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E. A. Henry
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L. G. Mann
R. K. Sheline
W. Stöffl
L. E. Ussery

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In-beam Spectroscopy Using the (t,p) Reaction: Recent Results Near A=100

E. A. Henry,* R. J. Estep,** R. A. Meyer,* J. Kantele,‡ D. J. Decman,*
L. G. Mann,* R. K. Sheline,** W. Stöffl,* and L. E. Ussery‡‡

*Lawrence Livermore National Laboratory, Livermore, CA 94550.
**Department of Chemistry, Florida State University, Tallahassee, FL 32306.
‡Department of Physics, University of Jyväskylä, Jyväskylä, Finland.
‡‡Los Alamos National Laboratory, Los Alamos, NM 87545.

INTRODUCTION

Charged particle spectroscopy using the (t,p) reaction has been employed for more than two decades to study the low-energy structure of nuclei. This reaction has contributed significantly to the elucidation of single-particle and collective phenomena for neutron rich nuclei in virtually every mass region. We have begun to use the (t,p) reaction in conjunction with in-beam γ-ray and conversion-electron spectroscopy to bring additional understanding to low-energy nuclear structure. In this report we briefly discuss the experimental considerations in using this reaction for in-beam spectroscopy, and present some results for nuclei with mass near 100.

EXPERIMENTAL METHODS

Until now the only methods available for studying the beta unstable nuclei with a mass near 100 were the prompt γ-ray decay and beta decay of fission products, charged-particle spectroscopy using two-neutron transfer reactions, and, to a limited extent, in-beam spectroscopy using reactions like (^{18}O,^{16}Oγ). In-beam spectroscopy using the (t,pγ) reaction has several features that make it an attractive technique to complement these methods. 1) Even-even nuclei that have two neutrons more than the heaviest target can be studied by the (t,pγ) reaction with useful cross sections. 2) The levels in the product nucleus are populated by both direct and compound nuclear reactions. Thus the set of levels that are identified at low excitation energies can be quite complete. 3) The spin distribution of levels populated is broader than is usually the case in beta decay. The ground state band is often populated up to the 8^+ member. In the same experiment 0^+ states can also be populated, probably by the direct reaction mechanism. 4) The (t,p) reaction has a unique signature, an energetic proton that identifies that particular channel.

The disadvantages of this reaction place some real constraints on its use. 1) The (t,p) cross section is only about 5 percent of the total cross section. 2) The dominant reaction, usually (t,2n), produces abundant prompt γ rays. 3) Reactions such as (t,n) and (t,d) [as well as (t,p)] often result in short-lived beta decaying products. 4) The usual in-beam techniques such as angular distributions are complicated by the necessity to use the outgoing proton to identify the reaction. As a result of the first three disadvantages, much of the γ-ray and electron count rates are not from the (t,p) reaction and thus experiments of reasonable duration have limited statistics.

We have developed γ-ray and conversion-electron spectroscopy techiques that take advantage of the energetic proton as an indicator of the (t,p)

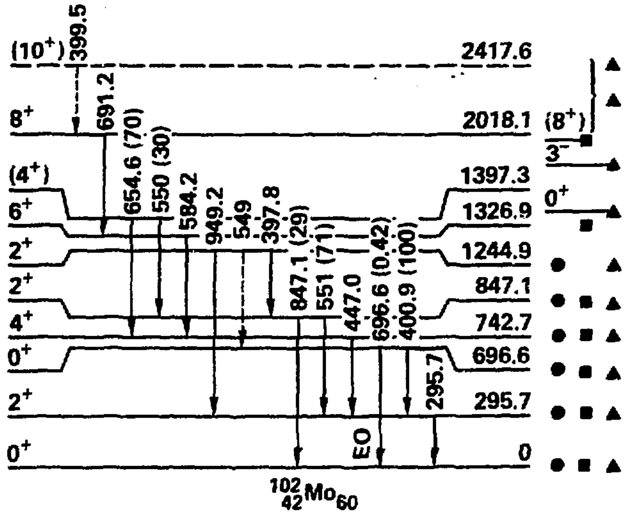


Fig. 1. Level scheme of ^{102}Mo determined from (t,pγγ) studies. Previous studies are beta decay (circles), (^{18}O, ^{16}Oγ) (squares), and (t,p) triangles.

reaction. Our conversion-electron spectrometer and its use with the (t,p) reaction have been described in the literature [DEC84, STO84]. For γ-ray spectroscopy, a 1-mm thick cylindrical plastic scintillator detects the protons to gate germanium detectors. A thin tapered cylindrical aluminum absorber inserted into the scintillator prevents reaction deuterons and scattered tritons from reaching the scintillator, while allowing energetic protons to do so. The geometric solid angle for the scintillator is about 30% of 4π. Typically, when the γ-ray singles rate is 10,000 cps, the pγ coincidence rate is 20-80 cps, and the pγγ coincidence rate is 1-5 cps. The γ rays associated with the (t,p) reaction are the dominant ones in the spectrum that is gated by the proton detector, with those from the (t,2n) reaction being attenuated by a factor of fifty or more.

NUCLEAR STRUCTURE STUDIES NEAR A=100

In 1970 Cheifitz et al. [CHE70] presented experimental evidence of rotation-like nuclear structure for ^{102}Zr and several nearby nuclei. They found that as N=50 or Z=50 closed shells were approached, indicators of deformation (e.g. E_4+/E_2+) varied farther from the rotational limits, but were also significantly different from the values for spherical nuclei. Experimentally, many of the nuclei in this mass region display complex low energy structure. Thus the experimental knowledge of the structure of nuclei surrounding the deformed region near A=100 must be as complete as possible to confidently apply a theoretical description. We report here on preliminary results from four in-beam studies of nuclei in this mass region, and discuss the results briefly in the context of the nuclear structure of the region.

^{102}Mo. The (^{18}O,^{16}Oγ) reaction has been used by Koenig et al. [KOE81] in an attempt to establish the yrast levels in ^{102}Mo. Our pγγ coincidence data confirm the 4_1^+ and 6_1^+ levels established in that study (See Fig. 1). However, it is clear from our data that the $8_1^+ \rightarrow 6_1^+$ transition is at 691 keV, establishing the 8_1^+ level at 2018 keV. The 655-keV γ ray, assigned by Koenig et al. as

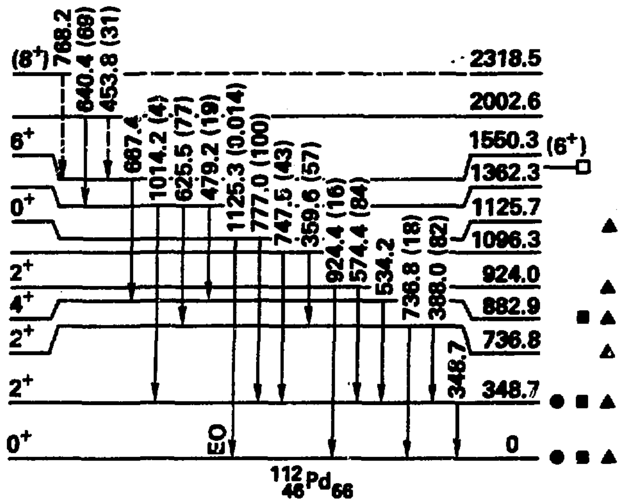


Fig. 2. Level scheme of ^{112}Pd determined from (t, pγγ) studies. Previous studies are beta decay (circles), fission fragment decay (squares), and (t,p) triangles.

the $8_1^+ \to 6_1^+$ transition, actually feeds the 4_1^+ level directly from a new level at 1397 keV. We suggest that this new level has a J^π value of 4^+.

Gamma rays with energies of 398 and 401 keV are known from previous studies and are observed as a multiplet in the (t,pγ) data. These γ rays depopulate the 2_2^+ and 0_1^+ levels, respectively. However, a gate on these γ rays reveals coincidences with all the members of the yrast band, not just the $2_1^+ \to 0_1^+$ transition as expected. A narrower gate set at about 399 keV reveals weak coincidences with the $8_1^+ \to 6_1^+$, $6_1^+ \to 4_1^+$, and $4_1^+ \to 2_1^+$ transitions. Though the statistics are poor, the intensities for these transitions in the coincidence spectrum are consistent with the 399-keV γ ray feeding the 8_1^+ level. We suggest that this transition may be the $10_1^+ \to 8_1^+$ yrast transition. If this assignment is confirmed, it will be the first experimentally observed backbend in the neutron rich nuclei near A=100. A backbend at the 10_1^+ level would agree with the calculation by Tripathi et al. [TRI84] of a pronounced backbend at the 10_1^+ level in ^{102}Mo.

^{112}Pd. Little has been known experimentally about the level structure of ^{112}Pd. Previous studies are in agreement only for the J^π assignment of the 2_1^+ level at 349 keV [CAS72,CHE70]. We have established five new levels in ^{112}Pd (see Fig. 2), and have been able to propose J^π assignments for some of the ^{112}Pd levels from decay patterns. The coincidence results established a ground state transition depopulating the 736 keV level, indicating that it is a 2^+ level. The level at 924 keV has a transition to the 2_1^+ level, and a γ ray seen in the proton gated singles is probably the ground state transition, suggesting a J^π value of 2^+ for that level also. Our data confirm that the 4_1^+ level occurs at 882 keV, in agreement with the results of the fission fragment decay studies, but that the previous tentative assignment of the 6_1^+ level was incorrect. Instead, we establish the 6_1^+ level at 1550 keV, and have evidence that suggests that the 8_1^+ level occurs at 2319 keV. New levels at 1096, 1362, and 2002 keV are based on the coincidence results.

Stachel et al. [STA82] have interpreted the structure of Ru and Pd nuclei in terms of the transition between the SU(5) (vibrational) and O(6) (γ-unstable) limits of the Interacting Boson Model (IBM). The energy ratios $E_{4_1^+}/E_{2_1^+}$ and $E_{6_1^+}/E_{2_1^+}$ are consistent with those of the O(6) limit for the heavier Pd and Ru nuclei. Stachel et al. point out that the energy ratio $E_{2_2^+}/E_{2_1^+}$ is not well reproduced in their calculation. Experimentally, that ratio is closer to the SU(5) limit than the O(6) limit, even for ^{112}Pd. However, if the suggested 2_3^+ level at 924 keV in ^{112}Pd is instead the 2_2^+ level within the model space, the $E_{2_2^+}/E_{2_1^+}$ ratio is just above that of the O(6) limit. In ^{112}Pd the $E_{0_2^+}/E_{2_1^+}$ energy ratio is higher than for the lighter Pd nuclei, but still only midway between the SU(5) and the O(6) limits. Stachel et al. suggest that the 0_2^+ level is an intruder level similar to those known in nearby Cd nuclei. Taken together, this evidence indicates that ^{112}Pd cannot be described by the simple O(6) limit of IBM alone. Recent calculations show that complete structures resulting from intruder states must be included with a large degree of mixing occurring between the two configurations [KUS85].

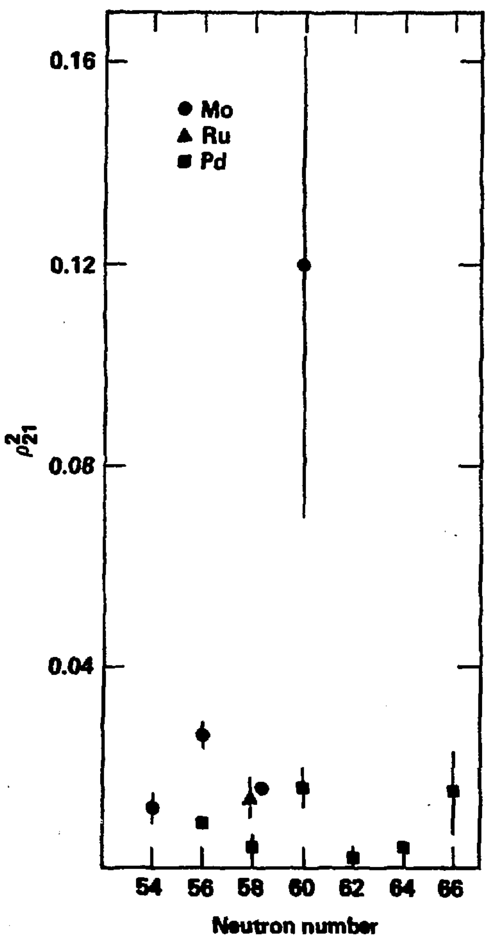
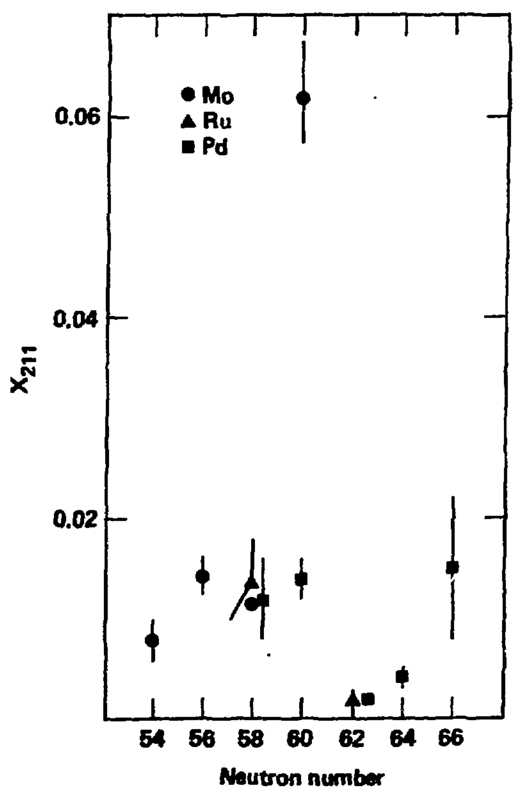


Fig. 3. Systematics of ρ^2_{21} and X_{211} near A=100. Results for ^{96}Mo, ^{102}Ru, and $^{102-106}$Pd are from literature data.



E0 Transitions. We have measured E0 transitions in the neutron rich nuclei ^{100,102}Mo, ^{106}Ru, and $^{108-112}$Pd using the (t,p) reactions and coincidence techniques. Listed in Table 1 are the values for the E0(K) branching ratios from our measurements. Where half-life information and E2 branching ratios are available from our own measurements or from the literature, ρ^2 and X values have been determined (see Fig. 3). The ρ^2_{21} and X_{211} values for ^{102}Mo are larger than in our previous report [DEC83] because of the additional γ-ray recently observed at 399 keV in that nucleus.

^{102}Mo has been described as a transitional nucleus which is quite close to being rotational, as its neighbor ^{104}Mo is. If we use Rasmussen's model [RAS60] for the X value ($X_{\beta 11} \propto \beta^2$), we find that the deformation parameter β for ^{102}Mo is about 2.3 times that of ^{100}Mo. This suggests that the 0_2^+ level in ^{102}Mo might be characterized as the beta-vibrational level in a rotating nucleus. However, while the yrast levels of ^{102}Mo appear to be evolving toward a rotational character, the lower energy levels might be better characterized by a model that mixes vibrational and γ-unstable limits of the IBM-1 [SAM82]. From (t,p) charged particle studies it is known that the 0_2^+ level has a substantial two-neutron component, however. This suggests that IBM-2 may be a better model with which to describe ^{102}Mo.

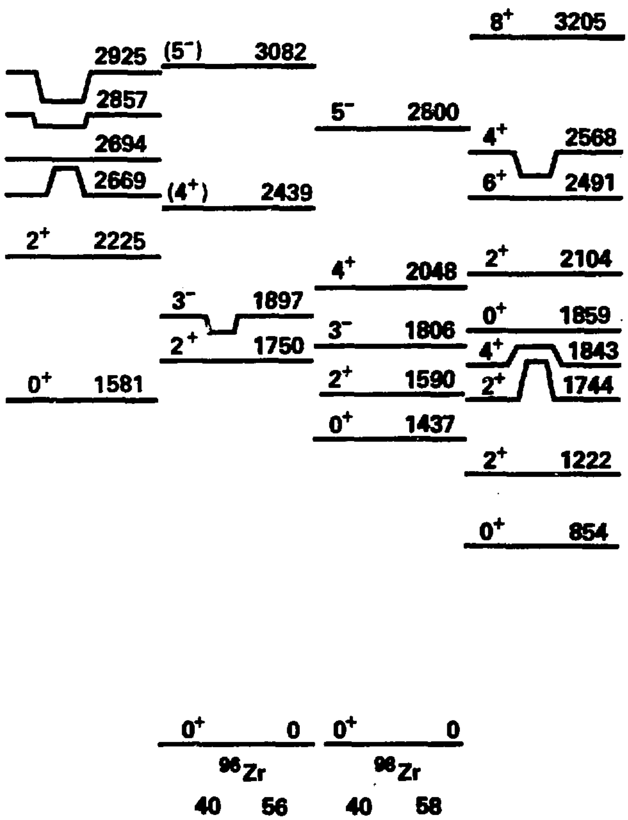


Fig. 4. Levels of ^{96}Zr and ^{98}Zr from (t,pγγ) studies. Levels are grouped according to their decay properties.

Table 1. E0(K) branching ratios for 0_2^+ levels.

Nucl.	$\frac{I_{E0(K)}}{I_{total}}$. (X10^6)
^{100}Mo	71200 ± 3600
^{102}Mo	4780 ± 780
^{106}Ru	30 ± 12
^{108}Pd	43 ± 19
^{110}Pd	122 ± 29
^{112}Pd	126 ± 57

The measured ρ^2_{21} and X_{211} values for ^{106}Ru and $^{108-112}$Pd are quite small. This would be consistent with the suggestion that these nuclei are evolving from the SU(5) and the O(6) limit of the IBM as neutrons are added [STA82], since the $0^+_2 \to 0^+_1$ transition is forbidden in both limits. As pointed out earlier however, Stachel et al. suggest that the 0^+_2 levels in Pd nuclei may be due to intruder states since their energies are much to low compared to a calculation using the IBM. It may be that the somewhat higher vlaues of ρ^2_{21} and X_{211} for ^{112}Pd reflect this influence.

<u>^{96}Zr and ^{98}Zr.</u> The preliminary results of our studies for the levels in ^{96}Zr and ^{98}Zr are shown in Fig. 4. The levels for each nucleus are segregated into two groups. Levels within a group γ decay with their largest reduced transition rates to other levels within the group. For ^{98}Zr, the strongest E0 transitions are between the two groups, rather within them, indicating possible shape differences between the 0^+ levels in the two groups. In ^{96}Zr, the (4^+) and (5^-) assignments indicated are not definite, but these levels seem to be the lowest that could have these J^π assignments. For some levels the group preference based on the γ decay criterion is modest. However, on the whole, a coherent pattern is developed.

Bengtsson et al. [BEN84] show that there is extra stability toward a spherical shape in the ^{96}Zr ground state brought on by the $2d_{5/2}$ neutron subshell closure. Focusing on the group that includes the ground state in each nucleus, we see the repeated pattern of levels with J^π of 2^+, 3^-, and, possibly, 4^+ and 5^- at energies which are reasonably close in the two nuclei. The comparison in Fig. 5 suggests that, insofar as excited states in ^{98}Zr are concerned, there may be some additional stability toward spherical shapes afforded by filling the $3s_{1/2}$ neutron orbital. The closeness of the energies of the two ground state groups should not be taken too seriously. The two accompanying "bands" must undoubtedly mix with the respective ground state groups to bring them closer together in energy. Nevertheless, this comparison graphically demonstrates the complex interplay between possible models for nuclear structure in this region.

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