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# Penning trap mass measurement of $^{72}$Br

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The LEBIT Penning trap mass spectrometer was used to perform an improved-precision mass measurement of $^{72}$Br and the low-lying isomeric state, $^{72m}$Br, giving a mass excess of -59 062.2(1.0) keV and -58 960.9(1.2) keV, respectively. These values are consistent with the values from the 2012 atomic mass evaluation [Chin. Phys. C **36**, 1603 (2012)] and the NUBASE2012 evaluation of nuclear properties [Chin. Phys. C **36**, 1157 (2012)]. The uncertainties on the mass of the ground state and isomeric state have been reduced by a factor of seven.

$^{72}$Br is a nuclide that has a well-known, low-lying isomer, and that has been previously measured in a Penning trap mass spectrometer[1] in the study of nucleosynthesis, specifically of rapid proton capture (rp) process reactions [2]. The Low Energy Beam and Ion Trap (LEBIT) facility [3] at the National Superconducting Cyclotron Laboratory at Michigan State University was used to perform an improved precision mass measurement on both the ground and isomeric states of this nuclide. The measurements were performed as part of the commissioning of a new gas cell [4] at the NSCL for stopping fast rare isotope beams and their conversion into very low-energy, so-called "stopped", beams.

The LEBIT facility at the NSCL houses the only Penning trap mass spectrometer currently capable of performing high-precision mass measurements of rare isotopes produced by projectile fragmentation. In this experiment, $^{72}$Br was produced by impinging a 150 MeV/u primary beam of $^{78}$Kr on a beryllium target at the Coupled Cyclotron Facility at the NSCL. The resulting beam then passed through the A1900 fragment separator [5], which contained an aluminum achromatic wedge, to separate the secondary beam, which was composed of 36.9% $^{72}$Br, 34.5 % $^{71}$Se, 14.3 % $^{70}$As, 3.4% $^{73}$Kr, and 2.0% $^{69}$Ge . The beam entered the thermalization area, where the beam passed through an aluminum degrader system and a fused silica wedge before entering the gas cell with an energy of less than 1 MeV/u. A schematic of the gas cell and LEBIT facility can be seen in Fig. 1. The gas cell contains high purity helium gas at a pressure of 70 torr. The thermalized ions are transported by RF and DC fields as well as gas flow. They were then extracted into an RF quadrupole ion-guide, transported through a magnetic dipole mass separator with a resolving power greater than 500 that separated the $^{72}$Br$^{+}$, and finally reached the LEBIT facility. In the LEBIT facility, the $^{72}$Br$^{+}$ ions first enter the cooler-buncher, a two-staged helium-gas-filled RFQ ion trap [6]. In the first stage, moderate pressure helium gas is used to cool the ions in a large diameter RFQ ion guide; in the second, the ions are accumulated, cooled, and released to the LEBIT Penning trap in pulses of approximately 100 ns [7]. To further purify the beam, a fast kicker and dynamic capture process of the Penning trap are used as a time-of-flight mass separator. After the capture of the ion of interest, the time-of-flight cyclotron resonance technique [8] was used to determine the cyclotron frequency $\omega_c = 2\pi\nu_c = q/m \cdot B$. The mass $m$ can then be determined for a known charge $q$ and magnetic field strength $B$.

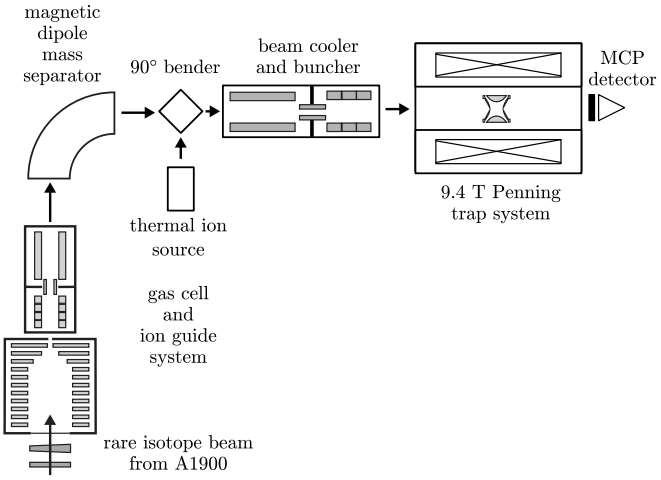


FIG. 1. A schematic diagram showing the major elements of the gas cell and LEBIT facility.

$^{72}$Br has a low-lying, long-lived isomeric state; compared to the ground state half-life of 78.6(2.4) s, the isomer $^{72m}$Br has a half life of 10.3(0.3) s [9]. Both states were produced in approximately equal amounts; this differs from the previous measurement [1], where $^{72m}$Br composed only 8(5)%, likely because of the differences in production methods used. To measure these states, a 750-ms continuous quadrupole excitation was used for simultaneous frequency measurements of both the ground state and isomer. An example of these two time of flight resonances can be seen in Fig. 2. The cyclotron resonances for each of the states were fit to

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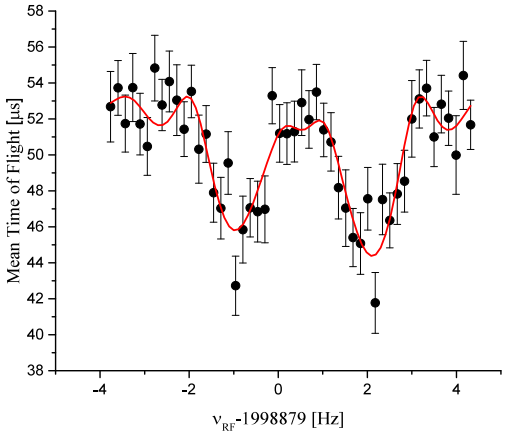


FIG. 2. (color online). A sample time-of-flight cyclotron resonance used for the determination of the frequency ratio of $\nu_c(^{72}\mathrm{Br}^+)/\nu_{\mathrm{ref}}^{\mathrm{int}}$. This example of a bromine resonance shows both the ground state cyclotron resonance (right), and the isomer $^{72m}\mathrm{Br}^+$ (left). The solid red curve represents a weighted fit of two theoretical profiles [10] to account for the production of each state.

the superposition of the theoretical excitation curves [10] for each isomer, weighted to account for the different production of each state; this gives the cyclotron frequencies for ground state $^{72}\mathrm{Br}^+$ and the first excited isomer, $^{72m}\mathrm{Br}^+$. Between measurements of $^{72}\mathrm{Br}^+$, the strength of the magnetic field was calibrated with measurements of a reference ion, $^{85}\mathrm{Rb}^+$. The $^{85}\mathrm{Rb}^+$ was produced on the heated filament of the thermal ion source located before the cooler-buncher; after its production, it was measured in the same way as the $^{72}\mathrm{Br}^+$. The experimental result is the ratio of these cyclotron frequencies, $R = \nu_c(^{72}\mathrm{Br}^+)/\nu_{\mathrm{ref}}^{\mathrm{int}} = 1.180371263(18)$ and $R = \nu_c(^{72m}\mathrm{Br}^+)/\nu_{\mathrm{ref}}^{\mathrm{int}} = 1.180369478(20)$, where the statistical uncertainty is given and $\nu_{\mathrm{ref}}^{\mathrm{int}}$ is linearly interpolated from the reference measurements bracketing the measurement of the cyclotron frequencies of $^{72}\mathrm{Br}$ and $^{72m}\mathrm{Br}$. Mass-dependent shifts in $R$, primarily from trap field imperfections, have been determined from a recent series of measurements of the well-known masses of $^{39}\mathrm{K}^+$, $^{85}\mathrm{Rb}^+$, $^{133}\mathrm{Cs}^+$, and several carbon clusters to be $\Delta R = 2 \times 10^{-10}$/u, and the appropriate correction for the mass difference between $^{72}\mathrm{Br}^+$ and $^{85}\mathrm{Rb}^+$ (13 u) has been applied, so $R' = R(1+\Delta R \cdot 13)$; this amount was also included in the calculation of the uncertainty. The mass excess of each of these states is then calculated using the well-known mass of $^{85}\mathrm{Rb}$ and of the electron ($m_e$), since the binding energy of the electron is negligible compared to the uncertainty.

$$M(^{72}\mathrm{Br}) = (M(^{85}\mathrm{Rb}) - m_e)\left(\frac{1}{R'(^{72}\mathrm{Br}^+)}\right) + m_e \quad (1)$$

Five measurements of the $^{72}\mathrm{Br}^+$ and $^{72m}\mathrm{Br}^+$ cyclotron frequencies were taken. Nonlinear magnetic field drift is not accounted for in this data analysis, because previous work has shown that its effect on the ratio $R$ should be less than $1 \times 10^{-9}$ in cases such as this one, where each measurement was completed in less than an hour [11].

The presence of isobaric contaminants in the trap during a measurement could lead to a systematic frequency shift [12]; this effect was minimized by ensuring no contaminants were present at a level exceeding a few percent and by limiting the total number of ions in the trap. The Birge ratios [13] for the measurements were 0.70(21) and 0.92(21) for the ground state and first excited isomer, respectively; as each is less than one, this indicates that statistical uncertainties have not been underestimated.

TABLE I. A comparison of measured mass excess of $^{72}\mathrm{Br}$ and $^{72m}\mathrm{Br}$ with mass excess evaluation AME12 and NUBASE2012.

| Measurement | Mass Excess (KeV) | Ref. |
|---|---|---|
| $^{72}\mathrm{Br}$ | -59 067(7) | [1, 14] |
| $^{72}\mathrm{Br}$ | -59 062.2(1.0) | This work |
| $^{72m}\mathrm{Br}$ | -58 966(7) | [15] |
| $^{72m}\mathrm{Br}$ | -58 960.9(1.2) | This work |

TABLE II. A comparison of $^{72}\mathrm{Br}$ isomeric state energy levels.

| Isomeric state | ΔE (KeV) | Ref. |
|---|---|---|
| $^{72m}\mathrm{Br}$ | 100.76(15) | [9, 15] |
| $^{72m}\mathrm{Br}$ | 101.3(1.5) | This work |

The measured mass excesses and uncertainties of $^{72}\mathrm{Br}$ and $^{72m}\mathrm{Br}$ are shown in Table I, along with the same mass excesses from AME2012, which was determined from the previous Penning trap measurement, and NUBASE2012, respectively [1, 14, 15]. Table II shows the calculated excitation energy, compared with the value in NUBASE2012 for the same state [15]. The measured mass values from this work are consistent with the previous values and are a factor of seven more accurate. The calculated excitation energy is also consistent with the more-accurate NUBASE2012 value.

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