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Abstract:

We have searched for new delayed proton emitters in ^{24}Mg and ^{28}Si bombardments of Ca targets to extend our knowledge about the proton drip line in the A = 60-65 mass region. Definitive evidence for the A = 4n+1, $T_z = -3/2$ nuclide ^{61}Ge is presented, but a search for the next member in this series, ^{65}Se, proved fruitless.

Introduction

We are interested in ascertaining the properties of nuclides at or near the proton drip line, many of which have been characterized via their beta-delayed proton decay channel. Certain of these nuclei have large beta-delayed proton branching ratios because the superallowed beta transition to the isobaric analog state in the daughter populates a state which is unbound to proton emission. Typically the delayed proton spectrum in these cases is dominated by transitions from the isobaric analog state to low-lying states in the proton daughter. This phenomenon has been observed for all members of the $T_z = -3/2$, $A = 4n+1$ series of nuclei from ^{17}Ne to ^{57}Zn and also for a number of $T_z = -2$ and $-5/2$ nuclei. In the present work we have extended the $T_z = -3/2$, $A = 4n+1$ series by firmly establishing the delayed proton decay of ^{61}Ge first observed by Vieira$^{1)}$. Additionally, we have also searched unsuccessfully for the next member of this series, ^{65}Se.

The mass excesses of the isobaric analog states deduced from delayed proton measurements can be used to test the isobaric multiplet mass equation (IMME) which relates, through a simple relationship quadratic in T_z ($= \frac{N-Z}{2}$), states of the same isospin in a given isobar. Completion of isospin quartets and quintets tests the existence of cubic and quartic deviations from IMME. For $A < 41$, almost all of the $A = 4n+1$ isospin quartets have been completed. While there is little immediate prospect of completing such quartets for $A \geq 41$, observation of the strong beta-delayed proton emission of $T_z = -3/2$, $A = 4n+1$ nuclei, particularly for $A > 57$, provides studies near the proton drip line. Mass excess calculations have been performed to predict the location of the proton drip line; these involve applying the Kelson-Garvey mass relation$^{2)}$, supplemented with Coulomb displacement energy predictions using the results of a recent fit$^{3)}$. These calculations typically yield the most precise estimates of the masses of unknown proton-rich nuclei. The delayed proton energy corresponding to the decay of the isobaric analog state to the ground state of the daughter can also be estimated utilizing this approach. However, lack of $T_z = 0$ and $+1/2$ nuclei prevents application of this technique for $A \gtrsim 70$.

Good estimates of masses in this region, especially in relation to the proton drip line, are important input into calculations of the astrophysical rp process$^{4)}$. In particular, if ^{65}As is unbound, the rp process would effectively be terminated at ^{64}Ge. Our calculations indicate that ^{65}As is unbound to proton emission by 570 ± 300 keV (the uncertainty is dominated by the experimental uncertainty in the mass of ^{64}Ge). While this leaves unanswered the question of whether ^{65}As would be a ground state proton emitter in laboratory experiments, it would almost certainly be an unbound nucleus in the astrophysical environment envisioned for the rp process with $T \approx 200$-300 keV.

Experimental Method and Results

Delayed proton emitters in the mass 60 to 65 region were produced in fusion-evaporation reactions using ^{24}Mg and ^{28}Si beams from the Lawrence Berkeley Laboratory 88-Inch Cyclotron incident upon natural calcium targets. Reaction products were thermalized in helium and transported via NaCl aerosols through a 70 cm capillary to a shielded detector box. The radioactive products were deposited on a rotating wheel (used to remove long-lived activities) directly in front of a three-element silicon semiconductor detector telescope. By comparing the measured yields at different wheel speeds under otherwise identical conditions, the half-lives of unknown proton groups could be estimated relative to known ones. Many proton peaks were identified on the basis of known decay schemes; these yields and those of new activities were compared as a function of beam energy with yields calculated using the fusion-evaporation code ALICE5).

In Fig. 1 the delayed proton spectrum obtained in a 90 MeV ^{24}Mg + Ca bombardment is shown. The peak at 3.10 MeV is identified as being due to ^{61}Ge decay. First, its energy is in good agreement with the 3.21 MeV energy calculated for the isobaric analog state of ^{61}Ga decaying to the ground state of ^{60}Zn. Second, its yield reaches a maximum at this bombarding energy, compared to data obtained at 77 and 120 MeV, which is consistent with the maximum predicted by the ALICE code. The yields of ^{53m}Co and ^{59}Zn are also in good accord with the ALICE calculations. ^{25}Si is believed to be produced in transfer reactions in the target chamber entrance foils where the beam energy is sufficiently high (6.4 MeV/A) for such reactions to occur. The peak at 2.51 MeV cannot be attributed to any known delayed proton emitter and is not associated with ^{61}Ge.

In the search for ^{65}Se, two wheel speeds were run for each ^{28}Si bombarding energy. Figure 2 shows spectra from the highest energy bombardment at 128 MeV. ^{61}Ge is again produced, via the α3n evaporation channel. ^{41}Ti is produced in reactions with the oxygen contaminant in the target. It is apparent from a comparison of the yields of peaks in the two spectra that ^{61}Ge has a shorter half-life than ^{53m}Co and is comparable to or shorter than ^{41}Ti (80 ms).

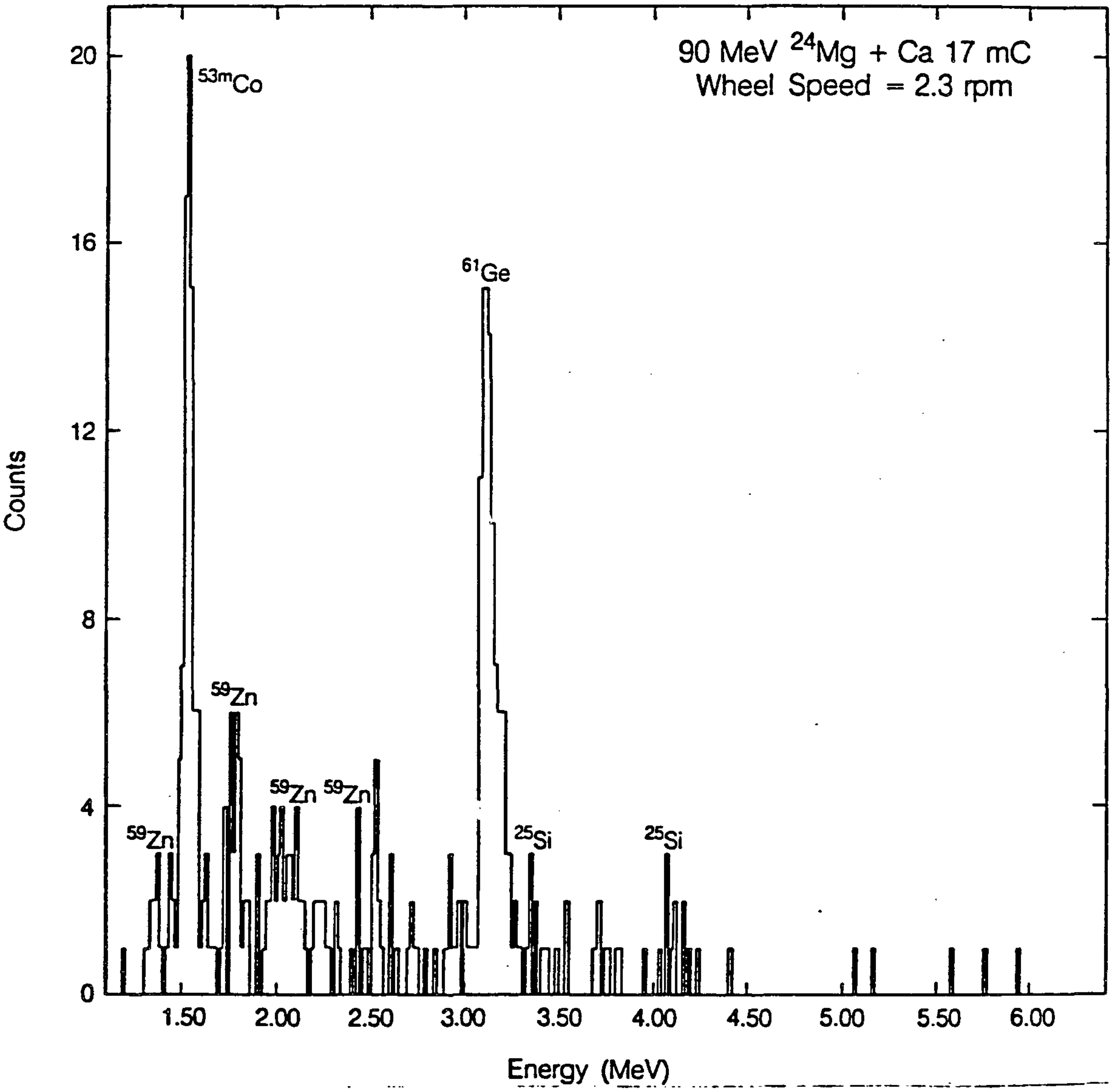

Fig. 1 Delayed proton spectrum arising from the ^{24}Mg + Ca reaction at E_{Mg} = 90 MeV.

Spectra were also obtained at 73, 81, 97 and 113 MeV. The peak assigned to ^{61}Ge is significantly reduced at 113 MeV (see Fig. 3) and is not observed at 97 MeV, consistent with predictions for ^{61}Ge, thus confirming its

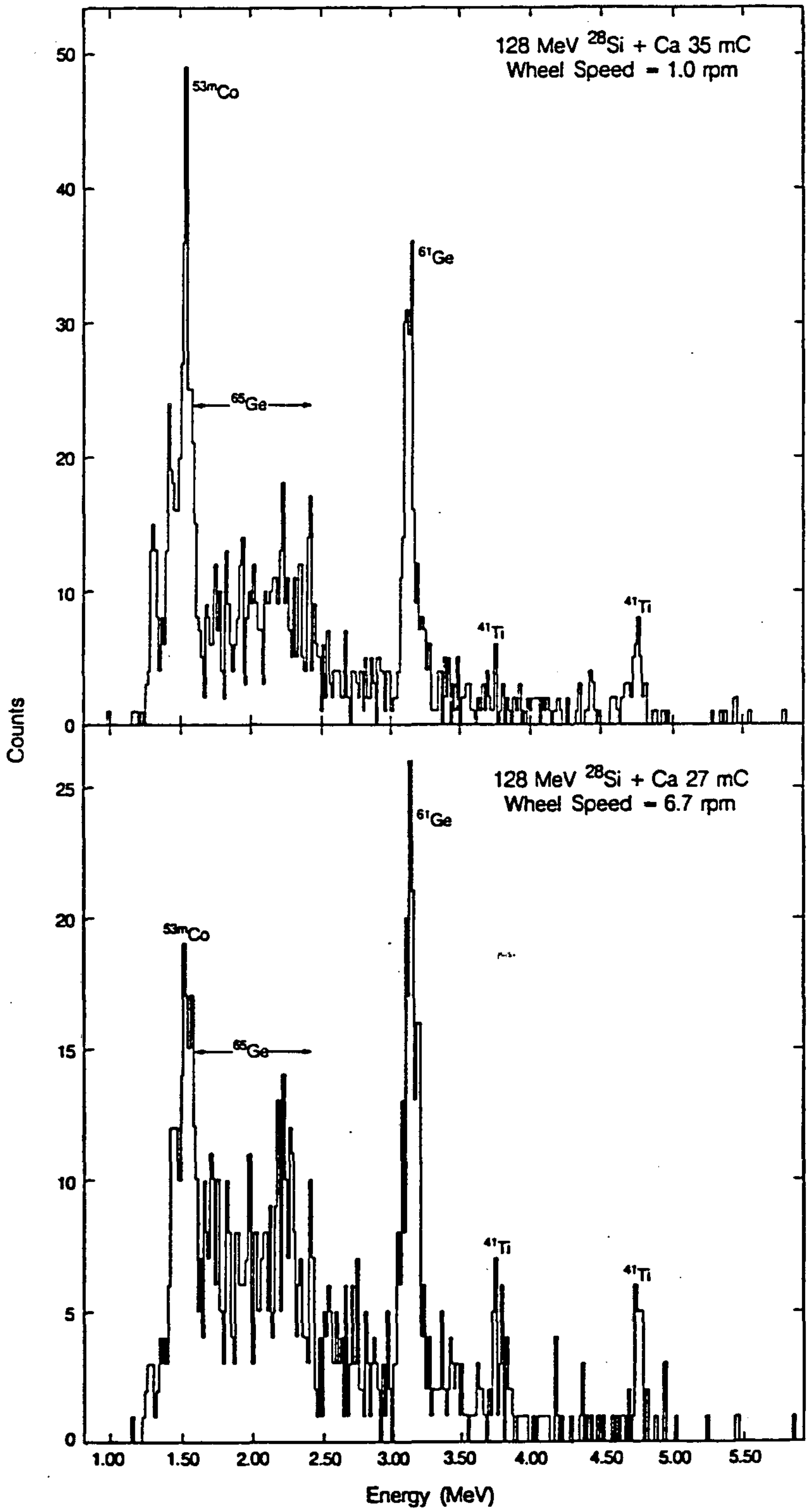

Fig. 2 Delayed proton spectra arising from the ^{28}Si + Ca reaction at E_{Si} = 128 MeV and two different wheel speeds.

identification. However, there is no evidence for the decay of ^{65}Se, which is expected to have a maximum proton energy of 3.75 MeV (analog state to ground state transition, which if made in very low yield would be obscured by the main ^{41}Ti group). Its yield should be greatest in Fig. 3 (113 MeV) and should also be observable at 97 and 128 MeV. As its yield is expected to be comparable to ^{61}Ge (and other members of this series in analogous reactions), its absence is puzzling.

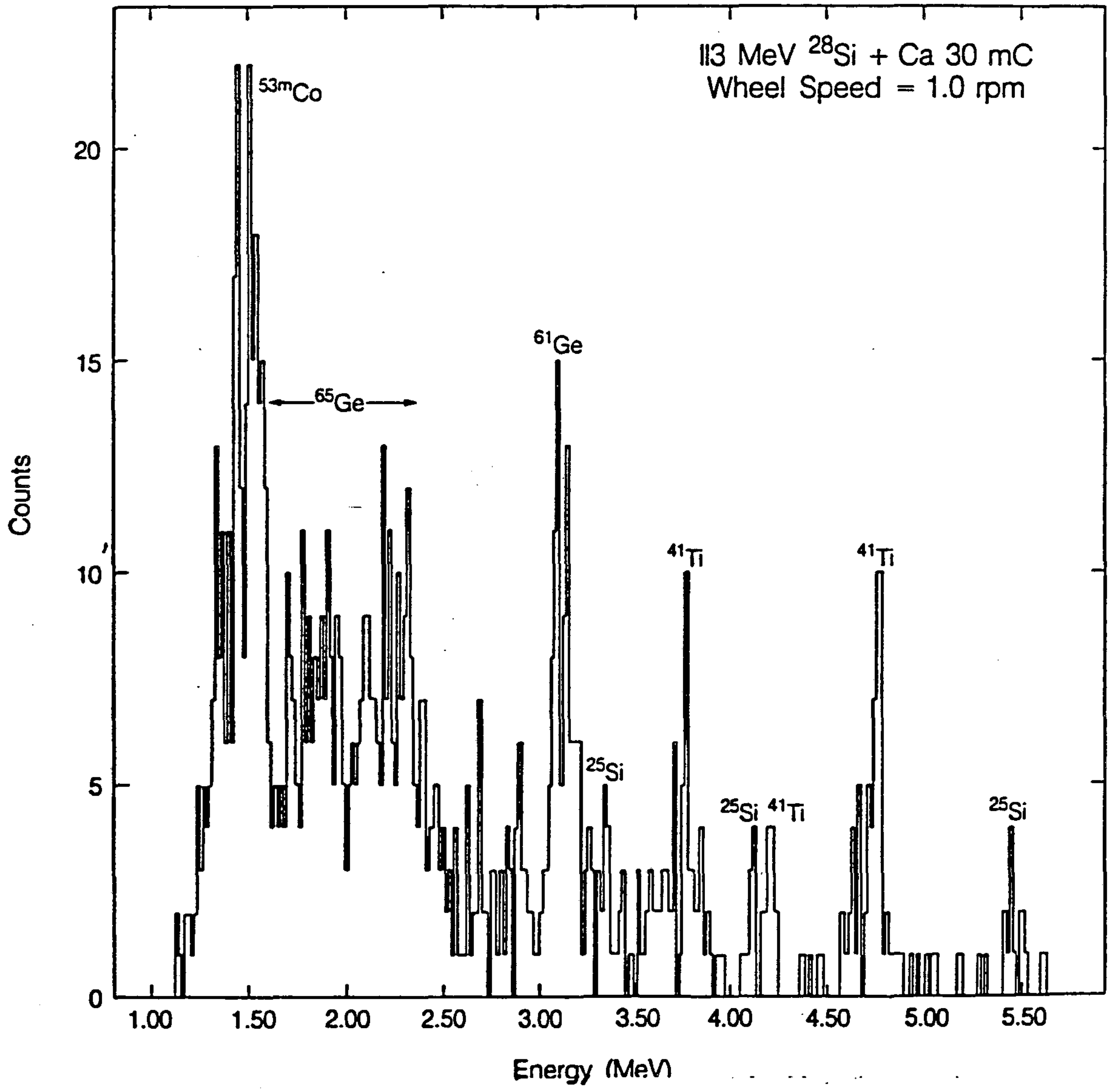

Fig. 3 Delayed proton spectrum observed in the 113 MeV ^{28}Si + Ca reaction at the slowest wheel speed.

A spectrum of broad peaks from ^{65}Ge appears between 1.5 and 2.5 MeV in all the ^{28}Si data. Some unidentified peaks also appear in these spectra. There exists a number of potential weak delayed proton emitters in this mass region that may be contributing to the low energy part of these spectra. These uncharacterized nuclei belong to the $T_z = -1/2$ or -1 series: in particular, ^{60}Ga, ^{61}Ga, ^{62}Ge, ^{63}Ge, ^{66}Se and ^{67}Se are likely to be weak β-p emitters. Because at least two such activities may contribute at each beam energy, it has not been possible to identify any of them unambiguously.

Conclusions

We have observed a 3.10 MeV peak in our delayed proton spectra which coincides with that observed by Vieira$^{1)}$, and we have shown that it is due to the beta-delayed proton decay of ^{61}Ge. This proton energy is in good agreement with that estimated for the transition from the isobaric analog state in ^{61}Ga to the ground state of ^{60}Zn.

It is difficult to understand our failure to observe the delayed proton decay of ^{65}Se, since all lighter members of this series from ^{45}Cr to ^{61}Ge have been observed in heavy-ion reactions. In some of these cases it has been found that the proton decays of the isobaric analog states are fragmented between the ground and low-lying excited states of the proton daughter. However, we have not observed any peaks at lower energies in the proton spectra that vary with bombarding energy in the way expected for the decay of ^{65}Se.

Our mass calculations indicate that ^{65}Se should be bound to direct proton emission. For particle emission to compete with beta decay, these calculations would need to be in error by ~1 MeV, which would be a large error since the known masses of proton-rich nuclei can generally be predicted by the Kelson-Garvey technique to within about a few hundred keV. Another possible explanation is that the aerosol in our helium-jet does not effectively transport selenium.

A systematic study of the beta decays of $T_z > -3/2$ nuclei in this mass region would be of interest in trying to understand this anomaly. Identifying the decay of ^{65}As would be interesting in this context and for astrophysical reasons. There is a strong possibility that this nucleus is a ground state proton emitter with a measurable half-life and would provide a further example of this decay mode$^{6)}$.

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