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First Experimental Determination of Half-Life for New Nuclide ^{65}Se

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By using experimental data obtained from the measurement of β-delayed proton decay of ^{65}Se produced in the ^{40}Ca(^{28}Si,3n) reaction, the absolute detection efficiency of particle telescope for rotating radioactive source was fitted and calculated. The half-life of ^{65}Se was thus accurately determined to be $9.6^{+5.3}_{-4.1}$ ms and its β-delayed proton energy of ^{65}Se was 3.70±0.08MeV. The partial decay scheme of ^{65}Se β-delayed proton decay was revised.

Key words: new nuclide, half-life, detection efficiency, partial decay scheme.

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1. INTRODUCTION

It is a basic and important process to measure the half-life of the new nuclei far from β-stability. From this work, the β-decay probability, the decay mode, and the branching ratio of β-delayed particle emission of the nuclide can be determined, which is helpful in judging the nuclear decay mechanism.

Generally, the half-life measurement in the experiment is processed as follows: first, the time-scaled sequential spectra of nuclear decay were measured and then the half-life of the nuclide was obtained with the decay relationship. This is a presentable and generally an effective method. Sometimes, however, it is difficult to measure the half-life and to assign the nuclei near the proton drip line because of its short lifetime (several ten milliseconds or even less than a millisecond), and a low cross-section (order of micro barn). In order to search for a new nuclei far from the β stability valley with short lifetimes and low cross-sections, a technique called as Helium-jet has been developed in

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experiment. The detail of its work principle can be found in Ref. 1. The products in target chamber were rapidly transported to the detection chamber where the products were jetted onto a rotating collection disk to form a radioactive source. With the disk rotating, the radioactive source was detected by particle telescope (consisting of ΔE, E, and E_{reject} Si(Au) surface barrier semiconductor detectors). By modulating the disk speed, the detector will be sensitive only to the activity with a specific lifetime and the one with a different lifetime will be depressed. By observing and comparing the activity of a unknown nuclide relative to the activity of a known nuclide as the function of rotation speed, the half-life of the unknown nuclide can be relatively determined.

We therefore developed a new method with which the half-life of the nuclide measured in a continuous procedure can be effectively determined, i.e., taking the assumed half-life of the nuclide as a fitting parameter and combining it with experimental data to fit and calculate the absolute detection efficiency of particle telescope for rotating the radioactive source, the half-life of an unknown nuclide can be determined directly and precisely.

We know the macro production cross section can be expressed as:

$$\sigma = \frac{R}{P \cdot \eta \cdot \Phi \cdot N \cdot B}, \tag{1}$$

where R is the integral counts in a specified peak in spectra, P the transportation coefficient of He-jet system, η the absolute detection efficiency of detectors (or particle telescope), Φ the integral beam intensity, N the target thickness, and B the particle branching ratio in precursor's β-delayed particle decay. For the same nuclide produced in the same reaction, transported with the same system but collected with different disk speeds, we can get following formula:

$$\frac{\eta_1 (g, t_{w1}, t_{1/2})}{\eta_2 (g, t_{w2}, t_{1/2})} = \frac{R_1 \times \Phi_2}{R_2 \times \Phi_1}, \tag{2}$$

where η is the absolute detection efficiency of particle telescope, which is the function of g (geometric factors of detectors), t_w (disk rotation speed), and $t_{1/2}$ (the half-life of the nuclide). In calculation of η, all possible factors have been considered, e.g., the product's decay in the transportation process from the target to the collection chamber, the effects of source's half-life, and the disk speed on the detection efficiency during which the source was moving with the disk and was being detected, and the radioactive distribution of the area source; the distance between the point of the source injected and the central axial line of the telescope, the limits of multi-collimators, and the effect of the deviation of the source's moving track from standard annulus on detection efficiency. The detection efficiency obtained from this method is the absolute detection efficiency. Reference 2 has detailed the calculation method. From formula (2), it can also be found that the error of the nuclear half-life obtained with this method will be very small because of using dividing efficiencies greatly diminishes the systematic errors in half-life determination.

In 1989, one of our authors has analyzed in detail the experimental results of ^{28}Si+^{40}Ca reaction performed at LBL. The new nuclide ^{65}Se was identified with β-delayed proton energy of 3.75 ± 0.05 MeV and half-life of $10.8^{+4.1}_{-3.7}$ ms. These results have been published on this journal [3], and adopted by the Chart of the Nuclides-Strasbourg 1992. The criteria used at that time were:

$$\frac{\sigma_{\text{Alice}}(^{61}\text{Ge})}{\sigma_{\text{exp}}(^{61}\text{Ge})} = \frac{\sigma_{\text{Alice}}(^{65}\text{Se})}{\sigma_{\text{exp}}(^{65}\text{Se})}, \tag{3}$$

$$\frac{\sigma^{113\,\text{MeV}}_{\text{Alice}}(^{65}\text{Se})}{\sigma^{128\,\text{MeV}}_{\text{Alice}}(^{65}\text{Se})} = \frac{\sigma^{113\,\text{MeV}}_{\text{exp}}(^{65}\text{Se})}{\sigma^{128\,\text{MeV}}_{\text{exp}}(^{65}\text{Se})}, \tag{4}$$

i.e., the ratio of Alice cross-section to the experimental one for ^{61}Ge is equal to that for ^{65}Se; the ratio of Alice cross section at 113 MeV of projectile (^{28}Si) energy to the one at 128 MeV should be equal to the ratio of the measurement for the same nuclei ^{65}Se. In other words, the ratios of the Alice cross section to the experimental one for different nuclides should be equal, and the ratios of Alice to the experimental cross section at different projectile energies for same nuclide should also be equal. It has been proved by many experimental facts that there is an obvious difference between Alice cross-section and the experimental cross section for different nuclides, but the difference between the cross section ratios is still very small, especially between the ratios of the neighboring nuclides. The above criteria are therefore basically dependable. In 1993, the experiment of $^{28}Si+^{40}Ca$ was performed again at LBL. They claimed that they observed β-delayed proton decay of ^{65}Se. But the half-life of ^{65}Se was not determined in an experiment [4]. In this paper, we will give the half-life of ^{65}Se obtained with the above-mentioned new method, i.e., by using experimental data to fit calculations of absolute detection efficiency for a particle telescope without any theoretical hypotheses.

2. EXPERIMENTAL RESULTS AND ANALYSES

The proton decay spectra of precursors produced in $^{28}Si+^{40}Ca$ reaction at beam (^{28}Si) energies of 113 MeV and 128 MeV and measured with a particle telescope are shown in Figs. 1 and 2, respectively, in which the spectra at beam energy of 128 MeV were obtained at two disk speeds (1.0 rpm and 6.7 rpm, i.e., 1.0 revolution per minute and 6.7 revolutions per minute). In the spectra the peak at 1.57 MeV comes from the direct proton decay of low level isomer ^{53m}Co [5], and other peaks come from the β-delayed proton decay of precursors ^{65}Ge, ^{61}Ge, and ^{41}Ti, respectively [6]. ^{41}Ti was discovered experimentally in 1966 and is a well-known β-delayed proton decay precursor. The energies and relative intensities of proton peaks of ^{41}Ti are shown in Table 1.

There are two important discoveries after analyzing these spectra in detail: First, the intensity ratio of 3.75 MeV peak to 4.73 MeV peak differs from the existing data. The intensity of 3.75 MeV peak is clearly enhanced in which there must be a new proton activity. According to theoretical

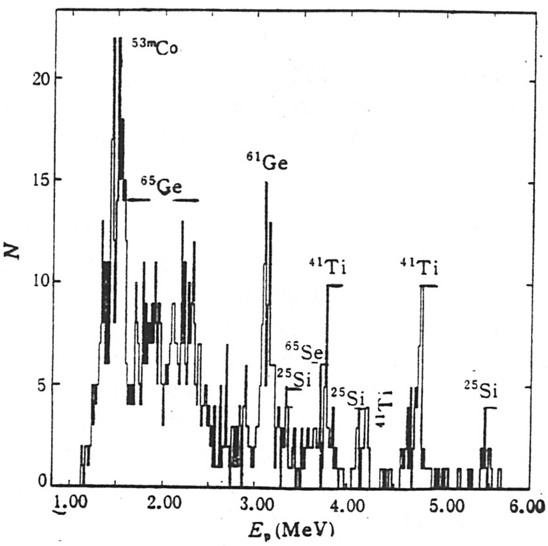

Fig. 1

Delayed proton spectrum obtained in ^{28}Si(113 MeV)+Ca reaction. Integral beam is 30 mC (millicoulomb), rotation speed of collection disk is 1.0 rpm (1.0 revolution per minute).

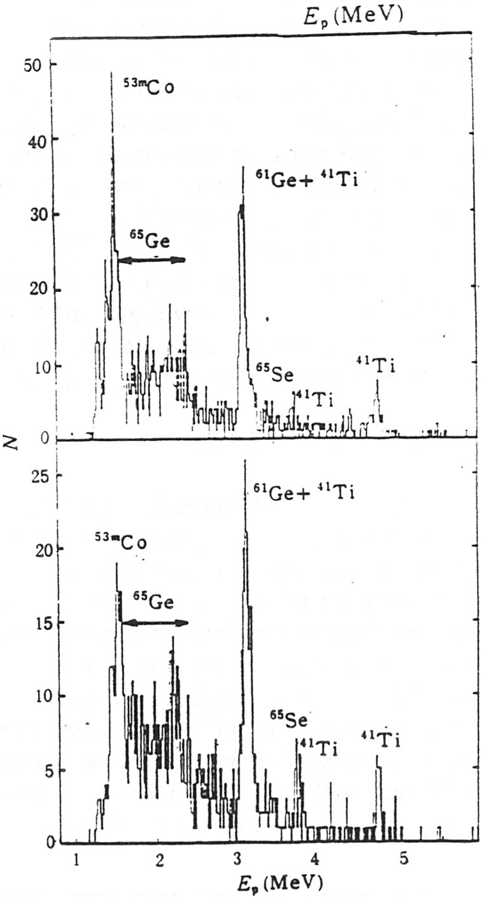

Fig. 2

Delayed proton spectra obtained in ^{28}Si(128 MeV)+Ca reaction. Upper part: integral beam is 35 mC, rotation speed of disk is 1.0 rpm; bottom part: integral beam is 27 mC, rotation speed of disk is 6.7 rpm.

prediction [7], the energy of β-delayed protons from ^{65}Se is situated in the region of 3.62 MeV to 3.74 MeV. Second, when the disk speed became faster, the absolute counts of proton activity at 3.75 MeV were increased, which makes us draw two important conclusions: (1) The new proton activity at about 3.75 MeV must be attributed to a short lifetime decay, because the counts of activity with a short lifetime can be relatively increased only if the disk speed becomes faster (i.e., the collection time becomes shorter); (2) differing from the original imagination, the active source was not injected to the right front of the particle telescope (detectors). If the activity was injected to the right front of the detectors, it does not matter if it has a longer or shorter lifetime: the counts from it will be absolutely depressed, although the ratio of the counts from a shorter lifetime activity to the counts from the longer one will be increased, i.e., the counts with a longer lifetime activity will be more diminished than those with a shorter lifetime activity when the disk speed becomes faster. We therefore concluded that the radioactive source was not injected to the point in the right front of the detectors, but to the point A as indicated in Fig. 3 (point C is the point on disk faced the center of detectors).

Before determining precisely the half-life of the nuclide by fitting experimental data with Eq.(2), it is necessary to obtain the integral counts under specified peaks. We then compute the two spectra

Table 1
The main proton energies and their relative intensities of ^{41}Ti (E_p > 30 MeV).

Energy of proton peak (MeV)	3.08	3.69	3.75	4.64	4.73
Relative intensity	60.3	15.5	31.0	22.1	100

Table 2
The proton counts belong to ^{61}Ge, ^{41}Ti, and ^{65}Se, respectively.

Proton peak E_p (MeV)	3.08—3.11 (MeV)			3.69—3.75 (MeV)			4.64—4.73 (MeV)
Nuclide and relative intensity	^{41}Ti(60.3) +^{61}Ge	^{41}Ti (pure)	^{61}Ge (pure)	^{41}Ti(46.5) +^{65}Se	^{41}Ti (pure)	^{65}Se (pure)	^{41}Ti(122.1) (pure)
Integral count (35 mC, 1.0rpm)	215	24	191	27	19	8	49
Integral count (27 mC, 6.7rpm)	164	14	150	41	11	30	29

shown in Fig. 2 obtained at an beam energy of 128 MeV with disk speeds of 1.0 rpm and 6.7 rpm, respectively. Because of the poor statistics and the bad resolution, the peak at 4.73 MeV actually includes the contributions from two proton peaks of ^{41}Ti at 4.73 MeV and 4.64 MeV, and the peak at 3.75 MeV from two proton peaks of ^{41}Ti at 3.75 MeV and 3.69 MeV. As mentioned above, the abnormal intensity ratio of the 3.75 MeV peak to the peak at the 4.73 MeV suggests the possibility of new proton activity with short lifetime existing in this region, in addition, the theory predicts [7] the β-delayed proton energy ranging between 3.62 to 3.74 MeV, it is reasonable to assume that the peak at 3.75 MeV is the common contributions of ^{41}Ti and ^{65}Se. With the same reason, the peak at 3.11 MeV could be considered as the common contributions of ^{61}Ge and the proton peak of ^{41}Ti at 3.08 MeV. Based on the relative intensities of ^{41}Ti listed in Table 1 and by using spectral separation analysis methods, the integral proton counts belong to ^{61}Ge, ^{41}Ti, and ^{65}Se in proton energy regions of 3.08—3.11 MeV, 3.69—3.75 MeV, and 4.63—4.73 MeV were obtained, respectively, as shown in Table 2.

According to the really experimental situation, the geometric conditions of detectors were defined in which an important thing is to determine AC, as mentioned above, the distance by which the radioactive source deviated from the center line of the particle telescope (see Fig. 3). By fitting experimental data with Eq.(2) and the known half-lives of ^{41}Ti and ^{61}Ge (80 ms and 40 ms, respectively), the values of AC were obtained. It was surprising that they were so close each other (3.36 mm and 3.44 mm, respectively), which also verify the correctness of our analyses. Taking the average AC (3.40 mm) and again with Eq.(2) fitting the experimental data related to ^{65}Se (including geometric factors, integral counts, integral beams, etc.), the half-life of ^{65}Se was obtained to be 9.62 ms.

The errors due to parameter uncertainties in half-life determination merit some discussion. First, the errors caused by uncertainties in the geometric condition were estimated. For example, the half-life changed from 9.62 ms to 9.66 ms as the active radius of the ΔE detector changed from 4 mm to 6 mm, the half-life varied from 9.62 ms to 9.74 ms as the distance between disk and the ΔE detector changed

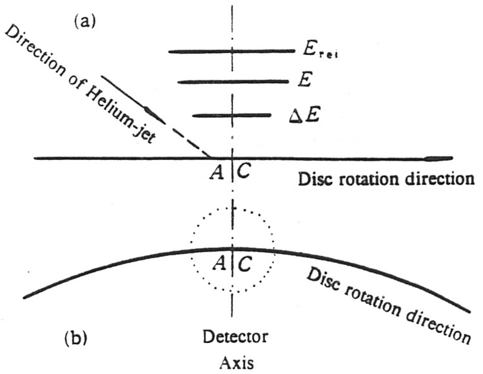

Fig. 3
The schematic position of jetted radioactive source on the collection disk: (a) side view; (b) vertical view.

from 10 mm to 5 mm, i.e., the errors in half-life determination due to geometric condition uncertainties are very small. Similarly, the influence in half-life determination caused by the unstable disk speed ($\sim 1\%$) is also very small and can be negligible. The error in half-life determination was therefore mainly caused by the statistical fluctuation of the integral counts under proton peak. Considering the worst statistical situation, the error that varied from +5.3 ms to −4.1 ms was obtained. In addition, by using a spectral separation analysis and fitting method, the energy of β-delayed protons of ^{65}Se was obtained to be 3.70 ± 0.08 MeV.

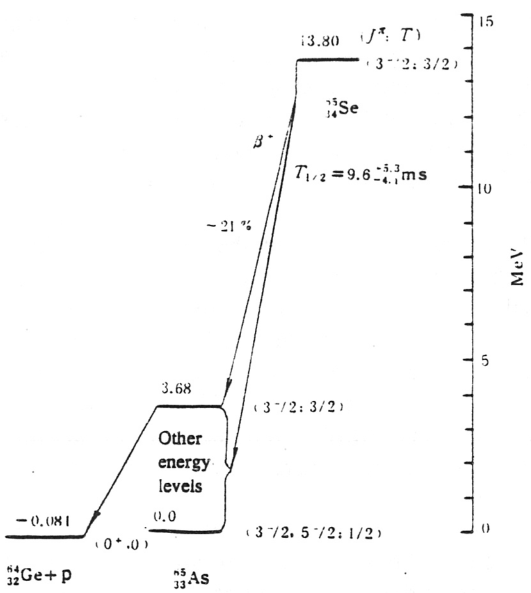

Fig. 4
The partial decay scheme of ^{65}Se. All energies are given in MeV.

3. CONCLUSION

Entirely based on the experimental data and with the spectral separation analysis method, the absolute detection efficiency of the particle telescope for rotating the radioactive source was fitted and calculated. The half-life of ^{65}Se was obtained as $9.6^{+5.3}_{-4.1}$ ms and its β-delayed proton energy was 3.70 ± 0.08 MeV, which are consistent with the values reported in Ref. 3. The half-life was also in good agreement with the one predicted by Y. Yoshizawa *et al.* [8]. Deriving the half-life of ^{65}Se entirely based on experimental data was unprecedented. By using its β-delayed proton energy of 3.70 ± 0.08MeV and assuming log*ft* = 3.3 for the corresponding super allowed β-transition, the branching ratio of β-delayed proton decay of ^{65}Se was obtained as $\sim$21%. The partial decay scheme of ^{65}Se β-delayed proton decay was therefore revised as shown in Fig. 4 in which the mass-excesses of ground states for ^{64}Ge and ^{65}As were taken from the G. Audi and A.H. Wapstra atomic mass evaluation [9] and the J^{π} value of ^{65}Se from the one of its mirror nuclide ^{65}Ga.

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