RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 36, NUMBER 6 DECEMBER 1987

Absolute gamma intensities in the $A=98$ transitional nuclei and shape coexistence in ^{98}Y

H. Mach
Clark University, Worcester, Massachusetts 01610

R. L. Gill
Brookhaven National Laboratory, Upton, New York 11973
(Received 6 May 1987)

Absolute gamma intensities have been measured for the strong transitions in the decay chain $^{98}Rb \rightarrow {}^{98}Sr \rightarrow {}^{98}Y \rightarrow {}^{98}Zr$ and $^{98}Nb \rightarrow {}^{98}Mo$ and found approximately four times higher than those currently adopted. As a consequence, several contradictions in this critical chain of nuclei are resolved. Shape coexistance is established in ^{98}Y with a $J^{\pi}=1^-$ "spherical" ground state and with a previously reported deformed band with band head at 495.7 keV.

The purpose of this Communication is to present a simple solution to a number of contradictions in experimental results which exist in the $A=98$ chain of transitional nuclei with particular emphasis on ^{98}Y. The $A \sim 100$ region is of fundamental importance to the understanding of the deformation processes throughout heavy nuclei since it provides an opportunity to study a rapid onset of deformation in close vicinity to stable nuclei and with structures amenable to shell model calculations. Studies of these nuclei have focused[1] on the role of the neutron-proton interaction in the deformation process, and therefore information on odd-odd nuclei is particularly vital. The odd-odd ^{98}Y ($N=59$, $Z=39$) is positioned in the center of the transitional region, neighboring the nearly spherical[2] ^{96}Y and fully deformed[3] ^{100}Y isotopes. Furthermore, the coexistence of spherical and collective structures is well established[4] in neighboring even-even nuclei, and thus shape coexistence is also expected at low excitation energy in ^{98}Y. Although a fully deformed band with a band head at 495.4 keV has been already reported,[5-7] so far there is no evidence of spherical structures arising from coupling of a valence neutron particle and a proton hole to the almost spherical ^{98}Zr core. Indeed, the interpretation of most levels in ^{98}Y is particularly difficult due to conflicting experimental results pertaining to the crucial spin-parity assignment to the ground state (g.s.).

β decay from the 0^+ g.s. of ^{98}Sr strongly feeds[5] both the 600.3 keV level (30%, $\log ft=4.5$) and the ^{98}Y g.s. (65%, $\log ft=4.5$), and thus requires positive parity assignments.[5] However, such assignments are in conflict with the $E1$ and $M1$ character[6,8] of the $481.1-119.4$ keV γ-ray cascade connecting these levels. We note, however, in regard to the β decay that the absolute γ and $E0$ intensities and g.s. β feedings in the $A=98$ chain have been deduced by normalizing to the 787.4 keV γ or 734.6 keV $E0$ lines in ^{98}Mo as local standards,[5] despite the fact that the absolute intensities of those ^{98}Mo transitions themselves remain a subject of controversy.[5,9] The absolute intensity of the $E0$ 734.6 keV line, $I_{abs}=5.5(11)$, measured from the ratio of the $E0$ conversion electrons to the continuous β spectrum, differs[5,9] from $I_{abs} \approx 30$ deduced[9] from the $E0$ intensity of 0.02 per ^{235}U fission. (The absolute intensity is expressed as the number of γ or $E0$ transitions per 100 β decays of the parent.) In order to understand the origin of those discrepancies, we have measured the absolute intensities in the $A=98$ chain by normalizing to an independent standard.

The measurement was performed at the TRISTAN mass separator on line to the High Flux Beam Reactor at Brookhaven National Laboratory. The activity was produced by thermal neutron induced fission of an enriched ^{235}U target inside an ion source with a high efficiency for Rb.[10] The source was operated at relatively low temperature to suppress direct production of ^{98}Sr and ^{98}Y. The mass-separated ^{98}Rb activity was continuously deposited onto an aluminum stopper for a period of 41 h. The β activity was monitored by a thin plastic detector, while the γ activity was measured with Ge and thin-window Ge detectors with efficients of 22% and 26%, respectively, and with full width at half maximum (FWHM) energy resolution of 1.9 keV at 1.3 MeV. γ-ray singles spectra were accumulated over short periods of time at the beginning and at the end of the irradiation process and γ-γ coincidences were measured with both Ge detectors. The strongest γ lines provided internal energy calibrations, while the efficiency calibrations were performed off-line using standard sources.

Figure 1 shows a γ-singles spectrum obtained with the 22% Ge detector at the end of the irradiation process. We have identified lines from individual decays in the $A=98$ mass chain[5] and from $A=97$ nuclei[11] populated in the β-delayed neutron decay of ^{98}Rb. The identification of the $^{98}Sr \rightarrow {}^{98}Y$ lines required a detailed analysis of the coincidence data. Relative γ intensities compare closely to the values adopted for each decay scheme.[5,11]

We obtained the absolute γ intensities for the strongest transitions in the $A=98$ chain by a direct comparison to the $A=97$ lines. Those key transitions are labeled in Fig. 1. We used the β-delayed neutron branching[12] of 13.4(9) per 100 decays of ^{98}Rb, and the absolute intensity[11] of 94.75(30) for the 743.3 keV transition in ^{97}Nb. The degree of saturation for the ^{97}Zr decay ($T_{1/2}=16.90(5)$ h) was estimated to be 81.6(9)% at the time of the measurement. We found no trace of direct $A=97$ or 99 mass contaminations (i.e., the key lines from the $^{97}Rb \rightarrow {}^{97}Sr$ were absent), nor for any direct production of ^{98}Y (no lines from the high-spin isomers). The low temperature of the ion source severely reduced direct production of ^{98}Sr. Nevertheless, in a very conservative estimate, up to 5% of additional γ intensity may exist in the decay chain following the decay of ^{98}Sr. Although we have not included this value in the following analysis, its inclusion would not alter the conclusions drawn. Furthermore, the beam intensity was kept constant to $\approx 4\%$, which allowed a direct comparison of long- and short-lived decay products. The absolute intensities within the $A=97$ chain are in excellent agreement with the adopted values.[11] The new absolute intensities for the key transitions in the $A=98$ chain are presented schematically in Fig. 2.

The key result is that the β branchings into excited levels are found to be approximately four times higher than the adopted values,[5] resulting in a substantial reduction in the g.s. β feedings. The differences between our results and the adopted values can be traced to one number, namely, the absolute intensity for the "standard" 787.6 keV ^{98}Mo line. The relative intensities for the lines in the $A=98$ chain remain approximately the same, since before they have been normalized[5] to the ^{98}Mo line and are normalized in our work to the ^{97}Nb transition. The impact of the new results on the individual decays is discussed next.

Rb→Sr. The absolute intensities for the 144.2 and 289.4 keV transitions represent the number of gamma transitions per 100 decays of ^{98}Rb excluding the delayed neutron branch. About 50% of the beta intensity remains unaccounted[5] for by the level scheme of ^{98}Sr, and thus, it is reasonable to assume that a large fraction of it feeds the g.s. with $\log ft \approx 5$, suggesting $J^\pi = 1^+$ for the low spin isomer of ^{98}Rb.

Sr→Y. The key issue in ^{98}Y is the spin-parity of the ground state. However, since the decay scheme of ^{98}Sr to ^{98}Y is largely unknown,[5] we present in Fig. 3 a partial scheme deduced from our coincidence data and complemented by published results.[5,6,8] We have identified all the major lines in the singles spectra and thus there should be no transitions of significant strength missing from the scheme. The multipolarities of the 51.5, 119.4, 120.9, 170.7, and 204.0 keV transitions are taken from Ref. 6, while those for the 428.4, 444.6, 480.9, and 563.8 keV lines are from Ref. 8. Using the coincidence intensities, we have deduced the total electron conversion coefficients for the 36.5 and 52.5 keV transitions to be 1.0(3) and 1.3(3), respectively, leading to the $E1$ and $M1$ assignments for those lines. However, the coefficient for the 36.5 keV line is lower than the theoretical value[13] of 2.0, which creates uncertainty as to the amount of β feeding to the 564.0 keV level. The transition multipolarities are consistent with the requirements of the decay scheme and provide evidence that the parities of the g.s. and the 600.3 keV levels must be opposite. This is fully consistent with the new β branchings discussed next.

The absolute intensity for the 119.4 keV transition, $I_{abs}=73(6)$, implies little or no β feeding to the g.s., since the γ and the e^- intensity for the 119.4 keV $M1$ line and the other known γ transitions feeding the g.s., exhaust the 100% intensity limit, $I_{tot}=106(9)\%$. This is further evidence that all intense transitions have been included in the decay scheme. Moreover, the balance between feeding and de-exciting intensities implies no significant β feeding to the 119.4 and 170.8 keV levels, and perhaps also to the 564.0 keV state.

Three levels in ^{98}Y (see Fig. 3), at 547.7, 600.3, and 986.1 keV, are strongly populated in the β decay of even-even ^{98}Sr ($\log ft = 4.3-5.1$), which implies $J^\pi = 1^+$. On the basis of γ-ray transition multipolarities, the three lowest-lying states, including the g.s. must have negative parity. Furthermore, the g.s. has spin $J=1$, since it decays by fast first-forbidden transitions, with $\log ft \approx 6$, to a number of 0^+ and 2^+ levels in ^{98}Zr. Moreover, the transition to the 0^+ "spherical" g.s. of ^{98}Zr is particularly fast. The $\log ft$ of 5.8 for this first-forbidden transition is

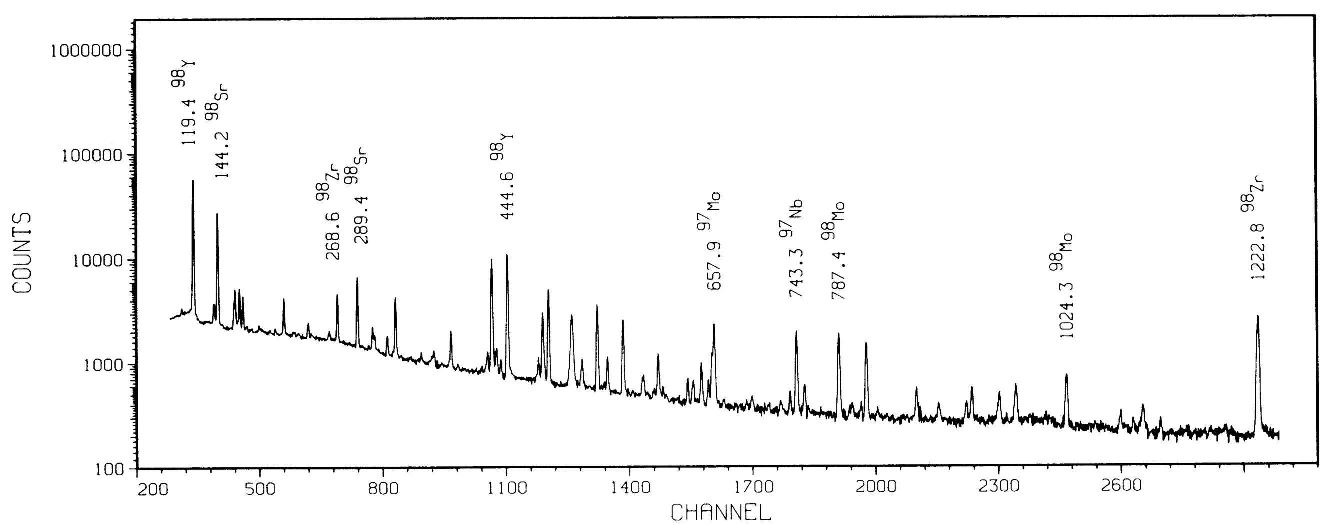

FIG. 1. γ-singles spectrum obtained after 41 h of continuous beam accumulation. The key transitions are labeled by the energy, in keV and isotopic association.

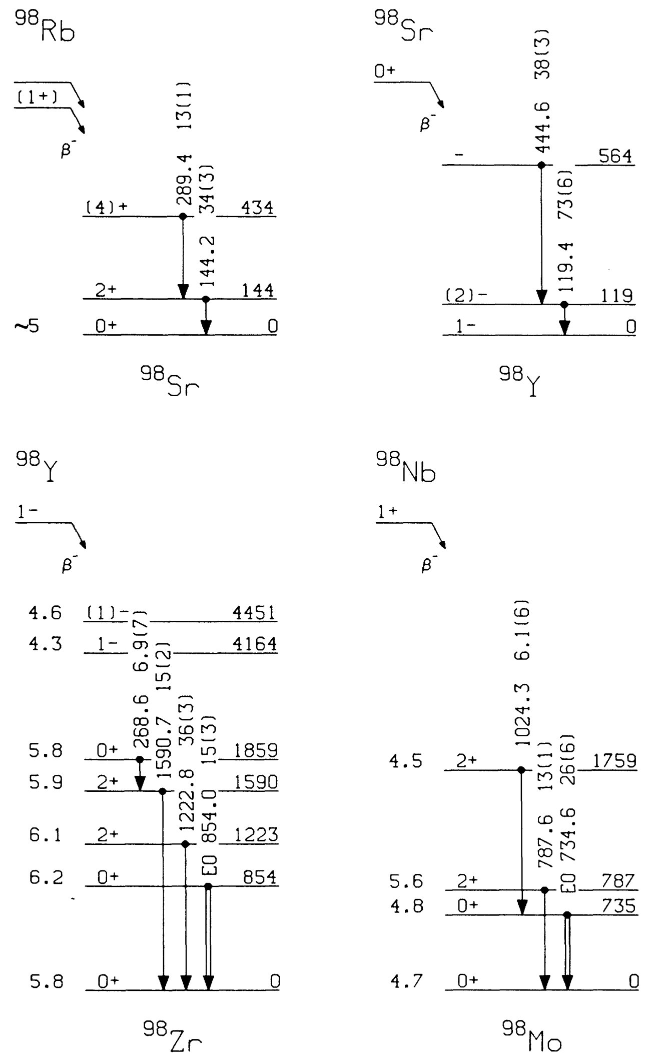

FIG. 2. Absolute intensities for the key γ and $E0$ transitions as well as β-branching ratios and logft values deduced in this work are illustrated for the ground state β decays in the $A=98$ mass chain. Relative intensities are taken from Ref. 5.

lower than the accepted[14] lower limit of 5.9. Such fast first-forbidden transitions occur in the vicinity of doubly magic nuclei where there is a strong overlap between pure spherical configurations.[15] Indeed there is substantial evidence[2,16] to consider both ^{96,98}Zr as almost doubly magic nuclei; in particular, one of the fastest $0^- \rightarrow 0^+$ transitions with a log$ft=5.6$, is observed[2] in the ^{96}Y$^g \rightarrow$ ^{96}Zr^g decay.

The fast β-decay transition indicates that the ^{98}Y g.s. arises from a simple coupling of one neutron particle and one proton hole to the spherical even-even ^{98}Zr core, and thus, can be also interpreted as spherical. The 39th proton in the $\pi 2p_{1/2}$ orbit[1] can only couple with an odd neutron in either the $3s_{1/2}$ or $2d_{3/2}$ orbit to form a $J^\pi=1^-$ state. However, the $3s_{1/2}$ neutron must be excluded as the main component of the β decay since it leads to an empty $3s_{1/2}$ subshell contrary to the expectation[16] that the almost magic character of the ^{98}Zr g.s. structure is due to the $3s_{1/2}$ subshell closure. From the $\pi 2p_{1/2}$ and $\nu 2d_{3/2}$ coupling one would expect 1^- and 2^- to be the lowest-lying levels in ^{98}Y. Indeed, the two lowest-lying levels in ^{98}Y, the $J^\pi=1^-$ g.s. just discussed, and the 119.4 keV levels, are the most plausible candidates. These negative parity levels are interconnected by an almost pure[6] $M1$ transition and are almost equally strongly populated by γ transitions from other levels as evident in Fig. 3. These empirical facts are analogous to those for the two lowest-lying levels in ^{96}Y, the 0^- ground state, and the 1^- 122.3-keV levels, which have been interpreted[17] as formed by coupling of the $p_{1/2}$ proton to a $s_{1/2}$ neutron.

A deformed band with the band head at 495.7 keV has been recently investigated in some detail.[6,7] Two configurations, $(p[422\frac{5}{2}]n[404\frac{9}{2}])2^+$ and $(p[303\frac{5}{2}]n[404\frac{9}{2}])2^-$, have been proposed[6,7] for the band head. The latter one has been favored[7] on the basis of the Nilsson-model calculations, which also suggest the interpretation of the 830-ns isomer at 1180 keV as a double (i.e., proton and neutron) intruder state with the configuration $(p[550\frac{1}{2}]n[404\frac{9}{2}])8^-$. The present work confirms those predictions in that it firmly assigns negative parity not only to the 495.7 keV level, which feeds the $J^\pi=1^-$ g.s. by a sequence of M1 and E2 transitions (see Fig. 3), but also to the 830-ns isomer which feeds this band via the 110.8 keV $E2$ transition.[6] Thus, the 1^- ^{98}Y^g, which by virtue of its fast β decay to spherical g.s. of ^{98}Zr can also be assigned a simple spherical shell model configuration, is seen to coexist with a well-deformed structure.

Y→ Zr. 47% of the β feeding from the 1^- g.s. of ^{98}Y populates two high-lying levels in ^{98}Zr at 4164.4 and 4450.7 keV with logft value of 4.3 and 4.6, respectively. Therefore, spin-parity 1^- is proposed for both those levels provided that the comparable strength[5] of the γ-ray transitions to states of spin 0^+ and 2^+ can be taken to rule out $M2$ multipolarities. Indeed, two γ-$\gamma(\Theta)$ angular correlations involving a transition from the 4164.4 level in cascade with a spin $2\rightarrow 0$ transition show[18] a_2 coefficients of $-0.11(15)$ and $-0.28(2)$ consistent with $a_2=-0.25$ for a pure, $\delta(l+1/l)=0$, spin sequence $1\rightarrow 2\rightarrow 0$.[19] The nature of those negative parity levels remains an interesting topic for future studies.

The absolute intensity for the $E0$ 854.0 keV line in ^{98}Zr can now be revised from the previously adopted[5] value of 4.9(18) to the new value of 15(3), which essentially removes the inconsistency of the earlier result with the value of 26(5) deduced[9] from the $E0$ conversion electrons measured in the ^{235}U(n,f) reaction. The new value derived here was obtained from the ratio[5] of intensities for the $E0$ 854.0 keV and 1222.8 keV γ lines in ^{98}Zr and the new absolute intensity of the latter line.

The new γ and $E0$ intensities alter the important relative β feeding to the 0^+ g.s. and the 0^+ first excited state in ^{98}Zr as well as the associated logft values. The new values are log$ft=5.8$ (^{98}Zr^g) and log$ft=6.2$ (^{98}Zr*). The g.s. is a spherical configuration dominated by proton $(p_{1/2})^2$ component relative to $Z=38$, while the excited 0^+ state is a more collective state with a large $\pi(g_{9/2})^2$ amplitude. Since the β-decay matrix element connecting the odd $d_{3/2}$ neutron in ^{98}Y with a $p_{1/2}$ proton is large while

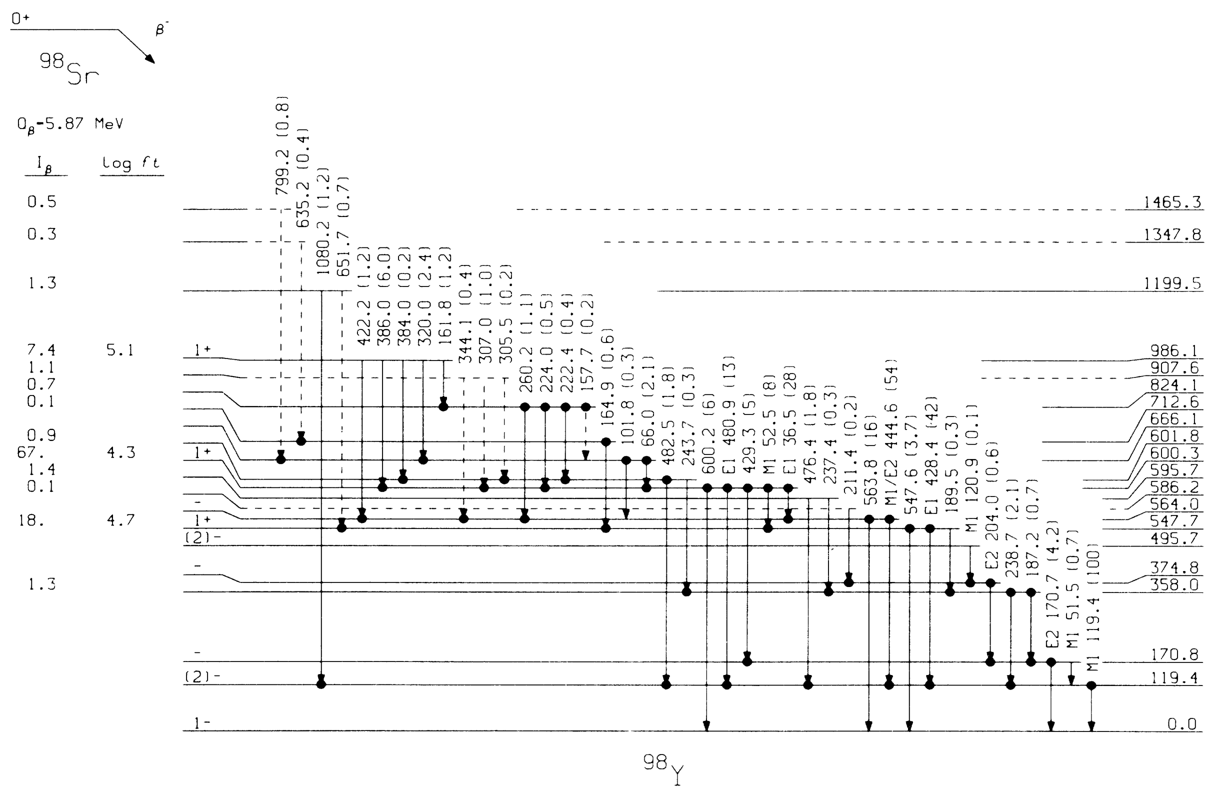

FIG. 3. Partial level scheme for the ^{98}Sr→ ^{98}Y β decay.

transition to a $g_{9/2}$ proton is highly hindered, the β feeding of the 0_2^+ state is due to an admixture of the g.s. configuration. Consequently, from the ratio of the comparative half-lives, *ft*, approximately equal to the square of the amount of mixing, one deduces a 30% admixture of the spherical configuration in the collective 0_2^+ state.

Nb→Mo. The absolute intensities of the "standard" 787.4 and 1024.3 keV γ lines in ^{98}Mo were found to be 13(1) and 6.1(6) in contrast to earlier adopted[5] values of 3.2(5) and 1.6(3). Furthermore, the ratio of $E0$ intensities[5] for the 854.0 keV (^{98}Zr) and 734.6 keV (^{98}Mo) lines, 0.56(6), leads to the new absolute intensity of 26(6) for the latter line in agreement with $I_{abs} \approx 30$ deduced in Ref. 9. The revised β feedings to the 0_1^+ and 0_2^+ levels in ^{98}Mo give new log*ft* values of 4.7 and 4.8, respectively. By analogous arguments as before, this suggests an almost equal mixing of those 0^+ levels provided the 1^+ g.s. of ^{98}Nb is a pure "deformed" configuration. The configuration mixing calculations of Sambataro and Molnár,[20] who predicted a 40/60% mixture of the involved 0^+ configurations, are consistent with those results.

In conclusion, new absolute γ intensities for the $A=98$ mass chain have been found higher than the currently adopted values by a factor of approximately four. The difference can be traced to the absolute intensity for 787.6 keV ^{98}Mo line. The new results alter the relative and absolute β-feeding branches to g.s. and excited states for $A=98$ nuclei, and thereby the experimentally deduced mixing of spherical and deformed states. These results provide solutions to a number of outstanding discrepancies in these key transitional nuclei and suggest that the g.s. of ^{98}Y is the spherical $(\pi 2p_{1/2}\nu 2d_{3/2})1^-$ configuration and that it coexists with the previously reported[5-7] deformed band at 495.7 keV. Finally, we have established a fast first-forbidden β transition between the ground states of ^{98}Y and ^{98}Zr, which alongside with ^{96}Y→ ^{96}Zr decay, forms a new region, other than ^{208}Pb and ^{16}O, of such fast transitions.

We acknowledge with appreciation discussions with R. F. Casten and G. Molnár. This work has been performed under Contracts No. DE-AC02-76CH00016 and No. DE-AC02-79ER10493 with the United States Department of Energy.

[1]P. Federman and S. Pittel, Phys. Rev. C **20**, 820 (1979).
[2]H. Mach *et al.* (unpublished).
[3]F. K. Wohn *et al.*, Phys. Rev. C **36**, 1118 (1987).
[4]See, for example, F. K. Wohn *et al.*, Phys. Rev. C **33**, 677 (1986).
[5]H.-W. Muller, Nucl. Data Sheets **39**, 467 (1983).
[6]G. Lhersonneau *et al.*, in *Recent Advances in the Study of Nuclei off the Line of Stability*, edited by R. A. Meyer and D. S. Brenner, American Chemical Society, Symposium Series 324 (American Chemical Society, Washington, DC, 1986), p. 202.
[7]R. A. Meyer *et al.*, Lawrence Livermore National Laboratory

Nuclear Chemical Division Annual Report No. UCID-10062-85/1, 1985.

[8]K. Kawade *et al.*, Z. Phys. A **304**, 293 (1982).

[9]B. Fogelberg, Phys. Lett. **37B**, 372 (1971).

[10]A. Piotrowski *et al.*, Nucl. Instrum. Methods **224**, 1 (1984).

[11]B. Haesner and P. Luksch, Nucl. Data Sheets **46**, 607 (1985).

[12]F. M. Mann *et al.*, Nucl. Sci. Eng. **87**, 418 (1984).

[13]F. Rösel *et al.*, At. Data Nucl. Data Tables **21**, 92 (1978).

[14]S. Raman and N. B. Grove, Phys. Rev. C **7**, 1995 (1973).

[15]J. Damgaard, R. Broglia, and C. Riedel, Nucl. Phys. **A135**, 310 (1969).

[16]R. A. Meyer *et al.*, Phys. Lett. **177B**, 271 (1986).

[17]G. Jung *et al.*, Nucl. Phys. **A352**, 1 (1981).

[18]K. Becker *et al.*, Z. Phys. A **319**, 193 (1984).

[19]H. W. Taylor *et al.*, Nucl. Data Tables **9**, 1 (1971).

[20]M. Sambataro and G. Molnár, Nucl. Phys. **A376**, 201 (1982).