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A SURFACE IONIZATION SOURCE FOR BEAM ENERGY CALIBRATION

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A surface ionization source has been constructed to produce Tl^+ ions having the same magnetic rigidity as light ions of a few MeV energy. The light-ion energy is determined by matching the paths of the light and Tl^+ ions through a magnetic spectrometer and by measuring the source voltage with a precision voltage divider and voltmeter. The absolute calibration has been verified by measuring the energy of alpha particles from a ^{212}Bi source and by measuring the $^{14}N(p, n)^{14}O$ reaction threshold.

1. Introduction

In the attempt to measure hadronic neutral current parity violation in the inverse alpha decay of the 3.563 MeV, 0^+ state of ^{6}Li, we search for a resonance in the $^2H(\alpha, \gamma)^6Li$ reaction at $E_\alpha = 6.238$ MeV (lab energy) [1]. It is required that the beam energy be known with an absolute accuracy of about 2 parts in 10^4 and that it be possible to match the beam energy from one data acquisition period to the next with an accuracy of 1 part in 10^4. In order to eliminate the uncertainties in the calibration of the accelerator beam analyzing magnet, especially those involved in interpolating or extrapolating calibration measurements at other energies, we have designed a system with which we can frequently (and with little effort) measure the energy of the beam at the $^2H(\alpha, \gamma)^6Li$ resonance energy.

For this purpose we built a surface ionization source. The source, operating at 30.47 kV, produced Tl^+ ions of the same magnetic rigidity as the 6.238 MeV α^{++} beam. Both beams could be brought down the beam line and through a Q3D spectrometer [2] to the focal plane, where the beam energy was measured by matching currents on the two halves of a split Faraday cup and measuring the voltage applied to the source extraction electrode with an accuracy of 0.01%.

The source is described in section 2, the procedure for its use is given in section 3, and two measurements for checking the absolute accuracy are given in section 4 (^{212}Bi source alpha particle energy measurements) and section 5 [$^{14}N(p, n)^{14}O$ threshold measurement]. A summary is given in section 6. All measurements described here were made at the Chalk River Nuclear Laboratory (CRNL), with the exception of the α source calibration, which was done at the Michigan State University (MSU) Cyclotron Laboratory. The description is that of the Chalk River configuration, unless otherwise noted.

Similar work has been carried out independently at the University of Auckland [3,4].

2. Description of the ion source

In the surface ionization process, an atom of low ionization potential (in our case thallium, $V_i = 6.1$ eV) is ionized by contact with a surface of high work function (in our case iridium, $\phi = 5.3$ eV) which is hot enough to thermally desorb the ion. Because of the surface nature of the interaction and the equipotential maintained by the metallic ionizer, the kinetic energy of the ions is determined by the voltage applied to the ionizer. (The kinetic energies for zero applied voltage have a Maxwellian distribution characteristic of the temperature of the ionizer; in our case $\frac{3}{2}kT$ is 10^{-5} times the applied voltage.) Thallium was chosen because it is relatively heavy (not requiring very high voltages for an ion of a given magnetic rigidity), has a relatively low ionization potential, and is easily evaporated to form an atomic beam. To match the rigidity of 6.24 MeV α^{++} particles, a voltage of 30.5 kV was required.

The ion source was mounted on a water-cooled copper flange and was housed in an O-ring-sealed

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aluminum box 20 cm long and 16×16 cm^2 wide. Two Lexan windows allowed viewing of the source. The source was pumped by a 160 l/s turbomolecular pump; a liquid nitrogen (LN_2) cold trap was located just upstream of the source. It is important to maintain good vacuums, particularly in the long beam line between the ion source and Q3D magnet chamber. Energy losses for 30 keV Tl^+ are a few keV/$\mu g \cdot cm^{-2}$, so that passage of the ions through several meters of beam line with vacuum as poor as 1×10^{-5} Torr would result in uncertainties in energy large compared to the accuracy required. A typical vacuum near the source (while the source was hot) was 3×10^{-6} Torr; most of the downstream beam line, about 7 m long, was maintained at 5×10^{-8} Torr by ion and sublimation pumps; the scattering chamber vacuum was about 3×10^{-6} Torr and the magnet chamber about 1×10^{-6} Torr, both maintained by turbomolecular pumps.

Schematic and detailed diagrams of the system are given in fig. 1. Natural, metallic thallium was evaporated from a stainless steel cylinder of inside volume about 0.3 cm^3, heated by a coil of Sodern "Thermocoax" to a temperature of about 600°C. This oven was mounted downstream of the ionizer below the beam axis, at an angle of 20°. The atomic beam was collimated by an aperture in the cylinder (1 mm diameter, 2 mm long) and passed through a 3 mm diameter hole in the ground electrode to the 6 mm diameter iridium ionizer, located at the center of the high voltage electrode. The iridium ionizer, made of foil 0.05 mm thick, was heated to about 2000 K by electron bombardment from a hot tungsten filament (at ground potential) located behind the iridium foil. The current through the filament was regulated to maintain a fixed electron bombardment current. A convenient feature of the design is that only a single high voltage electrode is required; the filament and its supply operate near ground potential.

The concave high voltage electrode was made of stainless steel; the convex ground electrode, of copper; radii of curvature were 5.7 cm and 4.4 cm, respectively, and the separation between the two was 1.3 cm. This geometry results in ion flow downstream of the ground electrode which is approximately paraxial [5]. The ionizer foil was bolted onto the high voltage electrode, and the electrode was mounted directly on the feedthrough of a 50 kV corona-free bushing.

The high voltage dc power supply was a Spellman RHSR30P60/FG supply, factory modified to reach

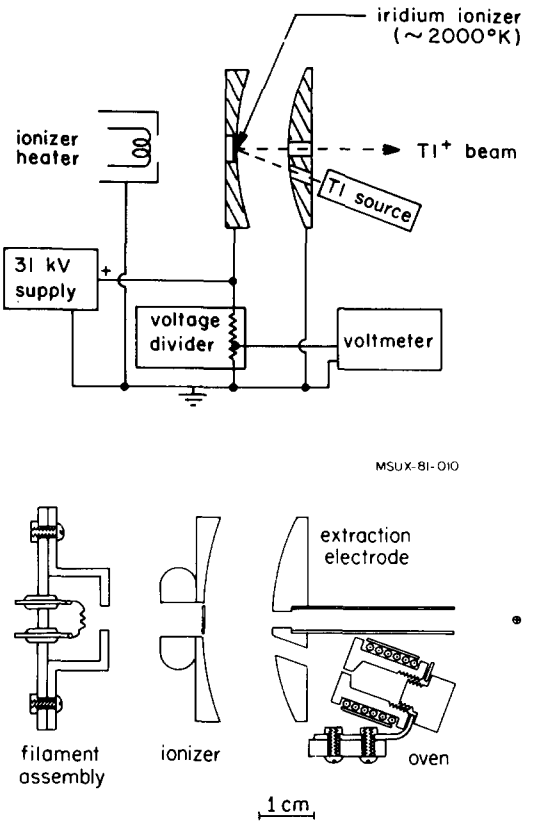

Fig. 1. (Top) Schematic drawing of source showing electrical connections. (Bottom) Scale drawing showing major elements and their relative placement in a cross-sectional view.

31 kV. Current capability was 2 mA. (Typically, the ionizer drew 1 mA and the voltage divider drew 0.6 mA. Ion beam currents were less than 0.1 mA.) Regulation was rated at ±10 ppm for ±10% line change, ripple less than 10 ppm rms, and stability better than 50 ppm per hour. Slight modifications in the circuit allowed us to float this power supply to 400 V, as required for the $^{14}N(p, n)^{14}O$ measurement described below.

The voltage applied to the source was measured with a Julie Research Laboratories KV-50 voltage divider and a digital voltmeter. The divider had an input impedance of 1000 Ω/V; the absolute accuracy was 0.01% on a "10 V" tap having a dividing ratio of 5000. The stability was rated at better than 15 ppm per year. The digital voltmeter used at Chalk River was a Fluke 8502A multimeter having a rated accuracy of 0.002% for 90 d. At MSU, a Hewlett–Packard 3490A digital voltmeter was used, having a rated accuracy of 0.013% for 90 d. The accuracy of

the 3490A voltmeter was checked with a Fluke 343-A dc voltage calibrator, having a rated accuracy of 0.003%; the voltmeter was found to be accurate to 0.01%. The voltage divider was independently calibrated by the Division of Physics of the National Research Council of Canada in Ottawa. The dividing ratio for the "10 V" tap for 30 kV applied voltage was found to be 4999.5 ± 0.007%, within 0.01% of the rated value of 5000.0. A dividing ratio of 4999.7 ± 0.01% was used for the $^{14}N(p, n)^{14}O$ calibration considered below and for calibrating the alpha beam energy in the $^{2}H(\alpha, \gamma)^{6}Li$ experiment. At the same time, the Fluke 8502A digital voltmeter was determined to be accurate to 0.001%.

Electrical connections between the power supply, voltage divider, and source were made with RG-8 cable. Toroids and spheres were used at the source bushing and at the voltage divider input to prevent corona discharge. All electronics were grounded to the vacuum chamber.

Typical ion source currents were 100 nA at a position 22 cm downstream from the source, 5 nA in the scattering chamber (7 m downstream), and 0.2 nA at the focal plane, following collimation by a slit 0.5 mm wide. The beam emittance was about 20 mm mrad.

3. Beam energy calibration procedure

For calibrating the alpha beam energy, a 0.5 mm wide slit was placed in the center of the CRNL Q3D scattering chamber, a 3 mm wide aperture at the entrance to the spectrometer 40 cm away, and a split Faraday cup in the focal plane. The slit and aperture are required to define the position and angle of the incident particles to the accuracy required (1 part in 10^4 in the energy determination), given the spectrometer aberrations and magnification. The source was turned on at least one hour before use, to allow the electronics to stabilize. The alpha beam was tuned through the beam line and Q3D magnet chamber by maximizing the total current on the split Faraday cup. The current was then balanced between the two halves of the cup with the analyzing magnet which, via a feedback system, controls the accelerator beam energy . The Tl^+ beam was next tuned through to the split Faraday cup (keeping the same slit and aperture) and the total current maximized. (The Tl^+ beam entered the beam line at a small switching magnet some 7 m upstream from the spectrometer.) The currents on the two halves of the Faraday cup were then measured as a function of the source voltage. With the Tl^+ beam on the high-rigidity side of the split Faraday cup, a current of 5–10% of the total current was still read on the low rigidity side of the cup. The origin of this low-rigidity current is not understood (it does not arise from ^{203}Tl ions, but could be due to slit scattering); the ambiguity introducing in determining the balance voltage is ±3 parts in 10^5. Finally, the alpha-particle beam measurement was usually repeated in order to check for Q3D field drifts.

The alpha beam energy, for the analyzing magnet setting giving equal currents on the two halves of the split Faraday cup, is calculated by matching the momentum to charge ratio (using relativistic formulas and ionic masses) for the α^{++} and Tl^+ beams, deriving the Tl^+ kinetic energy from the source voltage at the current balance point, as measured by the voltage divider and digital voltmeter. Corrections for the Maxwellian distribution of velocities characteristic of the hot ionizer and for the contact potential (discussed below) are applied.

Errors in the measurement result from uncertainties in voltage divider and voltmeter calibrations, spectrometer aberrations, uncertainty in determining the contact potential, and errors in balancing the Tl^+ and α^{++} beams on the split Faraday cup. The absolute accuracy is 1.6 parts in 10^4; reproducibility over a period of a few months should be good to 1.2 parts in 10^4.

To ensure that the vacuum was good enough to allow an accurate measurement, the pressure was raised by a factor of 10 at the source and by a factor of 3 along the beam line by bleeding nitrogen into the system. By matching the Tl^+ currents at the focal plane, it was found that the energy difference was zero within the accuracy of the measurement, 0.6 parts in 10^4.

For ions desorbed from an electrode made of one metal and collected by a different metal, the kinetic energy will differ from the applied potential by the contact potential between the two metals, the magnitude of which is given by the difference between the two work functions. With the magnetic analysis of the present measurements, it was not clear which two metals were relevant, so an experimental determination of the effective contact potential was made. Potassium, cesium iodide, and thallium were placed in the oven simultaneously, and the $^{41}K^+$, $^{133}Cs^+$, and $^{205}Tl^+$ ions were focused sequentially down the beam line; the currents were balanced on the split Faraday

cup, the magnetic field of the Q3D being held constant. (The source voltages were 28.3, 8.72 and 5.65 kV, respectively.) The voltage dependence on mass was extrapolated to infinite mass in order to extract the contact potential. The resulting potential was (0.3 ± 1.0) V, a value to be subtracted from the measured voltage before calculating the ion kinetic energy. The uncertainty introduced is small compared to the accuracy required for the $^{2}H(\alpha, \gamma)^{6}Li$ measurement.

4. Test of accuracy with alpha particles from a ^{212}Bi source

Rytz [6] has recently compiled experimental values of α-particle energies. The energies of the 6.051 and 6.090 MeV α-particles from a ^{212}Bi (ThC) source have been measured with an accuracy of less than 0.1 keV; the values were determined absolutely by length and field measurements on a magnetic spectrometer. As a test of the absolute calibration of the Tl^{+} source, we measured the energies of these alpha particles using a photographic plate mounted in the focal plane of the MSU Enge split-pole spectrograph. A slit 0.5 mm wide and 2.8 mm high was mounted in the center of the spectrograph scattering chamber; an aperture 1° (horizontal) by 2° (vertical) was used at the entrance to the spectrometer. The Tl^{+} source was mounted 45 cm upstream from the slit. The vacuum was 1×10^{-5} Torr at the ion source (pumped by a turbomolecular pump and a LN_2 cold trap). The magnet chamber was cryogenically pumped. The position of the Tl^{+} beam at the focal plane was measured in two different ways: by scanning over the edge of the photographic plate, recording the beam current on a Faraday cup mounted behind the plate, and by bombarding the photographic plate for a 25 min interval (current about 0.1 nA). The latter bombardment placed a line on the plate (located between the two alpha lines) that could be identified when subsequently scanning the plate. The two measurements of Tl^{+} position agreed to within 7 parts in 10^{5} (in energy). The average of the two values was used to determine the alpha energies. The scanning over the plate edge was performed both before and after the alpha source measurement to check for magnetic field drifts. To measure the position of the alpha particles at the focal plane, the alpha source (made a few hours before the measurement) was placed behind the slit in the center of the scattering chamber, and the plates

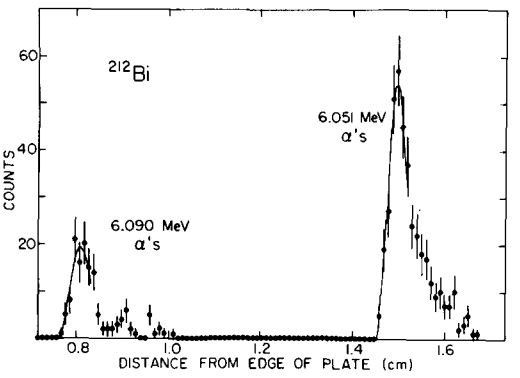

Fig. 2. Spectrum of α-particles from a ^{212}Bi source prepared by electrostatic collection of ^{228}Th daughters. The solid curves indicate the regions of data used and the calculated lines shapes, as described in the text.

were exposed for eight hours. The resulting spectrum is shown in fig. 2.

In order to determine the focal-plane position of α-particles emitted from the center of the source at 0° with no energy loss, it was necessary to correct the observed peak position for spectrometer aberrations resulting from the finite size and angular emittance of the source and for the energy loss in the source material. A lineshape for fitting the data was generated by numerically integrating the yield over the horizontal and vertical extent of the source (using the known spectrometer magnification), over the solid angle subtended by the spectrometer entrance aperture (using known spectrometer aberration coefficients), and over energy loss in the source, assuming a uniform thickness. Such a lineshape was generated for several source thicknesses. The data were fit, minimizing χ^2 with the peak height as a variable parameter, for varying peak position and source thickness. (Only the high-energy portion of the peak was fit.) The best-fit peak position and source thickness were thus determined. The best fit is shown in fig. 2. The source thickness corresponds to about 2.5 keV for 6 MeV α-particles.

The voltage divider tap used in these measurements had a dividing ratio of 50 and an accuracy of 0.001%. In a separate measurement, the dividing ratio of this "1000 V" tap was compared to that of the "10 V" tap having a dividing ratio of 5000 and an accuracy of 0.01% by making successive scans across the edge of a Faraday cup. For the beam on the edge of the cup, the deduced source voltages agreed within 8 parts in 10^{5}, when the dividing ratio of 4999.7 was

Table 1
Comparison of ^{212}Bi alpha-particle energies (in keV) measured with the Tl^+ source to those of Rytz (ref. 6).

Tl^+ source	Rytz
6090.1 ± 1.2	6089.94 ± 0.04
6051.1 ± 1.2	6050.83 ± 0.04

used for the "10 V" tap (see section 2). (Use of the "1000 V" tap does not give higher accuracy, as the input impedance of the voltmeter on the 1000 V scale contributes an additional uncertainty.) In calculating the alpha energies, the nominal value of the dividing ratio of the "1000 V" tap was used.

Two additional corrections were made before calculating the alpha energies. The measured voltages were reduced by 0.3 V (the value measured for the Chalk River configuration) to take into account a possible contact potential. In addition, the kinetic energy of the Tl^+ ions was increased by $\frac{3}{2}kT = 0.26$ eV, to account for the Maxwellian distribution of velocities characteristic of the 2000 K ionizer. No correction was made for Tl^+ spectrometer aberrations; such a correction would be at the level of 1 part in 10^5.

The results are given in table 1. The errors were calculated from the quadratic sum of the following contributions: (1) determination of alpha peak positions, 0.2 parts in 10^4 for the 6.05 MeV line and 0.4 parts in 10^4 for the 6.09 MeV line; (2) determination of Tl^+ peak positions, 0.4 parts in 10^4; (3) accuracy of voltage divider and voltmeter, 1.8 parts in 10^4; (4) determination of contact potential, 0.3 parts in 10^4; and (5) possible magnetic field drifts, 0.2 parts in 10^4. It can be seen that the central values are within 4 parts in 10^5 of the Rytz values, and that there is agreement well within errors.

5. Test of accuracy with the ^{14}N(p, n)^{14}O reaction

The threshold for the ^{14}N(p, n)^{14}O(β^+)^{14}N* (2.31 MeV) reaction was measured by observing the number of delayed 2.31 MeV gamma rays as a function of proton beam energy. The beam of intensity 100 nA was incident on a thick tantalum nitride target surrounded by a LN_2 shroud to prevent carbon buildup on the surface. Following a 70 s bombardment and a 1 sec delay, 2.31 MeV gamma rays were counted with a Ge(Li) detector for 70 s, and the cycle was repeated for counting times of about 20 min/run. Two passes over the threshold were made, each started with a clean target spot. After the experiments, the target showed no evidence of a surface deposit. The data are shown in fig. 3. The data were fitted under the assumption that the yield varies as the 3/2 power of the momentum above the threshold.

The beam energy was calibrated by steering the beam to the Q3D line and matching the proton and Tl^+ rigidities using the split Faraday cup in the focal plane, as described previously.

The result obtained for the threshold was E_p = (6352.4 ± 1.9) keV, uncorrected for atomic effects, or E_p = (6352.5 ± 1.9) keV, corrected for atomic effects [7]. A 0.26 eV correction to the Tl^+ kinetic energy was made to account for the Maxwellian velocity distribution, as in the ^{212}Bi calibration, and a 0.3 V contact potential correction was made. The error was calculated from the quadratic sum of the following contributions: (1) statistical error in determining the threshold, 2.5 parts in 10^4; (2) calibration of voltage divider, 1.0 parts in 10^4; (3) calibration of voltmeter, 0.2 parts in 10^4; (4) determination of contact potential, 0.3 parts in 10^4; (5) Q3D aberrations, 1.0 parts in 10^4; (6) accuracy with which the Tl^+ beam is balanced on the split Faraday cup, 0.3 parts in 10^4; and (7) accuracy with which the proton

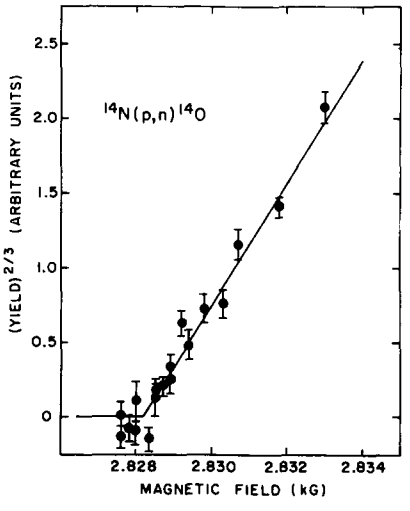

Fig. 3. Yield Y of 2.31-MeV γ-rays from the decay of ^{14}O, produced in the ^{14}N(p, n)^{14}O reaction. The quantity plotted is numerically $|Y|^{2/3}$, but with the sign of Y. The solid line is a fit to the data for extraction of the threshold, in which the yield was assumed to vary as the 3/2 power of the momentum above threshold.

beam is balanced on the split Faraday cup, 0.6 parts in 10^4.

There has not been an absolute measurement of the $^{14}N(p, n)^{14}O$ threshold. The most accurate published value for the $^{14}N(p, n)^{14}O$ threshold is reported by White and Naylor [7]: (6353.6 ± 0.4) keV. We obtain agreement, within errors. Our value is slightly below the value derived from the 1977 mass tables [8]: (6355.0 ± 0.5) keV. There have been two measurements of the mass of ^{14}O since the 1977 mass tables were published, one by Vonach et al. [9], which results in a $^{14}N(p, n)^{14}O$ threshold of (6352.6 ± 0.9) keV, and another by Barker and Nolen [10], giving (6355.3 ± 0.6) keV. Our result is in agreement with the first of these measurements, within errors, but slightly below the second.

6. Summary

We have constructed and tested a system for measuring the beam energy of a light-ion beam with an accuracy of better than 2 parts in 10^4, using a Tl^+ surface ionization source operating at 30 kV. For calibrating the beam energy, the Tl^+ and light-ion beams are collimated and passed through a magnetic spectrometer, where the current on the two halves of a split Faraday cup are balanced, the high voltage applied to the Tl^+ source being measured by a high-accuracy voltage divider and voltmeter.

The accuracy of the system has been checked by measuring the energies of 6.051 and 6.090 MeV alpha particles from a ^{212}Bi source and by measuring the threshold for the $^{14}N(p, n)^{14}O$ reaction. In the first case, agreement was obtained with the values compiled by Rytz, within the error of our measurement, 2 parts in 10^4. In the second case, agreement was obtained with some previously measured values, within our error of 3 parts in 10^4, but our value was slightly lower than others.

Whereas accuracies in measuring beam energies of less than 2 parts in 10^4 have been achieved by absolute magnetic and absolute velocity measurements, we regard the present system to be technically simpler to construct and use. Furthermore, with improvements such as more accurately calibrated electronics and a better-defined path into the spectrometer (reduction of errors arising from spectrometer aberrations), it should be possible to reduce the ion source measurement error substantially.

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