Search for the double-direct $(p,2p)$ reaction at 17 MeV*

L. Shabason, B. L. Cohen, and T. Congedo
University of Pittsburgh, Pittsburgh, Pennsylvania 15260
(Received 31 August 1976)

A method is developed for clearly distinguishing experimentally between $(p,2p)$ reactions which result from (p,p') reactions followed by proton boiloff, and those in which the two protons are both emitted within $\sim 10^{-22}$ sec in a direct reaction (referred to as "double direct"). Measurements involving coincidence detection and energy measurements on the two protons emitted at equal angles on opposite sides of the beam ($\theta_2 = \theta_1$, $\phi_2 = \phi_1 + \pi$) indicate that at 17 MeV bombarding energy in the $A = 50$–65 region, the boiloff process is predominant with cross sections of the order of 1 mb for exciting ground states or low-lying excited states. The cross section for the double-direct process is not more than about 10 μb. A crude theoretical estimate indicates that this is about the correct order of magnitude.

[NUCLEAR REACTION ^{51}V, ^{59}Co, ^{65}Cu$(p,2p)$, $E_p = 17$ MeV, exciting g.s., 1st excited; measured energy spectra, angular distributions, deduced cross sections for (p,p') followed by boiloff, and for completely direct reactions.]

The $(p,2p)$ reaction has been studied over a wide range of incident energies and has been employed to obtain a variety of information. At very high incident energies it is closely related to free proton-proton scattering and has been used to study single-particle levels and the momentum distribution of protons in the nucleus by analysis with plane wave impulse and plane wave Born approximations. This subject has been reviewed by Jacob and Maris.[1]

At lower energies, $(p,2p)$ reactions have been used to study proton-hole states[2] as a supplement to information obtainable from proton pickup reactions such as $(d,{}^3\mathrm{He})$, (n,d), and $(t,{}^4\mathrm{He})$. A study at 40 MeV by Griffiths and Eisberg[3] indicated that at that energy the double-direct reaction mechanism (i.e., both protons emitted in a direct reaction) is predominant, and this was corroborated by angular correlation studies in that energy region of the ^{88}Y$(p,2p)^{88}$Sr and ^{40}Ca$(p,2p)^{39}$K reactions.[4,5]

An early experiment by Cohen[6] attempted to study direct contributions to the $(p,2p)$ reaction on ^{58}Ni with 23 MeV protons. A difficulty arises at these low energies since $(p,2p)$ reactions can result from (p,p') reactions followed by boiloff of a second proton. In this paper we develop a method for separating off such reactions, allowing the double-direct reaction to be studied with high sensitivity. In addition we study target nuclei whose spectra are such that interference from boiloff processes is minimized.

EXPERIMENTAL

The experiment consists of bombarding a thin target with 17 MeV protons and detecting the two emitted protons in coincidence. Target thicknesses are determined by weighing and the α particle energy-loss method using ^{241}Am source. All target thicknesses are 1 mg/cm^2 or less. Outgoing particles are detected with two solid state detector telescopes placed symmetrically in the scattering chamber about the incident beam direction at angle pairs ranging from $\pm 30°$ to $\pm 135°$. Since all residual nuclei from $(p,2p)$ reactions are even-even with well separated low-lying states, the summed energies of the two telescopes uniquely identify the final state. The $(p,p\alpha)$ reaction on ^{12}C and

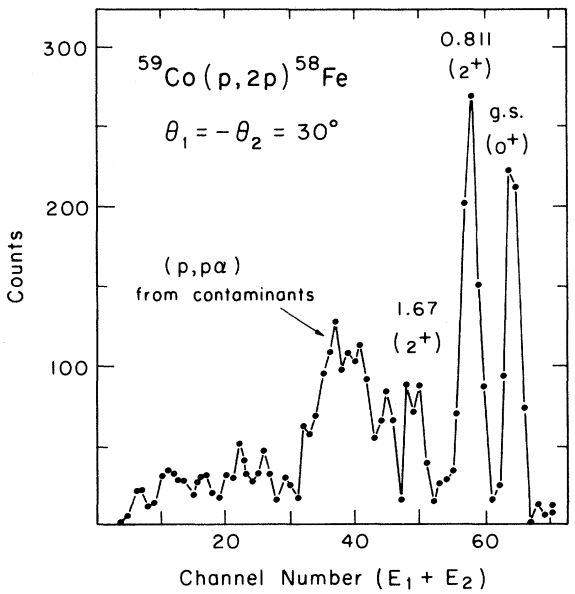

FIG. 1. Typical summed energy spectrum; the distribution of values of E_1+E_2 from the reaction ^{59}Co$(p,2p)^{58}$Fe.

^{16}O, whose Q values are -7.34 and -7.16 MeV, respectively, offer the only important interference in the summed energy spectra. The effect of these reactions was eliminated by placing appropriate absorbers in front of the detectors to shift the $(p,p\alpha)$ peaks out of the region of interest. A typical summed energy spectrum is given in Fig. 1. No further particle identification is required.

The detector telescopes consist of a 200 μm thick, 50 mm^2 area ΔE detector and a 2000 μm thick, 100 mm^2 area E detector. Count rates are adjusted for various targets and angles to optimize the true-to-random ratio and limit total count rates. This ratio is typically 10:1 for each peak studied. Beam currents range from 10 to 120 nA and each irradiation is typically 2 to 8 h.

A block diagram of the electronics is shown in Fig. 2. Timing signals are taken from the ΔE detector through a fast preamplifier and fed into a snap-off timing discriminator (STD). The outputs of these fast discriminators are sent to a time-to-amplitude converter (TAC) whose output is fed into a PDP-15 computer interface. A time resolution of 1.2 nsec is typical.

Since the maximum proton energy from the $(p,2p)$ reaction is known, energy windows are set with timing single channel analyzers (TSCA). The outputs of the TSCA's are used to create a slow coincidence and are also required to be in coincidence with an output of the TAC. The two energy signals are sent to the computer interface where they are digitally summed. The data are stored in a three dimensional array of time versus summed energy versus single proton energy whose dimensionality is $16 \times 128 \times 128$. Windows are set to fulfill time and summed energy conditions in order to project single proton spectra. Two additional windows fulfilling the same energy requirement but having different time requirements are also set. The average of these two is used as

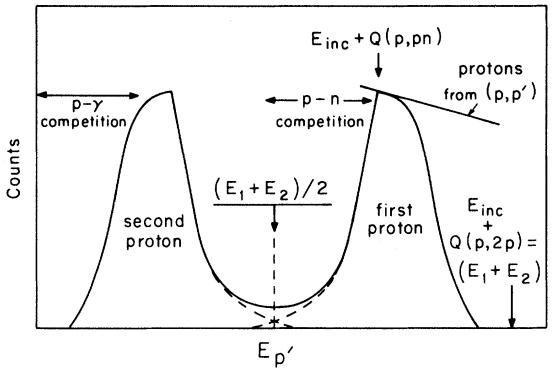

FIG. 3. Schematic representation of the energy distribution of protons emitted from $(p,2p)$ reactions leaving the final nucleus in a definite state [i.e., $Q(p,2p)$ has a single definite value] if the second proton is emitted in a boiloff process. Shape is explained in text.

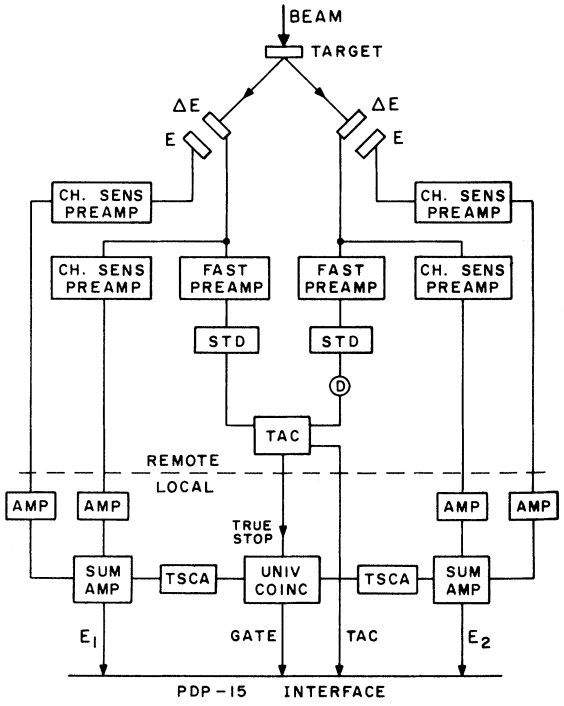

FIG. 2. Block diagram of the electronics used for data collection. See discussion in text.

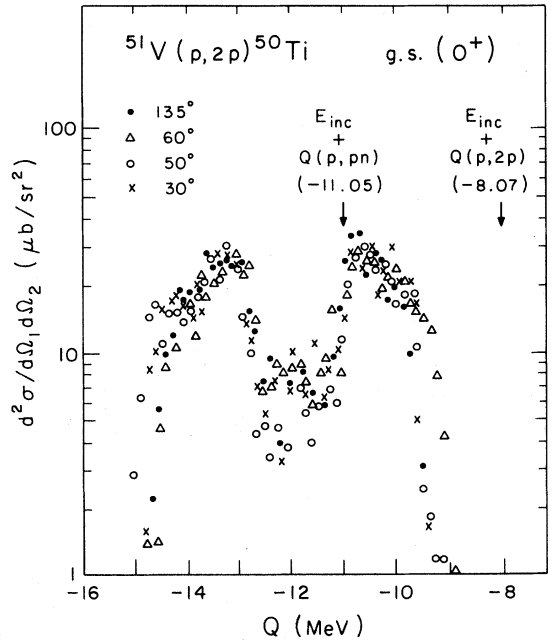

FIG. 4. Energy spectrum of protons from $^{51}V(p,2p)^{50}Ti$(g.s.).

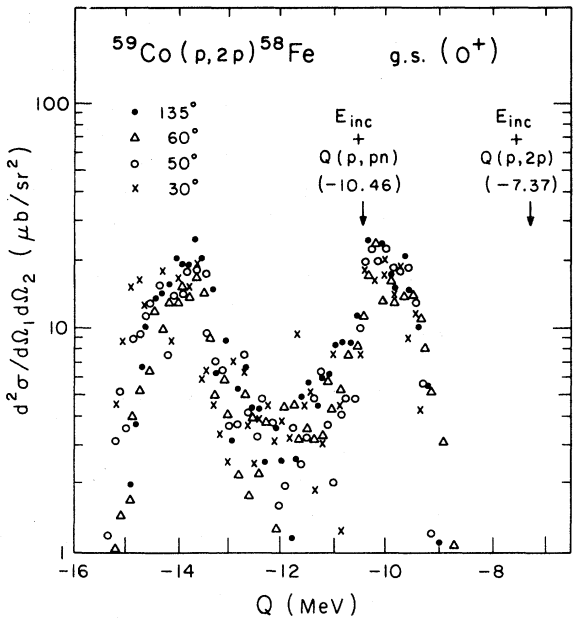

FIG. 5. Energy spectrum of protons from ^{59}Co(p, 2p)-^{58}Fe(g.s.).

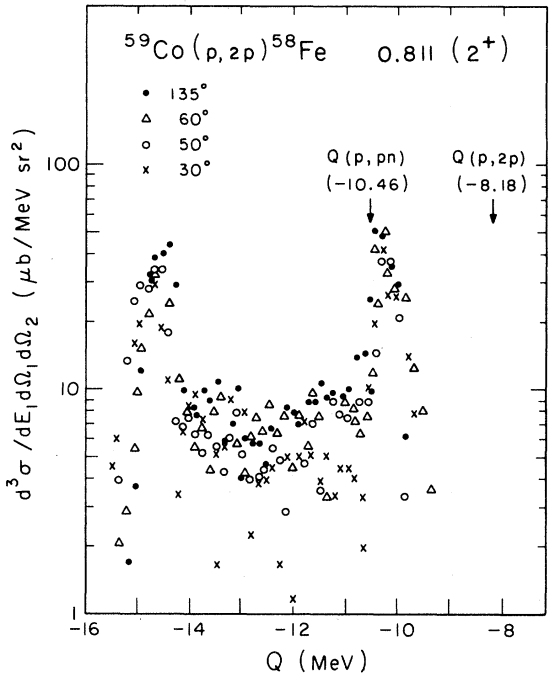

FIG. 6. Energy spectrum of protons from ^{59}Co(p, 2p)-^{58}Fe(0.81 MeV state).

the random coincidence spectrum and subtracted from the first projected spectrum.

ANALYSIS AND RESULTS

We divide (p, 2p) reactions into two categories based on the time delay between emission of the two protons:

(a) A double-direct reaction where the two protons are "simultaneously" emitted; i.e., the total time for the entire reaction is of the order of 10^{-22} sec.

(b) A (p,p') reaction leads to an excited nucleus which then decays by a proton boiloff with a time delay much longer than 10^{-22} sec.

In process (a), from phase space considerations we expect a spectrum with a maximum at one-half the total energy for the two protons. In process (b), however, the spectrum is quite different. For it, the energy spectrum in each detector [under the condition that it is from a (p, 2p) reaction exciting a definite final state] is as shown in Fig. 3. The point marked $E_{inc}+Q(p, 2p)$ is the sum of the energies of the two protons as determined by the Q value of the reaction; the spectrum must be symmetrical about half this energy. Low energy emitted protons are in competition with γ ray emission so the lowest (and therefore, by symmetry, the highest) energy portion of the spectrum is governed by this competition until at about 3 MeV (in the $A = 60$ mass region), proton emission becomes predominant and the curve flattens. How-

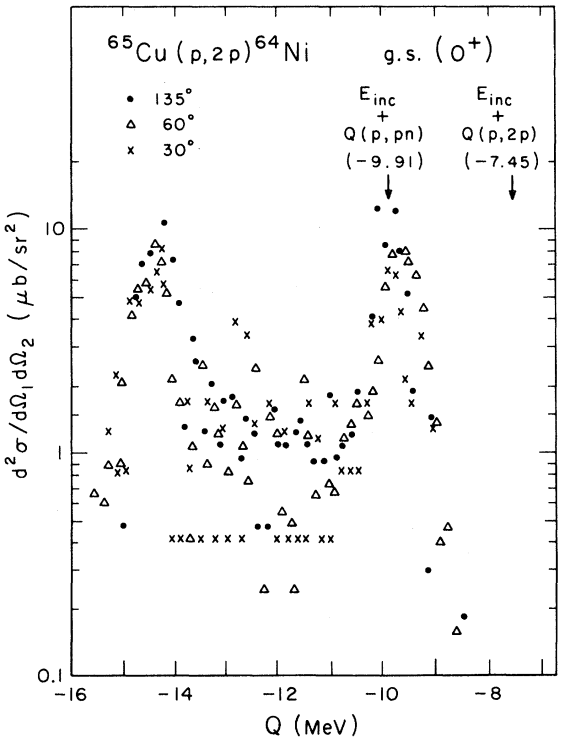

FIG. 7. Energy spectrum of protons from ^{65}Cu(p, 2p)-^{64}Ni(g.s.).

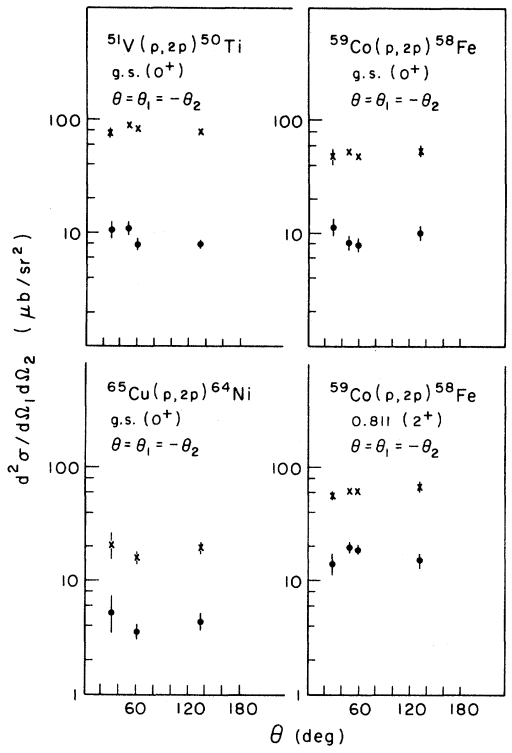

FIG. 8. Angular distributions for various cases studied of protons emitted from $(p,2p)$ reactions with $\theta=\theta_1=-\theta_2$. Crosses are for the entire energy spectrum and dots are for the portion of the energy spectrum near $E_1=E_2$, not including the peaks due to second proton boiloff. Vertical lines are one standard deviation due to counting statistics.

ever, if the first proton is emitted with energy less than $E_{\rm inc}+Q(p,pn)$, it can be followed by neutron emission, so most reactions are (p,pn) rather than $(p,2p)$ and the curve drops sharply.

Many spectra of the shape shown in Fig. 3 were measured and quantitatively explained in Ref. 7 (all data in that study were obtained at $\theta_1=-\theta_2=90°$).

We see that contributions from process (b) are at a minimum at half the total energy, which is where contributions from process (a) are expected to be maximal. This is an ideal situation for detecting process (a). Since it is expected to be characterized by a forward peaked angular distribution, its presence should be signaled by a rise in intensity near half the total energy as the detection angle is decreased.

To improve the sensitivity, target nuclei with low boiloff contributions were chosen. The other criterion in choice of targets was that $Q(p,2p)$ and $Q(p,pn)$ be such as to provide a large energy gap between the two peaks from boiloff reactions in Fig. 3.

Data were taken in coplanar angle pairs ranging from $\pm 30°$ to $\pm 135°$. Because data collection rates had to be reduced at forward angles to maintain reasonable total count rates, it was not found practical to take data at angles more forward than 30°. The spectra obtained at the various angles are shown in Figs. 4–7. In all cases the side peaks due to boiloff protons, show very little variation with angle. There is also no discernible increase in cross section in the central region of the spectrum where we expect the double-direct $(p,2p)$ contribution to appear. Figure 8 shows the angular distributions for reactions exciting various final states. In each case, the upper points (crosses) are the cross sections for the complete spectrum and the lower points (dots) are cross sections for the central region of the spectrum. These results are also given in Table I. There is no significant deviation from an isotropic angular distribution in any of the cases studied.

As a minimum, the difference between the crosses and dots in Fig. 8 represents the contribution of process (b), (p,p') reactions followed by proton boiloff. Since this accounts for at least 75% of the cross section in all cases, and since the remainder is characterized by an isotropic angular

TABLE I. Measured differential cross sections for the various cases studied. Column a is the cross section for the total spectrum and column b is the cross section for the central region around $E_1=E_2$.

	$d^2\sigma/d\Omega,d\Omega_2$ (μb/sr^2) Final state							
	^{50}Ti(g.s.)		^{58}Fe(g.s.)		^{58}Fe(0.811)		^{64}Ni(g.s.)	
	a	b	a	b	a	b	a	b
30°	77.2±4.1	10.8±1.6	47.5±7.6	11.2±2.1	54.4±3.4	14.0±2.4	21.6±4.8	5.6±2.3
50°	90.3±2.6	11.5±1.2	54.0±2.6	8.3±1.4	61.2±2.6	19.7±1.9		
60°	84.1±2.5	8.1±1.0	48.8±2.2	8.0±1.2	63.2±1.2	19.0±1.6	16.6±1.6	3.8±0.7
135°	80.6±2.5	8.1±1.1	55.2±6.3	10.1±1.6	67.9±6.4	14.8±3.2	19.6±2.1	4.4±0.9
Average	83.1	9.6	51.4	9.4	61.7	16.9	19.2	4.6

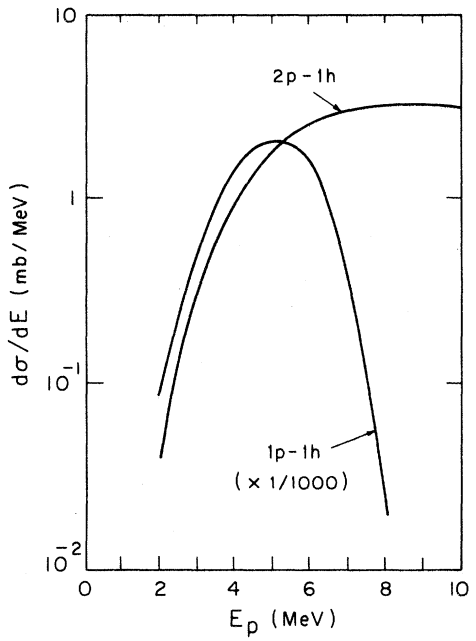

FIG. 9. Theoretical energy spectrum of protons emitted in transition from 2p-1h to 1p-1h states, and from 1p-1h to 1h states.

distribution, there can be little error in estimating the cross section for that process to be equal to the entire observed cross section. On this basis, the total cross sections for (p,p') reactions followed by proton boiloff at 17.0 MeV are 1.05 mb for $^{51}V \rightarrow {}^{50}Ti$(g.s.), 0.65 mb for $^{59}Co \rightarrow {}^{58}Fe$(g.s.), 0.77 mb for $^{59}Co \rightarrow {}^{58}Fe$(0.811 MeV state), and 0.24 mb for $^{65}Cu \rightarrow {}^{64}Ni$(g.s.).

From the isotropy of the angular distributions represented by the dots in Fig. 8, it seems evident that the cross section for the double-direct $(p,2p)$ reaction at $\theta_1 = -\theta_2 > 30°$ is not more than about 5 $\mu b/sr^2$ for any of the four cases studied. From this it seems reasonable to infer that the total cross section for that reaction is of the order of 10 μb or less

Since direct (p,p') reactions are basically a nucleon-nucleon collision inside the nucleus in which one of the nucleons escapes, and that reaction has a cross section of about 100 mb in this mass and bombarding energy region, it seems surprising that the other nucleon in the collision would not escape at least one time in ten thousand.

THEORY

In order to understand this result, a calculation of the cross section for the double-direct $(p,2p)$ reaction was carried out using preequilibrium theory[8] with the hybrid model of Blann.[9,10] The double-direct $(p,2p)$ reaction was taken to be a proton emission from a 2p-1h (two-particle–one-hole) state leaving a 1p-1h state, followed by a proton emission leaving the final nucleus in a 1h state.

TABLE II. Predictions of the hybrid model for the 1p-1h decay cross section.

Final state	σ (μb)
^{50}Ti(g.s.)	9.0
^{58}Fe(g.s.)	6.0
^{58}Fe(0.811)	1.5
^{64}Ni(g.s.)	5.0

The calculation used the parametrized intranuclear transition rate of Blann with constant single-particle level spacing $g_n = (A-Z)/14.1$ MeV and $g_p = Z/14.1$ MeV. Equation (6a) of Ref. 8 was evaluated numerically for each energy interval and the results summed to obtain the total cross section.

Figure 9 shows the energy distribution of protons emitted from 2p-1h and 1p-1h states. We see that the spectrum from the 1p-1h state peaks at approximately half the available energy as we expect, while the 2p-1h spectrum tends to higher energies. Unfortunately, the theory contains no angular information, so it predicts only a total cross section. In general we can expect only semiquantitative predictions from this type of calculation.

The results of the calculations for the cases studied experimentally are listed in Table II. These are the cross sections for production of a single-hole state; the differences among them are basically due only to differences in energetics. Hence, we still must multiply them by the fraction of the single-hole state contained in the particular nuclear state observed. This is essentially the spectroscopic factor well known from pickup reactions. The simplest case from this standpoint is $^{65}Cu(p,2p)^{64}Cu$. This is a $(p_{3/2})^1 \rightarrow (p_{3/2})^0$ transition which has a unit spectroscopic factor. From Table II we see that the cross section predicted for it is 5 μb which is of the same order as the upper limit observed experimentally. For the other cases, spectroscopic factors are less than unity, so the calculated cross sections are somewhat below the experimental upper limit.

The authors are indebted to M. Blann and A. Mignerey for several useful discussions on preequilibrium calculations, and to F. D. Snyder of this laboratory for his help in adapting the computer data taking program for this experiment.

*Supported by the National Science Foundation.

[1]G. Jacob and Th. A. J. Maris, Rev. Mod. Phys. 38, 121 (1966); 45, 6 (1973).

[2]F. Bertrand, C. Waddell, R. Eisberg, D. Ingham, and M. Makino, Nucl. Phys. A152, 337 (1970).

[3]R. J. Griffiths and R. M. Eisberg, Nucl. Phys. 12, 225 (1959).

[4]K. Richie, R. Eisberg, M. Makino, and C. Waddel, Nucl. Phys. A131, 501 (1969).

[5]K. H. Bray, S. N. Bunker, M. Jain, K. S. Jayaraman, C. A. Miller, C. A. Nelson, J. M. Nelson, W. T. H. van Oers, and D. O. Wells, Phys. Lett. B35, 41 (1971); K. H. Bray, S. N. Bunker, M. Jain, K. S. Jayaraman, C. A. Miller, J. M. Nelson, W. T. H. van Oers, and D. O. Wells, Can. J. Phys. 51, 1012 (1973).

[6]B. L. Cohen, Phys. Rev. 108, 768 (1957).

[7]C. L. Fink and B. L. Cohen, Phys. Rev. C 6, 1673 (1972)

[8]M. Blann, Annu. Rev. Nucl. Sci. 25, 123 (1975); M. Blann, in *Proceedings of the Europhysics Conference on Intermediate Processes in Nuclear Reactions*, edited by N. Cindro, T. Mayer-Kuckuk, and P. Kulisic (Springer-Verlag, Berlin, 1972); M. Blann, A. Mignerey, and W. Scobel, Equilibration Processes in Nuclear Reactions: Nucleons to Heavy Ions, lecture series presented at the Eighth Summer School in Nuclear Physics organized by Warsaw University, 24 August–6 September 1975 (unpublished), University of Rochester Report No. COO-349-28.

[9]M. Blann, Phys. Rev. Lett. 27, 337 (1971).

[10]M. Blann and A. Mignerey, Nucl. Phys. A186, 245 (1972).