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Masses and Proton Separation Energies Obtained from Q_α and Q_p Measurements[1]

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Abstract. For many nuclei beyond the proton drip line in the Z>72, N>82 region, both proton and α emission are energetically allowed. In the case of some proton emitters, there are α-decay chains emanating from both parent and daughter nuclei. This means that if the mass excess of one member of an α-decay chain is known, then the mass excesses for all members of both chains can be obtained. In addition, proton separation energies may be derived for nuclei in the α-decay chain of the proton emitter. The method of time- and space-correlations also allows the identification of isomeric states in these nuclei. As an example, a large number of mass excesses and proton separation energies for ground and metastable states have been derived from Q_α and Q_p values obtained from the proton emitters ^{165,166,167}Ir, ^{171}Au, ^{177}Tl, and their daughters.

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INTRODUCTION

The search for examples of proton radioactivity has resulted in the discovery of a large number of proton emitters in the region $50 < Z < 84$ [1]. Many of these proton emitters and their daughters are also α-emitters, and in some cases the α-decay chain from the daughter terminates on a nuclide closer to stability whose mass excess is known. This opens up the possibility of using α- and proton-decay Q-values to determine the mass excesses of a large group of nuclei connected by particle decay. The Q-values are derived from the measured kinetic energies of the emitted protons or α-particles. Where the decay chains are not connected to nuclei with known mass excesses, proton separation energies can be measured in some cases and derived in others.

For the α-decay of the parent nucleus (Z,A) to the daughter (Z-2,A-4), the fundamental energy relations used to convert between Q-value, mass (M) and mass excess (ME) are:

$$M(^4He)E_\alpha = M(Z-2, A-4)E_{recoil} \tag{1}$$

$$Q_\alpha = E_\alpha + E_{recoil} \tag{2}$$

$$ME(Z,A) = Q_\alpha + ME(Z-2, A-4) + ME(^4He) \tag{3}$$

In practice, one uses $M(^4He) \simeq 4$ and $M(Z-2, A-4) \simeq (A-4)$, so that Equation (3) becomes

$$ME(Z,A) = E_\alpha \left(\frac{A}{A-4}\right) + ME(Z-2, A-4) + ME(^4He) \tag{4}$$

Similarly, for protons, we have

$$ME(Z,A) = E_p \left(\frac{A}{A-1}\right) + ME(Z-1, A-1) + ME(^1H). \tag{5}$$

The proton separation energy is obtained from

$$S_p = ME(Z-1, A-1) + ME(^1H) - ME(Z,A) \tag{6}$$

Atomic mass excess values are used in all cases.

EXPERIMENTS AT ARGONNE

A number of proton emitters have been studied at Argonne National Laboratory, using a double-sided silicon strip detector (DSSD) coupled to the Fragment Mass Analyzer (FMA). The FMA [2] is a recoil mass spectrometer, separating reaction products from the primary beam, and dispersing them according to their mass/charge (M/q) at the focal plane. The DSSD allows time- and space-correlation of implanted ions with their subsequent charged particle decays. In those cases where the daughter nucleus decays by α emission, extremely clean spectra can be obtained by correlating the proton and α decays. Figure 1 shows such a situation, where M/q and time interval gating are used to pick out the very weak proton decay channels [3].

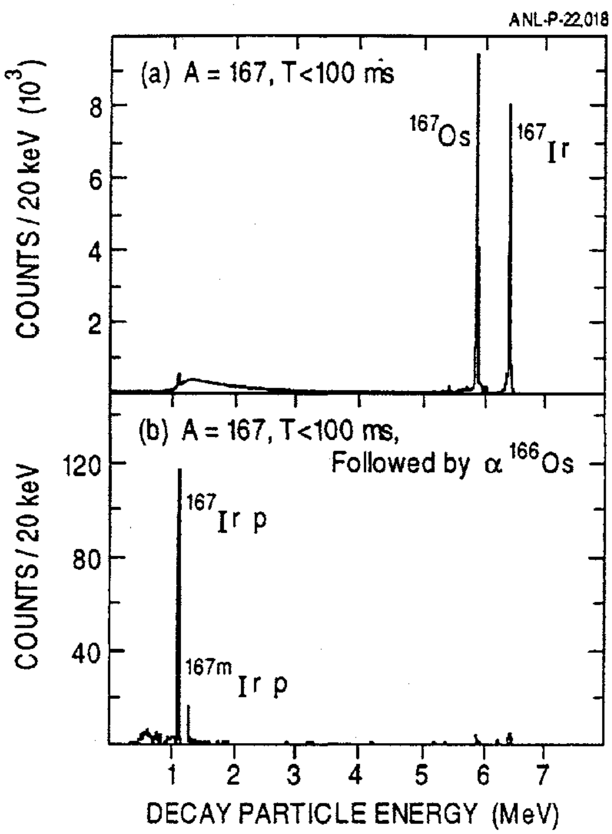


FIGURE 1. (a) Energy spectrum of decay events in the DSSD from 357 MeV ^{78}Kr + ^{92}Mo, after requiring that the decay occurred in the same pixel within 100 ms following a mass 167 implant. (b) Same as (a) with the additional requirements that a second decay event occured in the same pixel within 100 ms, having an energy of 6000 keV, the known α-decay energy of ^{166}Os.

Mass Excess Measurements from ^{167}Ir Decay

A long α-decay chain leads from ^{166}Os, the proton decay daughter of ^{167}Ir, to ^{150}Er, which decays by β^+/EC emission to ^{150}Ho. The Q_{EC} for the ^{150}Er decay to the 2^- state in ^{150}Ho has been measured to be 4108(15) keV [4]. Combining this with the mass excess of -61950(27) keV determined for the 2^- state in ^{150}Ho at ISOLTRAP [5], we obtain a mass excess for ^{150}Er of -57842(31) keV. Based on this number and the known Q_α values for its α-decay parents [4,6–8], we can derive mass excesses for the nuclides ^{154}Yb, ^{158}Hf, ^{162}W, ^{166}Os, ^{170}Pt, and ^{174}Hg from Equation (4).

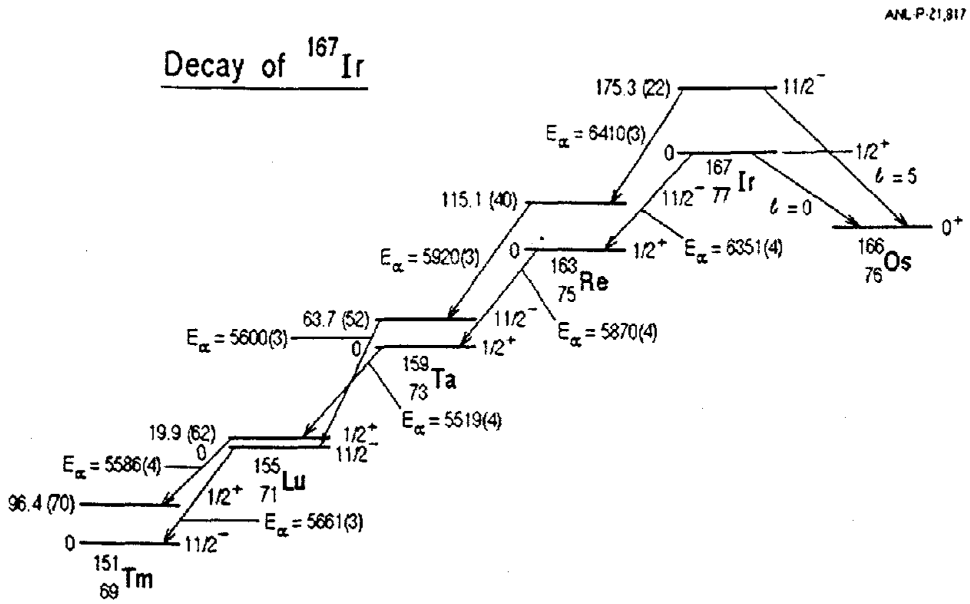


FIGURE 2. Proton and α decay scheme of ^{167}Ir.

Figure 2 shows the decay scheme ^{167}Ir [3]. The proton decay Q-value for ^{167}Ir [3] enables us to obtain its mass excess, using Equation (5) and the mass excess of ^{166}Os. The ground-state mass excesses of the ^{167}Ir α-decay daughters ^{163}Re, ^{159}Ta, ^{155}Lu, and ^{151}Tm, and that of the $1/2^+$ ^{171}Au ground state may be obtained from the ^{167}Ir mass excess and the measured α-decay Q-values [3,9]. Note that each of these odd-A isotopes has two α-emitting states, with spin $1/2^+$ and $11/2^-$. Table 1 gives the experimental mass excesses tied to ^{167}Ir by proton and α-decay, along with the corresponding values from the 1995 Atomic Mass Evaluation (AME95) [4].

TABLE 1. Mass excess values of ^{166}Os, its α- and proton-decay parents, and the α-decay daughters of ^{167}Ir.

Nuclide	Mass Excess (keV)[a]	AME95[b]
^{166}Os	-25 433(32)	-25 590(100)
^{170}Pt	-16 300(33)	-16 460(100)
^{174}Hg	-6 643(34)	-
^{167}Ir($1/2^+$)	-17 074(33)	-17 190(100)
^{171}Au($1/2^+$)	-7 559(37)	-7 660(250)
^{163}Re($1/2^+$)	-26 006(33)	-26 110(110)
^{159}Ta($1/2^+$)	-34 449(33)	-34 550(120)
^{155}Lu($11/2^-$)	-42 555(34)	-42 630(130)
^{151}Tm($11/2^-$)	-50 791(34)	-50 830(140)

[a] Experimental, see text for references.
[b] Ref. [4]

Mass Excess Measurements from ^{177}Tl Decay

As in the case of ^{167}Ir, the proton decay of ^{177}Tl results in a long α-decay chain extending from the daughter ^{176}Hg down to ^{148}Dy, whose mass excess has been measured at ISOLTRAP [5]. This allows the mass excesses of all the α- and proton-decay parents of ^{148}Dy to be obtained. The α-decay chain from ^{177}Tl has been traced down to ^{165}Re [9], permitting mass excess values for it, ^{169}Ir, and ^{173}Au to be derived. Knowing the Q_α for ^{180}Pb [10] also yields a mass excess for ^{180}Pb. Table 2 shows these mass excess values, compared with the values from AME95 [4].

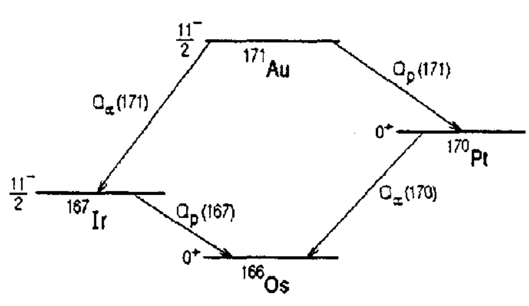
TABLE 2. Mass excess values of ^{176}Hg, its α- and proton-decay parents, and the α-decay daughters of ^{177}Tl.

Nuclide	Mass Excess (keV)[a]	AME95[b]
^{176}Hg	-11 770(20)	-11 720(40)
^{180}Pb	-1 930(25)	-
^{177}Tl($1/2^+$)	-3 318(28)	-2 910(230)
^{173}Au($1/2^+$)	-12 810(28)	-12 670(100)
^{169}Ir($1/2^+$)	-22 065(29)	-21 990(90)
^{165}Re($1/2^+$)	-30 641(30)	-30 690(70)

[a] Experimental, see text for references.
[b] Ref. [4]

Proton Separation Energies

For purposes of comparing with mass predictions, the proton separation energy $S_p = -Q_p$ is nearly as valuable as the mass excess. This quantity is easier to obtain since it involves mass differences. We obtain S_p directly from proton emitters, but also can derive this quantity for the α daughters of proton emitters, if the proton daughter nucleus is also an α-emitter. This is illustrated in Figure 3 for the case of ^{171}Au^m($11/2^-$) decay.



$$Q_p(167) = Q_p(171) + Q_\alpha(170) - Q_\alpha(171)$$

FIGURE 3. Q-value loop involving the $11/2^-$ states in ^{171}Au and ^{167}Ir.

Using measured values of Q_p and Q_α, proton separation energies can be derived for a large number of α-daughter nuclei of proton emitters. Figure 4 shows these S_p values, plotted along with predictions from the Liran-Zeldes mass formula [11].

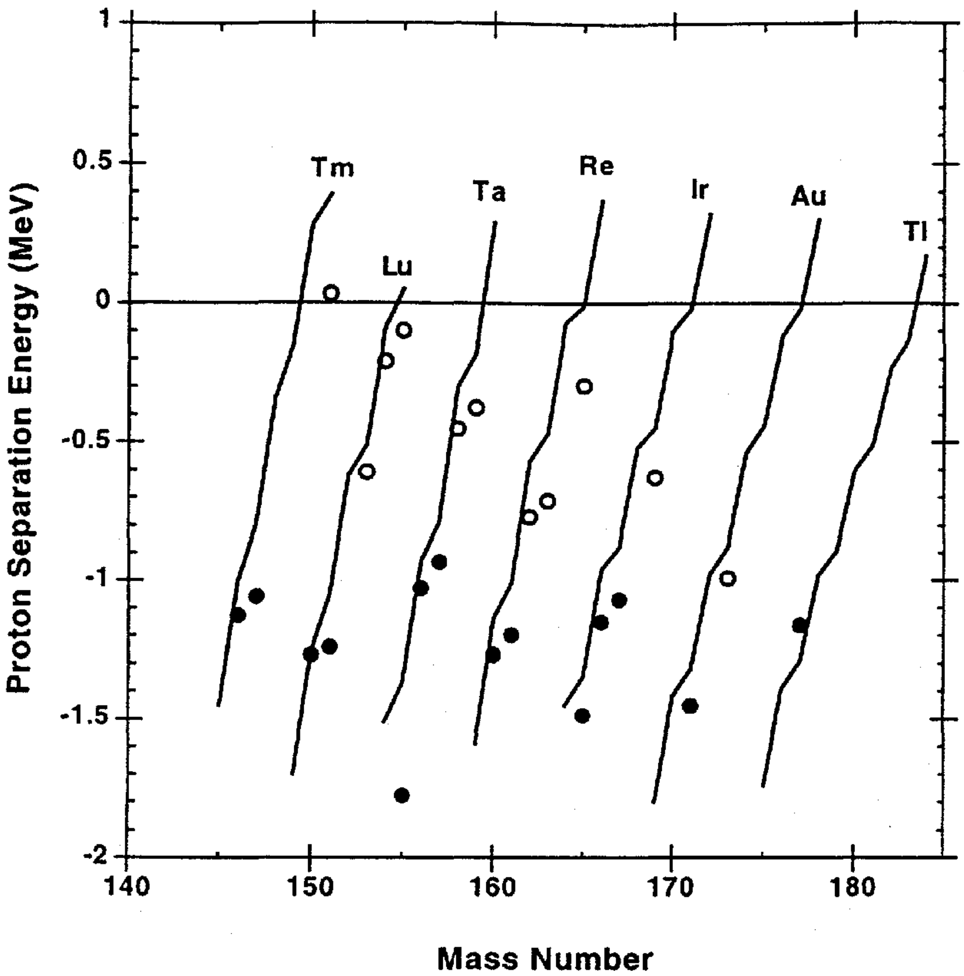


FIGURE 4. Proton separation energies for Tm, Lu, Ta, Re, Ir, Au, and Tl. Filled circles denote measured energies, open circles represent derived values, and solid lines are the Liran-Zeldes [11] prediction.

From Figure 4 one can see the beginnings of systematic trends in the proton separation energies. There are several sets of pairs of diagonal lines running from upper left to lower right. Extrapolating down the lower lines of the two central pairs, one sees that the yet-unobserved nuclides ^{164}Ir and ^{170}Au are possible candidates for proton emission. In addition, the $N = 82$ nuclide ^{155}Ta has a larger proton separation energy than might be concluded from its neighboring Ta isotopes. The

Liran-Zeldes prediction [11] seems to systematically over-bind the last proton by ~ 200 keV in this region of the drip line, except for the $Z = 81$ proton emitter ^{177}Tl.

CONCLUSIONS

Measurements of both proton- and α-decay Q-values for individual proton emitters have enabled the extraction of the mass excesses for nuclides well beyond the proton drip line. Knowledge of these mass excesses, along with proton separation energies, helps to precisely delineate the proton drip line. Both quantities also allow the testing of mass models at and beyond the proton drip line, far from the mass region where the models were developed.

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