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Measurement of the energy of the 6129-keV γ ray of ^{16}O†

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The precise isotopic mass-difference values of Smith and Wapstra have been used as a reference in the determination of the energy of the 6129-keV γ of ^{16}O. This transition is widely used as an energy standard in nuclear spectroscopy and in muonic x-ray studies. The value of the γ-ray energy was found to be 6129.170 ± 0.043 keV. The quoted uncertainty is approximately one order of magnitude smaller than that of previous determinations. Data from the measurements also indicate that the new and highly precise mass values form a self-consistent set.

[RADIOACTIVITY ^{16}O; measured E_γ referred to mass scale.]

INTRODUCTION

The 6129-keV ^{16}O γ ray has often been used as a standard energy calibration reference from which the energies of other energetic γ rays are determined.[1-3] The ^{16}O line provides a convenient reference since it arises from the decay of 7-sec ^{16}N, an activity which can be produced by fast-neutron irradiation of water. A flowing water line, placed in the vicinity of an accelerator target, will serve to generate the 7-sec activity and can also transport it to a convenient experimental site. A more portable source[4] of the 6129-keV γ ray can be made by utilizing the ^{13}C(α, n) reaction in a mixture of ^{244}Cm and ^{13}C.

In the past, three experimental groups have made measurements of the energy of the 6129-keV line: Berg and Kashy[5] (6127 ± 1.2 keV); Greenwood[6] (6128.9 ± 0.4 keV); and Chasman *et al.*[7] (6129.96 ± 0.46 keV). Recently it has been common practice to use the weighted mean of these three measurements (6129.3 ± 0.4 keV) as proposed by Marion.[8] Unfortunately this mean value is at or outside the error limits of all three measurements. All three measurements were made using Ge(Li) detectors with energy calibration derived from an extrapolation technique which makes use of the (assumed) $2m_0c^2$ energy difference between full-energy peaks and double-escape peaks. It is now known[9] that the electric field effects in Ge(Li) detectors make this procedure unreliable.

The energy of the 6129-keV line has significance extending beyond that of the energy of a level in ^{16}O since, for example, this line is used in muonic x-ray studies as a reference by which to judge nuclear size, nuclear polarization effects, and the validity of a variety of quantum electrodynamic corrections (cf. Ref. 2). It thus appeared that a remeasurement of this energy, using techniques which avoid some of the problems of previous measurements, was in order.

EXPERIMENTAL TECHNIQUE

Recent highly precise determinations of isotopic mass differences of a series of light nuclei[10] provide an energy scale in the multi-MeV region which does not rely on the "bootstrap" techniques of previous γ-ray energy measurements. As Wapstra[11] has pointed out, these new mass determinations offer the possibility of greatly improved calibration for energetic γ rays. Accurately known neutron binding energies serve to calibrate γ rays from the corresponding (n, γ) reaction. In the present measurements, the 6129-keV line of ^{16}O is compared simultaneously with lines from three different (n, γ) reactions using a Ge(Li) detector. In particular, the calibration was derived from the ground state neutron capture transitions of ^{13}C and ^{3}H and from three γ-ray cascades in ^{15}N which sum to yield the neutron binding energy of that nucleus (see Table I). Since a linear energy scale is overdetermined by the five calibration constants, it was possible to evaluate the nonlinearity of the detector system.

In order to "measure" (actually, compare) γ-ray energies accurately with a Ge(Li) detector, two geometrical conditions must be satisfied. First, the direction of incidence of the radiation from the reference source must be the same as that of the line to be measured. Second, the same region of the detector must be illuminated by both calibration and unknown lines. When neither radiation source is collimated (i.e., the situation which usually applies when comparing radioactive sources), the second condition is automatically satisfied. However, neutron-capture γ-ray sources are fre-

quently highly collimated due to shielding requirements and the desire to avoid extraneous reactor background in the spectrum. In the present measurements particular caution was taken to insure that both the above conditions were satisfied. The measurements were made using the neutron-capture γ-ray facility of the Los Alamos Omega West Reactor. A continuous source of the ^{16}N activity was obtained by circulating water from the primary cooling loop of the reactor through a coaxial vessel placed on a line between the (n,γ) calibration targets in the reactor thermal column and the Ge(Li) detector system. The Ge(Li) detector was a minimum of 3 m from the radiation sources. Measurements were made with various aperture-limiting collimators placed in front of the detector to demonstrate that the two conditions mentioned above were fulfilled.

The Ge(Li) detector, a 25-cm^3 closed-end coaxial type with resolution of 4.7 keV at 6 MeV, was operated inside a large (20×25 cm) annular NaI(Tl) detector. The Ge(Li)-NaI system was operated as a pair spectrometer: that is, Ge(Li) detector events were stored only if they were accompanied by a pair of 511-keV photons detected in the surrounding annulus. Thus only double-escape peaks appear in the spectra. To verify that the electronic gating required by the pair spectrometer mode did not introduce a distortion of the energy calibration, a comparison was made of data taken with and without the 511-keV gate. No energy shift was observed within the statistical accuracy of the data (~15 eV).

The electronics[12] used to amplify and digitize the Ge(Li) detector signal were selected for high integral linearity by using a computer-controlled precision pulser. To reduce the influence of differential nonlinearity, a series of 12 data runs were made, each with a somewhat different amplifier gain. The centroids of the spectral lines of each run were determined by fitting a Gaussian line shape to the data. The five calibration data points (two fixed energies and three sum-pair relations) from each run were used to evaluate the coefficients of a polynomial relation

$$E = a_0 + a_1 x + a_2 x^2 + \cdots \quad (1)$$

between energy (E) and spectral-line centroid (x) via a weighted least-squares adjustment. Polynomial orders higher than quadratic were found to produce no statistically significant improvement in the fit of the calibration data. Therefore only the first three terms of Eq. (1) were retained in the final analysis of the data. Using the quadratic approximation, the mean χ^2 per degree of freedom for the 12 data runs was 0.6. The nonlinearity of the detection system over the 4500- to 6300-keV region of interest can be represented by the gain-independent ratio: $a_2/a_1^2 \cong -2\times10^{-7}$ keV^{-1}.

TABLE I. Calibration energies as determined by mass measurements. See Ref. 10. The tabulated uncertainties are from the more comprehensive estimates of Ref. 11.

Reaction	Transition Energy[a] (keV)
^{2}H$(n,\gamma)^3$H	6257.372±0.038
^{12}C$(n,\gamma)^{13}$C	4946.426± 0.039
^{14}N$(n,\gamma)^{15}$N	4510 + 6324 = 10 833.395± 0.066
^{14}N$(n,\gamma)^{15}$N	5270 + 5563 = 10 833.395± 0.066
^{14}N$(n,\gamma)^{15}$N	5299 + 5534 = 10 833.395± 0.066

[a] γ-ray energies were derived from these values by appropriate compensation for nuclear recoil, via the relation $E_R = 5.3677\times10^{-7} E_\gamma^2 A^{-1}$ keV, where A is the mass number of the product nucleus.

RESULTS

A value for the 6129-keV ^{16}O line energy was derived for each data run using the calibration coefficients for that run (see Fig. 1). The statistical uncertainty in this energy was computed from the error matrix for the a_i (including correlation terms) and from the statistical uncertainty in the centroid of the line. The values from each run were then combined to yield the final result. The uncertainties in the final value can be divided into two categories: those arising from the present measurements and those inherent in the calibration. The former category can itself be divided into two parts: a purely statistical term (e_s), computed as described above, and a term (e_L) arising from any *uncorrected* nonlinearity of the detector system. Values for these quantities are given in Table II. The various elements which make up the second category are given in Ref. 11: E_s, the purely

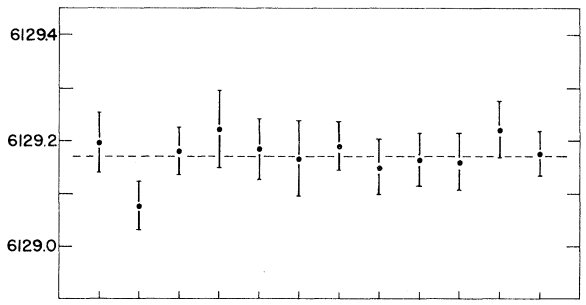

FIG. 1. The energy (keV) of the ^{16}O line obtained in each of the data runs. The weighted mean value is indicated by the dashed line.

statistical error; E_{n-H}, the uncertainty in the neutron-hydrogen mass difference; and E_{me}, the uncertainty in the mass-energy conversion factor (the ^{3}H values were used here since the 6250-keV line dominates the calibration near 6129 keV).

Only the first two terms of Table II enter into the uncertainty in the energy *difference* between the 6129- and 6250-keV γ rays; the value obtained for this difference is:

$$E_{6250-6129} = 121.196 \pm 0.020 \text{ keV} .$$

The absolute value of the 6129-keV ^{16}O line, including all the uncertainties of Table II, is

$$E_{6129} = 6129.170 \pm 0.043 \text{ keV} .$$

Note that the uncertainty in this value is dominated by the last two terms in Table II. These same systematic errors will be present in any energy determination based on mass-difference data.

Aside from determining the energy of the 6129-keV line, the data of the present measurements can be interpreted as a measure of the internal consistency of the mass data of Ref. 10. For example, the ^{3}H and ^{13}C binding energies can be fixed at the mass values and the ^{15}N binding energy "adjusted" [along with the three coefficients of Eq. (1)] to fit the γ-ray data. Since a low χ^2 was obtained when the ^{15}N binding energy was fixed at the mass value (see above), it is apparent that the γ-ray data are in substantial agreement with the mass data. In fact, the value of the ^{15}N energy obtained in the adjustment suggested above is within the statistical uncertainty (51 eV) of the value of Ref. 10. Thus the present analysis indicates that the new and highly precise mass values of Smith and Wapstra for the three isotopes of Table I form a consistent set.

TABLE II. Estimated uncertainties of the measurement (eV).

e_s	e_L	E_s	E_{n-H}	E_{me}
14	15	15	30	17

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