comes very close to producing an accidental tricritical point. Near the triple point $F(m)$ is a very flat function of m, and it is likely that in this region of the phase diagram large fluctuations will make the Hartree-Fock approximation used here very inaccurate. Associated with the first-order transition is a discontinuous entropy change ΔS and a latent heat $l = T\Delta S$. Since in this model the moments disappear rather than disorder, the entropy change has no particular relation to $N \ln 2$.[5] Because we have chosen a narrow conduction band, the entropy change over most of the first-order phase transition is close to $N \ln 4$ since there are $4N$ single electron states in the conduction band. For a more realistic model, ΔS would probably be considerably less. Similarly, if we had used a conduction band of finite width, the susceptibility above and below the first-order transition would be roughly independent of temperature, but a discontinuity in the susceptibility of either sign could occur at the transition temperature.

This simplified model, in which only the Heisenberg interaction was included (to demonstrate its effect) and in which both bandwidth and hybridization effects have been neglected, yields qualitatively good agreement with experiments on NiS. An arbitrary density of states for the itinerant electrons, an interband electron-electron interaction (in the Hartree-Fock approximation), and more complicated localized states ($S \neq \frac{1}{2}$), can be incorporated into the model merely at the expense of computer time.[6] Hybridization may be a small effect for rare-earth compounds exhibiting MNM transitions, but for the transition-metal compounds its inclusion may be essential for a realistic model. The difficulty in including hybridization is a major stumbling block in attaining an improved two-band model of the MNM transition.

The author wishes to thank Professor R. G. Goodrich and Professor A. K. Rajagopal for their discussions and helpful suggestions.

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Germanium-64

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(Received 15 May 1972)

The new isotope ^{64}Ge has been produced via the reaction ^{64}Zn(^{3}He,3*n*)^{64}Ge, chemically isolated, and its decay studied. Since ^{64}Ge is therefore nucleon stable, it can in principle have an important role in the synthesis of mass 64 by α capture during explosive stellar events, as proposed by Arnett, Truran, and Woosley. However, from the measured half-life (62.3 ± 2.0 sec) and β-decay systematics, it appears that this mechanism is probably responsible for a negligible fraction of the observed abundance of mass 64.

Recently Arnett, Truran, and Woosley[1] (ATW) have shown that the elements on the high-mass side of the iron peak in the elemental abundance curve can be synthesized in an explosive stellar event. The process involves, for example, a quasiequilibrium among ^{4}He, ^{56}Ni, ^{60}Zn, and ^{64}Ge, and the resulting abundances for mass 60 and 64 depend primarily on the corresponding binding energies. Since ^{64}Ge has never been observed experimentally, ATW used for that isotope a value of the binding energy calculated by Garvey *et al.*[2] The abundances obtained[1] for masses near 64 are typically 2 orders of magnitude smaller than those observed in nature.

This discrepancy could possibly be removed if ^{64}Ge were more tightly bound, since production of that nuclide by radiative α capture would then be enhanced. In that hope, a number of intensive searches for ^{64}Ge were undertaken[3-7] with a view to obtaining an experimental estimate of its mass. The fact that none of these searches was successful raised doubts about the nucleon stability of ^{64}Ge and its possible contribution to the synthesis of mass 64.

This Letter reports the detection of ^{64}Ge produced via the reaction ^{64}Zn(^{3}He,3n)^{64}Ge near 50 MeV. Conclusive identification has been made by (a) chemical separation of germanium, (b) observation of γ rays from the decay of ^{64}Ge to known excited states in the daughter nucleus ^{64}Ga, and (c) observation of the growth of the daughter activity.

In view of the expected low yield from the reaction ^{64}Zn(^{3}He,3n)^{64}Ge, it is fortunate that the ground state of ^{64}Ga is 0^+,[8] since the isospin selection rule[9] then requires most of the β decay of ^{64}Ge to lead to excited states in ^{64}Ga. Furthermore, one expects the reaction ^{64}Zn(p,n)^{64}Ga to populate many of the same states. γ rays from that reaction have been studied in beam by the present authors,[10] by Davids, Matthews, and Whitmire,[11] and by Hansen, Gregory, and Dietrich.[12] The latter two investigations included threshold measurements, and a level scheme for ^{64}Ga has been constructed[11,12] on that basis.

Sources of ^{64}Ge were prepared by irradiating 10-mg/cm^2 targets of 99.66%-enriched ^{64}Zn on thick copper backings with the ^{3}He beam from the Michigan State University cyclotron. The beam energy was degraded from 70 to 50 MeV with a Zn absorber. Following a 2-min irradiation the target was transported by pneumatic "rabbit" to a laboratory where (with the adaption of the method of Porile[13]) the ^{64}Zn was dissolved in concentrated HCl containing KClO$_3$. The volatile GeCl$_4$ was vacuum distilled at room temperature into a cold trap in front of a Ge(Li) detector. No evidence of activities other than germanium isotopes and their daughters was seen in the spectra except for ^{10}C, which also forms a volatile tetrachloride. Counting was begun approximately 25 sec after the end of irradiation and continued for eight periods of 50.0 sec each.

Figure 1 shows portions of the 0–50-sec and 100–150-sec spectra resulting from a total of twelve irradiations. The strongest lines decay

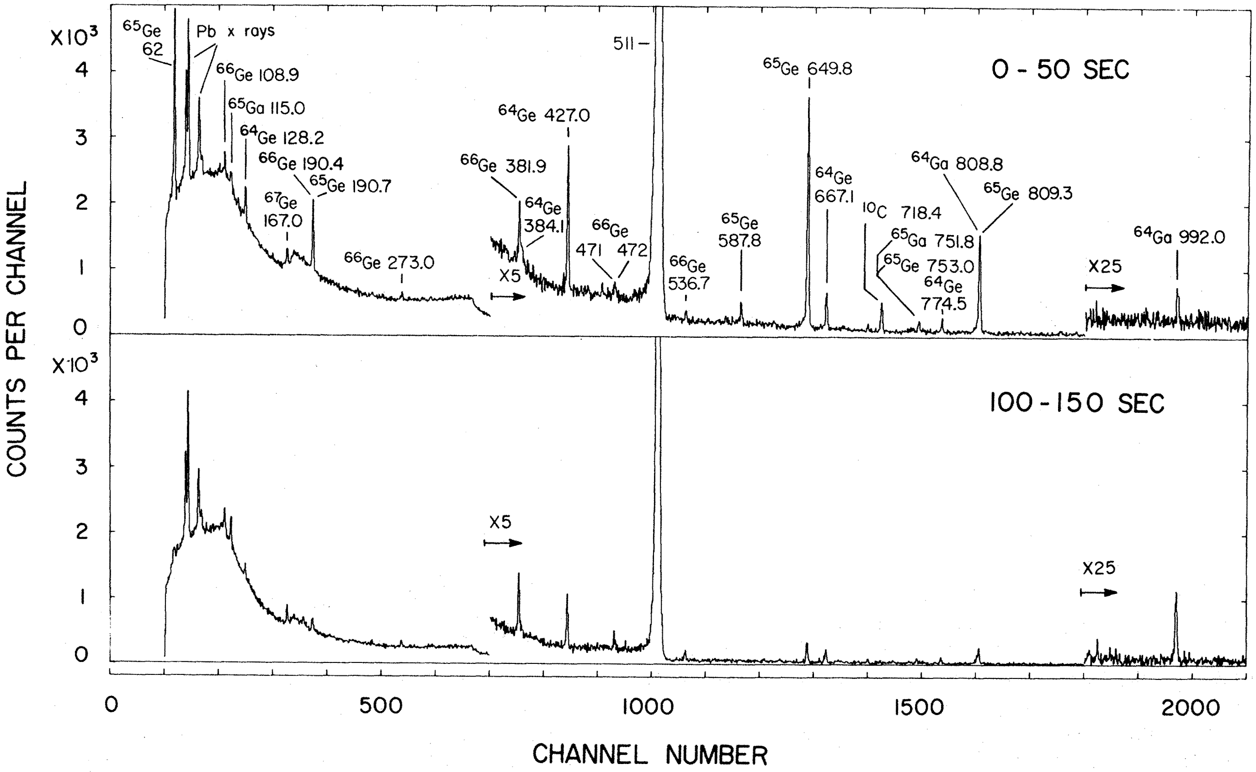

FIG. 1. Low-energy portions of γ-ray spectra accumulated at two different times after the chemical separation of germanium. The rapid decay of ^{65}Ge ($t_{1/2}=30$ sec) and the slower decay of the new isotope ^{64}Ge ($t_{1/2}=62$ sec) are apparent. The growth of the 115-keV line from ^{65}Ga and the 992-keV line from ^{64}Ga, the daughter activities, can also be seen.

with a short half-life (30 ± 2 sec) and are attributed to ^{65}Ge (despite the large disagreement with the previous half-life[13]), on the basis of the rapid growth of the ^{65}Ga daughter and the good energy fit with levels observed[14] in ^{64}Zn(^{3}He,d)^{65}Ga.

Other lines, at 128.2 ± 0.2, 384.1 ± 0.3, 427.0 ± 0.3, 667.1 ± 0.3, and 774.5 ± 0.3 keV, decay with a (weighted average) half-life of 62.3 ± 2.0 sec and are assigned to the decay of the new isotope ^{64}Ge. All of these lines have been seen in the ^{64}Zn($p,n\gamma$)^{64}Ga experiments. A relative excitation function for ^{64}Ge and ^{65}Ge shows that lines from ^{64}Ge are weak at 29 MeV and undetectable at 20 MeV (the calculated threshold[2] is 21 MeV), while the ^{65}Ge γ rays remain strong. From the known excitation function for the reaction ^{64}Zn(^{3}He,n)-^{66}Ge,[5] the cross section for ^{64}Zn(^{3}He,$3n$)^{64}Ge at 50 MeV is estimated to be 50 μb.

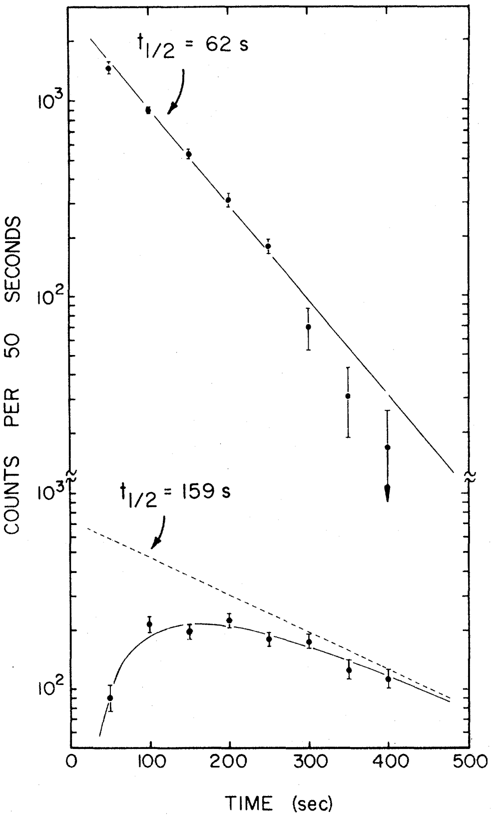

FIG. 2. Upper graph, decay of the 427-keV γ ray from ^{64}Ge. The straight line represents the adopted half-life, 62.3 sec, fitted by least squares for intensity. Lower graph, growth and decay of the 992-keV line from the daughter activity ^{64}Ga. The solid curve is a calculation assuming the measured half-lives of ^{64}Ge and ^{64}Ga, fitted by least squares for the initial activities of the two isotopes. The initial activity of ^{64}Ga found in this way is, within error, zero; thus essentially all the observed ^{64}Ga results from ^{64}Ge decay.

In Fig. 2 are shown the decay of the 427-keV line from ^{64}Ge, and the growth and decay of the 992-keV line from the daughter ^{64}Ga, whose half-life is 159 ± 2 sec.[15] Correction has been made for weak γ rays of 427 keV in the decays of ^{66}Ge and ^{64}Ga.

With the help of the ^{64}Zn($p,n\gamma$)^{64}Ga results, a decay scheme for ^{64}Ge has been deduced as shown in Fig. 3. Absolute γ-ray intensities have been obtained by normalizing to the measured growth of ^{64}Ga daughter activity. Provided none of the observed γ rays is in cascade or appreciably converted, (79 ± 10)% of the decay of ^{64}Ge has been accounted for. The 86-keV line is masked in these experiments by Pb x rays, and the 43-keV line lies below the threshold of the analog-to-digital converter. The 667-keV γ ray originates below 930-keV excitation[12] in ^{64}Ga, and the 775-keV one below 1460 keV, but their exact locations are not known. Spin and parity assignments of 1^+ have been made where logft values indicate an allowed β transition. The logft values shown have been calculated assuming mass excesses ΔM of − 58.83 MeV[11] for ^{64}Ga and − 54.03 MeV[2] for ^{64}Ge. This mass excess for ^{64}Ge seems quite realistic because the ft values so obtained are similar to those in neighboring nuclei. One can set an approximate lower limit on the mass excess by assuming that the logft value for the transition to the 427-keV state is unlikely to be

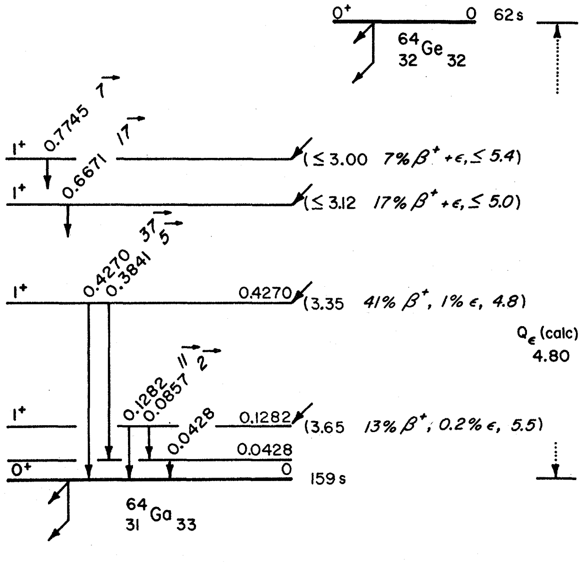

FIG. 3. Decay scheme for ^{64}Ge. The notation and conventions of Nuclear Data Sheets have been adopted. The logft values have been calculated assuming the mass excess for ^{64}Ge derived by Garvey *et al.* (Ref. 2). No direct measurement of the mass excess has been made.

less than 4.5, the smallest found in a survey of 134 transitions in the decays of $^{60-63}$Zn, $^{64-68}$Ga, and $^{66-69}$Ge. This leads to $\Delta M(^{64}\mathrm{Ge}) \geq -54.5$ MeV and, correspondingly, an α-separation energy $S_\alpha \leq 2.7$ MeV.

This limiting value of S_α for ^{64}Ge is only 0.5 MeV greater than that assumed in the calculations of ATW; its use would cause only minor changes in the predicted abundances.[16] Thus it appears that an (α, γ) capture chain proceeding along the $N = Z$ line cannot synthesize the observed abundance of mass 64.

We wish to thank K. L. Kosanke and W. C. McHarris for their help, L. F. Hansen for communicating her unpublished results, and W. D. Arnett, C. N. Davids, D. R. Goosman, N. S. P. King, and C. S. Zaidins for valuable discussions and data.

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*Work supported by the National Science Foundation.

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[16] In a quasiequilibrium dominated by an (α, γ) capture chain, the final abundance of ^{64}Ge is approximately proportional to $\exp(S_\alpha/kT)$, where T is the temperature at freeze out. Assuming $T = 3\times10^9$ °K, the discrepancy in the production of mass 64 could not be removed with an $S_\alpha < 3.5$ MeV. A $\log ft < 3.9$ would be implied if $S_\alpha > 3.5$ MeV.

Two-Neutron Transfer Reactions on Rare-Earth Nuclei

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(Received 22 May 1972)

The angular-momentum projection method is applied to the description of (t,p) and (p,t) reactions on deformed nuclei. The difference between the deformations of a target nucleus and that of a residual nucleus is taken into account in the calculation of the spectroscopic amplitude. The calculation is especially focused on the ground-state to ground-state (p,t) transitions. The neutron-number dependence of the calculated distorted-wave Born-approximation cross sections is in good agreement with the experimental results.

Two-neutron transfer reactions have been studied in transition and deformed nuclei in the rare-earth region, and a great deal of experimental data have been recently accumulated.[1-4] The experimental data have been analyzed by several authors[5-11] from theoretical viewpoints. In the framework of the plane-wave Born approximation, Yoshida[5] has predicted that the cross section of the ground-state to ground-state transition for nuclei in superconducting states is proportional to $(\Delta/G)^2$, where Δ and G are the gap energy and pairing interaction strength, respectively. The enhancement of the cross section in the ground-state (g.s.) transition has been successfully explained by this theory. The calculation of the cross section in the distorted-wave Born approximation (DWBA)[10] gave almost the same results as did the Yoshida prediction. However, those theories did not explain successfully the neutron-number dependence of the experimen-