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Measurement of the ^{52}Fe mass via the precise proton-decay energy of ^{53}Co^m

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Abstract. The proton decay of ^{53}Co^m(3174.1 keV, $19/2^-$) was investigated via the fragmentation of a ^{58}Ni primary beam. The proton-decay energy was determined with an improved precision to be 1558(8) keV. With this new result and the mass of ^{53}Co^m, the ^{52}Fe mass excess was derived to be −48330(8) keV, which is in good agreement with the AME12 value. A new recommended value of −48331.6(49) keV is given.

Nuclear mass continues to be of great importance for various aspects of nuclear physics, for instance, it is the basic building blocks of nuclear structure and nuclear astrophysics. In the study of nuclear structure, the mass of nucleus is an important parameter to validate the model theories and provide a limitation on parameters of theories. In nuclear astrophysics, masses of many nuclei far from line of stability play a vital role in the calculation of stellar nucleosynthesis. Since there is difficulties in measuring the key reaction of nuclear synthesis directly, the precise nuclei mass data can help us judge the importance of each possible nuclear synthesis path. ^{52}Fe is one of the nuclei at the $N = Z$ line of which the precise masses can offer a sensitive test for the exchange symmetry between neutrons and protons in fp-shell [1, 2]. ^{52}Fe is also very important in the study of astrophysical $rp-$process [3] as it is the endpoint of the rp-process at a temperature of $T = 4 \times 10^8$ K and a density of $\rho = 10^4$ g/cm^3 [4]. Furthermore, ^{52}Fe is indicated as a waiting point in stable nuclear burning on an accreting neutron star [5]. Its proton capture rate, which has a direct correlation with its mass, is one of the most important nuclear physics input parameters for the calculations of steady state burning on an accreting neutron star. Therefore, the mass of ^{52}Fe is an important input parameter in both nuclear structure and nuclear astrophysics.

Mass measurements are pursued worldwide. There are a variety of ways that can determine the nuclear mass. The methods of measurement can be classified into two groups, direct and indirect method. The indirect measurement is an important way to determine the masses of nuclei, especially for the nuclei where the direct measurement is very difficult. There are two main indirect methods, radioactive decay Q-value and nuclear reaction Q-value [6]. The mass excess of ^{52}Fe was first determined to be −48335(10) keV by measuring the $Q_{\beta+}$ of ^{52}Fe(β^+)^{52}Mn in 1956 [7] and then derived to be −48331(8) keV with the reaction Q-value measurement of ^{54}Fe$(p,t)^{52}$Fe in 1978 [8].

The renowned proton-unstable spin-gap isomer ^{53}Co^m(19/2$^-$) was first observed by Jackson et al. in 1970 [9]. Recently, the mass of ^{53}Co^m was precisely determined to be −39482.9(16) keV at JYFLTRAP [10]. Therefore, the mass of ^{52}Fe which is the daughter nucleus of the proton decay of ^{53}Co^m can be determined by the proton-decay energy of ^{53}Co^m. The decay energy was first determined to be 1560(40) keV by Jackson et al. [9] in 1970. In the same year, Cerny et al. [11] confirmed the proton radioacitvity of ^{53}Co^m and derived the decay energy to be 1570(30) keV. In 1972, Cerny et al. [12] published their further results and modified the decay energy to 1590(30) keV. In 1976, Vieira et al. [13] determined the decay energy to be 1590(30) keV. However, due to the large uncertainties of the results in those works, they make no improvement to the mass precision of ^{52}Fe. Thus, a further precise measurement of ^{53}Co^m proton-decay energy is important.

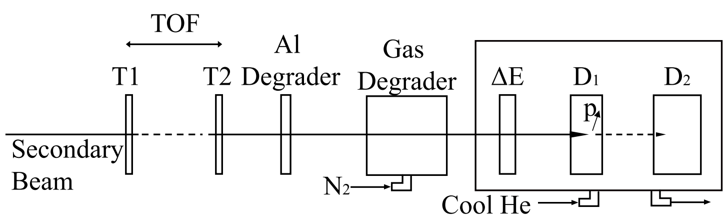

Figure 1. Schematic layout of the detection setup.

The experiment was performed at the RIBLL (Radioactive Ions Beam Line in Lanzhou) facility [14] of HIRFL (Heavy Ion Research Facility in Lanzhou). Projectile fragmentation (PF) method was used to produce a series of radioactive heavy ions. A ^{58}Ni^{25+} primary beam with an intensity of 30 enA and an energy of 68.3 MeV/u is fragmented on a natural beryllium target with a thickness of 503 μm. The main focus of the system was ^{53}Ni and several other nuclei including ^{53,53m}Co were also produced simultaneously. A schematic setup of detectors is shown in Fig. 1. The stopping depths of the ions in D_1 were adjusted by the two degraders mentioned ahead. The target chamber was cooled down to −20 ℃ with cool helium gas in order to suppress the dark current of the DSSSDs and improve the energy resolution.

The proton energy in D_1 was calibrated by measuring the β-delayed protons of ^{41}Ti. For β-delayed proton decay, since the ion is stopped in the detector, the energy loss of β particle as well as proton is summed up. However, due to the small rate of energy loss, β particle escapes from the detector and leaves an energy of tens to hundreds keV in the detector depending on the implanted depth and the angle of the β particle with respect to the detector plane. A tail on the high-energy side of the proton peak is yielded by the β-particle energy loss and the proton peak shifts tens keV towards the high-energy side, which is called "β pile-up", as is shown in Fig. 2. In order to reduce the impact of β pile-up, we implanted ^{41}Ti ions at the back edge of D_1. With the β coincidence with D_2, the transport length of β particle was significantly reduced and the energy loss of β particle in D_1 was suppressed.

A linear regression routine with errors in both variables was performed. Peaks 1, 2, 5 and 8 in Fig. 2 are used in the linear regression with errors in both variables to minimize reduced χ^2. The comparison of ^{41}Ti proton energy between Ref. [15], which is based on the experimental data of Ref.

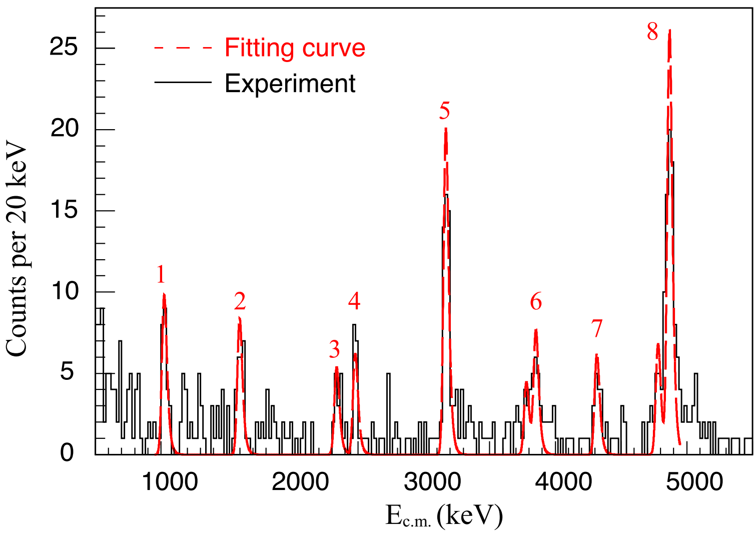

Figure 2. (color online) ^{41}Ti β-delayed proton spectrum and the fitting result.

[16] and other works, and this work is shown in Table 1. According to the asymptotic standard error of the fitting parameters, the calibration error of D_1 is derived to be 7.4 keV.

Table 1. The peaks of β-delayed proton groups of ^{41}Ti.

Peak no.	E_p(keV)	
	This work	Nuclear Data Sheets [15]
1	986(6)	986(2)
2	1546(8)	1542(2)
3	2265(10)	2271(3)
4	2403(7)	2414(3)
5	3076(8)	3083(4)
6	3744(12)	3749(5)
7	4196(12)	4187(4)
8	4735(10)	4735(3)

A gate of implanted ^{53}Co was applied to the ΔE-TOF two-dimensional particle identification spectrum according to the simulation with LISE++ and the calibration with the primary beam, as shown in Fig. 3. Because of the energy pile-up of ΔE detector, ^{53}Co was submerged in the pile-up of ^{51}Fe ions. However, since ^{51}Fe doesn't have proton radioactivity, the β decay of ^{51}Fe only generated a β background but wouldn't hinder the identification of the protons emitted by ^{53}Co^m. We performed a validation of the ΔE-TOF identification by checking the half-life of nuclei nearby such as ^{51}Fe and ^{52}Co. The half-lives of ^{51}Fe and ^{52}Co were determined to be 308(5) ms and 112(4) ms, which are in good agreement with the recommended values of 305(5) ms [17] and 115(23) ms [18], respectively.

The energy spectrum of ^{53}Co^m proton decay obtained in this work is shown in Fig. 4. The initial spectrum is shown in Fig. 4(a). Figure 4(b) shows the random coincidence background taken from

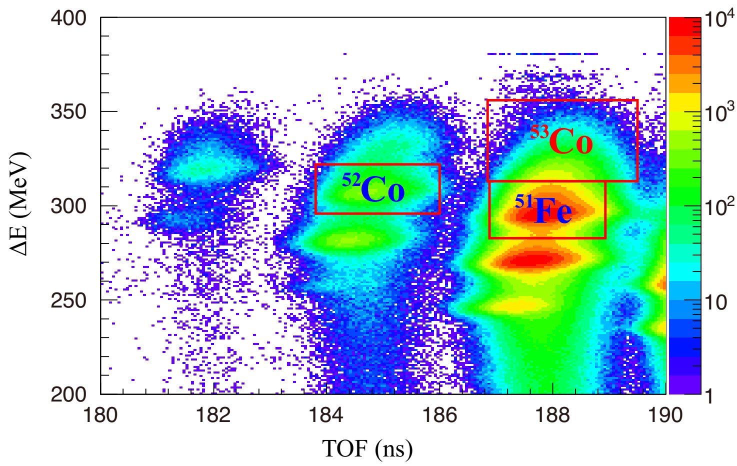

Figure 3. (color online) Two-dimensional identification plot of ΔE and TOF. The gates of ^{52,53}Co and ^{51}Fe ions are indicated.

the time-irrelevant area which mainly came from β particles emitted by other ions. Figure 4(c) shows the spectrum where the background has been subtracted. After subtracting the background, a evident peak at the desirable energy region is observed, which is assigned to the proton decay of ^{53}Co^m. Because the decay mode of ^{53}Co^m is proton decay without any electron emitted, the shift of β pile-up mentioned above in Fig. 2 should be subtracted. As was mentioned in Refs. [19–21], the stopping power of electrons in the energy range of 2 to 50 MeV can be determined with an accuracy of less than 10%. We estimated the shift of proton peak arising from β pile-up near 1500 keV to be 13(2) keV via the GEANT4 simulation. This shift has been added to the energy scale of Fig. 4.

The centroid energy of the peak in Fig. 4 was fitted to be 1558 keV, with an energy resolution of 30 keV(FWHM) and a peak energy error of 1.2 keV. In order to further confirm the origin of the 1558 keV peak, we analyzed the decay-time spectrum gated by it and obtained a half-life of 237(48) ms which is in agreement with the recommended half-life of ^{53}Co^m, 247(12) ms [22]. Therefore, the proton-decay energy of ^{53}Co^m was determined to be 1558(8) keV. The uncertainty of 8 keV came from the energy calibration of D_1 (7.4 keV), the shift of β pile-up (2 keV) and the peak fit (1.2 keV).

The comparison of the proton-decay energy of ^{53}Co^m in the previous and present works is shown in Fig. 5. It is seen that our result is in good agreement with the previous data and the precision is significantly improved.

Combined with our new result about ^{53}Co^m proton-decay energy and the mass of ^{53}Co^m taken from Ref. [10], the mass excess of ^{52}Fe was calculated as ME(^{52}Fe) = ME(^{53}Co^m) – ME(p) – $E_{\mathrm{c.m.}}$ = −48330(8) keV in which ME is the mass excess of the nucleus and $E_{\mathrm{c.m.}}$ is the proton-decay energy. The result is in good agreement with the AME12 value −48332(7) keV [23]. With the previous results and the value obtained in this work, we calcuated the maximum likelihood estimator and gave a new recommended value of the ^{52}Fe mass excess ME(^{52}Fe) = −48331.6(49) keV.

In summary, we have measured the proton decay of ^{53}Co^m at Lanzhou radioactive beam line RIBLL. The proton-decay energy of ^{53}Co^m was derived with a much improved precision. The ^{52}Fe

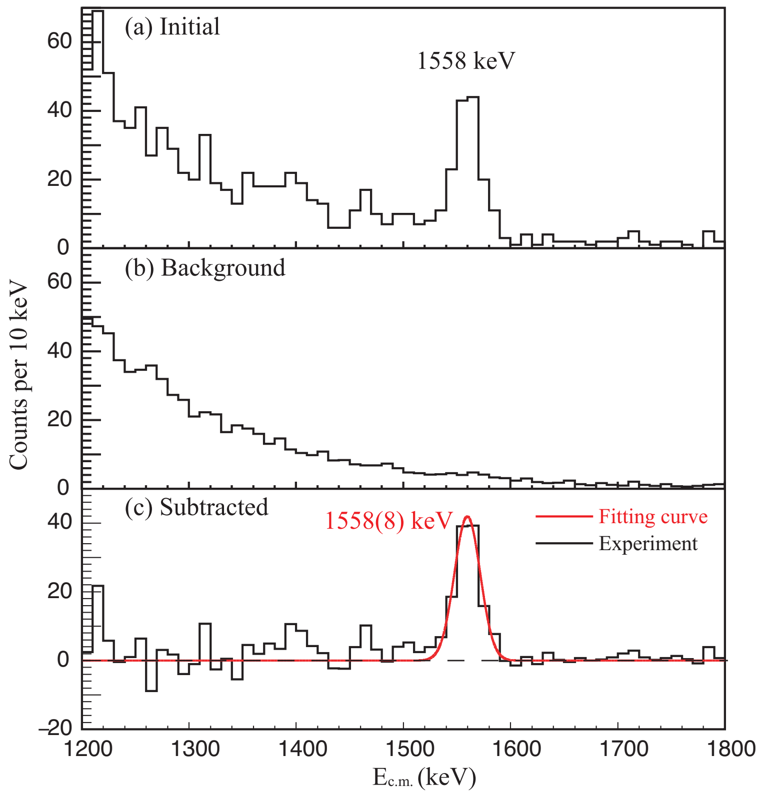

Figure 4. (color online) Energy of the $^{53}Co^m$ proton decay. (a) The initial spectrum of $^{53}Co^m$ proton decay. (b) The random coincidence background taken from the time-irrelevant area. (c) The spectrum of $^{53}Co^m$ proton decay where the background shown in (b) has been subtracted.

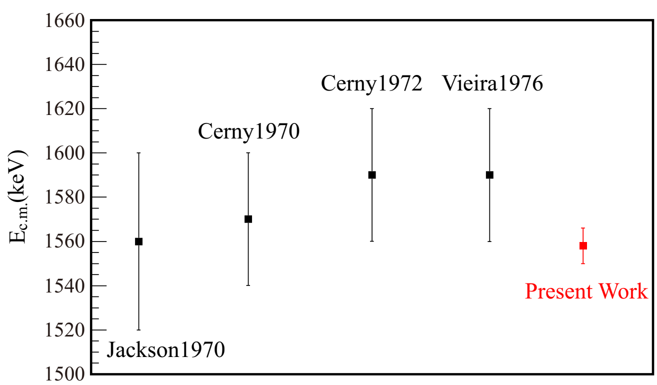

Figure 5. The comparison of the proton-decay energy of $^{53}Co^m$ in the previous works [9, 10, 12, 13] and present work.

mass excess was obtained using the proton-decay Q-value method, which provides a cross-checking for the previous results. And a new recommended value of the ^{52}Fe mass excess was given.

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