NUCLEAR SPECTROSCOPY WITH AN ON-LINE TIME-OF-FLIGHT MASS-IDENTIFICATION SYSTEM: HEAVY $T = \frac{1}{2}$ MIRROR NUCLEI*

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Abstract

The construction and use of an on-line He-jet fed time-of-flight mass-identification system are described. Using this system the $f_{7/2}$ $T = \frac{1}{2}$ nuclide ^{47}Cr has been produced and identified. We obtained a half-life for it of 460.0±1.5 msec, yielding a logft of 3.63 for its superallowed decay to ^{47}V. We have also obtained a preliminary half-life of 219±6 msec for ^{55}Ni.

1. On-Line Time-of-Flight Mass Identification

Because the half-lives of nuclei get drastically shorter as one moves away from stability and the production of these nuclei also produces many impurities, it is obvious that a fast, on-line mass-identification system is a desirable tool for the study of such nuclei. Traditionally, two principle means have been used to make mass identifications -- magnetic separation and time-of-flight (TOF). A number of laboratories have constructed mass-identification systems based on the magnetic principle, but serious problems remain concerning the interface between the target and the magnet. Somehow the atoms must be taken from the target, ionized, and sent through the analyzing magnet. These difficulties, plus the expense of a magnetic system, made us decide to build a TOF system at Michigan State University. A TOF system had been constructed and was working at Texas A&M University[1]), and our instrument, called SIEGFRIED, is patterned after the one at Texas A&M.

In the TOF system, the decay (originally α decay was used, but any sort of decay producing a sufficient recoil energy should work -- our system is optimized for β-decay recoils) of the nuclei provides the ions that are accelerated down a flight tube. The interface between the target and SIEGFRIED is a He-jet recoil-transport system[2]). The explicit details of the chain of events follows below; refer to Fig. 1.

a. Atoms which have recoiled from an in-beam target are thermalized and brought to SIEGFRIED by a He-jet with a 0.4-mm×9-m capillary.

b. These "target recoils" are sprayed through a skimmer (to separate them from most of the He) and hit the collector. Presumably the target recoils are attached to some sort of large "molecules", often called clusters by He-jet enthusiasts. Many of these cluster-recoil combinations stick to the collector surface.

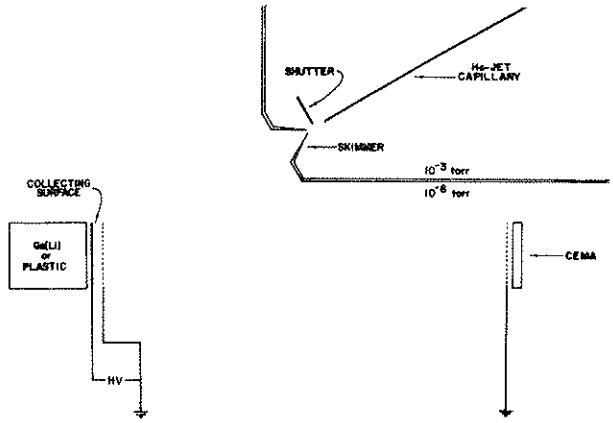

Fig. 1. Schematic diagram of SIEGFRIED on-line time-of-flight mass-identification system.

c. When one of the target recoils undergoes β decay, a number of events happen "simultaneously" in the time scale of interest. These simultaneous events, listed below, will be collectively referred to as a β event.

1) A β particle and ν are emitted.

2) The nucleus recoils. This recoil will be called the "β recoil".

3) Electron shake-off occurs, leaving the atom ionized.

4) If the β decay was to an excited state in the daughter, γ rays will be emitted. If the β particle was a β^+, 511-keV $\gamma^{\pm}$ quanta will be emitted.

d. If the β recoil is in the proper (forward) direction, the atom may leave the collecting surface. This produces an ion in the electric field maintained between the collector and the first grid. Any positive ions which appear in the electric field are accelerated down the flight tube and detected by the CEMA (Channel Electron Multiplier Array).

e. The time between detecting a β event and a CEMA event gives us the TOF and thus the mass.

A shutter is inserted between the He-jet capillary and the skimmer. This is necessary because the cyclotron produces a plasma in the He-jet chamber which is not yet relaxed when the helium-impurity mixture arrives at SIEGFRIED. The many ions produce a high count rate in the CEMA detector, which causes a very high chance-coincidence rate in the TOF spectrum. Therefore, SIEGFRIED is used in a pulsed mode in which the shutter opens, the He-jet deposits some activity, the shutter

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closes, and data taking begins. The shutter rate is chosen to optimize the efficiency for the nucleus of interest. Typically, it would be set to be open for 2 half-lives and closed for 3 or 4 half-lives. (The shutter makes it feasible to measure half-lives with SIEGFRIED.)

Small refinements have been made to SIEGFRIED in the past year to improve efficiency and resolution. At this time SIEGFRIED is in routine use and works quite well. A typical mass spectrum is shown in Fig. 2. This mass spectrum was collected in about an hour from an Al target with about 0.75-μA of ^{3}He at 70 MeV. (One should note that the recoil energy is a significant component of the total energy of the recoil going down the flight path. Thus, peaks are shifted to apparent lower masses with increasing β-decay energy. This also contributes the major fraction of the peak width.)

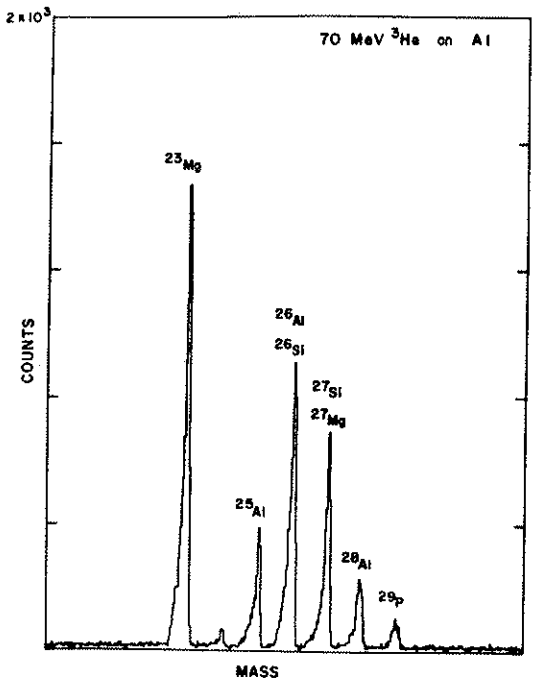

Fig. 2. A typical TOF mass spectrum obtained with SIEGFRIED.

2. Heavy $T = ½$ Mirror Nuclei

$T = ½$ mirror nuclei have been important for studying details of the Fermi interaction and CVC theory in nuclei. However, extending such studies up into the $f_{7/2}$ shell has not been previously practicable because of the distance of these nuclei from stability and the complexity of reactions for producing them and their neighbors. Both protons and α's are poorly bound in them, so charged-particle emission competes favorably with neutron evaporation -- and many of the resulting nearby nuclei have quite similar half-lives.

The first nuclear problem to be assigned to SIEGFRIED was the measurements of the half-lives for the $T = ½$ mirror nuclei: ^{45}V, ^{47}Cr, ^{49}Mn, ^{51}Fe, ^{53}Co, and ^{55}Ni. The excitation function for producing ^{45}V is shown in Fig. 3 and that for producing ^{47}Cr in Fig. 4. (Calculations for the plots were done with the ALICE code written by Blann and Pasil[3].) The graphs for the rest of the mirrors are very similar to ^{45}V for the odd-Z cases and similar to ^{47}Cr for the even-Z cases.

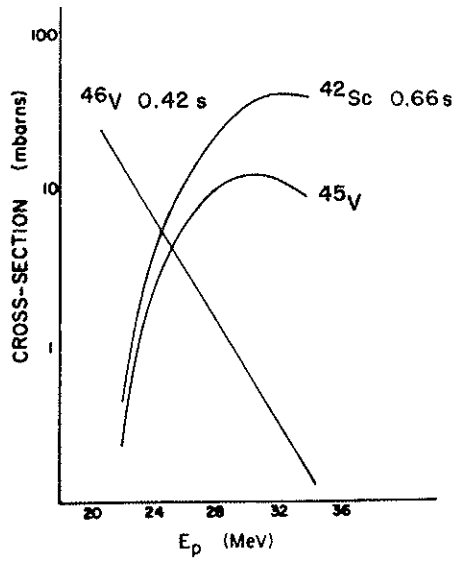

Fig. 3. Nuclides produced by protons on ^{46}Ti.

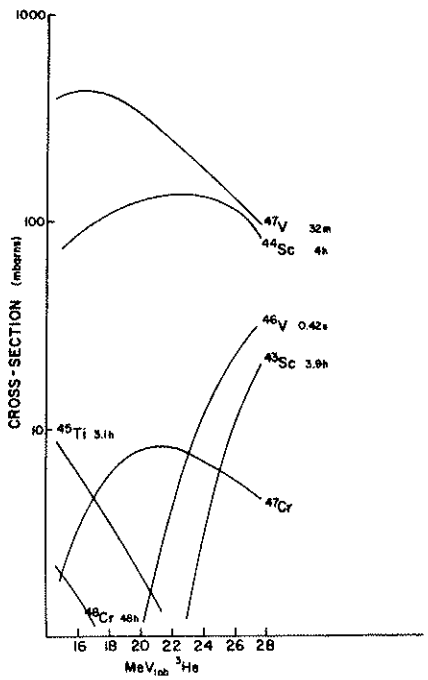

Fig. 4. Nuclides produced by ^{3}He on ^{46}Ti.

It was decided to study ^{47}Cr first, since it has the largest cross-section and one of the longest expected half-lives. From Fig. 4 we see that the biggest problem in the study of ^{47}Cr is ^{46}V. ^{46}V should have nearly identical properties (Q, $t_{½}$, etc.) to ^{47}Cr except for mass. Thus, SIEGFRIED can serve the purpose of verifying that ^{47}Cr is being made and can verify that ^{46}V is not made at ^{3}He energies below 18 MeV. The results of our attempt to measure

the half-life of ^{47}Cr in SIEGFRIED is shown in Fig. 5. The beam was 22-MeV ^{3}He on a ^{46}Ti target. The upper plot shows the mass spectrum; the bottom plots show the counts vs time-after-shutter-closure for the mass-47 and mass-46 peaks. The β event was detected with an NE102 plastic scintillator and events below ≈1 MeV were discarded to eliminate the ^{47}V from the mass-47 peak. SIEGFRIED thus proves that we are making ^{47}Cr and that its half-life is about the same as that of ^{46}V.

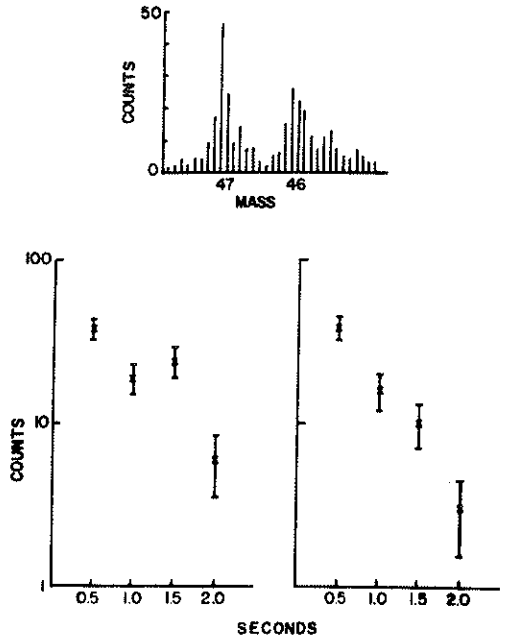

Fig. 5. (top) TOF mass spectrum showing ^{47}Cr and ^{46}V produced by 22-MeV ^{3}He on ^{46}Ti. (bottom left) Half-life curve for ^{47}Cr obtained from the mass spectrum. (bottom right) Half-life curve for ^{46}V obtained from the mass spectrum.

Figure 6 shows what happens to the mass spectrum when we reduce the ^{3}He beam energy to 16 MeV. If ^{46}V is still produced, it is less than 5% of the ^{47}Cr made. Thus, we are relatively safe in using the same beam to study ^{47}Cr without SIEGFRIED. We must do this because it appears that SIEGFRIED is too inefficient to make a half-life measurement of the order of 1%; sufficient statistics would require too much time to collect. Accordingly, a new system was built to measure half-lives in the He-jet by using a chopper. The physical setup is shown in Fig. 7. This is much more efficient because we can use greater He flows; there is no skimmer and we do not require a coincidence. We detect high-energy β events in plastic and divide the counts into 13 spectra by synchronizing an oscillator with the chopper. The data so collected are shown in Fig. 8. The background results from the γ activity which is not stopped by the chopper, and it is very constant. The background is calculated and subtracted by a computer code KINFIT, written in the MSU Chemistry Department for fitting kinetics data[4].

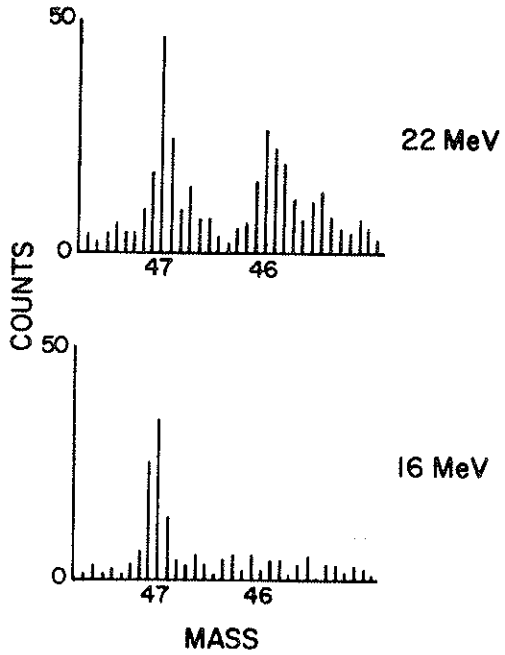

Fig. 6. TOF mass spectra in the region of A = 47 for 22- and 16-MeV ^{3}He on ^{46}Ti.

KINFIT also allows us to insert various amounts of ^{46}V into the equation to see what effect it has. Here the closeness of the half-lives for ^{46}V and ^{47}Cr is an asset because a little ^{46}V does not change the calculated half-life for ^{47}Cr by very much. The results of the KINFIT analysis are shown in Table I. Our final values for the half-life of ^{47}Cr is 460.0±1.5 msec. Taken with its mass, measured by the (^{3}He, ^{6}He) reaction[5], we obtain a logft of 3.63 for this mirror decay.

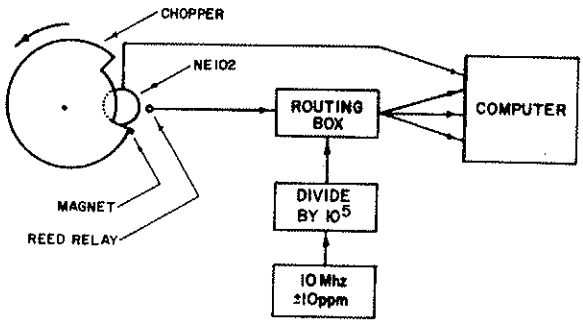

Fig. 7. Schematic diagram for using a chopper on the He-JRT system and routing half-life information in a computer. The He-JRT points at the plastic scintillator is pulsed by the chopping wheel.

In a similar fashion we have used the chopper to measure ^{55}Ni. For this nucleus we have a preliminary half-life of 219±6 msec; however, we have not yet confirmed this in SIEGFRIED. We also used the chopper to measure ^{46}V. This was done as a test of the chopper since ^{46}V has already been measured to have a $t_{½}$ of 423±2 msec[6]. Our value is 420±3 msec.

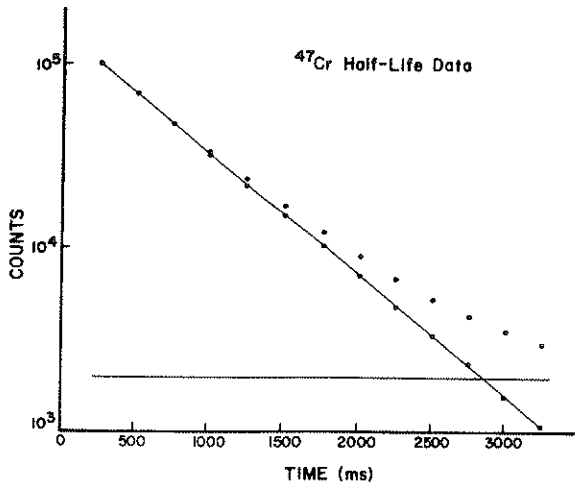

Fig. 8. ^{47}Cr half-life curve obtained with the He-JRT system and a chopper.

Table I. ^{47}Cr Data Analysis Using KINFIT

Counts = $A \cdot \exp(-\lambda t)$ + Const $\exp(-\lambda_{^{46}V} t)$ + B

Const	$t_{\frac{1}{2}}$	σ
0	460.0 msec	1.22
1%A	460.8 msec	1.23
2%A	461.2 msec	1.25
5%A	462.4 msec	1.28
10%A	464.6 msec	1.35

3. Conclusion

These mirror decays present one of the more difficult challenges to our system. We feel that the greatest difficulty in seeing them with SIEGFRIED is because of the He-jet rather than SIEGFRIED itself. Most of the activity decays in route to SIEGFRIED, making SIEGFRIED appear less efficient than it really is. We are now beginning experiments with some longer-lived activities to see just how efficient SIEGFRIED is. We are also looking for the proper solution to speeding up our He-jet. It now appears that our transit time is about 2 seconds. Only about 300 msec of this time is spent in the 9-m capillary; the rest is the time it takes the target recoils to enter the capillary. The best remedy is greater helium flow, but SIEGFRIED's vacuum pumps presently are not capable of handling more helium. For the present, then, SIEGFRIED works best with half-lives of greater than ≈1 sec. Hopefully, this will be remedied soon, but, in spite of this problem, we still believe that SIEGFRIED is an excellent alternative to magnetic mass identification.

Acknowledgement

Inasmuch as it was decided that having too many representatives from one laboratory participate in a single (exotic) conference was inappropriate, we could not deliver this paper in person. We therefore are very grateful to Prof. Walter Benenson for agreeing to present this paper in addition to his own at the Cargese Conference.

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