MASS MEASUREMENTS OF PROTON-RICH NUCLEI WITH JYFLTRAP*

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The Penning trap setup JYFLTRAP, connected to the IGISOL facility, has been extensively used for atomic mass measurements of exotic nuclei. On the proton rich side of the chart of nuclei mass measurements have mostly contributed to fundamental physics and nuclear astrophysics studies with about 100 atomic masses measured.

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1. Introduction

Accurate knowledge of atomic masses and binding energies of exotic nuclei is of great importance for various physics studies [1]. It is often more convenient to know mass differences which allows determination of decay energies or Q values. Atomic mass measurements with JYFLTRAP have so far provided valuable data for fundamental physics studies such as verification of the Standard Model of the weak interaction by contributing via determination of the V_{ud} matrix element of the Cabibbo–Kobayashi–Maskawa quark mixing matrix [2]. Also, JYFLTRAP has contributed to testing of the isobaric mass multiplet equation (IMME) by measuring the mass of ^{23}Al [3] and ^{31}S [4]. Furthermore, systematic mass measurements of astrophysically interesting nuclei have led to quenching of the astrophysical SnSbTe cycle [5].

In this contribution a short overview of mass measurements in these studies are given.

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2. Experimental setup

The JYFLTRAP setup [6,7] consists of two geometrically identical Penning traps. The trap system is not used solely for mass measurements of short-living nuclei but also as a high-resolution ion beam purifier, reaching a mass resolving power $R = M/\Delta M_{\mathrm{FWHM}}$ of up to 10^6 [8].

The short-living ions of interest are produced using the IGISOL method [9, 10]. In the case of proton rich nuclei, the ions are produced with fusion evaporation reactions. Those close to stability are usually produced with (p,xn) or $(^3\mathrm{He},xn)$ reactions using the light-ion ion guide. There, the production target is placed in a small $\sim 2\ \mathrm{cm}^3$ gas volume where recoiling reaction products are stopped.

Another production mechanism is a heavy-ion induced fusion evaporation reaction. Here, the target placement is different as the target is located in front of the stopping gas volume. The primary beam is stopped in a small carbon block located before the ion guide entrance window. The recoiling reaction products exit the target in a cone towards the gas chamber through a thin window of either nickel or havar. The ions passing through the window are finally stopped in a flowing helium gas flow and are extracted through a narrow nozzle and accelerated to 30 keV. A schematic view of the IGISOL and JYFLTRAP setups are shown in Fig. 1.

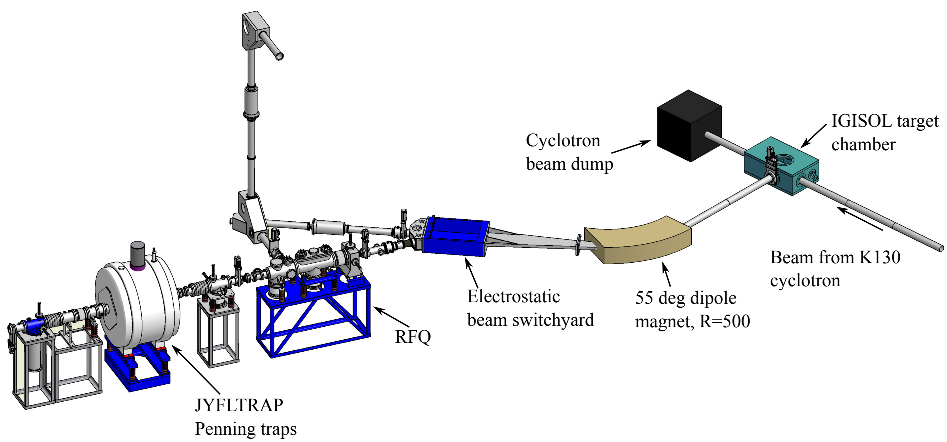

Fig. 1. The IGISOL and JYFLTRAP setups. The primary ion beam from JYFL K130 is incident from right. The recoiling reaction products are stopped in gas and extracted towards the 55° dipole magnet with 30 keV energy. After mass separation, the selected ions are injected via the RFQ cooler-buncher [11] to the JYFLTRAP Penning trap setup for either high-resolution beam purification or atomic mass measurements.

2.1. Atomic mass measurement with JYFLTRAP

The JYFLTRAP setup has two Penning traps located in two homogenous regions of the same superconducting 7 T solenoid. The first trap in line, the purification trap [6], is dedicated for isobaric purification of the beam with the sideband cooling technique [12] reaching mass resolving power $R = M/\Delta M_{\rm FWHM} = 10^5$. This is often enough to separate even nuclear isomeric states such as $^{26}{\rm Al}^{\rm m}$ [13].

The other trap, the precision trap is used for atomic mass measurements or for high-resolution beam purification [14] reaching up to $R = 10^6$ [8]. Recently Ramsey's method of time-separated oscillatory fields has been used in mass measurements to boost the obtained precision [15, 16].

In a Penning trap the ion mass m is determined by measuring its cyclotron frequency

$$\nu_{\rm c} = \frac{1}{2\pi}\frac{q}{m}B\,, \tag{1}$$

where q is the charge of the ion and B the magnetic field which is calibrated using a well known reference mass. At JYFLTRAP (similar to any online Penning trap facility) the cyclotron frequency is measured employing the time-of-flight ion-cyclotron resonance (TOF-ICR) technique [17, 18]. An example TOF-ICR curve is shown in Fig. 2.

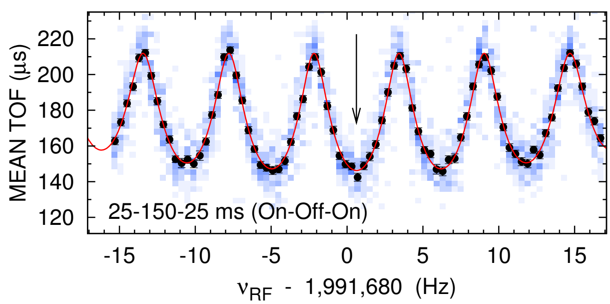

Fig. 2. (Color online) An example TOF-ICR curve of ^{54}Co ions ($T_{1/2} \approx 200$ ms) measured with Ramsey's method of time-separated oscillatory fields. The (blue) pixels indicate detected ions — the denser the pixel the more ions it represents. The points with error bars are average time-of-flights for each frequency and the solid (red) curve is a fit to this data. The arrow indicates the fit center $\nu_{\rm c}$.

3. Mass measurement results

By the end of June 2010, atomic masses of about 100 neutron deficient nuclei have been measured with JYFLTRAP as shown in the chart in Fig. 3. These contribute to various fields in physics, summarized in the sections below.

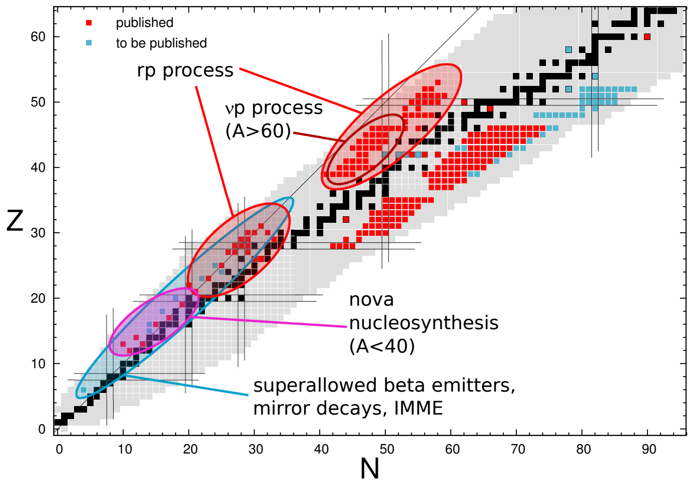

Fig. 3. Chart of the nuclei whose masses have been measured at JYFLTRAP. Areas with different physics motivations have been indicated.

3.1. $Q_{\rm EC}$ values of superallowed β emitters

Superallowed beta decays occur between nuclear 0^+ isobaric analog states. These are pure Fermi decays, rendering the decay matrix element to be very simple. According to the conserved vector current (CVC) hypothesis, the decay ft values should be the same for any superallowed decay and is given by

$$ft = \frac{K}{G_{\rm V}^2|M_{\rm F}|^2} = {\rm const.}\,, \tag{2}$$

where K is constant, $G_{\rm V}$ the vector coupling constant for semileptonic weak interactions and $M_{\rm F}$ the Fermi matrix element ($M_{\rm F}=\sqrt{2}$ for $T=1$ decays). However, additional theoretical corrections are needed since, for instance, isospin is not an exact symmetry and thus needs to be corrected. The corrected ft value, denoted $\mathcal{F}t$ is given as

$$\mathcal{F}t = ft\ \left(1+\delta_{\rm R}\right)\left(1-\delta_{\rm C}\right) = \frac{K}{2G_{\rm V}^2\left(1+\Delta_{\rm R}^{\rm V}\right)} = {\rm const.}\,, \tag{3}$$

where $\delta_{\rm C}$ is the isospin-symmetry-breaking correction, $\delta_{\rm R}$ the transition-dependent radiative correction and $\Delta_{\rm R}^{\rm V}$ the transition-independent radiative correction.

To deduce the ft value, three experimental quantities are needed: $t_{1/2}$, BR and $Q_{\rm EC}$. t represents the partial half-life and depends on the half-life t of the parent state and also on the branching ratio BR to the final 0^+ state. The statistical rate function f depends strongly (in its fifth power) on the $Q_{\rm EC}$ value.

The most recent survey [2] lists the relevant experimental data and theoretical corrections. Currently, there are 13 superallowed transitions that significantly contribute to the world average $\mathcal{F}t$ value. Other cases are usually limited by the poor knowledge of the branching ratio or in some cases also by the half-life.

JYFLTRAP is ideally suited for $Q_{\rm EC}$ value measurements because both the decay parent and daughter nuclei are simultaneously available in the ion beam produced by the IGISOL method. Since the $Q_{\rm EC}$ value is just the mass difference of the parent and daughter states, it is sufficient to measure the cyclotron frequencies of these two states with a Penning trap if the daughter (or parent) state mass is known with moderate precision. The $Q_{\rm EC}$ value expressed with cyclotron frequencies is written:

$$Q_{\rm EC} = M_m - M_d = \left(\frac{\nu_d}{\nu_m} - 1\right)(M_d - m_e) - \Delta B_{m,d}\,, \tag{4}$$

where M_m and M_d are the masses of the parent and daughter atoms, respectively; ν_d/ν_m is their cyclotron frequency ratio with singly-charged ions, m_e is the electron mass; and $\Delta B_{m,d}$ arises from the electron binding-energy differences between the parent and daughter atoms. Since the term $(\frac{\nu_d}{\nu_m} - 1) < 10^{-3}$, the precision of the daughter atomic mass has very little contribution to the obtained $Q_{\rm EC}$ value. Additionally, since both are mass doublets having the same mass-over-charge ratio, mass-dependent systematic errors cancel out. Overall, a $Q_{\rm EC}$ value precision $\Delta Q/M$ of about 2×10^{-9} has been reached.

Until now (December 2010), the $Q_{\rm EC}$ values of ^{10}C, ^{26}Al$^{\rm m}$, ^{26}Si, ^{30}S, ^{34}Cl, ^{34}Ar, ^{38}K$^{\rm m}$, ^{38}Ca, ^{42}Sc, ^{42}Ti, ^{46}V, ^{50}Mn, ^{54}Co and ^{62}Ga have been determined at JYFLTRAP (see also Fig. 3). Most of the cases had their $Q_{\rm EC}$ values already precisely determined (see compilation by Hardy and Towner [2]) prior to Penning trap measurements. The measurements at JYFLTRAP have not merely improved the $Q_{\rm EC}$ value precision but have also found significant deviations to old data in the cases of ^{46}V, ^{50}Mn and ^{54}Co [13, 19].

In addition to the superallowed β decays, the mass differences of $T_z = \pm\frac{1}{2}$ mirror nuclei provide data for fundamental studies which in the future can test the validity of the CKM matrix [20] provided that the decay branching ratio, half-life and the ratio of the Fermi and Gamow–Teller branches are known to similar precision. At JYFLTRAP some mirror Q values have already been measured [21].

3.2. Masses for testing IMME

It is shown with the isobaric mass multiplet equation (IMME) that the masses of the $2T+1$ nuclear states belonging to a given isospin multiplet are related

$$M(A,T,T_z) = a(A,T) + b(A,T) \times T_z + c(A,T) \times T_z^2 \,, \qquad (5)$$

where T_z is the z projection of the isospin T [22]. The assumption here is that any charge-dependent effects and Coulomb force between the nucleons can be treated by the first-order perturbation theory. Higher order terms may arise, for instance, from isospin mixing between the isobaric analog and neighbouring states. The most significant deviations from Eq. (5) have been found in the $A=8$, $T=2$ quintet and the $A=9$, $T=3/2$ quartet [23].

Since the compilation in Ref. [23], the *sd*-shell nuclei in particular have been studied further to obtain more accurate data. To get the energies of the isobaric analog states of interest, not only the ground state masses are required with high precision but also the excitation energies of the excited states. JYFLTRAP has contributed to these studies by measuring the ground state mass of ^{23}Al, which is the $T_z = -3/2$ nucleus of the $(A,T) = (23,3/2)$ quintet. The new measurement provides about two orders of magnitude improvement over the existing mass value [3]. Using the new data from JYFLTRAP, the fit of the coefficients in Eq. (5) to the data is excellent.

The other case in which JYFLTRAP has contributed is the $(A,T) = (32,2)$ quintet. Here, a new mass value for ^{31}S was obtained which improved the ground state mass of the $T_z = -1$ nucleus ^{32}Cl. The proton separation energy from Ref. [24] was used to link the ^{31}S and ^{32}Cl masses. A slight deviation of $1.4\,\sigma$ to the previously adopted value was found. With this result the earlier observed significant breaking down of the quadratic IMME form persists [4].

3.3. Masses of astrophysical interest

Atomic masses are one of the key input parameters in the modeling of astrophysical processes such as nucleosynthesis in novae or the rapid proton capture (rp) process taking place in hydrogen-rich environments. The rp process [25] is a series of rapid proton captures and β^+ decays close to the proton dripline. A particularly interesting issue is the existence of an endpoint to the rp process.

The atomic masses enter the picture by the fact that the astrophysical reaction rates have an exponential dependence on the proton separation energies. Before the recent JYFLTRAP measurements [5], reaction network calculations indicated that the rp process could not proceed past tellurium isotopes and is limited by a SnSbTe cycle [26].

Even more recently, masses near $N = Z = 28$ were measured [21]. Classically, the doubly magic nucleus ^{56}Ni was considered to be the endpoint of the rp process [27]. The new mass values considerably reduce the uncertainties in the astrophysical reaction rate calculations. In some cases larger than $1\,\sigma$ deviations to AME2003 mass values [28] were observed.

4. Summary

More than 100 atomic masses of neutron deficient nuclei have been determined with the JYFLTRAP mass spectrometer. Since the IGISOL method allows the production of both parent and daughter ions simultaneously, the decay Q values can be determined with very high precision. This is extremely beneficial for studies such as IMME and CVC tests, where precision is of greatest importance. Furthermore, systematic measurements of mass values near and at the astrophysical process paths provide high-precision decay energies allowing for more accurate astrophysical reaction network calculations.

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