohen and Rubin.[6] They have measured cross sections for "first" protons, in studies with 14.5-Mev protons incident on targets in the region from $Z=22$ to $Z=30$. The authors concluded that the proton-neutron ratio was about four times higher in these proton induced reactions than in comparable neutron induced reactions. However, the total reaction cross sections used in this estimate were apparently too low, in the light of the recent findings that the total reaction cross section for 10-Mev protons in copper is about 900 mb.[41] In a very approximate extrapolation to higher energies, it is estimated that the total reaction

[35] M. H. MacGregor, W. P. Ball, and R. Booth, Phys. Rev. **108**, 726 (1957).

[36] This is an approximate average of results reported by D. L. Allan, Nuclear Phys. **10**, 348 (1959); P. V. March and W. T. Morton, Phil. Mag. **3**, 143, 577 (1958); R. N. Glover and K. H. Purser, reference 28; R. N. Glover and E. Weigold, Nuclear Phys. **24**, 630 (1961); and I. Kumabe and R. W. Fink, *ibid.* **15**, 316 (1960).

[37] This is a crude estimate, based on the guess that direct (n,n') events are about twice as likely as direct (n,p) events.

[38] R. N. Glover and E. Weigold, reference 36.

[39] This is an approximate average of results obtained with photographic plates, reported by I. Kumabe, J. Phys. Soc. Japan **13**, 325 (1958), and results obtained by activation methods. For a summary of activation results see S. K. Mukherjee, A. K. Ganguly, and N. K. Majumder, Proc. Phys. Soc. (London) **77**, 508 (1961).

[40] J. R. Huizenga and G. J. Igo, Argonne National Laboratory Report ANL-6373, 1961 (unpublished); Nuclear Phys. **29**, 462 (1962).

[41] This is an average of results reported by G. W. Greenlees and O. N. Jarvis, *Proceedings of the International Conference on Nuclear Structure, Kingston* (University of Toronto Press, Toronto, 1960), p. 217; V. Meyer and N. M. Hintz, Phys. Rev. Letters **5**, 207 (1960); and R. D. Albert and L. F. Hansen, *ibid.* **6**, 13 (1961); Phys. Rev. **123**, 1749 (1961).

cross section for copper and neighboring targets is about 1160 mb at 14.5 Mev. As in the neutron data analyses made above, a subtraction of 250 mb is made from this number for "extraneous" events. Then, using the smooth curve of Fig. 7, a proton yield can be predicted. It is found that the experimental proton yields exceed the predicted yields, as Cohen and Rubin concluded, but that the excess can be represented by a relatively constant cross section of 180±50 mb.

These protons were observed at 90° and their energy spectra were found to be in agreement with the statistical theory. Thus, taken very literally, the present discussion might seem to lead to the conclusion that there are here three contributions to the proton yield: (1) direct protons, assumed above to contribute 100 mb to the "extraneous" events; (2) the normal group of evaporated protons, as predicted by Fig. 7; and (3) a further group of evaporated protons, amounting to 180 mb, which occur preferentially with incident protons. However, there is no convincing evidence supporting this division, and it appears that the proton yield in proton bombardments is still not fully understood. (The possible presence of excess evaporation protons in proton bombardments suggest the corresponding possibility of excess neutrons in neutron bombardments. Were such an effect confirmed, it would imply that the Γ_p/Γ_n ratios in Fig. 7, for incident neutrons, should be raised slightly, since in the calculation for Fig. 7, no allowance was made for such extra neutrons.)

Figure 7 appears to provide a good empirical correlation of the relative proton and neutron yields, at least for incident neutrons and alpha particles. To understand the empirical curve (straight line) defined by the data of Fig. 7, it is necessary to consider in detail the relation between the relative emission probabilities and the difference term $Z-Z_0$. According to the statistical model,[2]

$$\frac{\Gamma_p}{\Gamma_n}=\int E_p\sigma_p(E_p)\omega(U_p)dE_p\Big/\int E_n\sigma_n(E_n)\omega(U_n)dE_n$$

where E is the kinetic energy of the emitted particle, $\sigma(E)$ is the inverse reaction cross section, and $\omega(U)$ is the level density of the residual nucleus at excitation energy U. For simplicity, it will be assumed that $\sigma_n(E)$ is independent of energy and that $\sigma_p(E)$ has the classical form:

$$\sigma_p=\sigma_n(1-V'/E),\quad E>V'$$
$$\sigma_p=0,\qquad E<V',$$

where V' is an effective Coulomb barrier height. If $\omega(U)$ is expanded and T is introduced in the usual way, where $1/T=(d/dU)\ln\omega(U)$ (and T is not necessarily independent of U), it follows that Γ_p/Γ_n assumes the simple approximate form

$$\Gamma_p/\Gamma_n=\exp[(S_n-S_p-V')/T].\qquad(2)$$

This is presumably the equation of the straight line of Fig. 7, since S_n-S_p is linearly related to $Z-Z_0$ by Eq. (1).

Equations (1) and (2) together imply that Γ_p/Γ_n should depend only on $Z-Z_0$ (aside from the small variation of T and V' with A). This is confirmed in Fig. 7, where data for targets of high and low A are randomly interspersed along the straight line.

Figure 7 and Eq. (2) can together be used to determine empirical values of the parameters V' and T. V' is equal to S_n-S_p, when $\Gamma_p/\Gamma_n=1$. It is found in Fig. 7 that $(Z-0.45A)=1.70$ at this point, and with Eq. (1) for S_n-S_p, this leads to the estimate $V'=5.5$ Mev. This value for the effective Coulomb barrier height, V', appears qualitatively reasonable, but possibly slightly higher than might be anticipated from observed spectra (e.g., Lassen and Sidorov[14] find that "first" protons are peaked at 5.4 Mev in the 19.3-Mev (α,p) measurements).

The temperature, T, can be found empirically from the slope of the straight line of Fig. 7. From (1) and (2) above,

$$T=\frac{(d/dZ)(S_n-S_p-V')}{(d/dZ)[\ln(\Gamma_p/\Gamma_n)]}=\frac{B-dV'/dZ}{(d/dZ)[\ln(\Gamma_p/\Gamma_n)]}.$$

In this mass region, $dV'/dZ\cong V'/Z=0.2$ Mev. The measured slope of Fig. 7, i.e., the denominator of the last expression, is 1.71. With $B=2.9$ Mev, as above, this gives $T=1.58$ Mev as the temperature determined here from proton and neutron yields.

This result is essentially identical to the temperature of 1.55 Mev reported by Storey, Jack, and Ward[17] from an analogous analysis of proton yields, based directly on corrected separation energies. This temperature is somewhat higher than the temperature most often reported in observations of particle spectra (see Sec. III), but the difference is not large, especially in view of the variations among the spectral measurements themselves.

In general, it is concluded that Fig. 7 provides an unusually simple correlation of the experimental ratios of Γ_p/Γ_n in the intermediate mass region and that the observed straight line can be understood in terms of elementary statistical-theory considerations.

VI. COMPARISON OF OBSERVED AND PREDICTED PROTON YIELDS

Total cross sections for events involving the emission of pairs of protons are determined in this section from the data of the present experiment. As a test of the applicability of the statistical model, the experimental results are then compared with predictions based on the relative neutron and proton evaporation probabilities, found in Sec. V from data of other experiments.

The comparison is made, for simplicity, for only those $2p$ events in which the first two evaporated particles are protons (as distinguished, for instance, from events involving a neutron followed by two protons). The most quantitative comparison is for the results obtained in the bombardment of Ni^{58}, which was the most intensively studied target, although comparisons are also made for Ni^{60} and Ni^{62}.

The total cross section for $2p$ events with Ni^{58} was determined from the differential cross section at 90° and from the angular distribution. The same angular distribution was used for estimates of the cross sections for alpha particles of 27 and 32 Mev, since the same backward anisotropy was observed at these incident energies. With an angular distribution of the form discussed in Sec. IV, the total cross sections for $2p$ events were found to be 510 mb at 27 Mev and 560 mb at 32 Mev. A probable error of 50 mb is assigned to each of these results, corresponding to the estimated uncertainty in the determination of the 90° differential cross section. In principle, uncertainties in the angular distribution, including possible differences between these distributions for the "first" and "second" protons, could contribute to the overall uncertainty. However, in the present case, this is estimated to be a minor source of uncertainty. The angular distribution used in this calculation is symmetric about 90° and was based on points taken between 90° and 160°. Thus, the slight forward peaking which was found in the 32-Mev measurements is not taken in consideration, and the stated cross section only includes the symmetric part of the $2p$ yield. This will be referred to below as the "compound" yield, on the assumption that the symmetric part is attributable to compound nuclear processes. This is the appropriate experimental yield to compare to predictions of the statistical theory. In addition, however, there is a small direct contribution, as discussed in Sec. IV. No forward peaking was observed in the 27-Mev data, and therefore the entire yield at this energy is, in the sense in which the term is used, a "compound" yield.

A small fraction of the observed events at 32 Mev may be due to evaporation sequences in which three protons are emitted. The probability of detecting such events, if they occur, is three times the probability of detecting events in which only two protons are emitted. An approximate estimate of the likelihood of three proton events, based on the type of evaporation calculation mentioned in Sec. III,[24] suggests that they introduce an overestimate in the cross section of about 20 mb. This should be subtracted from the measured cross section. Thus, the compound $2p$ cross section at an incident energy of 32 Mev is reduced to 540±50 mb. The result stated above for 27-Mev alpha particles is unchanged, since at this lower energy there is no significant possibility of three-proton events. At 42 Mev, three-proton events are much more probable, and in view of the complicated cascade problems no calculations of the $2p$ cross section is attempted here.

It was estimated, in Sec. III, that only about 60% of the observed $2p$ events at 32 Mev begin with the emission of two protons, the remainder coming from events such as n-p-p. On the other hand, at 27 Mev it is very unlikely for three-nucleon events to occur. Thus the experimental cross section in Ni^{58} for compound events beginning with the emission of two protons is 510±50 mb at 27 Mev and 320±50 mb at 32 Mev. (The quoted error at 32 Mev includes some allowance for the uncertainty in the determination of the 60% factor, used above.)

These experimental results can be compared with predictions based on the ratios, Γ_p/Γ_n, displayed in Fig. 7. Such a comparison presumes that the compound systems of the present experiment are not significantly different in mass and excitation energy from the compound systems considered in the construction of Fig. 7. The mass criterion is clearly satisfied, but the mean excitation energy is higher in the present experiment than for the data of Fig. 7. However, as discussed at the end of this section, the possible error introduced in the Ni^{58} result from this discrepancy is small. Therefore, the smooth curve in Fig. 7 is used for predicting Γ_p/Γ_n in this experiment. From these relative widths, and assuming knowledge of the reaction cross section for all "extraneous" events, such as $(\alpha,\alpha p)$, one can calculate

TABLE I. Comparison of the calculated and experimental cross sections for events which start with the evaporation of two protons, in the bombardment of Ni^{58} with 27-Mev and 32-Mev alpha particles. (All cross sections are in mb.)

		27 Mev	32 Mev
A	$\Gamma_p/(\Gamma_n+\Gamma_p)$ for compound nucleus Zn^{62} [a]	0.666	0.666
B	$\Gamma_p/(\Gamma_n+\Gamma_p)$ for compound nucleus Cu^{61} [a]	0.435	0.435
C	Fraction of events in which excitation energy of Cu^{61} is between proton and neutron binding energies[b]	1/4	0
D	Probability that first two nucleons will be protons: $A\times[C+B\times(1-C)]$	0.384	0.290
E	Total reaction cross section[c]	1500	1580
F	Cross section for reactions involving emission of α particles[d]	250	320
G	Direct interaction cross section (estimated)[e]	100	100
H	Cross section for events in which only nucleons are evaporated: $E-F-G$	1150	1160
I	Calculated cross section for events which start with evaporation of two protons: $D\times H$	440±50	340±50
J	Experimental cross section for events which start with evaporation of two protons[f]	510±50	320±50

[a] From Fig. 7, as discussed in text.
[b] Based on spectra of reference 24.
[c] From optical-model calculation of Huizenga and Igo, reference 40.
[d] From activation measurements of S. Tanaka, J. Phys. Soc. Japan **15**, 2159 (1960) and Houck and Miller, reference 10.
[e] This estimate is very crude, as the data necessary for a reliable estimate is not available.
[f] See text.

the expected cross section for events which begin with the emission of two protons. Such a calculation is outlined in Table I, and compared to the experimental results for Ni^{58}. The agreement displayed in Table I is believed to be very satisfactory.

To test the dependence of the $2p$ yield on proton richness, data were also taken with Ni^{60} and Ni^{62} targets, and the results again compared with predictions based on Fig. 7. For these isotopes, data were only taken at 32 Mev, and considerably less data were obtained even at this energy than for Ni^{58}. For Ni^{60} the observed $2p$ yield was found to be approximately 15% of the Ni^{58} yield. An examination of the energy distributions, indicates that the fraction of observed events which start with the emission of two protons is about the same for Ni^{60} as for Ni^{58}. From Fig. 7 it is calculated that the yield for these events in Ni^{60} should be 4.3% of the nucleon reaction cross section, or 15% of the corresponding yield in Ni^{58} (compare to line *D* of Table I). This is in fortuitously good agreement with the experimental result.

For Ni^{62} the observed $2p$ yield was found to be less than 6% of the yield from Ni^{58}. The latter result is stated only in terms of an upper limit, since spurious events, such as contributions from impurities or accidentals, are relatively more important here where the true rate is low. An investigation was made of suspected carbon, nitrogen, and oxygen impurity contributions for all nickel targets used. This was done by studying characteristic-impurity events and $2p$ events with special targets rich in the impurity elements, and then searching for these same events with the nickel targets. It was concluded that, of all these cases, a significant impurity contribution could only arise from an oxygen contribution to the Ni^{62} data at 30°. Here, due to an unusually large oxygen content coupled with a low total $2p$ rate, the impurity events might have amounted to about 30% of the observed events. The stated upper limit of 6% corresponds to the measured rates, and no corrections for possible spurious events have been included. The calculated $2p$ yield, again based on Fig. 7, is here about 1% of the Ni^{58} yield. While this is not inconsistent with the experimental upper limit, the difference is large.

A possible partial explanation of the Ni^{62} difference may lie in the neglect, mentioned above, of the dependence of Γ_p/Γ_n on nuclear temperature. For the present experiment, at 27 and 32 Mev, the mean excitation energy in the first emission is higher than that for the data analyzed in Fig. 7, and therefore, presumably, the temperature is higher. The effect of increasing temperature, all other things being unchanged, is to bring the ratio, Γ_p/Γ_n, closer to unity. As long as Γ_p/Γ_n is close to unity for the first emission, as for Ni^{58} and Ni^{60}, the effect of an incorrect temperature is small, but when it is quite different from unity, as for Ni^{62}, the effect is greater [see Sec. V, Eq. (2)]. A crude estimate of the magnitude of these effects was made, assuming that the temperature varies as the square root of the excitation energy and that the residual excitation energy for first protons in the 32-Mev data was twice the residual excitation energy for the data of Fig. 7 (the residual excitation energy for second protons was approximately the same). This estimate suggests that the calculation based on Fig. 7 may have overestimated the 32-Mev Ni^{58} yield by 7%, underestimated the Ni^{60} yield by 15%, and underestimated the Ni^{62} yield by a factor of 2. If corrections considering these temperature effects were included, the over-all agreement between the observed and calculated results at 32 Mev would remain essentially the same. In the absence of reliable information concerning the dependence of temperature on excitation energy, no such correction has been inserted in the results discussed earlier in this section. Even without such corrections, the measured compound $2p$ yields in nickel isotopes are interpreted to be in good over-all agreement with the predictions of the statistical theory.

VII. CONCLUSIONS

It has been found in the present experiment that pairs of coincident protons are copiously emitted in alpha-particle bombardment of Ni^{58}. For instance, with 32-Mev incident alpha particles, the cross section for events in which two or more protons are emitted is more than one-third of the total reaction cross section. The angular distribution of these protons is quite anisotropic, with a pronounced minimum at 90°.

The observed energy distributions, angular distributions and yields were compared to predictions of the statistical theory of nuclear reactions. It is concluded that there is extensive agreement, and therefore that most of the observed events (and by implication most of the unobserved ones as well) involve formation of an excited compound nucleus, with subsequent particle evaporation. (For instance, with 32-Mev alpha particles, over 90% of the observed $2p$ events are attributed to compound nuclear processes.)

The comparisons made were unfortunately not fully quantitative. This is related in part to important uncertainties in the present statistical model, concerning the energy dependence of nuclear level densities, the Coulomb barrier, and angular momentum effects. Furthermore, there exists, at least in principle, the possibility that some noncompound mechanism might account for any individual result considered. Thus the conclusion that the present results are in harmony with the statistical theory rests on the comprehensive nature of the approximate agreement, rather than on any one decisive argument.

Specific items in this over-all agreement include: the absence of strong correlations in the energy of the two protons; the approximate evaporation character of the spectra; the similarity of the spectra at different incident energies and different angles of observation; the approximate agreement between an average temperature derived from these spectra and temperatures found in comparable experiments; the symmetries observed in the angular distributions; and the agreement between observed and predicted proton yields.

ACKNOWLEDGMENTS

We are very grateful to Richard W. West for his active participation in many of the experimental runs, and to Dr. Zev Fraenkel for his calculations and comments related to particle emission spectra. We are indebted to the staff of the cyclotron laboratory for very helpful cooperation in all phases of this work.

PHYSICAL REVIEW VOLUME 126, NUMBER 3 MAY 1, 1962

Seniority of the $f_{7/2}^4$ Levels in Cr^{52}†

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(Received December 6, 1961)

The seniorities of recently observed levels in Cr^{52} are considered. The energies as well as $M1$ transition rates agree rather well with a $f_{7/2}^4$ assignment. On the other hand, there is not enough experimental information about the possible operation of the $E2$ selection rule ($\Delta v=2$ but no $\Delta v=0$) for this configuration.

In a recent paper[1] the level structure of Cr^{52} has been experimentally investigated. The following levels were assigned the $f_{7/2}^4$ proton configuration (the neutrons are in the closed shell of 28): ground state ($J=0$), 1.434 Mev ($J=2$), 2.369 Mev ($J=4$), 2.766 Mev ($J=4$), 2.965 Mev ($J=2$), and 3.112 Mev ($J=6$). The positions of the lower 2^+ level and the 6^+ level agree very well with those found in $f_{7/2}^4$ configurations.[2,3] The existence of two 4^+ levels as well as another 2^+ level can be simply interpreted. In the $f_{7/2}^n$ configurations with two-body forces between the protons, the seniority is a good quantum number, and the pairing property holds. Therefore, in the $f_{7/2}^4$ configuration the positions above the $J=0$, $v=0$ ground state of the $J=2$, 4, 6 levels with seniority $v=2$ should be the same as in the $f_{7/2}^2$ configuration. The other possible levels of the $f_{7/2}^4$ configuration have seniority $v=4$ and spins $J=2$, 4, 5, 8.

The validity of the description in terms of a pure jj-coupling $f_{7/2}^4$ configuration can be checked by considering the rate of $M1$ transitions between the levels.[4] The $M1$ operator is proportional in this case (j^n configuration of identical particles) to $\mathbf{J}$. It has therefore vanishing matrix elements between *any* two orthogonal states (even if they have the same spin and parity). In V^{51}, for example, there is a very slow $M1$ transition between the first excited $\frac{5}{2}$ state (at 0.32 Mev) and the $\frac{7}{2}$-ground state. In Cr^{52}, no transition was detected between the two 4^+ states (at 2.369 and 2.766 Mev). This shows that the $M1$ transition between these two levels is considerably attenuated (as compared to the $E2$ transition between the 4^+ level at 2.766 Mev and the 2^+ level at 1.434 Mev). It would be of interest to have more accurate limits on the rate of this transition so that the attenuation factor could be obtained. This attenuation, however, does not indicate at all whether the seniority is or is not a good quantum number. This question is irrelevant in the V^{51} case where there is only one state with a given spin of the $f_{7/2}^3$ configuration. In Cr^{52}, however, there are two states with $J=4$, as well as two states with $J=2$, and the validity of the seniority quantum number could be investigated. Since the $M1$ selection rule does not give any information about this problem, other effects should be considered.

Another selection rule that can be checked in the Cr^{52} case concerns $E2$ transition probabilities. The matrix elements of even tensor operators taken between states with the same seniority, vanish in the middle of a shell, i.e., in the $j^{(2j+1)/2}$ configuration of identical particles. A special case of this is the vanishing of the quadrupole moment in such configurations. Thus, in this case, in any transition the seniority must change by 2 (this is the maximum possible change for single-particle jumps). As well known, most $E2$ transition probabilities are largely enhanced compared to "single-particle rates". Still, we may be able to approximate the effective $E2$ operator to be used with shell model wave functions by a sum of equally enhanced single-particle operators each of which is a tensor of degree 2. Every such tensor is proportional, within the given configuration, to $r^2Y_{2m}(\vartheta,\varphi)$ with a factor that

† This work was supported in part by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.

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