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Measurement of the ^{158}Tb electron-capture Q value

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An ultralow energy K-capture branch in the decay of 180-yr ^{158}Tb has recently been suggested to offer very favorable energetics for investigating the electron neutrino mass. The ^{158}Tb Q value relative to ^{158}Gd has been measured by means of a (p,d) reaction on a radioactive ^{158}Tb target. The ground state electron capture Q value of 1215.4(4.3) keV, inferred here, precludes ^{158}Tb K electron capture to the 1187 keV state of ^{158}Gd.

INTRODUCTION

The possibility of a nonzero electron neutrino mass is a topic of broad current interest. Nuclear beta transitions or orbital electron capture (EC) with very low decay energy provide sensitive means for determining the mass of the neutrino. The effect of a finite neutrino mass on the ratios of EC rates from different electronic shells is of the order of

$$[1-m_\nu^2/(\Delta M_{\text{g.s.}}-W_i)^2]^{1/2} ,$$

where m_ν is the mass of the electron neutrino, $\Delta M_{\text{g.s.}}$ is the mass difference between the masses of the parent and daughter atoms, and w_i is the binding energy of the captured electron in the daughter atom. Clearly, the lower the available energy for the transition, the more sensitive the limits on the neutrino mass.

Raghavan[1] recently reported a K electron capture branch of ^{158}Tb to the excited state at 1187.13 keV in ^{158}Gd with an energy release of only 156(17) eV. The existence of such a K-capture branch requires a minimum electron capture Q value of 1237.37 keV, the sum of the excitation energy of this state and the 50.24 keV K electron binding energy in gadolinium. This value is not consistent with the value of 1216.0(1.8) keV obtained from the mass tables[2] or the 1217.6(4.3) keV value recently reported by Burke.[3] A new result by von Dincklage *et al.*[4] suggests a Q value of 1233(4) keV. One possible explanation for the Raghavan result is that the 180-yr (Ref. 5) ^{158}Tb state is a long-lived isomer as, for example, the naturally occurring ^{180}Ta. In the present paper, we measure this mass difference using the 180-yr ^{158}Tb directly as a target; this precludes the possibility of a long-lived odd-odd nucleus isomer.

EXPERIMENT

Establishment of accurate absolute Q values via a single charged particle transfer reaction is a challenging task. However, one may obtain relative Q values with an error of only a few keV by comparing sequentially the energetics of two or more reactions. In the present case, we compare the Q values for the (p,d) reaction on the two isobars ^{158}Tb and ^{158}Gd.

The reactions were investigated with both the radioactive ^{158}Tb target and stable ^{158}Gd target, using a 29.9 MeV proton beam from the Princeton AVF Cyclotron and the quadrupole-dipole-dipole-dipole (QDDD) spectrograph system.

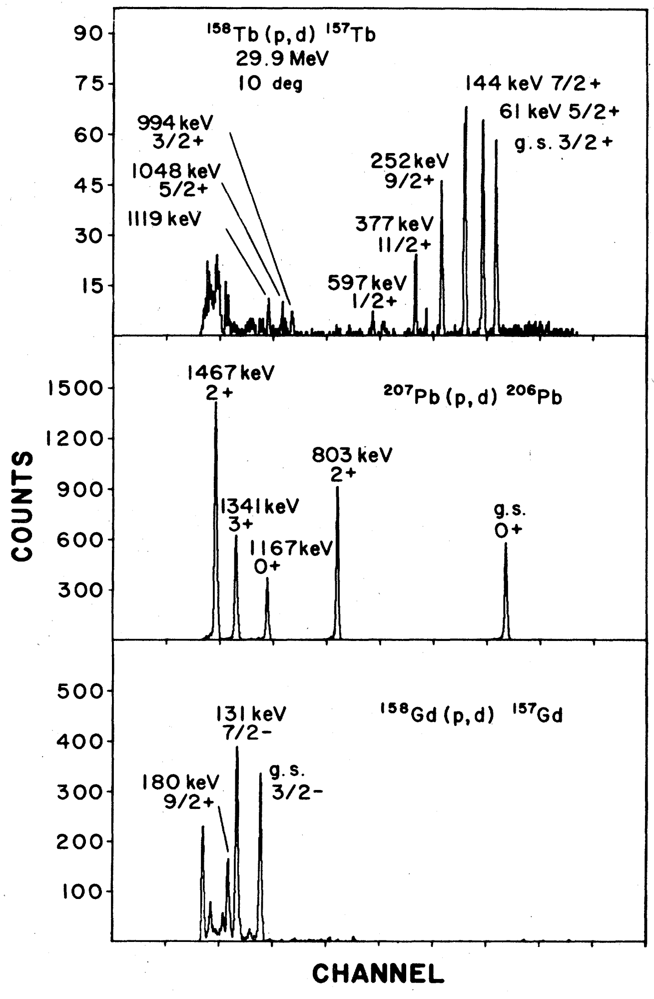

FIG. 1. (p,d) spectra from ^{158}Tb, ^{207}Pb, and ^{158}Gd observed with 29.9 MeV protons at 10 deg.

The radioactive ^{158}Tb was prepared by intense neutron irradiation of enriched ^{156}Dy in the Brookhaven High Flux Beam Reactor. After irradiation, the sample was first chemically separated using ion exchange chromatography; the Tb fraction was then mass dispersed using the Princeton Isotope Separator equipped with a high temperature thermal ionization source. The ^{158}Tb was deposited on 40 $\mu g/cm^2$ carbon foil to prepare a source with thickness $\sim 8\ \mu g/cm^2$.

The experimental technique used for these measurements is standard for charged-particle nuclear spectroscopy. The ^{158}Tb, the ^{158}Gd, and a 80 $\mu g/cm^2$ ^{207}Pb target were sequentially exposed to the proton beam and the deuteron groups analyzed in the QDDD magnetic spectrograph equipped with a resistive division position sensitive gas proportional counter. The spectra are shown in Fig. 1. The ^{206}Pb spectrum served for calibration of the energy scale. Each mass 158 target spectrum was recorded three times with ^{206}Pb calibration spectra taken immediately before and after.

Positions of the peaks in the spectra were obtained using a peak-fitting program and the energies of the peaks were determined with a calibration computer program which accounts for the target thickness effects, the spectrograph optics settings, and relativistic kinetic effects.

Energy calibration of the spectrograph was accomplished in two ways. The first involved the ^{206}Pb spectrum as the single calibration to infer the ground state Q-value difference. The second method involves linear calibration in the regions of interest (i.e., ground states of ^{157}Tb and ^{157}Gd) by comparing the ^{206}Pb ground state to the ground state ^{157}Tb rotational band and the ^{206}Pb 1167 keV excited state to the ground state band of ^{157}Gd.

RESULTS AND CONCLUSION

The electron capture Q value of the ^{158}Tb to ^{158}Gd transition is given by

$$\begin{aligned} Q &= Q[^{158}\mathrm{Tb(p,d)}^{157}\mathrm{Tb}] - Q[^{158}\mathrm{Gd(p,d)}^{157}\mathrm{Gd}] \\ &\quad + Q[^{157}\mathrm{Tb(EC)}^{157}\mathrm{Gd}] \\ &= \Delta Q(\mathrm{p,d}) + Q[^{157}\mathrm{Tb(EC)}^{157}\mathrm{Gd}]\ . \end{aligned}$$

The difference in the transfer reaction Q values, ΔQ(p,d), was determined to be 1158.1(4) keV. The value of 62.9(0.7) keV for Q_{EC} was taken from the report by Beyer *et al.*[6] The advantage of the present approach is that the difference in Q value between the two (p,d) reactions can be related to the well-known energy of the second excited state of ^{206}Pb. Accordingly, the Q value of the ^{207}Pb(p,d)^{206}Pb reaction does not enter the determination. In this case, the error of our measurement arises primarily from the uncertainty in the thickness of the ^{158}Tb target.

The result from the present experiment for the electron capture Q value of ^{158}Tb is 1215.4(4.3) keV. This value agrees within experimental error with the mass table result and the value reported in Ref. 3. It is in disagreement with the value suggested by von Dincklage *et al.* These authors omitted consideration of the beta spectrum shape factor; also, the ^{158}Gd-^{158}Dy mass difference is required in addition to the beta end point energy to derive the desired K-capture Q value from such a measurement.

The Q value for the ^{158}Tb EC established in these experiments indicates that K electron capture of ^{158}Tb to the 1187 keV state cannot take place. The possibility that the long-lived odd-odd ^{158}Tb exists as an isomer with an excitation energy $\sim$20 keV higher than the ground state which would permit this K electron capture is excluded by our results.

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