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Masses of technetium isotopes*

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The masses of ^{96,97,98}Tc are determined by investigations of (p,n) and $(^3\mathrm{He},d)$ reactions on molybdenum targets. The new values have a precision better than 10 keV.

[NUCLEAR REACTIONS ^{96,97,98}Mo(p, n), E_p=4.0–5.0 MeV, ^{96,97}Mo$(^3\mathrm{He}, d)$, $E_{^3\mathrm{He}}$=19.0–23.0 MeV; measured Q, deduced mass excesses.]

I. INTRODUCTION

In a study[1] of the states of the nucleus ^{98}Tc by both the ^{98}Mo$(p, n)^{98}$Tc and ^{97}Mo$(^3\mathrm{He}, d)^{98}$Tc reactions, alignment of energy levels could not be obtained without making a relative shift of at least 20 keV in the sets of Q values obtained by each method. These Q values, and consequently the implied mass of ^{98}Tc, had been determined with respect to the ^{65}Cu$(p, n)^{65}$Zn reaction in the former case, and the ^{96}Mo$(^3\mathrm{He}, d)^{97}$Tc reaction in the latter. On the other hand, recalibration of one set of Q values against the ^{98}Mo$(^3\mathrm{He}, d)^{99}$Tc reaction, appearing from a small isotopic impurity of ^{98}Mo in the ^{97}Mo target, resulted in much better agreement.

In the latest compilation of atomic masses,[2] the mass of ^{97}Tc is constrained by a single measurement of the Q value for the ^{97}Mo$(p, n)^{97}$Tc reaction,[3] whose quoted error is 8 keV. The mass of ^{99}Tc is well constrained by a network of β-chain and mass-doublet mass relationships. There is, however, good evidence[4] that the mass of ^{91}Nb, also determined in Ref. 3, may be in error by about 25 keV. Thus, it was thought that the mass of ^{97}Tc might also be in error and ought to be reexamined.

II. MASS OF ^{97}Tc

The mass of ^{97}Tc has been remeasured by the ^{97}Mo$(p, n)^{97}$Tc reaction. Protons of energy 4.300 MeV were obtained from the Ohio University tandem Van de Graaff accelerator and bombarded a rolled ^{97}Mo foil of thickness 0.24 mg/cm^2. Neutrons were detected in two liquid-scintillator detectors of 10-cm diam located at angles of 29 and 65°. Each was about 8 m from the target. Pulse-shape discrimination was used to separate neutrons from photons. The beam was pulsed at a 5 MHz repetition rate with an average intensity of several microamperes and an over-all time resolution of about 1.3 ns for the γ flash. Neutron energies were determined by time-of-flight methods.

Each detector was calibrated with respect to the ^{55}Mn$(p, n)^{55}$Fe reaction on a target about 0.13 mg/cm^2 thick. The ground-state Q value for this reaction is similar to that for the ^{97}Mo$(p, n)^{97}$Tc reaction and is quoted to a fraction of a keV.[2] In fact, the region of interest in ^{97}Tc is entirely enveloped by this state and four strongly populated excited states in ^{55}Fe whose energies are known to fractions of a keV.[5] Analysis of these five states resulted in excellent linear relations between peak locations and neutron flight times. Representative spectra are shown in Fig. 1.

Since a number of excited states in ^{97}Tc have energies that are known to small fractions of a keV,[6] they could be used also in the determination of the ground-state Q value. An average of all the available data, including all appropriate corrections for target-thickness effects, yields a value $Q_0 = -1.102 \pm 0.006$ MeV for the ^{97}Mo$(p, n)^{97}$Tc reaction. This corresponds to a shift of +26 keV from the value of Ref. 2 which is determined by the (p, n) measurement of Ref. 3.

The shift was confirmed by two separate measurements of the Q value for the ^{96}Mo$(^3\mathrm{He}, d)^{97}$Tc reaction. The first was made at Argonne National Laboratory. A beam of 23-MeV ^{3}He particles from the Argonne tandem accelerator bombarded ^{96}Mo and ^{97}Mo targets, each about 0.24 mg/cm^2 thick. Deuterons entered an Enge split-pole spectrograph and were recorded in photographic emulsions. A calibration reference was provided by the ^{98}Mo$(^3\mathrm{He}, d)^{99}$Tc reaction from a small impurity of ^{98}Mo in the ^{97}Mo target. The magnetic field of the spectrograph was not changed between runs with the two targets. From the location of the peaks for the lowest two states of ^{97}Tc at a single angle of 20°, the value $Q_0 = 0.229 \pm 0.008$ MeV was obtained for the ^{96}Mo$(^3\mathrm{He}, d)^{97}$Tc reaction, implying a shift

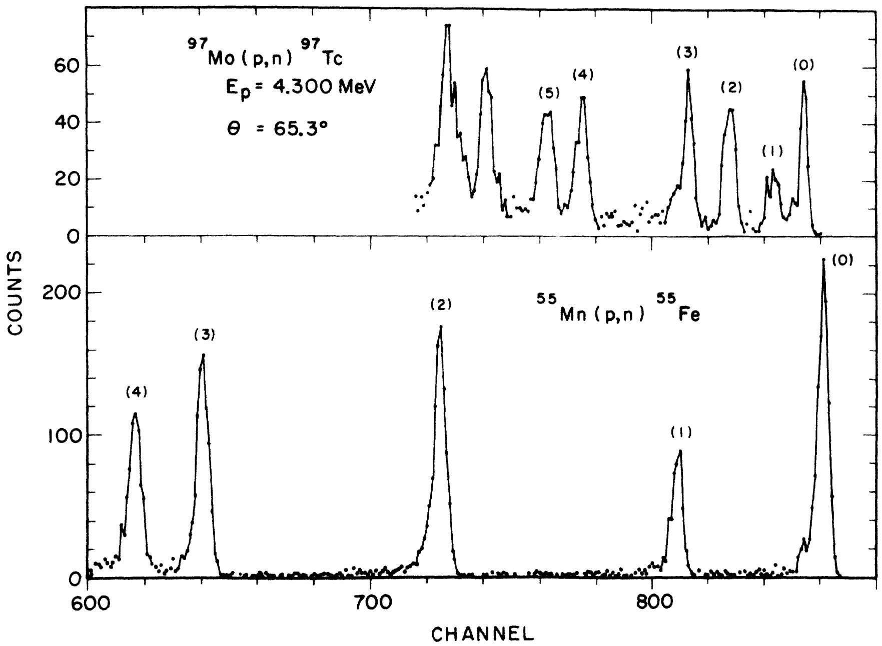

FIG. 1. Spectrum for the $^{97}Mo(p, n)^{97}Tc$ reaction compared with a calibration spectrum for the $^{55}Mn(p, n)^{55}Fe$ reaction at the same energy and angle. The abscissa represents neutron time of flight. Ground-state peaks are labeled by (0).

of +35 keV from the value of Ref. 2.

The second measurement was made at the University of Pittsburgh and involved a 19-MeV ^3He beam from the tandem accelerator and a similar Enge split-pole spectrograph. Deuterons were again recorded in photographic emulsions. An evaporated ^{98}Mo target, of thickness about 0.12 mg/cm^2, provided a calibration spectrum. No change in any spectrograph setting was made between the ^{98}Mo and ^{96}Mo targets. When account was taken of the relative target thicknesses, a value $Q_0 = 0.220 \pm 0.008$ MeV was obtained for the $^{96}Mo(^3He, d)^{97}Tc$ reaction, or a shift of +26 keV from Ref. 2.

III. MASS OF ^{98}Tc

The mass of ^{98}Tc was very poorly known, being determined solely[7] by the β decay to ^{98}Ru with an uncertainty of about 200 keV. The latter mass is known to a few keV from measurements of mass doublets.[8] The $^{98}Mo(p, n)^{98}Tc$ reaction has been used at Ohio University to measure the mass of ^{98}Tc. The procedure was similar to that used for ^{97}Tc, with a pulsed 4-MeV proton beam and two time-of-flight neutron detectors located near 27 and 52°. The $^{65}Cu(p, n)^{65}Zn$ reaction was used as a calibration reference.

Since the lowest two states of ^{98}Tc are unobserved in the (p, n) reaction,[1] the Q value to an excited state was determined. A strongly populated and isolated peak was selected and a value $Q = -2.597 \pm 0.010$ MeV was obtained. Comparisons with the spectra obtained from the $^{97}Mo(^3He, d)^{98}Tc$ reaction taken at Argonne and Pittsburgh, and with data from the $^{98}Mo(^3He, t)^{98}Tc$ reaction,[9] reveal that this state is located at 0.139-MeV excitation energy. Thus the ground-state Q value for the $^{98}Mo(p, n)^{98}Tc$ reaction is $Q_0 = -2.458 \pm 0.010$ MeV, or a shift of −88 keV from the value in the mass tables.[2]

The $(^3He, d)$ reactions may also be used to obtain the mass of ^{98}Tc. As before, the $^{98}Mo(^3He, d)^{99}Tc$

TABLE I. The Q values for (p,n) and $(^3He,d)$ reactions leading to technetium isotopes, and the mass excesses for the residual nuclei. The mass excesses are revised from the 1971 atomic mass compilation (Ref. 2).

Reaction	Q value (MeV)	Mass Excess (MeV)
$^{96}Mo(p,n)^{96}Tc$	−3.760(10)[a]	−85.820(10)
$^{96}Mo(p,n)^{96}Tc$	−3.755(6)[b]	−85.825(6)
$^{97}Mo(p,n)^{97}Tc$	−1.102(6)	−87.221(6)
$^{96}Mo(^3He,d)^{97}Tc$	0.229(8)[c]	−87.230(8)
	0.220(8)[d]	−87.221(8)
$^{98}Mo(p,n)^{98}Tc$	−2.458(10)	−86.432(10)
$^{97}Mo(^3He,d)^{98}Tc$	0.680(8)	−86.420(8)

[a] Reference 10.
[b] Reference 11.
[c] Argonne data.
[d] Pittsburgh data.

reaction is taken as the standard. The values $Q_0 = 0.680$ MeV and 0.676 MeV were obtained from the Argonne and Pittsburgh data, respectively. Since the Argonne data showed slightly better internal consistency, we adopt $Q_0 = 0.680 \pm 0.008$ MeV, a shift of −100 keV from the value in the mass tables.[2]

IV. DISCUSSION

The Q values for the (p, n) and $(^3\mathrm{He}, d)$ reactions reported here, and the implied mass excesses for technetium isotopes, are summarized in Table I. The measurements of the $^{96}\mathrm{Mo}(p, n)^{96}\mathrm{Tc}$ Q value in this laboratory were made in a manner similar to the others and is described elsewhere.[10] A second recently reported value[11] is also listed.

As noted in Ref. 3, the measured Q values for the $^{91}\mathrm{Zr}(p, n)^{91}\mathrm{Nb}$ and $^{95}\mathrm{Mo}(p, n)^{95}\mathrm{Tc}$ reactions were more negative than those inferred by previous mass measurements. A discrepancy of about 25 keV remains in the later measurements for $^{91}\mathrm{Nb}$ in Ref. 4. A shift of the same magnitude and direction is found in the present measurement for the mass of $^{97}\mathrm{Tc}$.

A careful consideration of the calibration procedures in Ref. 3 does not lead us to conclude that the Q value for the $^{95}\mathrm{Mo}(p, n)^{95}\mathrm{Tc}$ reaction is necessarily in error. However, a discrepancy identical with those mentioned above is found between Ref. 3 and measurements of $\beta+$ decay energies of $^{95}\mathrm{Tc}$.[12] A remeasurement of the mass of $^{95}\mathrm{Tc}$ might be appropriate.

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