Proton–Gamma Competition in the $Cu^{63}(p, 2p)Ni^{62}$ Reaction at 10.5 MeV*

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I. INTRODUCTION

The importance of gamma-ray emission in compound nuclear processes at excitations above the particle-emission threshold has been recently emphasized in several papers. Grover[1] has discussed the necessity of proper accounting for particle–gamma competition in the calculation of excitation functions. Delormé[2] has analyzed activation cross sections and the energy spectrum of protons emitted in (α, np) reactions to deduce an experimental measure of the relative proton and gamma emission probabilities. The experimental result was in satisfactory agreement with statistical theory predictions. In the present work, another attempt is made to clarify the role of gamma competition in compound nuclear processes, through a measurement of the relative proton and gamma emission widths.

The essential idea of the method is to determine from (p, p') measurements the cross section for populating levels in which the gamma–proton competition is of significance, and then to determine from $(p, 2p)$ measurements the proton yield from these levels. To eliminate complications of neutron competition the emitting nucleus should have a high neutron-separation energy and a low proton-separation energy. These criteria are met by Cu^{63}, as illustrated in the energy-level diagram of Fig. 1. In fact, for the available incident proton beam at 10.45 MeV, the $Cu^{63}(p, pn)Cu^{62}$ reaction is energetically impossible. When proton emission from the initial Zn^{64} compound nucleus populates levels of Cu^{63} at excitation energies above 6.12 MeV, the levels may decay either by proton emission to low-lying discrete states of Ni^{62}, by a gamma de-excitation cascade to the ground state of Cu^{63}, or by alpha-particle emission. The last possibility cannot be entirely ruled out in advance, but the Coulomb barrier is expected to strongly inhibit it.

II. EXPERIMENTAL

The measurements were carried out using the external proton beam of the University of Washington cyclotron, at an incident energy of 10.45 MeV. The determination of the $Cu^{63}(p, 2p)Ni^{62}$ cross section was made in a pair of solid-state-detector anticoincidence telescopes. Each telescope consisted of two detectors; the low-energy particles of interest were stopped in the front detector, and long-range particles (especially from elastic scattering) were rejected by the second detector. The energies of the two coincident charged particles were recorded in a 1024-channel (32×32) two-dimensional pulse-height analyzer gated by a conventional fast–slow coincidence system. Events leading to the ground state of Ni^{62} are characterized by a constant 4.17-MeV sum of the energies of the two protons, and are easily identified in the analyzer spectra by their location in a diagonal band. $Cu^{63}(p, p\alpha)Co^{59}$ events are also energetically possible, and in fact would fall close to the band of events associated with the Ni^{62} ground-state reaction, but the use of appropriate degrader foils in front of the counters made it possible to eliminate $(p, p\alpha)$ events from the data, as well as to confirm that the $(p, p\alpha)$ cross section is small.

Figure 2 shows a two-dimensional analyzer spectrum for a run in which both counters were at 90° to the beam direction (180° apart). The band corresponding to $(p, 2p)$ events going to the ground state of Ni^{62} is clearly visible. Almost no events can be seen near the dashed diagonal line at the lower total energy corresponding to $(p, 2p)$ events going to the Ni^{62} first excited state at 1.17 MeV. The counts at high summed energies are accidental events, and are relatively copious because the yield of 4-MeV protons from Cu^{63} is much greater than the yield of 2-MeV protons.

Figure 3 shows the spectrum of events in the ground-state band of Fig. 2 projected onto the energy axis of one counter. As indicated in the figure, the spectrum is a superposition of contributions from both first and second protons of the decay sequence. The total energy of the two protons is fixed at 4.17 MeV. At 2.08 MeV, the first and second protons contribute equally to the observed differential cross section of 4.38 ± 0.76 μ/b(sr^2-MeV), although at other energies the relative contributions are not determined by experiment. The separated contributions shown in Fig. 3 are based on theoretical calculations. They are not crucial to the discussion below, but they are of interest as a suggestion of the experimental spectrum.

On the basis of anisotropies observed between (90°–90°) and (135°–135°) emission-angle pairs, it was crudely estimated that the differential cross section integrated over all emission angles for both protons was larger by a factor of (1.20 ± 0.15) than the cross section which would be obtained from the (90°–90°) data by assuming isotropic emission. The total observed yield of coincident 2.08-MeV protons was multiplied by this anisotropy factor and by $8\pi^2$ (half of the full solid-angle

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[1] J. R. Grover, Phys. Rev. **123**, 267 (1961); **127**, 2142 (1962).
[2] J. Delormé, Nucl. Phys. **47**, 544 (1963).

factor because the emission sequence is not distinguished in the previous cross section), to give a total cross section for emission of 2.08-MeV proton pairs of 415±88 μb/MeV.

The cross section for population of states of Cu^{63} from which 2.08-MeV protons may be emitted is found from the single-counter differential cross section at 2.08 MeV. Figure 4 shows the energy spectrum, measured in a single-counter experiment, of protons emitted at 105° in the laboratory in the 10.5-MeV proton bombardment of Cu^{63}. Except at high proton energies and for the peaks due to inelastic scattering from carbon and oxygen contaminants in the target, the general shape and approximate angular isotropy of the spectrum is consistent with the assumption of a compound nuclear mechanism for the (p, p') reaction in Cu^{63}. The 105° spectrum was used rather than the 90° spectrum, to shift

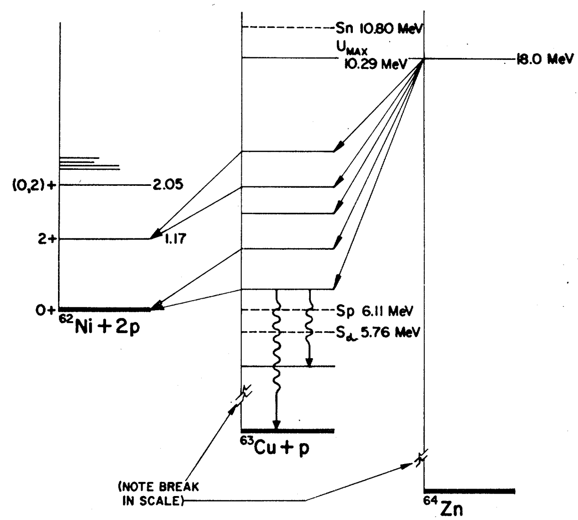

FIG. 1. Energies of compound states of Ni^{62} and Cu^{63} excited in a two-proton cascade from Zn^{64}, following the 10.45-MeV proton bombardment of Cu^{63}. Particle emission thresholds in Cu^{63} are indicated by dotted lines.

the C^{12} 7.66-MeV contaminant peak further from 2.08 MeV.

The observed differential cross section at 2.08 MeV is 300±100 μb/(sr-MeV). The correction for second-proton contamination, using the $(p, 2p)$ differential cross section, is about 10%. With this correction, and assuming isotropic first protons, the cross section for formation of states in Cu^{63} at 2.08 MeV above the proton separation energy is 3.4±1.3 mb/MeV. Combining this result with the previous $(p, 2p)$ cross section, one obtains a proton emission rate, (Γ_p/Γ_{tot}), of 0.12±0.05. The equivalent proton–gamma emission probability ratio (Γ_p/Γ_γ) is 0.14±0.06, assuming that only protons or gammas are emitted. The main uncertainties are due to poor statistics in the coincidence experiment, the possibility of background contamination in the single-

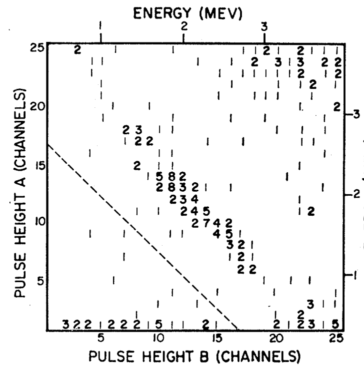

FIG. 2. Two-dimensional pulse-height distribution for coincident protons emitted in the proton bombardment of Cu^{63}. The observed particles were emitted at 90° with respect to the beam, on opposite sides of a scattering plane. The observed number of events for each pair of pulse heights is indicated. The dotted line corresponds to transitions to the 1.17-MeV first excited state of Ni^{62}.

counter spectrum, the sensitivity of the Cu^{63} excitation spectrum to uncertainties in the beam energy, and the uncertainty in the anisotropy correction factor.

III. DISCUSSION

In this section the experimental results are considered in the light of the statistical theory of compound nuclear reactions. The analysis is strongly influenced by the requirement that protons emitted from excited states in Cu^{63} to the 0^+ ground state of Ni^{62} must carry away all of the angular momentum of the emitting levels. Because gamma de-excitation will not be so severely restricted by angular momentum considerations, proton–gamma competition is sensitive to the spin as well as to the excitation energy of the emitting levels. The observed proton emission probability is an average of the emission probabilities, weighted by the spin population of the excited states. The inclusion of spin effects in the

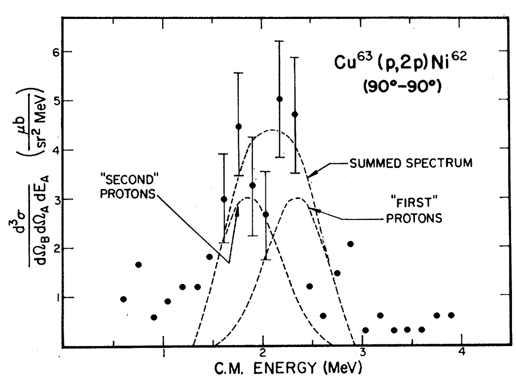

FIG. 3. Energy spectrum of events in the ground-state band of Fig. 2 observed by detector A. Statistical uncertainties are shown for several points. Corrections have been made in the energy scale for target for target degradation.

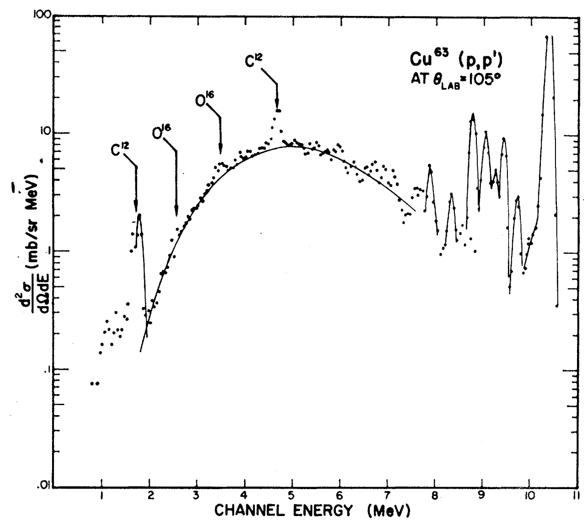

FIG. 4. Differential c.m. cross section for protons at 105° (lab angle) in the 10.45-MeV proton bombardment of Cu^{63}. The arrows label contamination peaks from inelastic scattering from the 4.43- and 7.66-MeV states in C^{12} and the doublets near 6.1 and 7.0 MeV in O^{16}.

statistical model is discussed in general terms by, for example, Ericson,[3] and with specific reference to gamma-particle competition by Grover[1] and Delormé.[2]

The first step of the present analysis is the determination of the spin population of the initial Zn^{64} compound nucleus. A calculation using optical-model transmission coefficients[4] for 10.5-MeV protons on Cu^{63}, and including target and projectile spins, yields a distribution having a mean angular momentum of $2.95\hbar$. About 70% of the population is in states of spin 2, 3, and 4. The redistribution of the spin population occurring with the evaporation of the first proton is determined by the rapid decrease with orbital angular momentum of the transmission coefficients for low-energy protons, and by the dependence on angular momentum of the final level density of the product nucleus, taken proportional to $(2J+1)\exp[-J(J+1)/2\sigma^2]$. For a value[5] of 4 for the spin cutoff parameter, σ, a quantitative estimate showed that the angular momentum distribution of states populated in the Cu^{63} intermediate nucleus was essentially the same as the Zn^{64} initial angular momentum distribution. The new mean spin was $3.2\hbar$.

In a complete theoretical prediction of the proton emission probability, one would next calculate separate proton and gamma emission widths for each value of the angular momentum of the emitting levels, and average the ratios over the initial spin distribution. Such an analysis has not as yet been completed. Instead an intermediate step has been taken, in which a calculation has been made of the dependence of the emission probability on the angular momentum of the emitting state. Relative proton widths were found using transmission coefficients for a totally absorbing square well[6] and a conventional spin dependence for the level density (see above). The gamma widths were assumed to be independent of spin. This determines the ratio $(\Gamma_p/\Gamma_\gamma)_J$ for each value of initial spin, aside from a constant multiplicative factor which is independent of spin. The average of these ratios, weighted by the initial spin population, was then compared to the experimental value of Γ_p/Γ_γ. The comparison serves to determine the constant multiplicative factor and hence to determine absolute values for $(\Gamma_p/\Gamma_\gamma)_J$ at each spin. For the levels of Cu^{63} at 2.08 MeV above the proton separation energy, these ratios were found to be approximately 2.5, 0.5, 0.07, 0.0065, and 0.0004 for states of spin $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$, respectively.

It is to be noted that this technique, which provides a means of "preparing" excited nuclei in a known region of excitation energy, could be applied to Cu^{63} more effectively at slightly higher incident proton energies. The $(p, 2p)$ yield would then be greater, facilitating detailed studies of Γ_p/Γ_γ and of angular distributions as a function of the excitation energies of the emitting and final nuclei.

[3] T. Ericson, Advan. Phys. **9**, 425 (1960).

[4] G. S. Mani, M. A., Melkanoff, and I. Iori, Centre d'Etudes Nucléaires de Saclay, Report No. 2379, 1963 (unpublished).

[5] T. Ericson, Nucl. Phys. **11**, 481 (1959).

[6] The transmission coefficients for low-energy protons were found using the expressions of M. M. Shapiro, Phys. Rev. **90**, 171 (1953), evaluated here with $r_0=1.60$ F and $K_0=1.0$ F^{-1}.