Germany.

‡A. v. Humboldt Fellow. Permanent address: Institute of Atomic Physics, Bucharest, Romania.

[1]A. M. Lane, Phys. Lett. 33B, 274 (1970).

[2]C. F. Moore, C. E. Watson, S. A. A. Zaidi, J. J. Kent, and J. G. Kulleck, Phys. Rev. Lett. 17, 926 (1966).

[3]S. A. A. Zaidi, W. R. Cocker, and D. G. Martin, Phys. Rev. C 2, 1384 (1970).

[4]T. Tamura and C. E. Watson, Phys. Lett. 25, 186 (1967).

[5]J. Zimanyi and B. Gyarmati, Phys. Lett. 41B, 571 (1972).

[6]R. Cocker and T. Tamura, Phys. Rev. 182, 1277 (1969).

[7]G. Clausnitzer, G. Graw, C. F. Moore, and K. Wienhard, Phys. Rev. Lett. 22, 793 (1969); K. Wienhard and G. Graw, in *Proceedings of the Third International Symposium on Polarization Phenomena in Nuclear Reactions, Madison, Wisconsin, 1970,* edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1970), p. 655.

[8]J. G. Cramer *et al.*, Phys. Rev. C 6, 366 (1972), and Ref. 14 therein.

[9]P. D. Kunz, the DWBA code DWUCK (private communication).

[10]G. Clausnitzer *et al.*, Nucl. Instrum. Methods 80, 247 (1970).

[11]W. Stach, Diplom-thesis, Universität Erlangen, 1973 (unpublished).

[12]J. L. Horton *et al.*, Nucl. Phys. A190, 362 (1972).

[13]J. A. R. Griffith, O.Karban, and S. Roman, Department of Physics, University of Birmingham, Report No. 711, 1971 (unpublished).

Cross-Section Measurements for the (p, n) Analog Transition in ^{181}Ta, ^{197}Au, and ^{209}Bi†

S. M. Grimes, J. D. Anderson, J. C. Davis, W. H. Dunlop, and C. Wong
Lawrence Livermore Laboratory, Livermore, California 94550
(Received 5 March 1973)

Cross sections for (p,n) transitions to analog states for targets of Ta, Au, and Bi have been measured. The cross section and decay width observed for Bi are inconsistent with those obtained from $(p,n\tilde{p})$ measurements. We propose an explanation for these discrepancies.

Because of the experimental difficulty of neutron measurements relative to charged-particle experiments, a number of investigations of the (p, n) reaction to analog states have utilized the subsequent proton decay of the analog state to determine cross sections for this transition. Low-lying analog states for medium and heavy nuclei are above the proton emission threshold and neutron decay can occur only through isospin mixing; thus, a significant fraction of the analog states would be expected to decay through proton emission. In general, this fraction is not known, but it would not depend on the proton bombarding energy. Measurement of the excitation function of the protons corresponding to decay of the analog state (denoted $\tilde{p}$) whould give the energy dependence of the analog (p, n) cross section itself and yield a lower limit for the absolute value of this cross section. In addition, since the $\tilde{p}$ decays lead to particle-stable states (of very small or zero width), the width of the $\tilde{p}$ peak should depend on the width of the analog state and kinematics. If the decay is to isolated final states, a determination of the analog state width from $\tilde{p}$ spectra is possible. Results have been published for both the energy dependence of the cross section and the width of the analog state based on $\tilde{p}$ measurements.

Unfortunately, both the width and cross-section measurements[1,2] have led to inconsistencies for lead. The analog-state widths deduced from $\tilde{p}$ measurements have been as much as a factor of 1.5 larger than those obtained from the (p, n) reaction or proton scattering. At the same time, the $\tilde{p}$ cross section, which should be a lower limit for the (p, n) cross section to the analog state, has been found to be larger than this value for ^{208}Pb. The present measurements were undertaken to extend the comparison to targets of Ta, Au, and Bi.

Cross sections for the (p, n) transition to analog states have been measured for targets of Ta, Au, and Bi at proton energies of 25 and 27 MeV with the time-of-flight spectrometer at the Lawrence Livermore Laboratory cyclograaff facility. Angular distributions for the three targets at 27 MeV are shown in Fig. 1. Integrated cross sections at both energies were obtained from five-

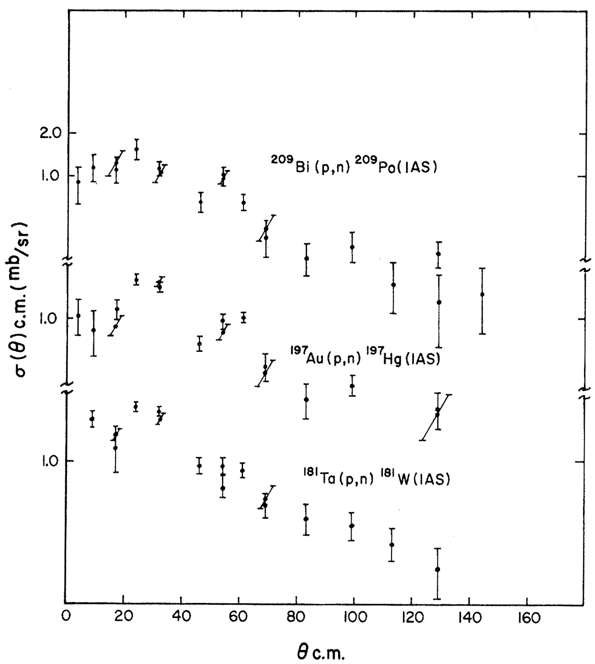

FIG. 1. Cross sections at E_p=27 MeV for the (p,n) transition to analog states for targets of ^{181}Ta, ^{197}Au, and ^{209}Bi.

term Legendre fits to the data and are presented in Table I with $\tilde{p}$ cross sections for the same three targets.[3,4] The Bi(p,n) cross sections are *smaller* than those from $(p,n\,\tilde{p})$ measurements as has been previously observed[1,2] for ^{208}Pb, but for the remaining targets the $\tilde{p}$ cross sections are, as expected, smaller than the (p,n) analog cross sections. The data also provide information on the widths of the analog states; a value of 235 ± 50 keV was obtained for Bi from the (p,n) reaction, which is inconsistent with the $\tilde{p}$ value[5] of 327 ± 31 keV. Similar disagreement[5,6] has been observed for ^{208}Pb.

Thus, the inconsistencies observed for ^{208}Pb are also present for ^{209}Bi but not for ^{181}Ta and ^{197}Au. An explanation of this phenomenon involves (1) population of analogs of excited states through other reaction channels, *and* (2) preferential decay of such analog states through emission of protons of approximately the same energy as the ground-state $\tilde{p}$ decays, which requires that the analogs of excited states have comparable spacing to states in the final daughter nucleus. Clearly, such a correlation in proton decay energy is plausible only near closed shells where a weak-coupling model may apply. We first discuss reaction mechanisms.

Calculation of the $\tilde{p}$ energy expected from (p,p')

TABLE I. $\sigma(p,n)$ and $\sigma(p,n\tilde{p})$ for ^{181}Ta, ^{197}Au, and ^{209}Bi.

Target	Bombarding energy (MeV)	$\sigma(p,n)$ (mb)	$\sigma(p,n\tilde{p})$ (mb)
^{209}Bi [a]	24.8		14.9
	25	5.4	
	26.1		14.5
	27	5.7	
	28.5		12.9
^{197}Au [b]	25	7.3	2.0
	27	6.8	2.0
^{181}Ta [b]	25	7.6	1.4
	27	7.6	1.3

[a] $\tilde{p}$ cross sections from Ref. 3.
[b] $\tilde{p}$ cross sections from Ref. 4.

reactions populating analog states indicates that proton decays from these states would not be included in the $\tilde{p}$ peak from the (p,n) reaction. The reaction $(p,2n)$ at 25- to 27-MeV bombarding energy cannot populate analog states. A remaining possibility is population through the (p,n) reaction of analogs of excited states rather than the ground-state analog. Such reactions could occur through two-step direct processes [i.e., (p,p') followed by charge exchange] or by pre-equilibrium decay of analog states in the compound nucleus. No additional peaks are observed in the neutron spectra, but because of the neutron continuum in this region, we estimate that cross-section values as large as 1 to 2 mb for a single level might not be observable, depending on the angular distribution.

Ordinarily, decay of excited analogs would occur through the emission of protons more energetic than the $\tilde{p}$ corresponding to the ground-state analog; because the proton energy is below the Coulomb barrier height, those transitions corresponding to the emission of the most energetic protons possible are favored. If the nuclei involved are near a closed shell, the density of levels at low excitation will be reduced and their character may differ significantly from level to level, i.e., configuration mixing is small. In such a case, the excited analog states may decay to states of the appropriate configuration in the final nucleus, which in the weak-coupling limit will have approximately the same excitation energy in the residual nucleus as the excited analogs have relative to the ground-state analog. This process would produce additional protons

TABLE II. Configurations for low-lying levels in ^{208}Bi and ^{209}Bi.

^{209}Bi excitation energy (MeV)	Dominant configuration	^{208}Bi excitation energy (MeV)	Dominant configuration
0	$1h_{9/2}$	0, 0.06	$1h_{9/2}3p_{1/2}^{-1}$
		5 levels between 0.51 and 0.65	$1h_{9/2}2f_{5/2}^{-1}$
		4 levels between 0.89 and 1.09	$1h_{9/2}3p_{3/2}^{-1}$
0.89	$2f_{7/2}$	0.94, 1.04	$2f_{7/2}3p_{1/2}^{-1}$
1.61	$1i_{13/2}$	1.63, 1.67	$1i_{13/2}3p_{1/2}^{-1}$
2.82	$2f_{5/2}$	2.89, 2.95	$2f_{5/2}3p_{1/2}^{-1}$

with approximately the same energy as the protons produced by decays of the ground-state analog, resulting in values for both the width and cross section which are too large.

For illustration, consider the nucleus ^{209}Bi. As is shown in Table II, the first three states have the dominant proton particle configurations $1h_{9/2}$, $2f_{7/2}$, and $1i_{13/2}$, respectively. The analog states of these levels will differ by the addition of a combination of $2f_{7/2}$, $1h_{9/2}$, $2f_{5/2}$, $3p_{3/2}$, $1i_{13/2}$, and $3p_{1/2}$ proton-particle, neutron-hole states. If the decay proceeds through emission of a low angular momentum proton (because of the sub-Coulomb barrier energy), the ground-state analog will decay to levels in ^{208}Bi consisting of a $1h_{9/2}$ proton coupled to a $3p_{3/2}$, $3p_{1/2}$, or $2f_{5/2}$ neutron hole; such states are found at 0.9-, 0-, and about 0.55-MeV excitation. Similarly, the first and second excited states will decay to states of $2f_{7/2}$ and $1i_{13/2}$ proton particles, respectively, coupled to $3p_{3/2}$, $3p_{1/2}$, or $2f_{5/2}$ neutron holes. Again, levels with these configurations in ^{208}Bi occur at energies shifted by the right amount to produce decays of the same energy as those from the ground-state analog. This explanation requires both population of excited analog states and applicability of the weak-coupling model. This latter assumption would break down for nuclei farther from closed shells, with the result that decay protons from excited analog states would then not fall in the peak corresponding to ground-state analog decays.

If this explanation is correct, the $\tilde{p}$ cross sections should agree with those measured for the (p,n) reaction below the threshold for excitation of analogs of excited states. This does not contradict present information, since (p,n) measurements have not been made near the ground-state threshold. Width measurements using $\tilde{p}$ decay, however, have been carried out[5] at energies too low to excite the excited analog states for ^{208}Pb, and it has been determined that the widths remain anomalous in this energy region. It should be emphasized, however, that such a determination relies on the knowledge of the angular distribution of the (p,n) reaction, in order to calculate the kinematic effects[7] caused by the recoil of the residual nucleus on the $\tilde{p}$ energy distribution. Since such measurements are available only at bombarding energies 2 or 3 MeV higher, extrapolated angular distributions have been used near the threshold. If, for example, the (p,n) reaction had a more isotropic angular distribution in this energy region than has been assumed, kinematic corrections could increase, and reduce the inferred width of the analog state. Such an angular distribution could occur if a compound-nucleus reaction mechanism from $T^>$ decay contributes to the (p,n) analog cross section near threshold.[8] Because nuclei near closed shells have reduced level densities at low excitation, proton decay channels (for which the Coulomb barrier cuts off decays except to relatively low-lying states) and neutron decay channels (for which isospin-allowed decay occurs only to the ground-state analog in this energy region) for compound-nucleus analog states are less numerous than for corresponding nonclosed-shell nuclei. In addition, proton decay will be inhibited by the isospin Clebsch-Gordan coefficient $1/(2T+1)$, where T is the isospin of the target. This factor is about $\frac{1}{40}$ in the Pb-Bi mass region, resulting in a significant enhancement of the yield in the neutron channel, for which the coefficient is $2T/(2T+1)$. Thus, the compound-nuclear contribution to (p,n) analog states near closed shells might not drop as fast as would be expected on the basis of the level densities at higher energies in these nuclei.

An experimental test of both parts of this explanation could be carried out by measuring (p,n) cross sections in coincidence with $\tilde{p}$ events. At energies beyond the threshold for populating excited analog states, coincidence measurements with adequate neutron energy resolution should yield cross sections smaller than the noncoincidence $\tilde{p}$ spectra. In addition, the neutron spectra gated by $\tilde{p}$ events should show peaks corresponding to excited analog states as well as the ground state. Correspondingly, the $\tilde{p}$ peak in spectra gated by the neutron peak should be somewhat narrower than the ungated $\tilde{p}$ peak. Finally, if the bombarding energy is lowered below the threshold for populating excited analog states, the coincidence measurements should show a more isotropic neutron angular distribution than higher-energy measurements. In this case, the coincidence $\tilde{p}$ peak should again show a narrower width than that in the ungated spectra, since in this case the kinematic effects are reduced because detection of the neutron defined the direction of the recoil nucleus.

By invoking neutron decay of $T^>$ states (compound nucleus) near threshold and pre-equilibrium ($T^>$) or multistep processes at higher energies populating excited analog states, one can account for anomalous widths and cross sections obtained from $(p, n\,\tilde{p})$ measurements on nuclei near closed shells.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]T. J. Woods, C. A. Whitten, and G. J. Igo, Nucl. Phys. A198, 542 (1972).

[2]G. J. Igo, C. A. Whitten, Jr., J.-L. Perrenoud, J. W. Verba, T. J. Woods, J. C. Young, and L. Welch, Phys. Rev. Lett. 22, 724 (1969).

[3]G. W. Hoffmann, W. H. Dunlop, G. J. Igo, J. G. Kulleck, J. W. Sunier, and C. A. Whitten, Jr., Nucl. Phys. A187, 577 (1972).

[4]W. H. Dunlop, private communication.

[5]G. M. Crawley and P. S. Miller, Phys. Rev. C 6, 306 (1972).

[6]G. M. Crawley, P. S. Miller, A. Galonsky, T. Amos, and R. Doering, Phys. Rev. C 6, 1890 (1972).

[7]C. A. Whitten, Jr., Phys. Rev. C 5, 1667 (1972).

[8]Contributions from nondirect processes to the reaction $^{51}V(p,n)^{51}Cr$ to the ground-state analog near threshold have been invoked to explain anomalous energy dependence and angular distributions by C. Wong, J. D. Anderson, J. C. Davis, and S. M. Grimes, Phys. Rev. C 7, 1895 (1973).

Determination of Compound Nuclear Lifetimes by the Blocking Technique*

Y. Hashimoto†
Rutgers University, New Brunswick, New Jersey 08983, and Bell Laboratories, Murray Hill, New Jersey 07974

and

J. H. Barrett
Solid State Division, Oak Ridge National Laboratory,‡ Oak Ridge, Tennessee 37830

and

W. M. Gibson
Bell Laboratories, Murray Hill, New Jersey 07974

(Received 16 March 1973)

We report the results of a comprehensive computer simulation of angular distributions of 4.0-MeV protons scattered by a 3-μm-thick Ge crystal and emerging near a ⟨110⟩ direction. They show that interpretation of measured blocking distributions to obtain short nuclear lifetimes is strongly dependent on the recoil direction and depth distribution of the recoiling compound nuclei in the crystal. This dependence is explained in terms of the associated flux peaking effect in particle channeling.

The technique of very short (10^{-14}–10^{-18} sec) nuclear lifetime measurements by use of the "particle-blocking" effect in single crystals is now well established and promises to become an important tool in studies of nuclear properties. The purpose of this Letter is to give a preliminary report of a detailed calculation of the effect for a particular case (elastic and inelastic scattering of 5-MeV protons in a germanium crystal) which demonstrates for the first time a crucial dependence on the recoil direction of the decaying compound nucleus and on emission depth in the crystal.

A large-scale Monte Carlo calculation was carried out in which the channeling trajectories of 2500 protons were determined by calculation of each binary scattering event between the protons and lattice atoms. The proton energy, incidence directions, and the path length of 3 μm were chosen to correspond to the emergent par-