PHYSICAL REVIEW C VOLUME 18, NUMBER 4 OCTOBER 1978

Energy levels of ^{96}Tc via the ^{96}Mo(p, $n\gamma$) ^{96}Tc reaction*

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(Received 29 December 1977; revised manuscript received 6 June 1978)

The low-lying levels of ^{96}Tc have been studied through use of the ^{96}Mo(p,$n\gamma$)^{96}Tc reaction with the observation of neutrons by the time-of-flight method and the observation of γ rays. Excitation functions of the neutrons and of the γ rays, and γ-γ coincidence spectra, were used to construct a ^{96}Tc energy level diagram. 45 γ rays have been assigned to 35 excited energy levels of ^{96}Tc, up to 1288 keV in excitation. The Q value for the ^{96}Mo(p,n)^{96}Tc$_{gs}$ reaction has been determined to be -3.754 ($\pm$0.006) MeV.

[NUCLEAR REACTIONS ^{96}Mo (p,$n\gamma$), E_p =3.7–5.8 MeV, enriched targets; measured Q, γ-ray spectra, branching ratios, neutron time-of-flight spectra; deduced ^{96}Tc levels, parities.]

I. INTRODUCTION

Recent reports[1,2] on reactions which produce ^{96}Tc have provided details about energy levels up to 632 keV through the ^{96}Mo(p,n)^{96}Tc reaction and up to 1063 keV through the ^{93}Nb(α,n)^{96}Tc reaction. References to other previous work are given in these papers. In the present report, energy levels up to 1288 keV have been observed through the (p,n) and (p,$n\gamma$) reactions; a number of these were not observed in the work of Ref. 2, presumably because in that work high-spin levels were favorably populated. Also, γ-ray branching ratios for the decay of levels are given, and the parities of several levels are determined.

II. EXPERIMENTAL PROCEDURES [3]

Thin targets of molybdenum, enriched to 96.8% in ^{96}Mo, have been bombarded with 3.7- to 5.8-MeV protons from the University of Kentucky 6-MV Van de Graaff electrostatic accelerator. Neutron spectra were obtained with the time-of-flight technique[4] using a typical flight path of 3.05 m and a liquid scintillator detector. The high sensitivity at 250-keV neutron energy of a 3.18-mm thick ^{6}Li-loaded glass scintillator was used in making a precise measurement of the Q value of this (p,n) reaction. Excitation curves of γ rays were obtained with a 5-mm thick planar Ge(Li) detector and a 35-cm^3 Ge(Li) detector. The observed γ rays which are ascribed to ^{96}Tc are listed in Table I. γ-γ coincidence spectra were obtained at E_p = 4.50 MeV, which is approximately 700 keV above the threshold, and at the IAR energy, 5.39 MeV, approximately 1600 keV above the threshold.

III. RESULTS

The isomeric level

The decay of the isomeric level was observed with the 5-mm Ge(Li) detector in a shielded chamber far from the target area, after bombardment of the ^{96}Mo foil for several hours. The energy of the radiation was found to be 34.2 (±0.2) keV, in agreement with Medicus *et al.*;[5] who reported 34.4 (±0.4) keV, and its half life was measured as 52 (±2) min, in agreement with Easterday *et al.*[6] and Medicus *et al.*, who reported 51.5 (±1.0) min.

TABLE I. γ rays which were observed in the proton bombardment of the ^{96}Mo target and which have been assigned to levels of ^{96}Tc. The energies are in keV.

34.2 ± 0.2	285.3 ± 0.2[a]	793.1 ± 0.3
85.2 ± 0.2	286.1 ± 0.2[a]	836.4 ± 0.8
86.0 ± 0.2	287.4 ± 0.4	894.8 ± 0.3
105.9 ± 0.2	294.4 ± 0.3	912.3 ± 0.3
125.6 ± 0.2	302.7 ± 0.4	935.3 ± 0.4
128.0 ± 0.2	341.5 ± 0.3	1006.3 ± 0.3
142.9 ± 0.2	380.7 ± 0.4	1026.3 ± 0.4
183.8 ± 0.2	392.8 ± 0.3	1041.7 ± 0.4
192.1 ± 0.2	409.9 ± 0.4	1252.7 ± 0.5
195.6 ± 0.2	411.1 ± 0.4	
202.5 ± 0.4	416.5 ± 0.4	
205.4 ± 0.2	423.3 ± 0.3	
214.3 ± 0.4	458.1 ± 0.3	
220.2 ± 0.2	494.0 ± 0.3	
221.0 ± 0.2[a]	529.8 ± 0.3	
231.3 ± 0.2	588.8 ± 0.4	
264.3 ± 0.2	613.1 ± 0.3	
280.5 ± 0.3	681.0 ± 0.6	

[a] This energy was taken from Ref. 2.

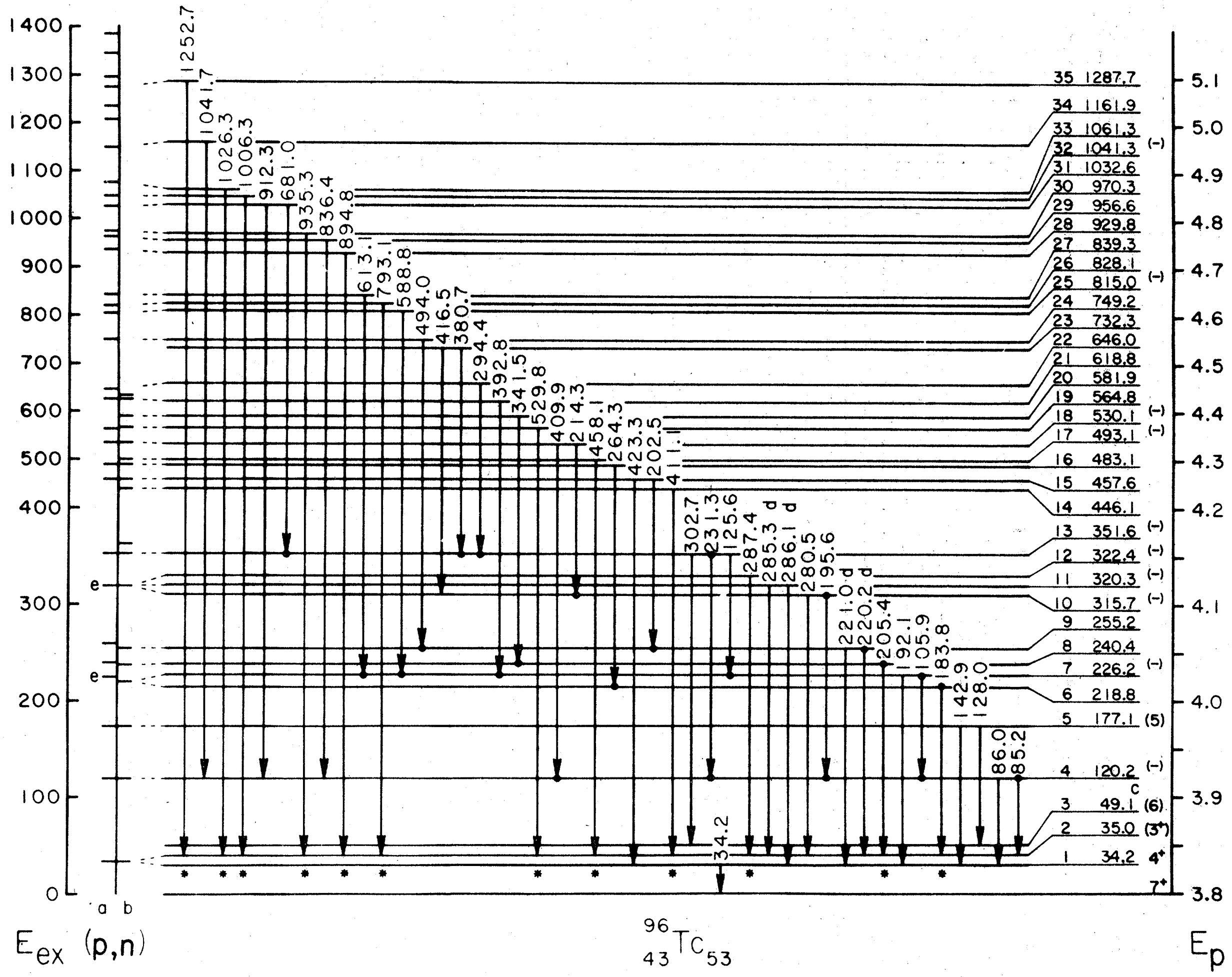

FIG. 1. Energy levels of ^{96}Tc. The levels on the left are those deduced from the neutron time-of-flight spectra of the present work (a), and of Ref. 1 (b). On the right are the proton bombarding energies corresponding to levels which can be populated by the $^{96}Mo(p,n)^{96}Tc$ reaction. The γ-ray and level energies are in keV. At (c) is the new level proposed in Ref. 2 and supported by our 302.7-keV γ ray. At (d) are the γ rays which were resolved by Ref. 2. The levels at (e) were known to be multiple levels because of the width of the neutron groups populating them compared to singlet groups in the time-of-flight spectrum. The asterisk indicates that for lack of decisive data the γ-ray transition has been assumed to terminate on the 35.0-keV level. A dot at the head or tail of a transition arrow indicates that the γ ray was observed to be in coincidence with a succeeding or preceding γ ray, respectively.

Q of the $^{96}Mo(p,n)^{96}Tc$ reaction

Before the Q value for the (p,n) reaction to the ground state of ^{96}Tc could be determined, it was necessary to prove that the observed highest energy neutron group actually does populate the 34.2- and 35.0-keV levels. This was done through comparison[3] of the excitation functions of the neutrons, the 34.2-keV γ rays from the isomeric state, and the 85-keV γ rays.

The Q value was determined through a measurement of the energy of the neutrons which populate the 35.0-keV level. In the first neutron group the 34.2- and 35.0-keV level contributions are not resolved; however, a Hauser-Feshbach calculation of the cross sections shows that at 4.0 MeV the cross section for populating the 3^+ 35.0-keV level is approximately 9 times larger than that for populating the 4^+ 34.2-keV level. Following calibration of the beam energy, and of the neutron energy vs time of flight, via the $^7Li(p,n)$ reaction, the proton energy corresponding to production of 250-keV neutrons at 0° was measured. From these data, a kinematical calculation produced the

TABLE II. γ-ray branching percentages, calculated from yields taken at 90° relative to the incident proton beam.

Level energy	E_γ (keV)	% branching
120.2	85.2	89.4
	86.0	10.6(± 1.0)
177.1	128.0	41.2(± 4.0)
	142.9	58.8
226.2	105.9	85.5
	192.1	14.5(± 1.5)
255.2	220.2	≈90[a]
	221.0	≈10
315.7	195.6	92.2
	280.5	7.8(± 2.5)
320.3	285.3	≈50[a]
	286.1	≈50
351.6	125.6	3.9(± 0.6)
	231.3	93.6
	302.7	2.5(± 1.0)
457.6	202.5	47.3(± 3.0)
	423.5	52.7
530.1	214.3	26.3(± 5.0)
	409.9	73.7
732.3	380.7	66.0
	416.5	34.0(±10.0)
1032.6	681.0	38.1(±10.0)
	912.3	61.9

[a]An estimate obtained from the spectrum in the work of Bini *et al.* (Ref. 2).

Q(35.0 keV) for the (p,n) reaction terminating in the 35.0-keV level. It is

$$Q(35.0\ \text{keV}) = -3.789\ (\pm 0.006)\ \text{MeV}.$$

Adjustment to the ground state gives

$$Q(\text{g.s.}) = -3.754\ (\pm 0.006)\ \text{MeV}.$$

The energy levels

Forty-five γ rays emitted by ^{96}Tc have been identified and have been assigned to levels in ^{96}Tc. Typically, each level was established by one or more of the following: the γ-ray threshold, the presence of γ-ray cascades, the γ-γ coincidence data, the presence of a neutron group in the TOF spectra,[3] or being enhanced in neutron or γ-ray yield at the IAR.[3] In the level diagram of Fig. 1 the level energies have been deduced from the γ-ray energies. γ-ray branching ratios are given in Table II. The appearance of the $d_{5/2}$ isobaric analog resonance[7] at 5.39 MeV in the yield of a particular γ ray was taken as sufficient proof that the γ ray was emitted from ^{96}Tc or from ^{96}Mo, whose γ-ray spectrum is well known. The presence of strong enhancement in the yield of γ rays from a level permits the tentative assignment of odd parity to that level.[3]

*Work supported in part by the National Science Foundation.

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