RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 57, NUMBER 3 MARCH 1998

Observation of the exotic nucleus ^{145}Tm via its direct proton decay

J. C. Batchelder,[1] C. R. Bingham,[2,3] K. Rykaczewski,[2,4] K. S. Toth,[2] T. Davinson,[5] J. A. McKenzie,[5] P. J. Woods,[5]
T. N. Ginter,[6] C. J. Gross,[2,7] J. W. McConnell,[2] E. F. Zganjar,[8] J. H. Hamilton,[6] W. B. Walters,[9] C. Baktash,[2] J. Greene,[10]
J. F. Mas,[2] W. T. Milner,[2] S. D. Paul,[2] D. Shapira,[2] X. J. Xu,[3,11,12] and C. H. Yu[2]
[1]*UNIRIB, Oak Ridge Associated Universities, Oak Ridge, Tennessee 37831*
[2]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*
[3]*University of Tennessee, Knoxville, Tennessee 37996*
[4]*Warsaw University, 00681 Warsaw, Hoza 69, Poland*
[5]*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[6]*Vanderbilt University, Nashville, Tennessee 37235*
[7]*Oak Ridge Institute for Science and Education, Oak Ridge, Tennessee 37831*
[8]*Louisiana State University, Baton Rouge, Louisiana 70803*
[9]*University of Maryland, College Park, Maryland 20742*
[10]*Argonne National Laboratory, Argonne, Illinois 60439*
[11]*Institute of Modern Physics, Lanzhou, 730000, China*
[12]*Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee 37831*

(Received 1 December 1997)

Proton emission from ^{145}Tm was observed for the first time via the ^{92}Mo(^{58}Ni,$p4n$) reaction, using the Holifield Radioactive Ion Beam Facility Recoil Mass Spectrometer in conjunction with a double-sided Si strip detector at the focal plane. The measured energy of the emitted proton is 1.728(10) MeV and its half-life is 3.5(10) μs, the shortest ever observed for ground-state proton radioactivity. When compared to the calculated WKB half-life for an $l=5$ transfer, the spectroscopic factor is 0.51(16), which is consistent with the value of 0.64 calculated via the BCS approximation for a spherical nucleus. Also, the half-life of ^{113}Cs was determined with a greater precision than previously available to be 16.7(7) μsec. [S0556-2813(98)50803-5]

PACS number(s): 23.50.+z, 21.10.Jx, 21.10.Tg, 27.60.+j

Nuclei that are energetically unbound to the emission of a proton are located beyond the proton drip line. Observation of protons emitted from these isotopes allows us not only to establish the limits of stability for a given element, but also gives information on the structure and mass of the parent nucleus. The emitted proton tunnels through the Coulomb and centrifugal barriers, and the decay probability depends strongly on the energy of the proton and on its angular momentum l. Because of this, the l value of the emitted proton can often be determined. The decay of odd-Z, even-N parent nuclei usually occurs to the ground state of the daughter even-even nucleus, hence providing the mass of the parent state relative to that of the daughter even-even nuclide.

A simple spherical WKB calculation of the expected rate of the tunneling process does not take into account the details of the nuclear structure effects. Therefore the difference between the calculated and experimental half-lives is due to nuclear structure effects (the overlap between the wave functions of the parent and daughter states) and is known as the spectroscopic factor. This is defined by McFarlane and French [1] as

$$S_p^{\mathrm{th}}=(2I_i+1)^{-1}\langle I_i \| a^{\dagger}(j) \| I_f\rangle^2, \tag{1}$$

where $a^{\dagger}(j)$ is the creation operator for a proton in orbital j, and I_i and I_f are the angular momenta of the parent (initial) and daughter (final) states, respectively. The ratio of the calculated half-life to the measured value is defined as the experimental spectroscopic factor:

$$S_p^{\mathrm{exp}}=\frac{T_{1/2}^{\mathrm{calc}}}{T_{1/2}^{\mathrm{exp}}}, \tag{2}$$

where $T_{1/2}^{\mathrm{exp}}$ is the total half-life divided by the fraction of the decay that goes by proton emission, and $T_{1/2}^{\mathrm{calc}}$ is the half-life determined using the WKB approximation for a spherical nucleus.

Recently, attempts [2,3] to understand the spectroscopic factors for known proton emitters have been undertaken. If one assumes that in the $65<Z<82$ region the active proton orbitals are $2s_{1/2}$, $1d_{3/2}$, and $0h_{11/2}$, and that these orbitals are degenerate, a low-seniority shell model [2] predicts that the spectroscopic factors scale as $p/9$, where p is the number of proton pairs below $Z=82$. Experimental values for those proton-emitters that decay from the $0h_{11/2}$ orbital (but not the $1d_{3/2}$) seem to follow this trend well. Åberg *et al.* [3] have calculated S_p^{th} via an independent quasiparticle BCS approximation [4]; their S_p^{th} values for proton decay from a $0h_{11/2}$ parent state are ~75% of the values obtained with the $p/9$ relationship [2].

A comparison of S_p^{th} values with experimental ones is rather inconclusive for nuclei with $Z<72$, because the known proton emitters in this region have either large error bars for their branching ratios (as is the case for ^{147}Tm: 15(5)% [5]), or theβ-decay branch is unknown (^{146}Tm [6] and ^{150,151}Lu [7]) and is estimated from the gross β-decay theory of Takahashi *et al.* [8]. If the estimate is in error by a factor of 2 or more, its use would result in a corresponding uncertainty in the spectroscopic factor. These nuclei lie to

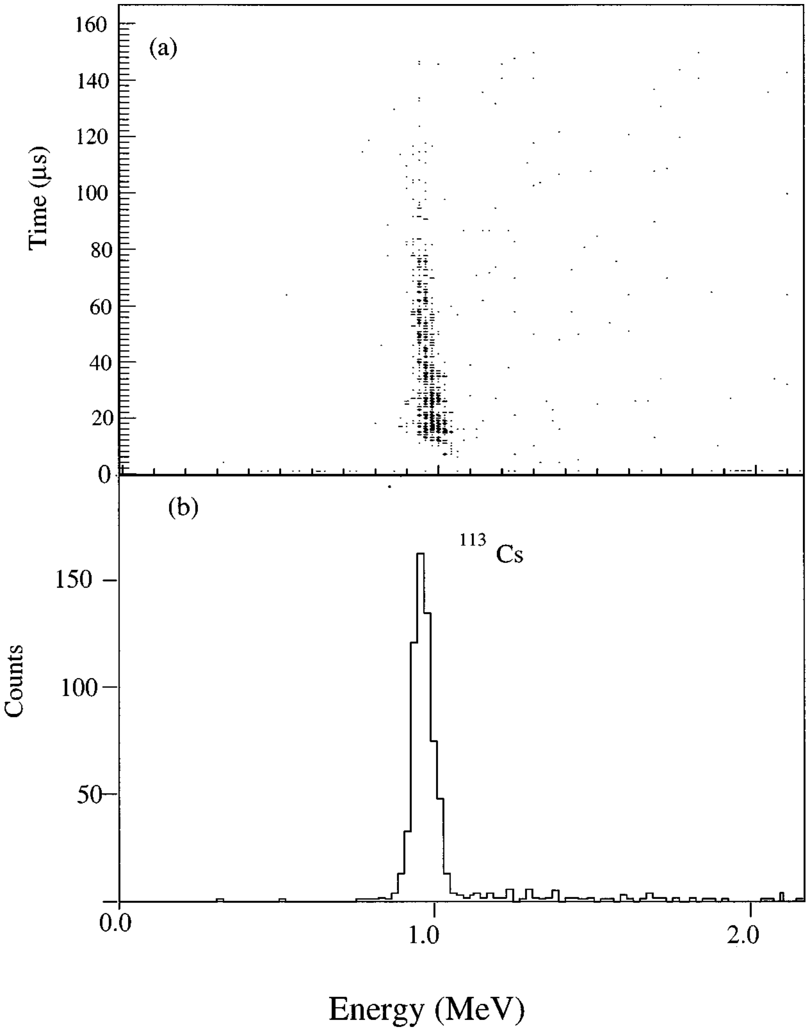

FIG. 1. (a) Shows the two-dimensional histogram of time (between recoil implantation and decay) vs the energy of protons emitted from ^{113}Cs. (b) Shows the corresponding one-dimensional energy spectrum.

the neutron-deficient side of the $N=82$ closed shell, so that the major competition with proton emission is β rather than α decay. Because β-decay branching ratios are difficult to measure accurately, large uncertainties exist in the corresponding partial proton half-lives. With this in mind we began a search for ^{145}Tm which was expected to have a proton half-life far too short for β-decay to compete, resulting in a 100% proton branching ratio.

Thulium-145 was produced via the ^{92}Mo(^{58}Ni,$p4n$) reaction. A 0.91-mg/cm^2 thick target of ^{92}Mo (97% enrichment) was bombarded with 315-MeV ^{58}Ni ions (307 MeV at the target midpoint) extracted from the Oak Ridge Holifield Radioactive Ion Beam Facility (HRIBF) Tandem Accelerator, with an average beam current on target of ~15 particle nA over a period of 50 hours. Recoil nuclei of interest were separated spatially according to their mass/charge (A/Q) values through the HRIBF Recoil Mass Spectrometer (RMS) [9,10,11], which was tuned to accept recoils of mass 145 with a charge of 27 and an energy of 103 MeV. A gas-filled position sensitive avalanche counter (PSAC) at the focal plane was used to identify the recoils. In similar reactions, the RMS transmission efficiency for the central ion has been determined to be 3–4 % [12]. Following the PSAC, only the central ions were implanted into a 64-μm-thick double-sided silicon strip detector (DSSD) [13] with 40 horizontal and 40 vertical strips. This strip arrangement results in a total of 1600 pixels, each acting as an individual detector. For each event in the DSSD, the time (from a continuously running clock), energy, and event type (recoil or decay, depending on whether it is in coincidence with the PSAC or not) were recorded. By using this time information, the half-life of the decaying nuclide could be determined. Individual strips were gain-matched in software through the use of (i) an external ^{241}Am source, (ii) ^{147}Tm and ^{147m}Tm protons [7,14] produced in the ^{92}Mo(^{58}Ni,$p2n$) reaction, and (iii) protons from ^{113}Cs [15,16,17] produced in the ^{58}Ni(^{58}Ni,$p2n$) reaction at a beam energy of 230 MeV.

The shortest time observable between a recoil and its associated decay with our setup is determined by the recovery time of the amplifiers after overload due to the implantation of the high-energy recoil. This effect causes decay events coming shortly ($<\sim$30 μsec) after the implant to have a slightly worse energy resolution because each amplifier's response is somewhat different. In the present experiment, ^{145}Tm proton decays were observed $>$10 μsec after the recoil event. The effect on the resolution is illustrated in Fig. 1(a) which shows the experimental two-dimensional histogram of time (between recoil and decay) versus the energy of

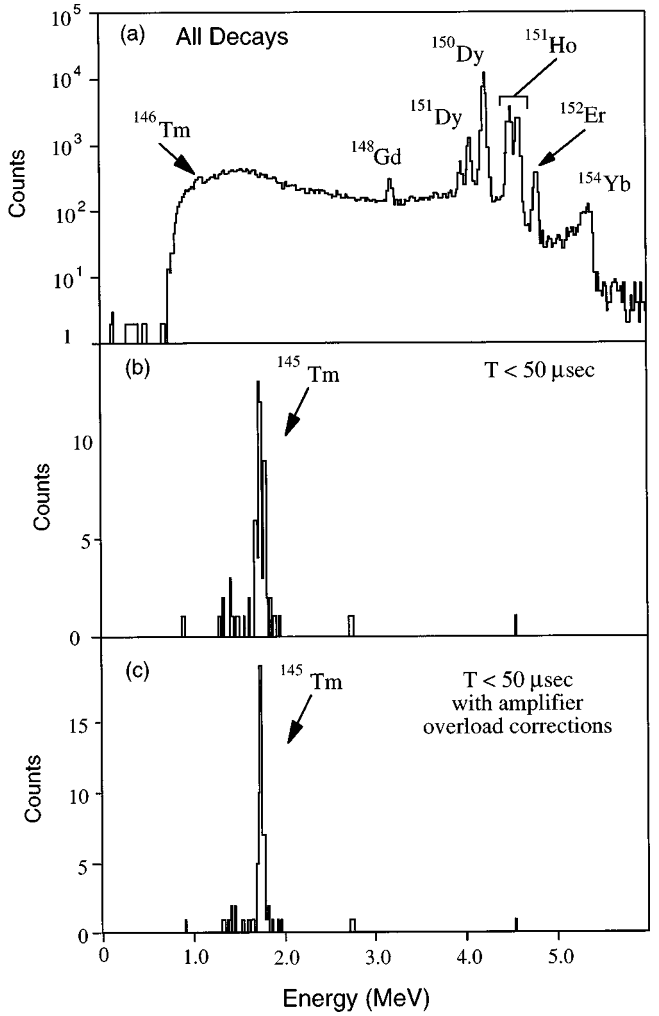

FIG. 2. (a) Total decay spectrum observed in the DSSD during 307-MeV ^{58}Ni bombardments of ^{92}Mo. The α peaks above 3 MeV arise from nuclei formed in reactions on isotopic impurities present in the ^{92}Mo target. (b) The same spectrum gated on $A=145$ recoils, with a time between decay and recoil implantation of <50 μs. (c) The spectrum in (b) with corrections to the resolution resulting from the amplifier overload of each strip.

protons emitted from ^{113}Cs. Figure 1(b) shows the corresponding one-dimensional energy spectrum. (Degrader foils located in front of the DSSD were used to keep the recoil energies at ~35 MeV for both the production of ^{113}Cs and ^{145}Tm.) Based on the data from ^{113}Cs, we were able to correct for this effect in our ^{145}Tm measurements. Energy calibration of the DSSD was accomplished by using the well-characterized decay energies of ^{113}Cs, ^{146}Tm, ^{147}Tm and ^{147m}Tm.

Figure 2(a) shows the total decay spectrum accumulated in the ^{58}Ni+ ^{92}Mo irradiation. One observes α-decay peaks of nuclei produced in reactions on isotopic impurities whose A/Q value is similar to that of the central ion. The lower energy side of the spectrum is dominated by a broad distribution of ''escape'' events resulting from α decays in the backward direction, i.e., only part of the energy is deposited in the DSSD. Also visible is a peak at 1.12 MeV which we attribute to protons from ^{146}Tm [6,18], and which provided us with an internal energy calibration. Figure 2(b) shows only those events that had a time between implantation and decay of <50 μs. In this spectrum, a peak with an energy of 1.728(10) MeV is clearly seen. We assign it to the proton decay of ^{145}Tm as no other nucleus with $A=145$ and $Z<69$ is proton unbound [19]. Since all the events in this peak came at very short times after recoil implantation, the energy resolution is poorer than what is normally observed for decays with longer half-lives. By correcting for the overload effect of the amplifiers, the resolution of this peak was improved as shown in Fig. 2(c). If the overall detection efficiency of the RMS is taken to be 3% (for this charge state fraction), the production cross section for ^{145}Tm is estimated to be 500 nb.

TABLE I. Comparison of the ^{145}Tm half-life with calculated values.

E_p	$T_{1/2}$	$0h_{11/2}$ $(\Delta l=5)$	$T_{1/2}$ (WKB) $1d_{3/2}$ $(\Delta l=2)$	$2s_{1/2}$ $(\Delta l=0)$
1.728(10)	3.5(10) μs	$1.8^{+0.3}_{-0.2}$ μs	0.7(1) ns	80(12) ps

As mentioned above, half-life information can be obtained by correlating the times of a recoil and the next decay event in a given pixel. The resulting half-life for the ^{145}Tm proton peak is 3.5(10) μs. This represents the shortest ground-state proton decay measured to date. During the course of calibrating the amplifier's overload response with ^{113}Cs, we were able to obtain ~600 proton events from this nucleus. The resulting $T_{1/2}$ obtained is 16.7(7) μs, in agreement with the earlier reported values of 17(2) μs [17], and 22(8) μs [15] but not with the 33(7)-μs half-life from Ref. [16].

A WKB approximation calculation for protons emitted from the $0h_{11/2}$ $(\Delta l=5)$, $1d_{3/2}$ $(\Delta l=2)$, and $2s_{1/2}$ $(\Delta l=0)$ orbitals of ^{145}Tm was performed with the experimental E_p as input. The optical potential was taken from the real part of the optical potential of Becchetti and Greenlees [20]. The calculated half-lives are $1.8^{+0.3}_{-0.2}$ μs, 0.7(1) ns and 80(12) ps, respectively, for $\Delta l=5$, 2, and 0. Comparing these (see Table I) to the experimental value of 3.5(10) μs clearly indicates a $\Delta l=5$ transfer and thus an $0h_{11/2}$ assignment for the parent state which based on level systematics in this mass region is probably the ground state in ^{145}Tm. Taking the WKB value of 1.8 μs for the theoretical half-life results in a spectroscopic factor of 0.51(16) for this $0h_{11/2}$ emitter. The error should be considered as a lower limit since uncertainties due to the optical potential are not included. The value for S_p^{th} obtained by Åberg *et al.* [3] using the BCS approximation is 0.64, which is within one standard deviation of the value reported here.

The experimental proton separation energies for ^{147}Tm, ^{146}Tm, and ^{145}Tm are compared in Table II with the predictions of various mass formulas [21,22,23]. The Möller-Nix formula [21] gives the closest match to the experimental data. It should be noted that the predictions from the more recent work by Möller-Nix-Myers-Swiatecki [23] (which allows ε_3 and ε_6 to vary) are not as accurate.

In summary, we have observed direct proton emission from the $0h_{11/2}$ ground state of ^{145}Tm with E_p and $T_{1/2}$ of

TABLE II. Comparison of experimental and predicted proton decay energies for ^{147}Tm, ^{146}Tm, and ^{145}Tm. All numbers are given in the laboratory frame of reference.

Mass formula	E_p (MeV) ^{147}Tm	^{146}Tm	^{145}Tm	Reference
Möller-Nix	−0.96	−1.25	−1.67	[20]
Möller *et al.*	−0.80	−1.08	−1.50	[20]
Comay-Kelson-Zidon	−0.77	−1.09	−1.40	[20]
Tachibana *et al.*	−0.86	−0.93	−1.44	[20]
Spanier-Johannson	−0.77	−1.09	−1.41	[20]
Jännecke-Masson	−0.66	−0.72	−1.28	[20]
Liran-Zeldes	−0.78	−0.99	−1.44	[21]
Möller-Nix-Myers-Swiatecki	−0.55	−0.60	−0.99	[22]
Experimental	−1.054[19]	−1.120(10)[19]	−1.728(10)	

1.728(10) MeV and 3.5(10) μs respectively. This nuclide, the third proton-emitting isotope of thulium (iridium is the only other element with three known cases [2]), has the shortest half-life measured for ground-state proton decay. The experimental spectroscopic factor and an $0h_{11/2}$ orbital assignment are consistent with an overall spherical description for this nucleus. However, as the best decay energy is predicted by a formula that includes significant deformation, it is possible that ^{145}Tm lies at the edge of the region where the spherical basis is ap-plicable.

The authors would like to thank the HRIBF staff for support of the RMS and associated detector systems during the recent commissioning stage. The work of Dr. Arthur James on the RMS is gratefully acknowledged. UNIRIB is a consortium of universities, the State of Tennessee, Oak Ridge Associated Universities, and Oak Ridge National Laboratory and is partially supported by the U.S. Department of Energy under Contract No. DE-AC05-76OR00033 with the Oak Ridge Associated Universities. Research at Oak Ridge National Laboratory is sponsored by the U.S. Department of Energy under Contract No. DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation. This work is also supported in part by the U.S. DOE under Contract Nos. DE-FG02-96ER40983 (University of Tennessee), DE-FG02-96ER40978 (Louisiana State University), DE-FG02-94-ER40834 (University of Maryland), W-31-109-ENG-38 (Argonne National Laboratory), DE-FG05-88ER40407 (Vanderbilt), and DE-FG05-87ER40361 (JIHIR). P.J.W., T.D., and J.A.M. would like to acknowledge support form EPSRC.

[1] M. H. McFarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).

[2] C. N. Davids, P. J. Woods, J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, T. Davinson, S. J. Freeman, D. J. Henderson, R. J. Irvine, R. D. Page, H. T. Penttilä, D. Seweryniak, K. S. Toth, W. B. Walters, and B. E. Zimmerman, Phys. Rev. C **55**, 2255 (1997).

[3] S. Åberg, P. B. Semmes, and W. Nazarewicz, Phys. Rev. C **56**, 1762 (1997).

[4] R. A. Sorenson and E. D. Lin, Phys. Rev. **142**, 729 (1966).

[5] K. S. Toth, D. C. Sousa, P. A. Wilmarth, J. M. Nitschke, and K. S. Vierinen, Phys. Rev. C **47**, 1804 (1993).

[6] K. Livingston, P. J. Woods, T. Davinson, N. J. Davis, S. Hoffman, A. N. James, R. D. Page, P. J. Sellin, and A. C. Shotter, Phys. Lett. B **312**, 46 (1993).

[7] P. J. Sellin, P. J. Woods, T. Davinson, N. J. Davis, K. Livingston, R. D. Page, A. C. Shotter, S. Hoffman, and A. N. James, Phys. Rev. C **47**, 193 (1993).

[8] K. Takahashi, M. Yamada, and T. Kondoh, At. Data Nucl. Data Tables **12**, 101 (1973).

[9] T. M. Comier, J. D. Cole, J. H. Hamilton, and A. V. Ramayya, Nucl. Instrum. Methods Phys. Res. A **297**, 199 (1990).

[10] J. D. Cole, T. M. Cormier, J. H. Hamilton, and A. V. Ramayya, Nucl. Instrum. Methods Phys. Res. B **70**, 343 (1992).

[11] C. J. Gross, Y. A. Akovali, M. J. Brinkman, J. W. Johnson, J. Mas, J. W. McConnell, W. T. Milner, D. Shapira, and A. N. James, *Application of Accelerators in Research and Industry*, AIP Conf. Proc. No. 392 (AIP, Woodbury, NY, 1997), Vol. 1, p. 401.

[12] C. J. Gross (private communication).

[13] P. J. Sellin, P. J. Woods, D. Branford, T. Davinson, N. J. Davis, D. G. Ireland, K. Livingston, R. D. Page, A. C. Shotter, S. Hofmann, R. A. Hunt, A. N. James, M. A. C. Hotchkis, M. A. Freer, and S. L. Thomas, Nucl. Instrum. Methods Phys. Res. A **311**, 217 (1992).

[14] P. O. Larsson, T. Batsch, R. Kirchner, O. Klepper, W. Kurcewicz, E. Roeckl, D. Schart, W. F. Feix, G. Nyman, and P. Tidemand-Petersson, Z. Phys. A **314**, 9 (1983).

[15] F. Heine, T. Faestermann, A. Gillitzer, and H. J. Körner, in *Proceedings of the 6th International Conference on Nuclei Far From Stability and 9th International Conference on Atomic Masses and Fundamental Constants*, Bernkastel-Kues, Germany, 1992, edited by R. Neugart and A. Wöhl (IOP, Bristol, 1992), p. 331.

[16] A. Gillitzer, T. Faestermann, K. Hartel, P. Kienle, and E. Nolte, Z. Phys. A **326**, 107 (1987).
[17] R. D. Page, P. J. Woods, R. A. Cunningham, T. Davinson, N. J. Davis, A. N. James, K. Livingston, P. J. Sellin, and A. C. Shotter, Phys. Rev. Lett. **72**, 1798 (1994).
[18] P. J. Woods. T. Davinson, N. J. Davis, S. Hoffman, A. N. James, K. Livingston, R. D. Page, P. J. Sellin, and A. C. Shotter, Nucl. Phys. **A553**, 485c (1993).
[19] G. Audi and H. Wapstra, Nucl. Phys. **A565**, 66 (1993).
[20] F. D. Becchetti, Jr. and G. W. Greenlees, Phys. Rev. **182**,1190 (1969).
[21] P. E. Haustein, At. Data Nucl. Data Tables **39**, 186 (1988).
[22] S. Liran and N. Zeldes, At. Data Nucl. Data Tables **17**, 431 (1976).
[23] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).