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SPECTROSCOPIC STUDIES NEAR THE PROTON DRIP LINE

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ABSTRACT

We have investigated nuclei close to the proton drip line by using heavy-ion fusion reactions to produce extremely neutron-deficient nuclides. Their nuclear decay properties were studied by using on-line isotope separators at Oak Ridge (UNISOR) and Berkeley (OASIS), the Oak Ridge National Laboratory velocity filter, and a fast helium-gas-jet transport system at Lawrence Berkeley Laboratory 88-Inch Cyclotron. Many isotopes, isomers, and β -delayed-proton and α -particle emitters were discovered. This contribution summarizes three topics that are part of our overall program: (a) decay rates of even-even α -particle emitters, (b) mass excesses of ^{181}Pb , ^{182}Pb , and ^{183}Pb , and (c) β -delayed proton emitters near $N = 82$.

DECAY RATES OF EVEN-EVEN ALPHA-PARTICLE EMITTERS

Half-lives for s-wave α transitions, i.e., decays between ground states of doubly-even nuclei, are taken to represent unhindered α -decay rates. The resultant reduced widths are regarded as standards against which widths of other types of α transitions are to be compared. Figure 1 shows s-wave α widths for nuclei with Z from 78 to 100 plotted as a function of neutron number. We utilized Rasmussen's formalism¹ to calculate the width, δ^2 , which is defined as: $\delta^2 = \lambda h/P$, where λ is the decay constant, h is Planck's constant, and P is the penetrability for the α particle to tunnel through a barrier. A rather regular behavior as a function of both neutron and atomic number is observed for these reduced widths. They are largest for nuclei two or four particles beyond a closed shell (with sharp minima occurring at the closed shell), followed by a decrease as one approaches the next closure. These trends can be understood in terms of single-particle models which have shown² that the extremely sharp break at $N = 126$ is essentially a shell structure effect. There is also a dip in values at $N = 152$ due to the subshell at that neutron number.

As stated above, the reduced widths around $N = 130$ are large; in particular, the available ^{218}Ra value (labeled as "Previous Measurement" in Fig. 1) exhausted 75% of the Wigner-sum-rule limit. Suggestions have been made³ that these large widths indicate α clustering on the nuclear surface; the distorting effect of these

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Fig. 1. Reduced widths for s-wave α transitions plotted as a function of N for isotopes with Z from 78 to 100.

clusters could account for reflection asymmetry observed in radium and thorium nuclei near $N = 130$. We remeasured⁴ the ^{218}Ra half-life by using the ORNL velocity filter and a novel technique in which reaction products, after being separated from the incident beam, are implanted in a Si(Au) detector and their subsequent α decays are observed in the same detector. We found the half-life of ^{218}Ra to be $25.6(11) \mu\text{s}$ instead of the adopted value of $14(2) \mu\text{s}$. It yields an α width which in Fig. 1 is indistinguishable from those of ^{216}Rn and ^{220}Th . This smooth trend of α widths from the $N = 130$ region to the well-deformed, prolate, Cm, Cf, and Fm nuclei weakens one argument quoted for the existence of α clusters in the heavy elements. It is the stabilizing effect of the shell closure that produces the sharp decrease in width values from $N = 130$ to $N = 126$.

However, contrary to an expected shell effect at $Z = 82$, the decay rates of $^{186}, ^{188}, ^{190}, ^{192}\text{Pb}$ (open points in Fig. 1 with N from 104 to 110) are less hindered than those of neighboring Hg isotopes. This implies that, midway between $N = 82$ and $N = 126$ the 82-proton shell is not magic.⁵ We recently used the UNISOR facility to identify the α decay of ^{194}Pb for the first time and to determine the isotope's α branch.⁶ The resultant width for ^{194}Pb (see Fig. 1) is much less than those of nuclei with $N < 110$ and less than the δ^2 for ^{190}Pt ($N = 112$), indicating that perhaps the $Z = 82$ gap is being restored for $N > 112$. The reduced α widths for ^{190}Hg and ^{192}Hg should be determined to be certain about this proposal; if our suggestion is correct, the ^{192}Hg width should exceed that of ^{194}Pb .

We also show in Fig. 1 widths for ^{182}Pb and ^{184}Pb based on our data⁷ and those of Ref. 8, respectively, assuming α branches of 100%. [From gross β -decay theory the calculated half-lives

for ^{182}Pb and ^{184}Pb ($\beta^+ + \text{EC}$) decay yield α branching ratios $> 90\%$.] These δ^2 values are appreciably smaller than the $^{186}, ^{188}, ^{190}\text{Pb}$ widths and may indicate that the influence of the $Z = 82$ shell reappears and retards the α decay of very proton-rich Pb isotopes.

MASS EXCESSES OF $^{181}, ^{182}, ^{183}\text{Pb}$

The (55_{-35}^{+40}) -ms half-life used to calculate the ^{182}Pb width was measured with the use of a rapid gas-jet-transport system at the LBL 88-Inch Cyclotron. In these experiments we identified ^{182}Pb (Ref. 7) and ^{181}Pb (Ref. 9) in ^{40}Ca bombardments of ^{147}Sm and ^{144}Sm , respectively. The α -particle spectrum accumulated in 222-MeV ^{40}Ca irradiations of ^{147}Sm is shown in Fig. 2. The (6.919 ± 0.015) -MeV peak is assigned to ^{182}Pb on the basis of excitation-function and cross-bombardment data and decay-energy systematics. Because the ^{182}Pb α -decay chain terminates at ^{146}Gd , our decay-energy measurement yields a rather precise mass excess for ^{182}Pb , i.e., -6823 ± 25 keV. The adopted¹⁰ mass excess for ^{182}Pb is -6874 ± 28 keV.

In our investigation⁷ two incident ^{40}Ca energies were used, i.e., 194 and 222 MeV, to enhance the production of ^{184}Pb [$^{147}\text{Sm}(^{40}\text{Ca}, 3n)$ product] and ^{182}Pb [$^{147}\text{Sm}(^{40}\text{Ca}, 5n)$ product], respectively. To obtain more definite data on ^{183}Pb and to provide additional cross-bombardment information we irradiated ^{147}Sm with 212-MeV ^{40}Ca ions. Figure 3 shows the accumulated α -particle spectrum. The 194-MeV spectrum was dominated by ^{184}Pb while the 222-MeV spectrum had only possible traces of ^{184}Pb and ^{183}Pb α activity (see Fig. 2). Figure 3 clearly represents an intermediate situation, namely, the intensity of ^{183}Pb is now somewhat greater than that of ^{184}Pb , and ^{182}Pb is seen with about the same intensity

Fig. 2. Alpha-particle spectrum measured during a bombardment of ^{147}Sm with 222-MeV ^{40}Ca ions. Energies shown are in MeV.

Fig. 3. Alpha-particle spectrum measured in bombardments of ^{147}Sm with 212-MeV ^{40}Ca . Energies shown are in keV.

as had been observed at 222 MeV. We assign a total of four α groups to ^{183}Pb . Previously, only two groups have been observed in ^{183}Pb α decay. A mass excess of -7720 ± 310 keV has been adopted¹⁰ for ^{183}Pb ; it is based on a Q_α value deduced from the highest-energy previously observed⁸ α group of 6798 keV. Since we now have seen an α peak of 6874 keV both the adopted Q_α value and mass excess of ^{183}Pb will have to be revised.

Because the production of $A < 182$ lead nuclei with ^{147}Sm necessitates unfavorable reactions wherein six or more neutrons have to be evaporated (there is fission competition at each evaporation step) we used ^{144}Sm as the target in our search for ^{181}Pb . Figure 4 shows the spectrum measured at 201 MeV with the ^{144}Sm target. In

Fig. 4. Alpha-particle spectrum measured in bombardments of ^{144}Sm with 201-MeV ^{40}Ca ions. Energies shown are in keV.

addition to nuclides with $Z < 80$, one observes ^{184}Pb and ^{183}Pb produced from heavier samarium isotopes present in the target material [^{147}Sm (3.9%), ^{148}Sm (2.2%), ^{149}Sm (2.3%), etc.]. A new peak is seen at 7044 ± 15 keV. We assign it to the α decay of ^{181}Pb because its yield as a function of energy and target behaves as one would expect for the $^{144}\text{Sm}(^{40}\text{Ca}, 3n)$ product, i.e., it is observed neither in $^{40}\text{Ca} + ^{147}\text{Sm}$ bombardments (Figs. 2 and 3) nor in data obtained at 212 MeV with the ^{144}Sm target.

Based on what is known about the α decays of ^{187}Pb , ^{185}Pb , and ^{183}Pb , we conclude that the 7044-keV peak is probably only the most intense of several ^{181}Pb α transitions. If one assumes that it proceeds between the ground states of ^{181}Pb and ^{177}Hg then the mass excess of ^{181}Pb can be estimated to be about -3.31 MeV based on the value of (-12950 ± 230) keV adopted¹⁰ for ^{177}Hg . Our decay-energy

even- Z $N = 81$ precursors $^{147}_{66}\text{Dy}$, $^{149}_{68}\text{Er}$, and $^{151}_{70}\text{Yb}$. Such structure is unusual for nuclei with $A \geq 70$ because of the large level densities in the β -decay daughters at excitation energies high enough for proton emission. We have shown^{12,13} that the proton peaks are associated with the β decays of the $s_{1/2}$ ground states in these $N = 81$ precursors and reflect regions of low densities of $1/2$ and $3/2$ levels in the range of 3.5 - 5.0 MeV in the $N = 82$ daughters. Protons emitted by the $h_{11/2}$ isomers in the same $N = 81$ precursors, because of energetics and angular-momentum considerations, sample levels in the daughters that have a centroid at about 7 MeV. Here the level densities are higher and the proton spectra associated with the $h_{11/2}$ states are structureless. For these three precursors one then finds peaks superposed on a statistical component which becomes progressively larger as the atomic number increases due to an increasing β -decay Q value. Gamma-ray decay studies, β -strength function measurements, and calculations of state densities and Gamow-Teller strength distributions, have led us to suggest¹³ that the structure in delayed-proton spectra near $N = 82$ may arise from the preequilibrium decay of doorway states populated in β decay.

Fig. 6. Beta-delayed protons from ^{147}Er [(a)] and (c)] and ^{149}Er [(b)] and (d)]; (a) and (b) show singles spectra, while (c) and (d) display protons observed in coincidence with positrons.

We have also studied the decay properties of the $N = 79$ precursors ^{145}Dy and ^{147}Er . Their β -decay daughters have the same atomic numbers as those of ^{147}Dy and ^{149}Er , respectively, but have 80 rather than 82 neutrons. A comparison of delayed-proton spectra from these four emitters should therefore provide information concerning the relative importance of the $N = 82$ and $Z = 64$ closures with regard to the observed proton structures.

The ^{145}Dy and ^{147}Er spectra were found to be basically structureless, though there were weak proton groups at the low-energy portions of the spectra. By requiring positron coincidences one can enhance the fraction of protons emitted from low excitation energies, i.e., from levels found^{15,16} to be associated with the pronounced peaks in the $N = 81$ data. Figure 6 compares the singles protons [parts (a) and (b)] and protons in coincidence with positrons [parts (c) and (d)] for ^{147}Er and ^{149}Er , respectively. The structure observed in Fig. 6(a) is indeed emphasized in Fig. 6(c) though in neither spectrum are the peaks as pronounced as they are for ^{149}Er [Figs. 6(b) and 6(d)].

Thus the intense structures disappear from observed spectra almost as soon as the β -decay daughters no longer have a major closed-shell configuration. The role of the $Z = 64$ subshell in lowering level densities must be a minor one. This and other points are addressed in a recent thesis¹⁴ where the results obtained at the OASIS facility for delayed-proton precursors, ranging from ^{119}Ba to ^{154}Lu , are described and discussed.

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