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Mass of ^{6}He †

R.G.H. Robertson*, E. Kashy, W. Benenson, and A. Ledebuhr

Cyclotron Laboratory and Department of Physics,
Michigan State University, East Lansing, MI 48824

ABSTRACT

A precise value for the ^{6}He mass excess has been obtained by comparison of the Q values for the ^{7}Li(d,^{3}He)^{6}He and ^{19}F(d,^{3}He)^{18}O* reactions, the latter populating the first excited state of ^{18}O. The measurements were performed at 0° in a magnetic spectrograph. The result for the ^{6}He mass excess is (17593.7 ± 1.1) keV, about 3 keV less than the previous value, and 3 times more accurate. The effect on the A=8 isobaric quintet and on the β-decay of ^{6}He is discussed.

NUCLEAR REACTIONS ^{7}Li(d,^{3}He)^{6}He, ^{19}F(d,^{3}He)^{18}O. E_d=20.8 MeV, θ =0°, magnetic spectrograph. ^{6}He, measured mass excess.

I. INTRODUCTION

With the exception of ^{6}He, the masses of all the light nuclei near the line of stability have been measured to a precision of the order of 1 keV or better. The mass of ^{6}He was measured in 1963 by Johnson, Pleasonton and Carlson[1], who examined the energy spectrum of ^{6}Li recoils following the β^- decay of ^{6}He and obtained a value for the decay energy accurate to 4 keV. No other measurement has approached that accuracy.

The ^{6}He mass is important in two respects. First, ^{6}He is a product of many reactions which lead to nuclei far from the line of stability[2], or serves in auxiliary calibration reactions[3], and its mass is becoming a limiting factor in the precision of some measurements of that type. Second, the ^{6}He β decay is the fastest Gamow-Teller transition, and as such has received much attention in investigations of the renormalization of the axial-vector coupling constant in nuclear matter[4,5]. An accurate determination of the *ft* value for the decay depends on precise knowledge of the ^{6}He-^{6}Li mass difference.

The present paper reports a measurement of the ^{6}He mass based on a comparison of the Q-values for the ^{7}Li(d,^{3}He)^{6}He and the ^{19}F(d,^{3}He)^{18}O* reactions, the latter populating the first excited state of ^{18}O at 1.982 MeV.

II. EXPERIMENTAL METHOD AND RESULTS

In general the comparison of two nuclear reactions as a means of measuring a mass is subject to uncertainties arising from a number of sources, among which are: (a) imperfect knowledge of, and random variation in, the beam energy, (b) uncertainties in detector calibration and stability, (c) target thickness and the distribution of

constituents throughout the target, and, (d) errors in the reaction angle. These effects have been minimized in this work by an appropriate choice of reactions and experimental conditions.

The method consisted of bombarding a natural LiF target with 20.8 MeV deuterons from the Michigan State University Cyclotron and observing outgoing ^{3}He particles in the focal plane of an Enge split-pole spectrograph. Groups from the (d,^{3}He) reaction populating the ground state of ^{6}He and the first excited state of ^{18}O fell very close together (less than 30 keV apart) in the focal plane. Under these conditions the influence of the beam energy is negligible, and focal plane calibration to the required precision is straightforward. Use of a LiF target confers the advantages of a stable binary compound. Finally, to obviate the need to measure and control the reaction angle, the experiment was performed at 0°, with the beam being stopped in a Faraday cup located between the first and second poles of the magnet.

Reaction products were detected on the focal plane, in a resistive-wire, charge-division proportional counter of length 20 cm backed by a plastic scintillator for particle identification. The experimental procedure was to cycle the spectrograph magnet and then record ^{3}He spectra at a series of increasing spectrograph fields which moved the ^{6}He-^{18}O* doublet along the length of the detector. Knowledge of the spectrograph calibration[6] permitted the detector calibration to be determined, and the doublet separation could then be extracted with high precision. The detector calibration was assumed to be linear over small distances. The principal uncertainty is the possible occurrence of small-scale nonlinearities in the detector (due for example to microscopic variations in wire diameter, dust on the wire, etc.), and such variations are presumed to average out in a set of measurements made at several locations on the detector.

Data were taken in groups of two to four consecutive field settings. Energy resolution ranged from 12 to 20 keV, depending on target thickness and beam conditions, and the doublet was not always completely resolved. Therefore, the doublet separation was derived by use of the peak-fitting code SAMPO,[7] which gave results in good agreement with direct centroid determination in those cases for which the peaks were well resolved. One of the doublet measurements, with the fitted shape, is shown in Fig. 1. The energy resolution is approximately 15 keV full width at half maximum in that spectrum. In all, fourteen measurements were taken, eleven with a 25 $\mu g\ cm^{-2}$ LiF target on a 20 $\mu g\ cm^{-2}$ carbon backing, with the LiF side facing the spectrograph. One measurement was made with the target reversed and two with an 8 $\mu g\ cm^{-2}$ target. The results are shown in Fig. 2. The data comprise a measurement of the quantity $Q_6 - Q_{18}{}^*$, where Q_6 and $Q_{18}{}^*$ are the Q-values of the ^{7}Li(d,^{3}He)^{6}He and ^{19}F(d,^{3}He)^{18}O(1.98216) reactions, respectively. However, to make a comparison between the present measurement and the previous one, the ordinate of Fig. 2 is the quantity

$$Q_6 - Q_{18}{}^* - (Q_6 - Q_{18}{}^*)_{1971} \ ,$$

where the last term is the Q-value difference that would be calculated using the 1971 mass table of Wapstra and Gove[8] (wherein the ^{6}He mass is essentially based on the measurement of Johnson et al.[1]). The error flags shown in the figure are the statistical uncertainties in the peak separations only, and the excess deviations from the mean are attributed to fluctuations in detector linearity. The two measurements made with the thin target are designated by open circles and that made with the target reversed by a triangle. The latter point shows a substantial deviation from the mean, but a point at almost the same detector position shows a similar effect. That

this effect is due to a detector linearity fluctuation (rather than a non-stoichiometric target composition) is further supported by the agreement between the thin and thick-target measurements.

Since the scatter in the data exceeds the statistical uncertainties, the average value of Δ has been obtained from a simple unweighted average, and the uncertainty from the internal error. One obtains in this way Δ=3.92(32) keV. Here, and throughout this paper, the uncertainty in the last digit of a number is placed in parentheses. An average in which each point has its statistical weight gives Δ=3.83 keV, while an unweighted average omitting the two lowest points gives Δ=3.96 keV. The first of these results is adopted.

The beam energy was known to 20 keV, which contributes an uncertainty of 25 eV to the result. The mean reaction angle, with a spectrometer entrance aperture 2° square, was 0.76°, and the uncertainty in this quantity contributes 150 eV to the result. It is estimated that target thickness uncertainties amounted to less than 20 eV, and that the probable systematic error introduced by the peak fitting procedure was not more than 200 eV. Combination of these uncertainties with the internal error in the data, 320 eV, leads to a final result

$$Q_6 - Q_{18}{}^* = 0.98(41)\ \text{keV} \ .$$

In the preliminary version of a new mass compilation, Wapstra and Bos[9] give for the mass excesses of ^{19}F, ^{18}O and ^{7}Li, -1487.38(13), -783.03(30) and 14908.20(90) keV, respectively. The excitation energy of the first excited state in ^{18}O is 1982.16(20) keV.[10] These quantities may be combined to give the mass excess of ^{6}He,

$$M(^6\text{He}) = 17593.7(11)\ \text{keV}.$$

The uncertainty in this result is dominated by that in the

^{7}Li mass. Prior to the present work, the ^{6}He mass excess (as given by Wapstra and Bos[9]) was 17597.0(35) keV. The weighted average of these two independent results is

$$M(^{6}\mathrm{He}) = 17594.0(11)\ \mathrm{keV}\ .$$

This mass excess is 3.0 keV lower than the Wapstra-Bos value[9] and 3.3 keV lower than the 1971 Wapstra-Gove value.

III. DISCUSSION

The improved accuracy in the mass of ^{6}He will influence certain measurements of nuclei far from the line of stability. For example, Tribble, Cossairt, May and Kenefick[3] have recently reported a new measurement of the mass of ^{8}He in which the (^{4}He,^{6}He) reaction serves as a calibration. They find, using the Wapstra-Bos masses, that the ^{8}He mass excess is 31.593(8) MeV. With the new ^{6}He mass reported here that value becomes 31.591(8) MeV, and the weighted average of all measurements[3,16–18] of the ^{8}He mass excess becomes 31.594(7) MeV. The revised ^{8}He mass in turn affects other masses measured via the (^{4}He,^{8}He) reaction, and in particular the mass of ^{8}C. Table I summarizes the experimental information on the A=8 isobaric quintet to date, and Table II gives the resulting coefficients of the isobaric multiplet mass equation (IMME). It can be seen that there continues to be evidence for a small but significant departure from the IMME.

An extensive series of measurements of the masses of T_z=–3/2 nuclei has been made with the (^{3}He,^{6}He) reaction[2], and some of those are subject to revision by the new ^{6}He mass. It should be pointed out that in many cases the results were almost independent of the ^{6}He mass because a different (^{3}He,^{6}He) reaction of similar Q-value was used as a calibration. For those cases no revision of the measured masses is occasioned by the present result. A complete reanalysis of the (^{3}He,^{6}He) reactions is deferred to an article presently in preparation.

Another area influenced by the new ^{6}He mass is the β-decay of ^{6}He. The present result corresponds to a decay energy of 3506.4(12) keV when the ^{6}Li mass excess is taken to be 14087.3(7) keV. Combining that value with the direct measurement of Johnson et al.,[1] 3509.4(40) keV, yields 3506.7(11) keV for the decay energy. Wilkinson and Macefield[19] have tabulated the statistical rate function f, which, for the ^{6}He decay, becomes 1005.5(15). However, there is now some question about the half-life of ^{6}He, because the recent measurement of Wilkinson and Alburger[20] gave a result, 808.1(20) msec, in disagreement with two previous measurements of comparable precision, 799(3) msec,[21] and 797(3) msec.[22] A reasonably conservative approach is to assign each of the three measurements equal weight and to treat the internal error as the uncertainty. One then obtains 801.4(42) msec for the half-life and 805.8(44) sec for the ft-value. This result differs from that given by Wilkinson and Alburger,[20] who used the old ^{6}He mass and their own measurement of the half-life to obtain 815.7(42) sec, but it seems premature to reassess the renormalization of the axial-vector coupling constant until the discrepancy in the half-life measurements is resolved.

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FIG. 1. Spectrum of ^{3}He particles resulting from 20.8-MeV deuteron bombardment of a LiF target. The smooth curve is an analytic fit to the data, used to extract the doublet separation.

FIG. 2. Plot of the quantity $\Delta = Q_6 - Q_{18}^* - (Q_6 - Q_{18}^*)_{1971}$ measured at different locations on the focal plane, as a function of position. The error bars shown are the statistical uncertainties only; the excess deviations from the mean are ascribed to detector non-linearities. The point designated by a triangle was measured with the target reversed, and those shown as open circles were measurements made with a very thin target.

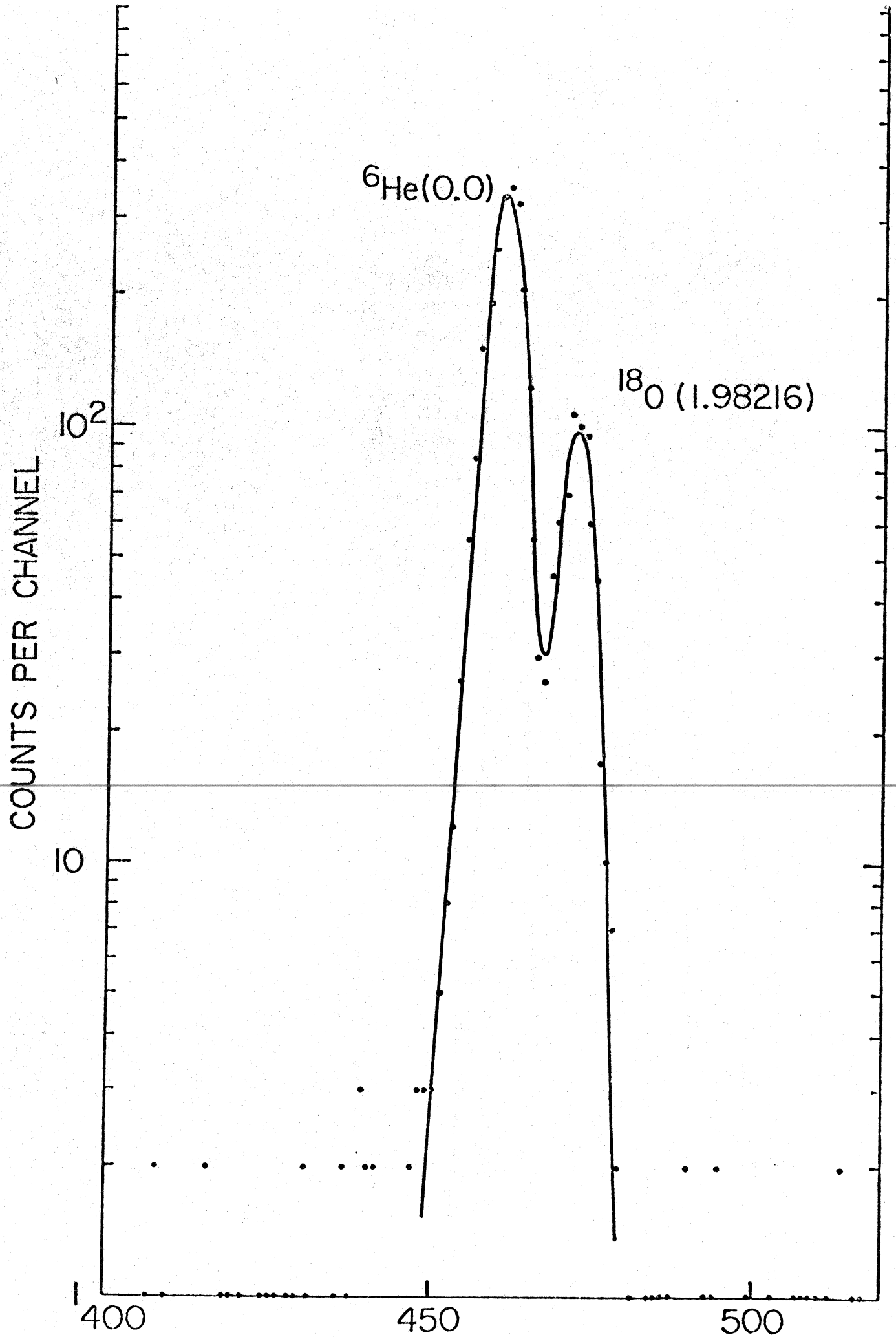
TABLE I. Summary of Properties of the A=8 Isobaric Quintet.

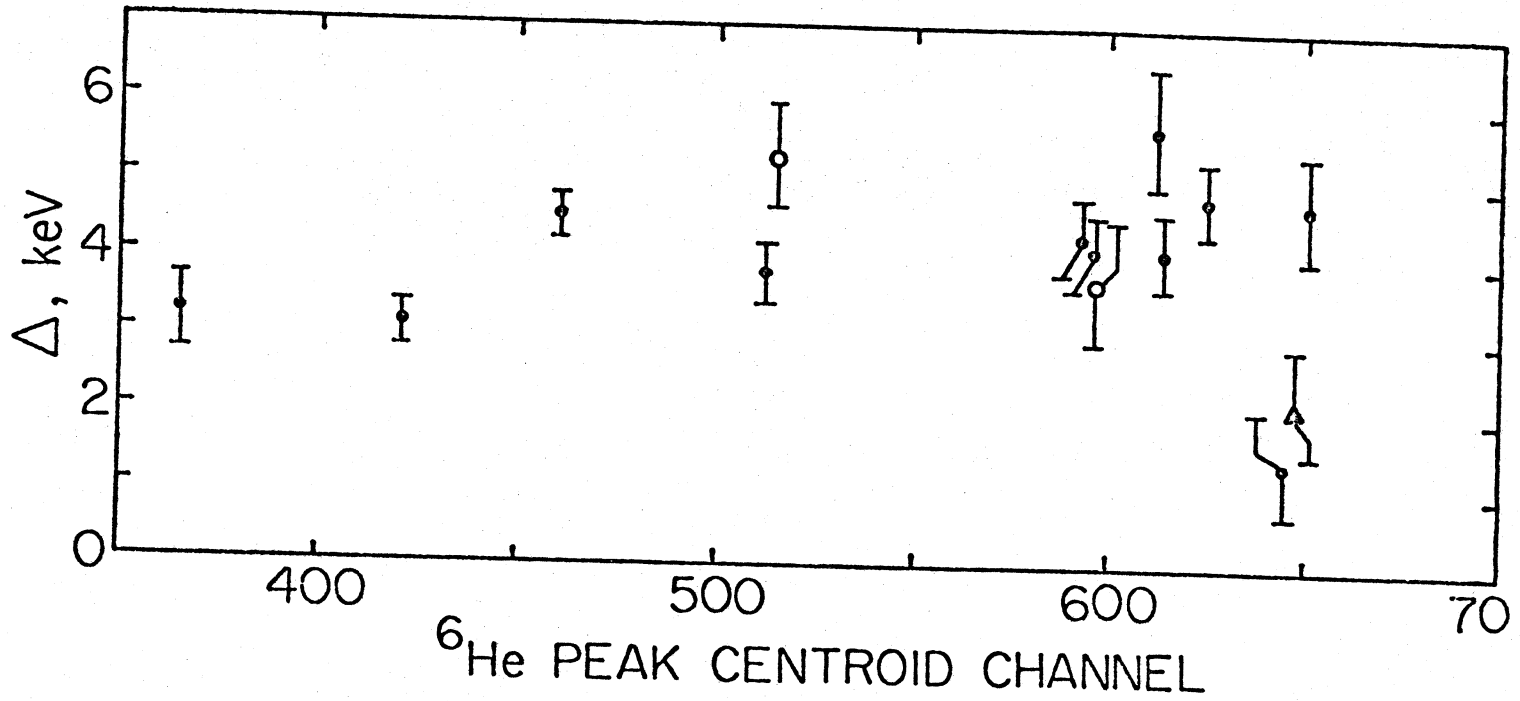
	T	Mass Excess (MeV)	Width $\Gamma_{c.m.}$ (keV)
^{8}C	-2	35.097(24)[a]	245(40)[e]
^{8}B	-1	33.542(9)[b]	32(25)[b]
^{8}Be	0	32.4358(18)[c]	5.5(20)[f]
^{8}Li	+1	31.7694(54)[b]	12[b]
^{8}He	+2	31.595(7)[d]	Bound

a Reference 11 (corrected by present work) and Reference 12.
b Reference 12.
c References 13, 14, 15 (corrected with masses from Reference 9).
d References 3 (corrected by present work), 16, 17, 18.
e References 11 and 12.
f Reference 15. (It is probable that this is the only correct measurement of the width.)

TABLE II. Coefficients of the IMME for the A=8 Quintet (keV).

a	b	c	d	e	χ^2
32434.6(17)	-882.3(40)	229.4(24)	-	-	7.7
32435.3(18)	-894.4(63)	225.8(28)	5.6(22)	-	1.5
32435.8(18)	-881.9(40)	213.7(69)	-	4.2(17)	1.8
32435.8(18)	-889.9(73)	217.3(74)	3.6(27)	2.6(21)	-


^{6}He(0.0)
^{18}O (1.98216)
COUNTS PER CHANNEL
10^2
10
1
400
450
500


Δ, keV
0
2
4
6
400
500
600
70
^{6}He PEAK CENTROID CHANNEL