STUDY OF THE PRODUCTION AND DECAY OF $^{89}$Mo ISOMERS AND $^{96}$Pd

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Abstract

The production and decay of 190-ms $^{89}$Mo, 2.15-min $^{89}$Mo, 8.2-min $^{88}$Mo, and 2.0-min $^{96}$Pd have been studied using sources produced at the Maryland Cyclotron. The resulting γ-ray spectra have extended the systematics of the N=47 and 48 isotones to higher Z and revealed sharp differences between the N=47 isotones and Z=47 isotopes. The low-lying $1^+$ states identified in $^{96}$Pd following the decay of $^{96}$Pd further supports the hypothesis of strong interaction between protons and neutrons with identical $\lambda$ values.

1. Experimental Procedures

The neutron deficient nuclides $^{88}$Mo, 2.15-min $^{89}$Mo, and 190 ms $^{89}$Mo were produced at the Maryland Cyclotron in proton irradiations of enriched $^{92}$Mo at beam energies ranging from 40 to 75 MeV. The study of activities with half lives greater than 1.5 min was done by manually transferring the target from the irradiation station to a high resolution large volume Ge detector in a low-background area. For the study of shorter-lived activities, a fixed target and detector setup was used and the

![Figure 1: Decay Scheme of 190-ms $^{89}$Mo and the Systematics of the Low-Lying $9/2^+$, $7/2^+$ and $1/2^-$ Levels and E3 Hindrances in the N=47 Isotones.](image)

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irradiation and counting periods determined by a variable speed rotating mechanical beam chopper (wheel). The wheel was designed to provide a 3:1 ratio between counting and irradiation time by the presence of four 22.5° slots in a 5 cm thick Al disc. The wheel could be rotated continuously from 2 rpm to 200 rpm and could also be controlled by a switch to provide longer irradiation and/or counting periods. The position of the slots in the wheel was monitored by an optical sensor whose output was coupled to the Cyclotron Computer to gate the storage of γ rays into twelve 8192 channel spectra as a function of time-after-irradiation. A manual start was used for this data collection system for the longer-lived activity studies.

Four 3 mg/cm² ⁹²Mo foils enriched to 96% were used in both studies to minimize the buildup of longer-lived activities, particularly 5.9-h ⁹⁰Mo and 14.6-h ⁹⁰Nb. Strong activities were also observed from the Nb isotopes produced in the ⁹²Mo(p,αn) reactions.

2. ⁹⁰Mo Studies

As the study of the ⁹²Mo(³He,5He)⁹⁰Mo reaction revealed the presence of ⁷/² and 1/² levels in the low-lying level structure of ⁹⁰Mo and a Q value of 5.6 MeV for ⁹⁰Mo decay, it was possible to estimate a half life for the E3 transition for a few hundred milliseconds for 1/²⁻ ⁹⁰Mo and a half life of 15 sec or greater for the ³⁺/EC decay of ⁹/²⁺ ⁹⁰Mo. Thus, the rotating wheel setup was used to make the initial studies for both isotopes. The wheel was rotated to give 50 ms irradiations and 1050 ms counting periods in the initial measurement of ⁹⁰Mo decay. For the initial study of ⁹⁰Mo, the wheel was manually operated to give 45-sec irradiations and 300 sec counting periods. Subsequent studies of ⁹⁰Mo decay were done using the manual target transfer procedure when the half life was found to be ~2 min.

2.1 ⁹⁰Mo Studies

The results of our study of ⁹⁰Mo decay are shown in Fig. 1 along with the data for other N=47 isotones. These studies reveal a sharply decreasing hindrance factor for the 1/²⁻/⁷⁺ E3 transition as ² increases and a ⁶/²⁺/⁹/²⁺ difference that peaks in ⁹²Sr. The hindrance was calculated as the ratio t¹/² (radiative)/t² where the theoretical E3 half life was calculated by the formula t²=0.693/35A²By²S. Extensive calculations of the level energies and transition rates of the N and S=47 nuclides by Paar using a cluster-vibration model.

\[
\begin{align*}
\text{2.15 m} & \quad 9/2^+ & \quad 0 \\
\text{89Mo} & \quad 21/2^+ & \quad 2150 \\
\text{42Mo} & \quad 17/2^+ & \quad 1935 & \quad 2050 \\
\text{17/2^+} & \quad 1550 \\
\end{align*}
\]

\[Q_{EC}=5.64 \text{ MeV}\]

\[\begin{align*}
9/2^- & \quad <35 & \quad 66 \text{ min} \\
9/2^+ & \quad 0 & \quad 122 \text{ min} \\
\end{align*}\]

Fig. 2 Decay scheme of 2.15-min ⁹⁰Mo and levels of ⁹⁰Nb observed in the ⁹⁰Y(³He,3nγ) ⁹²Mo(p,α) reactions.
have successfully accounted for many of the observed features of these nuclides particularly for the Z=47 isotopes. The 7/2+-9/2+ difference in the N=47 isotones, however, shows a very different behavior that reflects the strong interaction between the three-neutron g9/2 hole cluster and the occupancy of the g9/2 proton orbital which becomes significant for Z>38. This phenomenon is not important for the (g9/2)3 proton cluster in the Ag nuclides as the g9/2 neutron shell is fully occupied throughout the Ag isotopes. The filling of the g9/2 neutron orbitals in the Z=47 isotopes does not appear to play a significant role in the general properties of those nuclides.

2.2 89Mo Studies

Our results6) from the study of the decay of 89Mo are shown in Fig. 2 for 89Nb along with the levels observed in the study of the 89Y(3He,3nY) reaction7) and the 92Mo(p,α) reaction.8) These data show very little change in the overall structure of 89Nb relative to 87Y except for the 658-keV 41- level, as shown in Fig. 3. If that 7/2+ assignment is correct, then the presence of two additional g9/2 protons to the 87Y core permits the formation of a (g9/2)3 cluster and the sharp drop in the position of the 7/2+ level because of the substantial (g9/2)3 admixture in its wavefunction. The study of the level structure of 91Zr would particularly important to further observe how additional protons affect the position of this 7/2+ level in nuclides where no g9/2 neutrons are present. The behavior of the 7/2+ state in the N=52 isotones with increasing Z is well established, as shown in Fig. 4.

2.3 88Mo Studies

In seeking to confirm the identity of the 2.15-min activity associated with the 658.6-keV γ ray, we studied its yield at 40, 50, 70 and 75 keV. The threshold was found to lie between 40 and 50 MeV and the peak yield below 70 MeV. We also observed the 80-, 131-, and 171-keV γ rays attributed to 8.6-min 88Mo decay by Doron and Blann.9) We did not observe these γ rays at 50 MeV and only very small peaks were seen at 60 MeV. Significant peaks were observed at 75 MeV and a half life of 8±1 min determined. As all three of these γ rays are parts of complex structures, substantial uncertainty is associated with the half life measurement.

<table>
<thead>
<tr>
<th>ODD Z N=48</th>
<th>ISOTONES</th>
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<tr>
<td>1227 9/2+</td>
<td>1272</td>
</tr>
<tr>
<td>1203 11/2+</td>
<td>9/2+ (11/2+)</td>
</tr>
<tr>
<td>1155 11/2+</td>
<td>3/2, 5/2, or (9/2+)*</td>
</tr>
<tr>
<td>1077</td>
<td>1051</td>
</tr>
<tr>
<td>1024 13/2+</td>
<td>1003</td>
</tr>
<tr>
<td>1023 7/2+</td>
<td>1010</td>
</tr>
<tr>
<td>772</td>
<td>982</td>
</tr>
<tr>
<td>5/2+</td>
<td>3/2-</td>
</tr>
<tr>
<td>793</td>
<td>5/2-</td>
</tr>
<tr>
<td>658</td>
<td>5/2-</td>
</tr>
<tr>
<td></td>
<td>(7/2+)</td>
</tr>
</tbody>
</table>

Fig. 3 Comparison of 87Y and 89Nb levels.
3. **96Pd Studies**

These same facilities were also utilized to identify the closed shell nuclide 96Pd and study its decay. As the earlier identification of the "farther-from-stability" nuclides\(^{1,12}\) 15-sec 97Ag and 8-sec 98Cd permitted an estimate of 2-4 min for the half-life of 96Pd, the initial experiments utilized the manual transfer of the enriched 96Ru target to the detector area following irradiation of the target with 60-MeV \(^4\)He ions. Two strong \(\gamma\) rays at 125 and 500 keV were observed and placed as feeding the well established 2\(^+\) isomer in 96Rh, as shown in Fig. 5.

The positions of these two 1\(^+\) levels are of particular interest as they confirm a continued trend of 1\(^+\) states in the odd-odd \(N=15\) isotones that lie well below the odd \(N=16\) 1\(^+\) states in the adjacent odd \(N=17\) core. The odd \(Z\) isotones with \(Z>40\) and \(N>52\) are characterized by the presence of low-lying 9/2\(^+\) and 1/2\(^-\) states as shown in Fig. 4. In Fig. 6 we show the odd \(N\) nuclides with 51 neutrons. They are characterized by a 5/2\(^+\) ground state and an excited 7/2\(^+\) state whose position is lowered with increasing \(Z\) by both the increased size of the nucleus and the increased occupancy of its spin-orbit partner 99/2 protons. The significant feature of these odd-odd \(N=51\) isotones that include a single 5/2\(^+\) or 7/2\(^+\) neutron coupled to an increasing number of 99/2 protons lies in the very much lowered 1\(^+\)-2\(^+\) energy gap compared to the 5/2\(^+\)-7/2\(^+\) neutron gap responsible for these states. This lowered gap likely arises from the much stronger interaction between the 99/2 protons and the 7/2\(^+\) neutron relative to the interaction between the 99/2 protons and the 5/2\(^+\) neutron. It appears that the size of this interaction (\(-1\) MeV) is large and not very dependent on the occupancy of the proton orbitals. The importance of neutron-proton interactions where \(N=51\) has been recently discussed by Federman and Pittel\(^{13}\) and these studies serve as a source of a quantitative measure of that interaction.

Extrapolation of the trends observed here suggest that the 1\(^+\) level will lie below the 2\(^+\) level in 98Ag and possibly 100In as well.

![Level Structure](image)

**Fig. 4** Comparison of the level structure of the \(N=52\) isotones.
4. Acknowledgements

We wish to acknowledge the support of the University of Maryland Cyclotron staff in the design and construction of the mechanical beam chopper system, and the assistance of the late Professor N.S. Wall and Dr. M.D. Glasscock in the implementation of the data collection system. The support of the U.S. National Science Foundation and the U.S. Department of Energy through its predecessor agencies the Atomic Energy Commission and the Energy Research and Development Administration is gratefully acknowledged.

References


Fig. 5 Decay scheme of 2.0-min $^{96}$Pd.


The $7/2^+ - 5/2^+$ and $2^+ - 1^+$ Differences in N=51 Isotones

\[
\begin{array}{c}
\frac{2^+}{2186} & 7/2^+ & \frac{2201}{2201} \\
7/2^+ & 1355 & \frac{1520}{1363} \\
& 812 \text{ keV} & \frac{7/2^+}{1495} \\
& 954 & \frac{906 \text{ keV}}{942} \\
& 892 & \frac{7/2^+}{942} \\
& 367 & \frac{500}{686} \frac{1^+}{J25} \\
0^+ & 5/2^+ & 2^+ \text{ levels in the N}=51 \text{ Zr, Nd, Mo, Tc, Ru, Rh and Pd} \\
0^+ & 90\text{Zr} & 91\text{Zr} & 92\text{Nb} & 92\text{Mo} & 93\text{Mo} & 94\text{Tc} & 0^+ & 94\text{Ru} & 95\text{Ru} & 2^+ & 96\text{Rh} & 96\text{Pd} & 97\text{Pd} & \text{isotones along with the 2}^+ \text{ level in the adjacent N}=50 \text{ core.}
\end{array}
\]