Q-values for (d, p) and (d, t) Reactions on Even-A Tin Isotopes *

M. J. Bechara

Universidade de São Paulo, São Paulo, Brasil,

and O. Dietzsch **

University of Pittsburgh, Pittsburgh, U.S.A., and Universidade de São Paulo, São Paulo, Brasil

Relative Q-values for (d, p) and (d, t) reactions on all even-A tin isotopes have been determined by simultaneous detection in nuclear emulsions placed in the focal plane of a magnetic spectrograph of the particle groups corresponding to the ground state transitions. The results when combined to other input data for the atomic mass tables provide more accurate mass excesses for nuclides in this mass region.

1. Introduction

Even a brief comparison of the two most recent compilations of atomic masses of nuclides, i. e., the Mattauch, Thiele and Wapstra-(MTW) table [1] published in 1965 and the Wapstra and Gove-(WG) table [2] of 1911 will show the increase of precision attained in the intervening years in the determination of the atomic masses. Most of the progress specially in the region $A = 100 - 200$ has been due to new measurements of reaction energies. In fact, a great number of reaction Q-values in the above mass region, specially for (d, p) and (d, t), have been measured. Also the number of reaction energies for (n, γ) and (p, γ) determined with great accuracy has increased considerably in recent years due to the use of Ge (Li) detectors for measuring gamma-ray energies [2]. As a result many mass differences between neighbouring nuclides in the region $A = 100 - 200$ are known today to a very high degree of accuracy.

Tables of atomic masses like that of Wapstra and Gove make use of both nuclear reaction and mass spectroscopic data in the evaluation of "best values" for the atomic masses by a least-squares adjustment of the experimental data. Both this tabulation and the self-consistent set of Q-values [3] calculated from the adjusted masses, have quoted uncertainties which are appreciably less than those of either sources of input data. Measurements of high accuracy, either of masses or of reaction energies, are

therefore valuable for making a direct comparison with the mass table values. While accurate measurements of absolute Q-values for reactions involving the detection of charged particles having experimental errors of 1 keV or less are usually difficult to perform [4], very precise relative measurements are sometimes much simpler to carry out, and may thus provide a way of checking the consistency of the mass table values.

We present here the results of measurements of relative Q-values for (d, p) and (d, t) reactions on all even tin isotopes. The particle groups corresponding to all the ground state transitions were detected simultaneously under the same experimental situation thus keeping to a minimum the effects of possible systematic errors on the energy differences. A comparison with the mass tables is then made.

2. Experimental Procedure

Deuteron beams of 12 and 17 MeV from the University of Pittsburgh 3-stage Van de Graaff accelerator were used to bombard thin "line targets" of the tin isotopes. The beam-handling system and scattering chamber have been described in detail elsewhere [5, 6]. The maximum horizontal divergence of the incident beam was 15 mrad. The "line targets" consisted of deposits of the target material over a small rectangular area, about 0.5 mm wide and 3 mm high, centered on a thin carbon backing (20 μg/cm²). With such targets narrow beam-defining slits

** Permanent address: Instituto de Física, Universidade de São Paulo, C. Postal 20516, São Paulo, Brasil. Reprint requests should be addressed to this address.
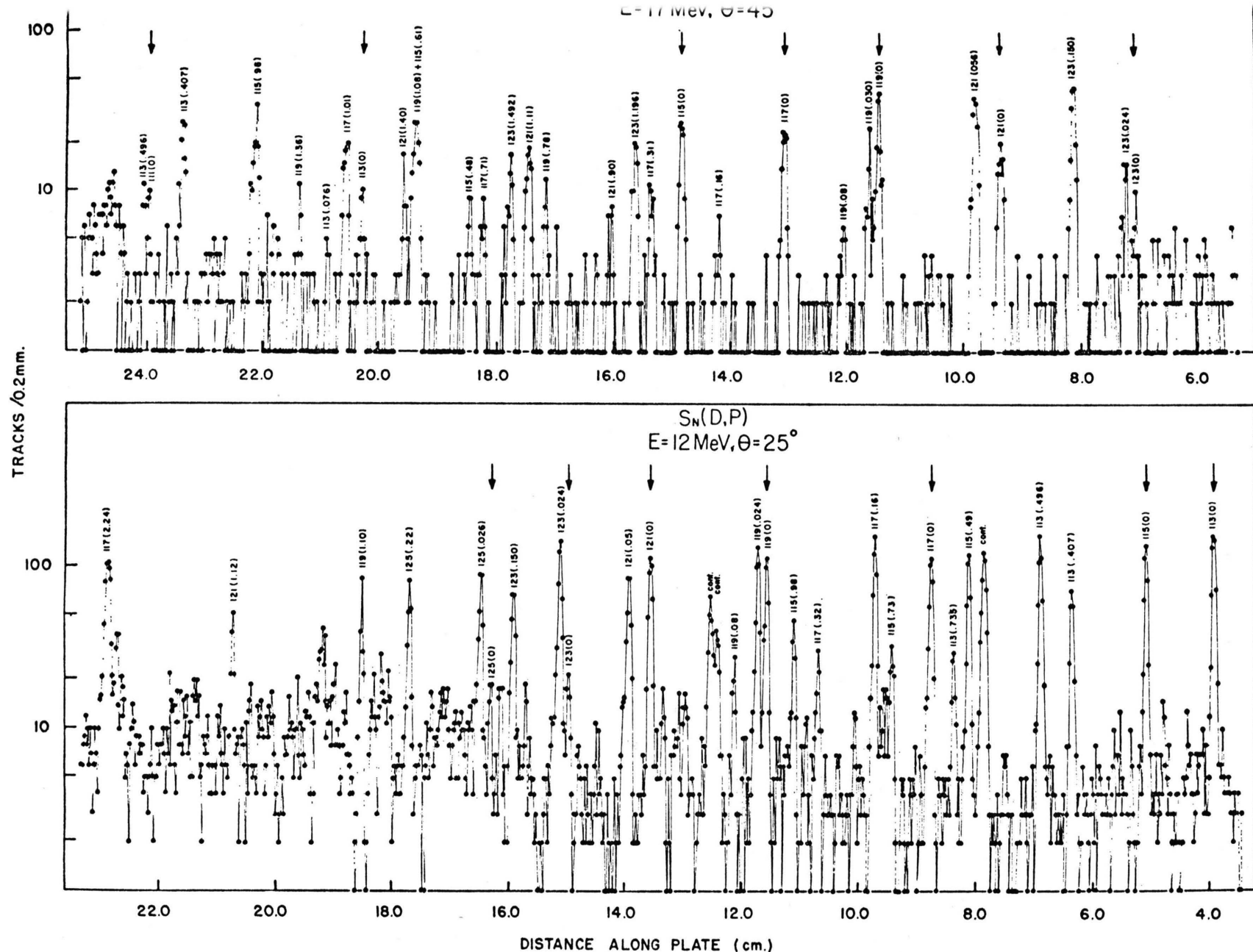
Fig. 1. Typical energy spectra of protons and tritons from Sn(d, p) and Sn(d, t) reactions, respectively, taken with the "blended" target. Numbers above peaks are the mass numbers of the residual nuclei with the corresponding excitation energies (in MeV) given in parenthesis. The arrows point to the peaks corresponding to the ground state transitions.

in front of the target are not required with the resulting advantage of elimination of slit scattering and thus a better peak-to-background ratio in the energy spectra. Most of the spectra were obtained with a target which contained approximately equal amounts ($\sim 13\%$) of all even tin isotopes. Besides this "blended" target, we also employed a target which was enriched to 80% in ^{112}Sn and which contained from 1 to 4% of each other even isotope. Both targets had a thickness of the order of 70 μg/cm^2. The incident beam was monitored by detecting the elastically scattered deuterons with two NaI scintillators placed at $\pm 38°$ relative to the beam direction.

The scattered protons and tritons were detected in Kodak NTB 25-micron nuclear emulsions placed in the focal plane of an Enge split-pole spectrograph[7]. In the detection of protons the emulsions were covered by a stepped aluminum absorber which reduced the proton energies to about 5 MeV. No absorbers were used in the detection of tritons from the (d, t) reactions. After development the plates were scanned by microscope to count the proton or triton tracks. Figure 1 shows typical energy spectra of protons and tritons from the Sn(d, p) and Sn(d, t) reactions respectively. The full width at half maximum (FWHM) of the proton and triton groups is ~ 9 keV. The predominant contributions[5] to the experimental energy resolution come from beam divergence, source size, energy loss in the target and plate scanning field width.

3. Results

Data for the (d, p) reactions were taken with the "blended" target at four different scattering angles between $20°$ and $36°$ and for an incident beam energy of 12 MeV. For the (d, t) reactions, exposures were made at laboratory angles of $30°$ and $45°$ for an incident beam energy of 17 MeV. Data taken at several angles between $10°$ and $42°$ with the ^{112}Sn target at a deuteron bombarding energy of 12 MeV were also used in the analysis of the (d, p) reactions.

Particle groups corresponding to the ground states or to excited states of odd-A tin nuclei were identified on the basis of existing information on the excitation energies and on the relative cross-sections for the corresponding reactions[8, 9]. In order to ascertain that the identifications were correct, careful comparisons were made with other spectra obtained under the same experimental conditions by bombarding several different targets, each of

them enriched to a high percentage in one of the following even-A tin isotopes: ^{112}Sn, ^{118}Sn, ^{120}Sn and ^{122}Sn.

Standard procedures were employed for calculating differences of energies for the particle groups corresponding to the ground-state transitions. The position along the plate of the point of maximum of each ground-state particle group was converted to an effective trajectory radius using the calibration of the spectrograph. The calibration curve (i. e., position along the plate L versus the effective radius of curvature ϱ) was determined in a separate experiment which employed deuteron groups which were elastically scattered from a ^{122}Sn target and which covered the same range of trajectory radii as in the present work.

The dependence of ϱ vs. L was assumed to satisfy the equation

$$\varrho = \varrho_0 + a(L - L_0) + b(L - L_0)^2$$

where L_0 represents the distance from the end of the focal plane about which the expansion is done, ϱ_0 is the effective radius of curvature at the distance L_0 and a and b are the linear and quadratic expansion coefficients, respectively. No attempts were made to determine ϱ_0 to a high precision since only relative values of ϱ were of interest. Our values for the calibration constants a and b are in very good agreement with two independent measurements obtained by other workers[10, 11] using different approaches. The present measurements for the (d, p) and (d, t) reactions were all done in an interval of 12 and 17 cm, respectively, of the spectrograph focal plane. Over this region of the focal plane, the small quadratic term has a very small influence on the ϱ vs. L curve. No higher order terms were considered.

For each ground state group the magnetic rigidity was obtained by multiplying the effective radius ϱ by the magnetic field measured by a NMR probe. The particle energy was obtained from the magnetic rigidity using relativistic relations[12], and total final kinetic energies were found for the various reactions. The difference of these energies gives directly the difference in Q-values for the respective reactions since the kinematic calculation takes into account the effect of different recoil energies for targets of different mass numbers. The results are presented in Table 1 where average values are given for the differences between Q-values for the (d, p) and (d, t) reactions on all even Sn isotopes relative

Table 1. Differences of Q-values for the (d, p) and (d, t) reactions on the even Sn isotopes relative to the Q-values for the (d, p) and (d, t) reactions on ^{118}Sn.

Target	ΔQ(d, p) (keV)	ΔQ(d, t) (keV)
^{112}Sn	−1257.8±3.0	1459.3±5.6
^{114}Sn	−1060.2±2.9	974.0±4.0
^{116}Sn	− 460.6±1.3	235.3±2.1
^{118}Sn	0.0	0.0
^{120}Sn	314.2±1.2	− 222.7±2.1
^{122}Sn	538.6±2.3	− 510.9±2.7
^{124}Sn	751.0±3.4	− 836.3±3.5

to the Q-values for the (d, p) and (d, t) reactions on ^{118}Sn.

The estimates of uncertainties were made by calculating for each Q-difference, ΔQ, the change in the Q-difference, Δq, associated with each uncertainty. We first review the uncertainties contributing to the statistical errors.

An uncertainty of 30 min of arc was assigned for the reaction angle and a dispersion of 3 keV for the incident energy. The counting and plotting random error is estimated to be 0.15 mm in the L-value differences. We have also assigned an uncertainty of 2.5 G to the magnetic field for an individual run. Combining in quadrature the uncertainties Δq we get for a determination of a Q-difference equal to 1 MeV an estimated random error of 4.5 keV and 5.0 keV for the (d, p) and (d, t) reactions, respectively. The internal error was then calculated for each average Q-difference from the formula

$$e_{\text{int}} = \left[\sum_{i=1}^{N} \left(\frac{1}{\Delta q_i} \right)^2 \right]^{-1/2}$$

where Δq_i is the estimated random error present in each ΔQ measurement and with N equal to the number of measurements.

The standard deviation of the mean (the external error) may also be calculated using the formula

$$e_{\text{ext}} = \left[(N-1)^{-1} \left(\sum_{i=1}^{N} w_i (\Delta Q_i - \overline{\Delta Q})^2 / \sum_{i=1}^{N} w_i \right) \right]^{1/2}$$

where $\overline{\Delta Q}$ is the average value for the Q difference and is given by

$$\overline{\Delta Q} = \sum_{i=1}^{N} w_i \Delta Q_i / \sum_{i=1}^{N} w_i \quad \text{and} \quad w_i = (\Delta q_i)^{-2} .$$

Since e_{ext} and e_{int} are comparable in all cases, we chose to represent with the larger of the two measures of random error the statistical error to be

combined with the estimates for the systematic errors.

Quantitative estimates of systematic errors which may be present in each measurement are not easy to evaluate, but to a reasonable degree of confidence they can be traced to an uncertainty in the absolute energy of the incident beam, to target thickness corrections and to uncertainties in the ϱ vs. L curve. Only the last of these give sizeable contributions (of the order of 0.2% and 0.3% of the measured ΔQ for magnetic rigidities corresponding to the (d, p) and (d, t) reactions, respectively), and were estimated taking into account the three independent calibrations referred to above. The final estimates of uncertainties are quoted in Table 1 along with the mean of the observations.

4. Discussion

The data presented in Table 1 should provide a mean of making independent checks of mass data based on measurements done with different techniques. They can also be used, when combined with absolute measurements made with Ge(Li) gamma detectors or with magnetic spectrographs [4, 13], to extend the high accuracy of such measurements to a wider interval of mass numbers.

In order to compare our data with the atomic mass table we have normalized the relative Q-values for the (d, p) and (d, t) reactions determined in the manner described above to the Q-values listed by Wapstra and Gove (WG) [3] for the corresponding reaction on ^{118}Sn. The results for the (d, p) reactions are presented in Table 2 and those for the (d, t) reactions in Table 3. The quoted uncertainties were obtained by combining in quadrature those listed in Table 1 and the uncertainties of 1.2 keV and 1.3 keV quoted by WG for the ^{118}Sn(d, p) and ^{118}Sn(d, t) reactions, respectively. The Q-values for

Table 2. Q-values for the Sn(d, p) reaction normalized to a value of 4260.4±1.2 keV for the ^{118}Sn(d, p) reaction.

Target	Q (keV) [a]	Q (keV) [b]
^{112}Sn	5518.2±3.2	5516 ±12
^{114}Sn	5320.6±3.4	5309 ± 7
^{116}Sn	4721.0±1.8	4717.9± 2.9
^{118}Sn	4260.4±1.2	4260.4± 1.2
^{120}Sn	3946.2±1.7	3955.5± 2.7
^{122}Sn	3721.8±2.6	3720 ± 6
^{124}Sn	3509.4±3.6	3507 ± 5

[a] This work, [b] Wapstra and Gove, Reference 3.

Table 3. Q-values for the $Sn(d, t)$ reaction normalized to a value of -3069.7 ± 1.3 keV for the $^{118}Sn(d, t)$ reaction.

Target	Q (keV) [a]	Q (keV) [b]
^{112}Sn	-4529.0 ± 5.7	-4544 ± 15
^{114}Sn	-4043.7 ± 4.2	-4062 ± 11
^{116}Sn	-3305.0 ± 2.5	-3308 ± 6
^{118}Sn	-3069.7 ± 1.3	-3069.7 ± 1.3
^{120}Sn	-2847.0 ± 2.5	-2846.8 ± 1.3
^{122}Sn	-2558.8 ± 3.0	-2547.1 ± 3.6
^{124}Sn	-2233.4 ± 3.7	-2235 ± 6

[a] This work, [b] Wapstra and Gove, Reference 3.

(d, p) and (d, t) reactions on all even A tin isotopes listed in the tabulation by WG are also shown for comparison. While there is in general good agreement, within the quoted uncertainties, between the two sets of Q-values, the results for $^{114}Sn(d, p)$, $^{120}Sn(d, p)$, $^{112}Sn(d, t)$, $^{114}Sn(d, t)$ and $^{122}Sn(d, t)$ differ from the tabulated values of WG by ~ 10 keV or more.

It seems worthwhile to try to trace the origins of these discrepancies. The measured Q-value for the $^{120}Sn(d, p)\,^{121}Sn$ reaction is lower by 9.3 keV than the tabulated value in WG; on the other hand the measured value for the $^{122}Sn(d, t)\,^{121}Sn$ reaction is also lower by 11.7 keV than the value reported in WG. Since there are no appreciable discrepancies between the measured and tabulated Q-values for the $^{120}Sn(d, t)\,^{119}Sn$ and $^{122}Sn(d, p)\,^{123}Sn$ reactions, it is quite probable that the difference arises because of an incorrect value for the tabulated mass of ^{121}Sn. Combining our measured Q-values for the

$^{122}Sn(d, t)\,^{121}Sn$ and $^{120}Sn(d, p)\,^{121}Sn$ reactions with the tabulated masses for ^{120}Sn and ^{122}Sn we get a mass excess for ^{121}Sn equal to -89192.2 ± 2.6 keV. This should be compared to the tabulated value of -89202.7 ± 3.1 keV.

The neutron separation energy given by the (d, p) reaction Q-value, 6170.8 ± 1.7 keV, differs by almost 10 keV from the adjusted value of WG, i. e. 6180.1 ± 2.7 keV, but is in good agreement within the assigned uncertainties, with the experimental value of 6173 ± 4 keV for the (n, γ) Q-value used by WG as a primary datum in the mass-adjustment. A recent measurement [14] of the (n, γ) Q-value gives $Q(d, p) = 3947 \pm 2$ keV, in excellent agreement with our value quoted in Table 2.

A similar situation exists in the case of the $^{114}Sn(d, p)\,^{115}Sn$ and $^{114}Sn(d, t)\,^{113}Sn$ reactions. Here the discrepancies seem to arise from the tabulated value for the mass of ^{114}Sn although the large uncertainties in the masses in this region preclude a more definite conclusion. The experimental Q-value for the (d, t) reaction leads to a neutron binding energy in ^{114}Sn of 10201.2 ± 1.6 keV which is ≈ 18 keV lower than that given in WG.

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