High-spin excitations in ^{92,93,94,95}Zr

N. Fotiades,[1,2] J. A. Cizewski,[2] J. A. Becker,[3] L. A. Bernstein,[3] D. P. McNabb,[3] W. Younes,[3] R. M. Clark,[4] P. Fallon,[4] I. Y. Lee,[4] A. O. Macchiavelli,[4] A. Holt,[5] and M. Hjorth-Jensen[6]
[1]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[2]*Department of Physics and Astronomy, Rutgers University, New Brunswick, New Jersey 08903*
[3]*Lawrence Livermore National Laboratory, Livermore, California 94550*
[4]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[5]*Faculty of Engineering, Oslo University College, N-0254 Oslo, Norway*
[6]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*
(Received 29 October 2001; published 11 March 2002)

The level structure of several Zr isotopes near $A=94$ (^{92,93,94,95}Zr) has been studied in the fission of the compound nucleus ^{197}Pb, formed in the ^{24}Mg$+^{173}$Yb reaction at $E(^{24}\text{Mg})=134.5$ MeV. Sequences of γ-ray transitions, observed in coincidence with known transitions in the complementary Mo fragments, have been newly assigned to ^{93,95}Zr. The previously known level scheme of ^{94}Zr has been considerably extended to higher excitations, and exhibits structural similarities to the level scheme of ^{92}Zr up to spin $10\hbar$. The level schemes of ^{93}Zr and ^{95}Zr can be generally interpreted as the coupling of a $d_{5/2}$ neutron to the levels of ^{92,94}Zr and ^{96}Zr, respectively. The observed experimental states are compared with theoretical shell-model calculations.

DOI: 10.1103/PhysRevC.65.044303 PACS number(s): 23.20.Lv, 27.60.+j

I. INTRODUCTION

The Zr isotopes between ^{90}Zr and ^{96}Zr are expected to be spherical with structural similarities that can be interpreted in terms of simple excitations across the subshell closures at $Z=40$ and $N=50,56$. On the other hand, the comparison of the relative excitations of certain states between these nuclei can give information on the interplay between proton and neutron excitations across these gaps.

Many properties of these nuclei, including energy spectra, have been well reproduced in shell-model calculations using a $\pi[2p_{1/2},1g_{9/2}]\nu[2d_{5/2},3s_{1/2}]$ space [1], which support the picture of simple excitations across the subshells. A more extended shell-model space, comprising the $\pi 1f_{5/2}$ and $\pi 2p_{3/2}$ orbitals, has been used to reproduce better the measured $B(E2)$ values for the first positive-parity states in ^{92,94}Zr [2]. More recently, g-factor measurements [3] have confirmed the expected dominance of the neutron $(2d_{5/2})^2$ particle/hole configuration in the 2^+ and 4^+ states in ^{92}Zr/^{94}Zr, respectively. Calculations in a large shell-model space by Zhang, Wang, and Gu [4] support a 70–80% contribution of the $2d_{5/2}$ neutron configuration in these excitations. There have also been recent calculations by Holt and co-workers, in a nontruncated $\pi[2p_{1/2},1g_{9/2}]\nu[2d_{5/2},3s_{1/2},2d_{3/2},1g_{7/2},1h_{11/2}]$ space [5] with a fully realistic effective interaction, which predict high-spin states.

It is difficult to study Zr isotopes with $A>90$ to moderate and high spins because they are too close to the line of stability to be readily populated in reactions that bring in high angular momentum. Alternatively, these isotopes can be studied via the prompt γ-ray spectroscopy of fission fragments following fusion reactions of much heavier nuclei. Such methods have been used recently to collect information on high-spin states of nuclei near the line of stability [6]. Identification of high-spin excitations in Zr isotopes near the line of stability is important to determine what extensions of the shell-model space are needed in this mass region.

In the present paper, excitations in $^{92-95}$Zr have been studied as fission products from a fusion reaction that produced a ^{197}Pb compound nucleus of high spin and excitation energy. This method enabled the use of coincidences with transitions in the complementary Mo fragments to assign transitions to ^{93,95}Zr and construct level schemes up to ~ 5 MeV excitation energy in the Zr isotopes. Extensions of the level schemes of ^{92,94}Zr to higher excitations were also made.

II. EXPERIMENT

The ^{197}Pb compound nucleus was formed in the ^{24}Mg $+^{173}$Yb reaction with a 134.5-MeV ^{24}Mg beam from the 88-Inch Cyclotron Facility at Lawrence Berkeley National Laboratory. The target was 1 mg/cm^2 in areal density and consisted of isotopically enriched ^{173}Yb evaporated on a 7-mg/cm^2 gold backing.

The Gammasphere array (92 Ge detectors) was used for γ-ray spectroscopy. A symmetrized, three-dimensional (γ-γ-γ) cube was constructed to investigate coincidence relationships between the γ-ray transitions. All previously known [7] Zr isotopes, from ^{92}Zr to ^{98}Zr, and Mo isotopes, from ^{94}Mo to ^{102}Mo, were identified in the present analysis. Additional information on the experiment and the analysis of the data are given in Ref. [8].

III. EXPERIMENTAL RESULTS

High-spin excitations in ^{92}Zr have been previously studied in heavy-ion fusion-evaporation reactions and the level scheme extended up to ~ 8 MeV excitation energy [9–11]. Additional states at low excitations are also known from

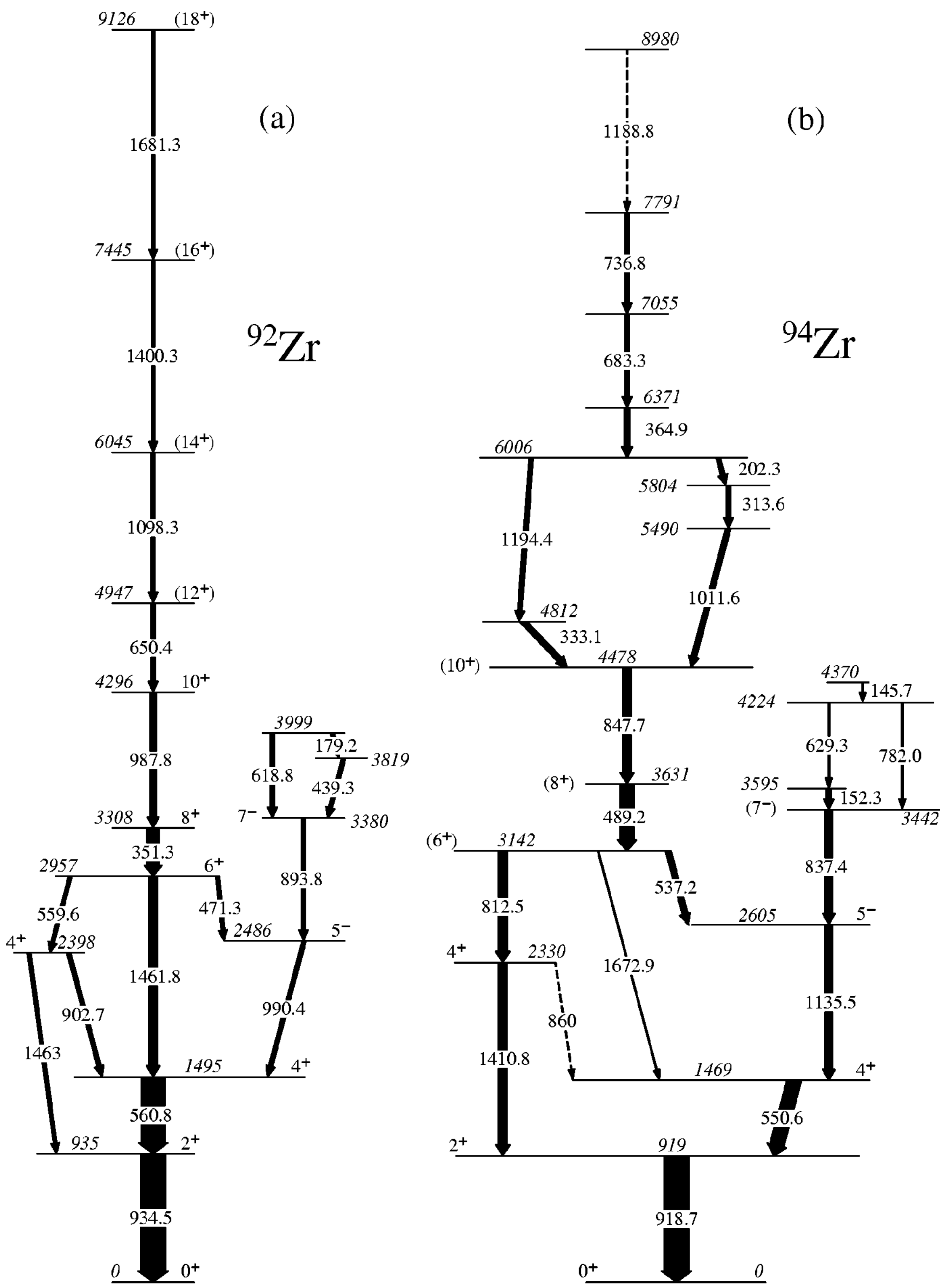

FIG. 1. Level schemes of ^{92}Zr and ^{94}Zr as obtained in the present paper. Transition and excitation energies are in keV. The widths of the arrows are proportional to the intensities of the transitions.

light-ion induced reactions and β-decay studies [11]. In the present paper, only three new weak transitions have been added, based on coincidence relations, to the level scheme displayed in Fig. 1(a): the 471.3-keV ($6^+ \rightarrow 5^-$), 559.6-keV ($6^+ \rightarrow 4_2^+$), and 1681.3-keV ($18^+ \rightarrow 16^+$) transitions. With the addition of the 471.3- and 559.6-keV transitions, the deexcitation path in ^{92}Zr now resembles the one observed in ^{94}Zr. Although in the present data the 1463-keV ($4_2^+ \rightarrow 2_1^+$) transition in Fig. 1(a) could not be separated from the strong 1461.8-keV ($6^+ \rightarrow 4^+$) transition, the placement of the 1463-keV transition had been previously established [7].

The only levels established previously in ^{93}Zr were low-

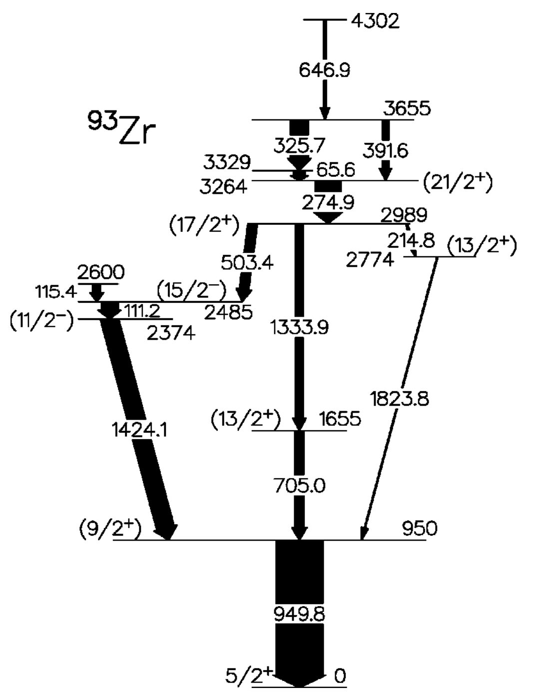

FIG. 2. Level scheme assigned to ^{93}Zr in the present paper. Transition and excitation energies are in keV.

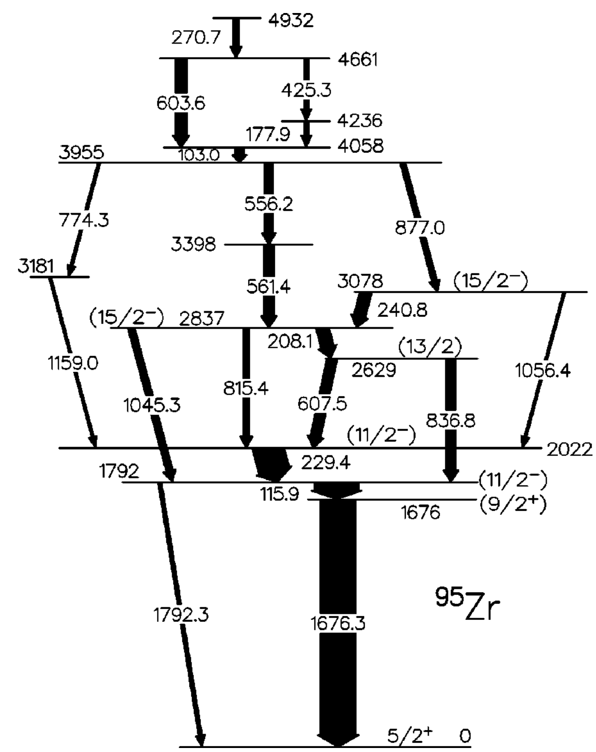

FIG. 3. Level scheme assigned to ^{95}Zr in the present paper. Transition and excitation energies are in keV.

spin states observed in light-ion induced reactions or β-decay studies [12]. Although transitions had been assigned to ^{93}Zr in an earlier study of fission fragments following a heavy-ion fusion-evaporation reaction [13], no levels were established because of the limited γ-ray energy range $E_\gamma < 2$ MeV. The assignments of these transitions to ^{93}Zr are confirmed in the present paper by coincidences with Mo fragments. The level scheme in Fig. 2 was constructed based on coincidence relations between ^{93}Zr transitions. The present data provide information up to $E_\gamma = 2.7$ MeV. No additional transition could be assigned to ^{93}Zr in the 2.0 MeV $< E_\gamma < 2.7$ MeV region.

In ^{94}Zr the levels below the 5^- state at 2605 keV were previously observed in light-ion reactions [14]. In the present paper the yrast levels above this state were established up to ~ 9 MeV in excitation energy, as shown in Fig. 1(b). Of particular interest are the (6^+), (8^+), (10^+), and (7^-) states that can be directly compared to the corresponding states in ^{92}Zr and to theoretical shell-model calculations.

The low-spin levels in ^{95}Zr were established from light-ion induced reactions and β-decay studies [15]. Transitions were assigned to ^{95}Zr in previous fission fragment studies [13]. In the present paper these transitions were observed in coincidence with known transitions in Mo complementary fragments and a comprehensive level scheme, based on coincidence relations and relative intensities, is proposed in Fig. 3.

The γ-ray transitions assigned to ^{93,94,95}Zr are summarized in Table I; intensities reported in Table I were not corrected for internal conversion because of limited knowledge of the multipolarities. However, since the internal conversion coefficients, even for low-multipolarity, low-energy transitions, in Zr isotopes are small, this correction is not expected to change significantly the intensities reported here. The possible exceptions are the 65.6-keV transition in ^{93}Zr and the 103.0-keV transition in ^{95}Zr. The intensities of the 774.3- and 1159.0-keV transitions of ^{95}Zr in Table I are equal within error; hence, their placement in the level scheme in Fig. 3 could be interchanged. The intensities reported in Table I for transitions of ^{95}Zr are in general agreement with those quoted in Ref. [13]. However, there are significant differences between the intensities of the transitions of ^{93}Zr observed in the present paper and those in Ref. [13]. Given the limited details reported in Ref. [13], a detailed comparison with the present results was not possible; therefore, the present measurements are adopted.

Spin and parity assignments of the new levels assigned to $^{92-95}$Zr in the present paper are difficult to deduce because of the lack of directional correlation information for the fission products. However, the tentative spin assignments in Figs. 1, 2, and 3 are supported by a comparison with known states in the neighboring Zr isotopes, as well as the results of theoretical shell-model calculations, as discussed below.

IV. DISCUSSION

The resemblance between the levels in ^{92}Zr and ^{94}Zr up to spin $10\hbar$ in Fig. 1 is striking, which suggests that similar orbitals are involved. The dominant neutron $(d_{5/2})^2$ particle/hole parentage of the $0^+, 2^+$, and 4^+ states in ^{92}Zr/^{94}Zr, respectively, has been experimentally established by measurement of the g factors of these states [3] and is supported by shell-model calculations [4,5].

A large gap is expected between the first 4^+ and 6^+

TABLE I. Energies and relative intensities of transitions assigned to ^{93,94,95}Zr.

^{93}Zr		^{94}Zr		^{95}Zr	
Energy [a] (keV)	Intensity (per thousand)	Energy [a] (keV)	Intensity (per thousand)	Energy [a] (keV)	Intensity (per thousand)
65.6	250(100) [b]	145.7	19(3)	103.0	202(80) [b]
111.2	360(70)	152.3	66(15)	115.9	≡1000
115.4	162(50)	202.3	85(20)	177.9	104(40)
214.8	41(5)	313.6	88(20)	208.1	302(60)
274.9	530(70)	333.1	101(30)	229.4	710(50)
325.7	369(60)	364.9	112(30)	240.8	276(50)
391.6	126(30)	489.2	560(90)	270.7	131(30)
503.4	203(40)	537.2	70(20)	425.3	102(30)
646.9	60(5)	550.6	581(80)	556.2	193(50)
705.0	191(50)	629.3	17(3)	561.4	240(60)
949.8	≡1000	683.3	58(10)	603.6	241(40)
1333.9	155(30)	736.8	54(10)	607.5	242(80)
1424.1	382(50)	782.0	21(4)	774.3	68(20)
1823.8	54(10)	812.5	391(80)	815.4	158(30)
		837.4	276(50)	836.8	220(40)
		847.7	354(60)	877.0	129(30)
		860	<10	1045.3	161(30)
		918.7	≡1000	1056.4	60(10)
		1011.6	99(30)	1159.0	62(20)
		1135.5	287(50)	1676.3	800(100)
		1188.8	<15	1792.3	90(30)
		1194.4	80(20)		
		1410.8	351(50)		
		1672.9	15(3)		

[a]The uncertainties of the γ-ray energies vary from 0.2 to 0.4 keV for the strong transitions and from 0.6 to 0.8 keV for the weakest ones.
[b]Most likely the 65.6-keV transition is of $M1$ or $E1$ character; internal conversion correction for $M1$ multipolarity could increase its intensity by a factor of ~ 1.5. The 103.0-keV transition is likely of $E2$ multipolarity, because no crossover transitions bypassing the 3955- and/or 4058-keV levels were observed. In this case the correction for internal conversion would approximately double the intensity reported in Table I, which supports its placement below the 4058-keV level in Fig. 3.

states, as previously observed in ^{92}Zr [9], due to the energy needed to excite a pair of protons from the $2p_{1/2}$ to the $1g_{9/2}$ orbitals to form the $(\pi g_{9/2})^2_{6^+,8^+}$ states. The same gap is present in ^{94}Zr. The (6^+) and (8^+) states that originate from this proton excitation are pushed to slightly higher excitations in ^{94}Zr compared to ^{92}Zr. The energy spacings between the 8^+, 10^+, and 12^+ states in ^{92}Zr are analogous to those between the 0^+, 2^+, and 4^+ states, supporting the interpretation of these excitations as the coupling of the $d_{5/2}$ neutron pair to two $g_{9/2}$ protons. A similar structure is observed in ^{94}Zr up to the (10^+) state. However, none of the levels above this state in ^{94}Zr is a good candidate for a 12^+ state, which corresponds to full alignment of the spins of the nucleons that form the $\pi(g_{9/2})^2\nu(d_{5/2})^2$ configuration. Based on the energy systematics of the 6^+ to 10^+ states, the 12^+ state in ^{94}Zr would be about 150–350 keV higher in excitation than the 4947-keV 12^+ state in ^{92}Zr. In contrast, the sequence of levels above the (10^+) state in ^{94}Zr is entirely different from the corresponding ones in ^{92}Zr, which suggests excitations of a different nature.

A large gap in energy between the 4^+ and 5^- states is also observed in ^{90}Zr [7] and ^{92}Zr, since the 5^- state includes a proton $(g_{9/2}p_{1/2})$ excitation [9]. The 5^- state in ^{94}Zr is the analog of the 5^- states in ^{90}Zr [7] and ^{92}Zr. The spacing between the 5^- and (7^-) states in ^{94}Zr is similar to the spacing between the 0^+ and 2^+ states in this isotope, as is also the case for the 5^- and 7^- states in ^{92}Zr and ^{90}Zr. These spacings suggest that the 7^- states in all three isotopes arise from the coupling of the $d_{5/2}$ neutron pair to the $\pi(g_{9/2}p_{1/2})$ configuration.

The spin assignments for ^{93}Zr are suggested by a weak coupling of the valence $d_{5/2}$ neutron to the excitations in the ^{92,94}Zr cores, as displayed in Fig. 4. The $5/2^+$ ground state and $(9/2^+)$ state at 950 keV can be readily associated with the 0^+ and 2^+ states of the cores, which are predominantly [4] $(\nu d_{5/2})^2$ configurations. Similarly, the proposed $(17/2^+_1)$ and $(21/2^+_1)$ states can be associated with coupling of the valence $d_{5/2}$ neutron to the 6^+ and 8^+ $(\pi g_{9/2})^2$ states of the core. The decay pattern of the 6^+_1 state in ^{92}Zr to lower-lying 5^-, 4^+_1, and 4^+_2 states is similar to that observed for the $(17/2^+_1)$ state, which suggests a $(15/2^-)$ assignment for the 2485-keV level and $(13/2^+)$ assignments for the states at 1655 and 2774 keV. However, the reduced branching ratios

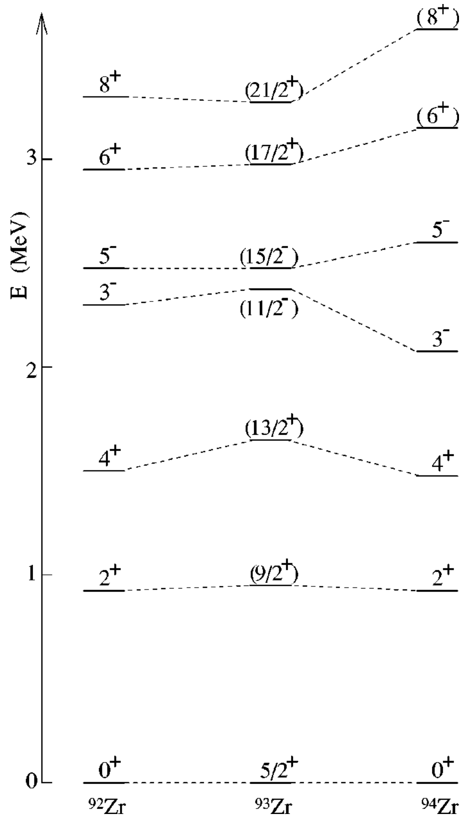

FIG. 4. Comparison between the excitations in ^{92,93,94}Zr.

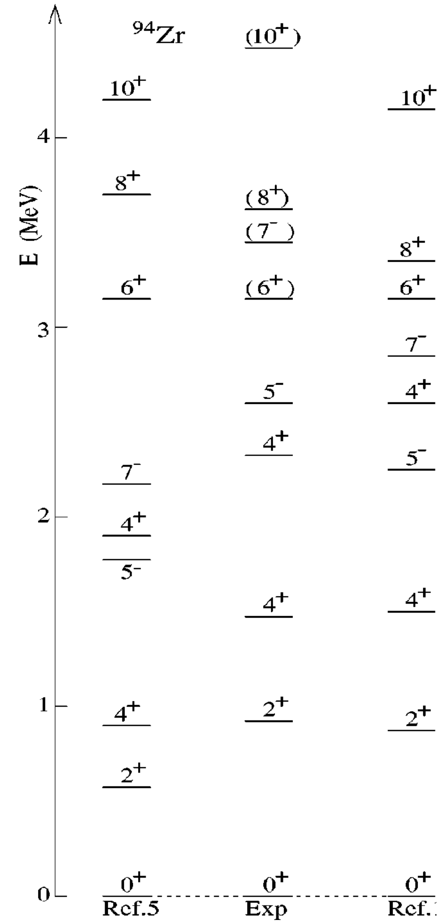

FIG. 5. Comparison between ^{94}Zr states observed experimentally in the present paper and theoretical shell-model predictions of Ref. [1], Fig. 6, and Ref. [5].

(i.e., taking into account the energy dependence of the transition probability) for the decay of the 6_1^+ state in ^{92}Zr and the $(17/2_1^+)$ state in ^{93}Zr are different. This is not unexpected since the 4^+ state in the core is predominantly $(\nu d_{5/2})^2$, while the $13/2_1^+$ state in ^{93}Zr must include components of the 4^+ core state outside of the $(\nu d_{5/2})^2$ configuration, since a $13/2^+$ state cannot be generated from $(\nu d_{5/2})^3$. This could explain the higher excitation energy of the $(13/2_1^+)$ state in ^{93}Zr compared to the 4_1^+ states in ^{92,94}Zr. That the energy of the proposed $(13/2_2^+)$ state in ^{93}Zr is also higher than the 4_2^+ states in the cores also suggests that core components outside of $(\nu d_{5/2})^2$ are important in this excitation in ^{93}Zr. The proposed $(11/2^-)$ state at 2374 keV could be associated with the 2363(10)-keV, $9/2^-,11/2^-$ state observed previously in light-ion transfer reactions [12].

^{95}Zr has only one neutron less than the subshell closure at $Z=40$ and $N=56$. Hence, the low-lying states are expected to originate from the coupling of a $d_{5/2}$ neutron hole to the levels of the ^{96}Zr core. However, the lack of directional correlations of the γ rays makes even tentative spin-parity assignments difficult. The coupling of the $d_{5/2}$ neutron hole to the $0^+,2^+,3^-$ levels of the ^{96}Zr core is a likely assignment only for the $5/2^+$, $(9/2^+)$, and $(11/2^-)$ states, respectively, of ^{95}Zr. The proposed $(11/2^-)$ state at 2022 keV could be the $9/2^-,11/2^-$ state at 2025 keV previously observed in light-ion transfer reactions [15] as a candidate for $\nu h_{11/2}$ strength.

Shell-model calculations for all Zr isotopes discussed in the present paper have been carried out by Gloeckner using a $\pi[p_{1/2},g_{9/2}]\nu[d_{5/2},s_{1/2}]$ space [1], as well as Holt and coworkers [5] using a larger neutron $s_{1/2}d_{5/2}g_{7/2}h_{11/2}$ space with realistic effective interactions, which provide predictions for high-spin states in these nuclei. At the time when these calculation were performed, high-spin states were only known in ^{91}Zr and ^{92}Zr for a direct comparison to the calculations [1,5,9]. In general, the comparison to the experimental energies showed that these calculations succeed in reproducing the positive-parity states, while underestimating the excitation of the negative-parity states. This comparison can be pursued further with many high-spin states established in ^{93}Zr, ^{94}Zr, and ^{95}Zr isotopes in the present paper.

In Fig. 5, the experimentally observed states of ^{94}Zr are compared to the theoretical calculations of Refs. [1,5]. The yrast positive-parity states up to (6^+) are reproduced very well by the calculations of Ref. [1]. In particular, the observed (6^+) state lies exactly where predicted. The (8^+) and (10^+) states, as well as all negative-parity states, are underestimated by the calculations, although the spacing between the (8^+) and (10^+) states is reproduced. In contrast, essentially all of the excitations are underpredicted by the calculations of Ref. [5] that used a realistic effective interaction, including the spacing between the (8^+) and (10^+) states.

In Fig. 6 the experimentally observed states of ^{93,95}Zr, for

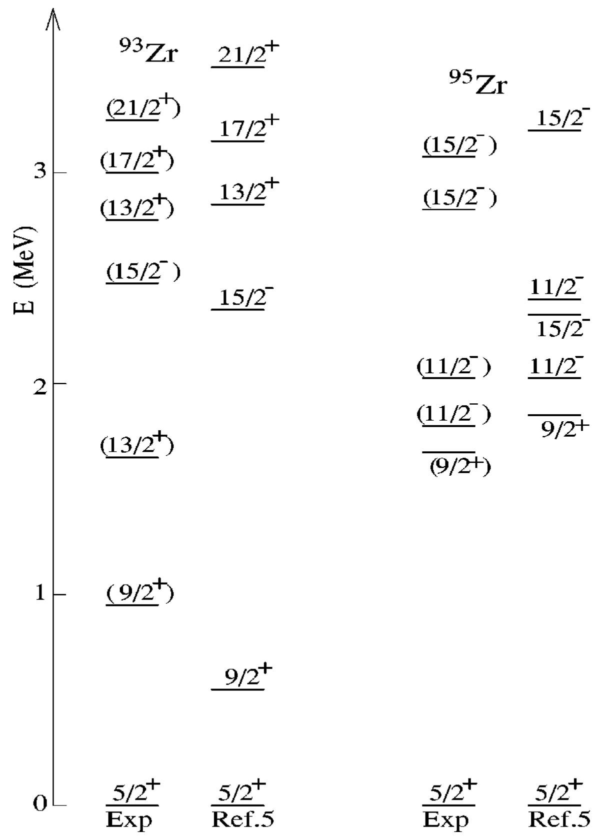

FIG. 6. Comparison between ^{93,95}Zr states observed experimentally in the present paper and theoretical shell-model predictions [5].

which tentative spin-parity assignments have been proposed, are compared to the theoretical calculations of Ref. [5]. For ^{93}Zr the agreement between experiment and theory is comparable to that for the ^{94}Zr core, except for the $13/2^+_1$ state in ^{93}Zr, which is grossly overpredicted. Unfortunately, the theoretical predictions for ^{95}Zr above 2 MeV can provide no guidance in proposing tentative spin-parity values to the levels displayed in Fig. 3. The spins and parities need to be determined for the extensive level schemes deduced for ^{93,95}Zr before additional comparison between theory and experiment would be fruitful.

Finally, we would like to highlight the high excitation energies and angular momenta to which the ^{92}Zr and ^{94}Zr isotopes have been observed in this study. The observation of a (18^+) state at more than 9 MeV excitation energy in the fission fragment ^{92}Zr is quite unusual. Studies of fission fragments produced in fusion-evaporation reactions typically allow up to spin $\sim 14\hbar$ and up to ~ 6 MeV excitation energy to be populated in a fission fragment (see, for example, Refs. [13,16]). Of course, the population of high-spin states depends strongly on the particular reaction and the fissioning compound nucleus.

V. SUMMARY

In conclusion, Zr isotopes near stability, produced as fragments following fission of a compound ^{197}Pb nucleus populated in a fusion-evaporation reaction, have been studied up to high-spin and excitation energy. γ-ray transitions have been assigned to ^{93}Zr and ^{95}Zr based on coincidences with known transitions in the complementary fission fragment Mo isotopes. Level schemes up to ~ 4.5 MeV excitation energy have been constructed for these isotopes. The previously known level schemes of ^{92}Zr and ^{94}Zr have been enriched and extended to higher excitations. The similarities in the levels of ^{92}Zr and ^{94}Zr up to ~ 3.5 MeV excitation energy are striking. The states in ^{93}Zr up to the same energy can be interpreted as originating from the coupling of the odd $d_{5/2}$ neutron to the levels of ^{92}Zr and ^{94}Zr. The states in ^{95}Zr up to ~ 2 MeV excitation energy can also be interpreted as the coupling of the odd $d_{5/2}$ neutron hole to the levels of the ^{96}Zr core. The observed experimental states are compared with theoretical shell-model calculations with a truncated space and empirical effective interactions [1] and a nontruncated space with a realistic effective interaction [5]. The calculations of Ref. [1] are able to reproduce well the excitation energies of the positive-parity states in ^{94}Zr, but underestimate the energies of the negative-parity states. In contrast, the calculations of Ref. [5], which have been extended to high spin, predict spectra for ^{92,94}Zr, which are compressed compared to the data, except at high spin where the agreement between experiment and theory is improved. While the excitation spectrum for ^{93}Zr is predicted [5] to be compressed compared to the data, the agreement between experiment and theory for the lowest levels in ^{95}Zr is surprisingly good. With the identification of high-spin states in these ^{92,93,94,95}Zr, these $Z=40$ isotopes with $50<N<56$, which should be amenable to shell-model calculations, continue to provide a challenge for theoretical interpretation.

ACKNOWLEDGMENTS

This work has been supported in part by the National Science Foundation (Rutgers), U.S. Department of Energy under Contract Nos. W-7405-ENG-36 (LANL), W-7405-ENG-48 (LLNL), and AC03-76SF00098 (LBNL) and the Research Council of Norway (NFR).

[1] D.H. Gloeckner, Nucl. Phys. **A253**, 301 (1975).
[2] H. Mach, E.K. Warburton, W. Krips, R.L. Gill, and M. Moszyński, Phys. Rev. C **42**, 568 (1990).
[3] G. Jakob, N. Benczer-Koller, J. Holden, G. Kumbartzki, T.J. Mertzimekis, K.-H. Speidel, C.W. Beausang, and R. Krücken, Phys. Lett. B **468**, 13 (1999).
[4] C. Zhang, S. Wang, and J. Gu, Phys. Rev. C **60**, 054316 (1999).
[5] A. Holt, T. Engeland, M. Hjorth-Jensen, and E. Osnes, Phys. Rev. C **61**, 064318 (2000), and private communication.
[6] N. Fotiades *et al.*, Phys. Rev. C **58**, 1997 (1998), and references therein.

[7] R. B. Firestone, V. S. Shirley, C. M. Baglin, S. Y. Frank Chu, and J. Zipkin, *Table of Isotopes* (Wiley, New York, 1996), and references therein.
[8] N. Fotiades *et al.*, Phys. Rev. C **57**, 1624 (1998).
[9] B.A. Brown, D.B. Fossan, P.M.S. Lesser, and A.R. Poletti, Phys. Rev. C **14**, 602 (1976).
[10] G. Korschinek, M. Fenzl, H. Hick, A. J. Kreiner, W. Kutschera, E. Nolte, and H. Morinaga, in *Proceedings of the International Conference on Nuclear Structure*, *Tokyo*, edited by T. Marumori (Physical Society of Japan, 1978), Vol. 1, p. 326.
[11] C.M. Baglin, Nucl. Data Sheets **66**, 347 (1992).
[12] C.M. Baglin, Nucl. Data Sheets **80**, 1 (1997).
[13] M.-G. Porquet *et al.*, Acta Phys. Pol. B **27**, 179 (1996).
[14] J.K. Tuli, Nucl. Data Sheets **66**, 1 (1992).
[15] T.W. Burrows, Nucl. Data Sheets **68**, 635 (1993).
[16] N. Fotiades *et al.*, Phys. Scr., T **T88**, 127 (2000).