Gamma decays of isobaric analog states relevant to neutrino detection

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Measurements have been made of the gamma ray branching ratios for the decay of the lowest isobaric analog states of ^{71}Ge and ^{81}Kr. These states could be populated by high-energy neutrinos in gallium- and bromine-based detectors. Although these states are unbound to particle decay, all channels with significant penetrabilities are isospin forbidden, so that gamma decay is a possibility. Our results indicate that these states decay mainly by neutron emission and therefore contribute very little to detection sensitivities for ^{71}Ga and ^{81}Br.

INTRODUCTION

The reported[1,2] discrepancy between the measured and predicted flux of solar neutrinos has spurred the development of new radiochemical neutrino detectors using gallium[3,4] or bromine.[5,6] Gallium-based detectors are presently under construction and are primarily sensitive to the *pp* solar neutrinos. In contrast, a bromine detector is suited for detection of ^{7}Be and ^{8}B neutrinos and awaits the development of an effective single-atom counting scheme.

The isobaric analog states (IAS) of the ground states of ^{69}Ga, ^{71}Ga and ^{81}Br (corresponding to excited states in ^{69}Ge, ^{71}Ge, and ^{81}Kr, respectively) can be populated via inverse Fermi beta decay transitions induced by the high-energy neutrinos produced by the β decay of ^{8}B in the sun. Because of the large overlap of the ground state with its IAS, these transitions have large cross sections. Therefore, if the IAS subsequently gamma decays, this channel can contribute to the measured flux of neutrinos. Such a gamma decay of the IAS could increase the ^{71}Ge production rate by about 2% [1.9 solar neutrino unit (SNU) out of 133.7 SNU in the standard solar model[7]] and the ^{81}Kr production rate[8] by about 6% (1.7 SNU out of 27.8 SNU in the standard solar model[7]). The impact on the ^{71}Ge production could be more significant if the *pp* neutrino flux is suppressed by the Mikheyev-Smirnov-Wolfenstein effect.[9,10] The spin part of the $M1$ gamma transition strengths from the IAS to lower-lying levels is proportional to the Gamow-Teller matrix elements between the gallium or bromine ground states and the low-lying states in germanium and krypton. Thus, if the IAS decays by gamma emission, a measurement of these $M1$ strengths would be a check of these matrix elements which are otherwise determined from (p,n) data.[11,12] In addition, for the detection of high-energy neutrinos produced by supernova events, the IAS could make a significant contribution to the detection rate, if it has a significant gamma decay branch.

The IAS in ^{71}Ge (at an excitation energy of $E_x = 8.932(13)$ MeV)[11,13] is unbound to proton decay (by 0.66 MeV) and alpha decay (by 4.49 MeV). The IAS in ^{81}Kr (at $E_x = 9.717(15)$ MeV)[14] is unbound to proton decay (by 0.61 MeV) and alpha decay (by 4.19 MeV). The penetrabilities of these decays are negligibly small. These isobaric analog states are also unbound to neutron decay (by 1.84 MeV in ^{81}Kr and 1.54 MeV in ^{71}Ge), but since the decay is isospin forbidden, the branching ratio is difficult to estimate. The IAS in ^{69}Ge (at $E_x = 7.00(5)$ MeV)[15] is only unbound to isospin forbidden alpha decay (by 3.39 MeV). The 39 h ^{69}Ge, produced from the 60% abundant ^{69}Ga, may be of interest for the detection of high-energy neutrinos, for which the IAS transition will dominate the cross section.

We have measured the branching ratios for gamma decay of the IAS in ^{71}Ge and ^{81}Kr using the $(^3\text{He},t\gamma)$ reaction. Outgoing tritons were detected at $\theta_{\text{lab}} = 0°$ in the focal plane of a quadrupole-dipole-dipole-dipole (QDDD) magnetic spectrometer. Gamma rays were measured in coincidence with these tritons using a 12.7 cm by 10.2 cm NaI crystal placed at about 30 cm from the target and at an angle of 125° with respect to the beam, as shown in Fig. 1. Since the IAS have $J = \frac{3}{2}$, the angular distribution of this gamma decay can have a maximum complexity given by the Legendre polynomial, $P_2(\cos\theta)$. Because the NaI detector was placed near a zero of $P_2(\cos\theta)$, it measured the total decay strength.

^{71}Ge

The ^{71}Ga$(^3\text{He},t)^{71}$Ge reaction was studied using a 29.9 MeV ^{3}He beam from the Princeton University AVF cyclotron and a target of 99.8% enriched ^{71}Ga of about 500 μg/cm^2 thickness. A spectrum of tritons from the population of the IAS in ^{71}Ge is shown in Fig. 2(a).

Six parameter data was recorded on magnetic tape for all events triggered by a particle in the QDDD focal plane detector. Triton particle identification was obtained from the focal plane detector system, triton momentum was determined by the focal plane position, and the energy of coincident gamma rays was determined by the NaI detector. One time-to-amplitude converter (TAC) was started by the NaI detector and stopped by a signal from the cyclotron radio frequency generator ("RF-TAC"). This parameter provides a prompt coincidence constraint on the data to eliminate neutron and

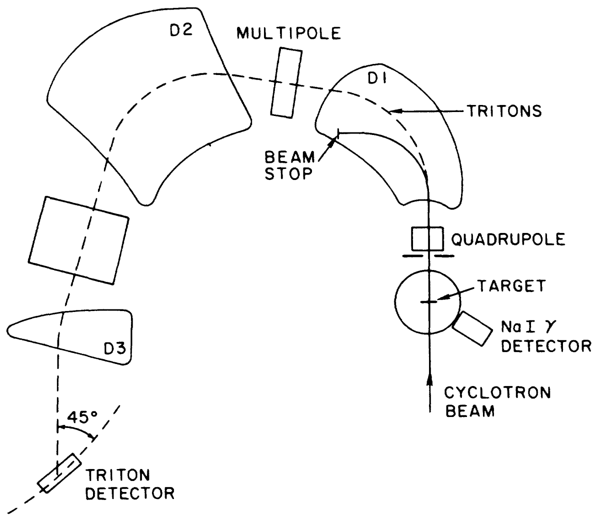

FIG. 1. Schematic of the experimental setup showing the beam stop inside the first dipole, the triton trajectory to the focal plane and the NaI position.

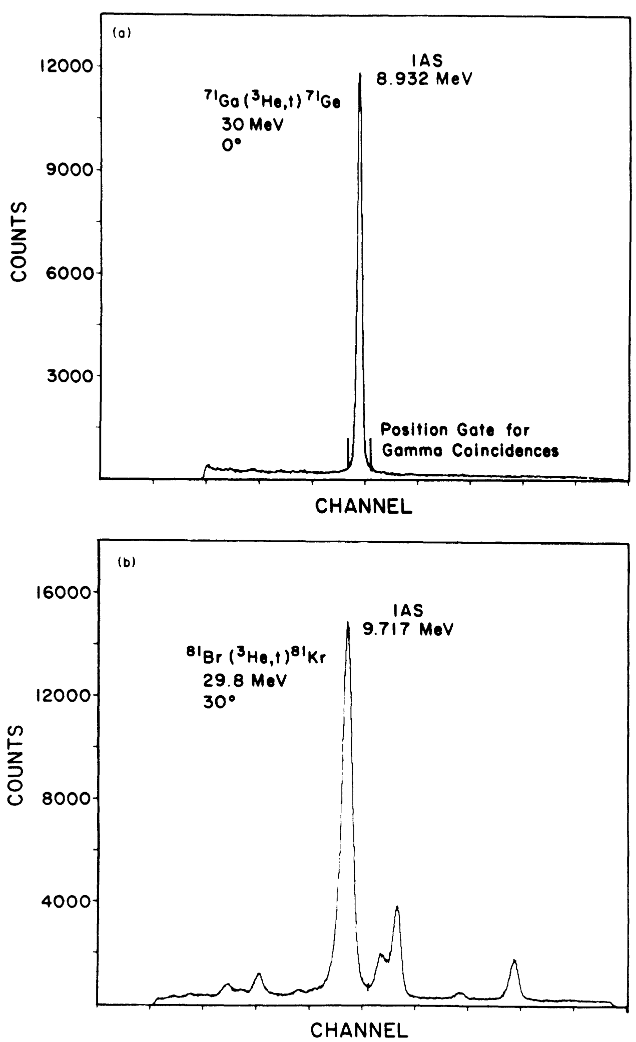

FIG. 2. Triton spectra obtained for the IAS in (a) ^{71}Ga(^{3}He,t)^{71}Ge reaction and (b) ^{81}Br(^{3}He,t)^{81}Kr reaction.

random backgrounds. A second TAC was started by the signal from the QDDD focal plane scintillator and was stopped by the NaI detector ("Reals-TAC"). This parameter provides a constraint on true versus random coincidences between the two detectors. The beam current was adjusted to provide a constant 80 kHz rate in the NaI detector.

Gamma ray spectra were accumulated with gates on the IAS peak in the triton spectrum, the prompt peak in the "RF-TAC" and the "Reals-TAC". Figure 3(a) shows the gamma rays in coincidence with the "real" events in the "Reals-TAC", and Fig. 3(b) shows the gamma rays in coincidence with the "random" events in the "Reals-TAC".

To calibrate the system, two reactions were used, ^{27}Al(^{3}He,d)^{28}Si and ^{27}Al(^{3}He,t)^{27}Si as seen in Fig. 4. The 1.78 MeV 2^+ state in ^{28}Si is strongly populated and has a 100% gamma branch to the ground state providing a gamma line shape and pileup measurement. The ob-

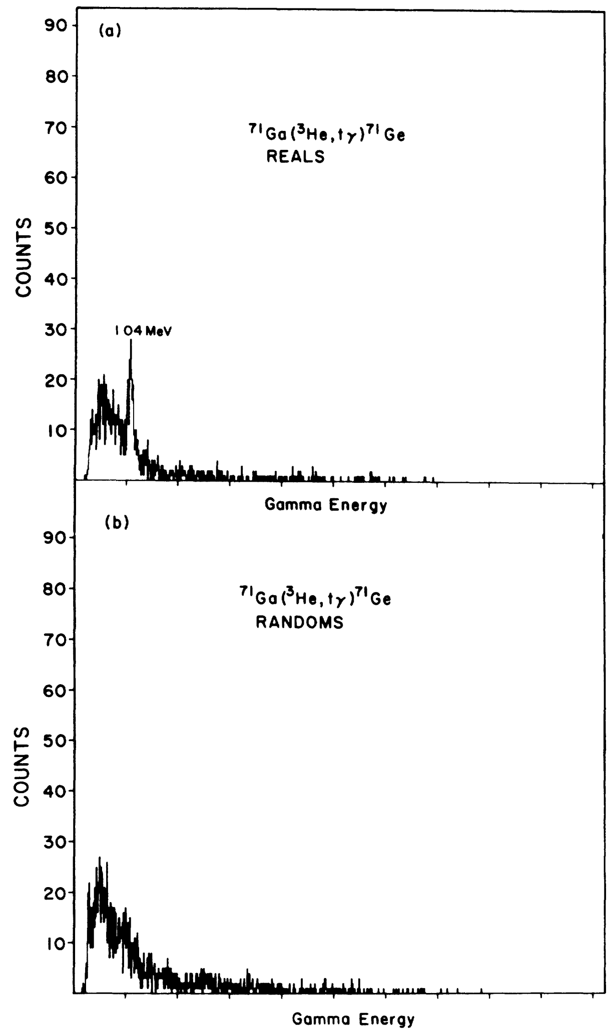

FIG. 3. (a) Spectrum of gamma rays in coincidence with tritons population the IAS in ^{71}Ge and the reals in the TAC's. (b) Spectrum of gamma rays in coincidence with the IAS in ^{71}Ge and the randoms in the TAC's.

served peak to total for the 1.78 MeV state is 0.329(4) compared to the expected value[16] of 0.35.

The 0.78 MeV $\frac{1}{2}^+$ state in ^{27}Si also has a 100% branch to the ground state which is isotropic and gives an efficiency measurement. The gamma rays in coincidence with these states are shown in Fig. 5. The observed peak to total for the 0.78 MeV states is 0.52(5) compared to the expected value[16] of 0.51. The overall coincidence efficiency was found to be 0.37(4)% by comparing the number of counts in the 0.78 MeV triton peak with the number of counts in the gamma photopeak. This compares to the expected efficiency of 0.37% as calculated for our geometry.

The ^{71}Ge IAS is energetically allowed to neutron decay to the ground state and the first two excited states of ^{70}Ge, or it may simply gamma decay to lower states in ^{71}Ge most probably by emitting high-energy gamma rays. Since the 1.22 MeV second excited state of ^{70}Ge decays 100% to the 1.04 MeV first excited state of ^{70}Ge, the gamma rays in coincidence with the tritons populating the ^{71}Ge IAS will show a 1.04 MeV peak for neutron decay to the first two excited states of ^{70}Ge, or no gamma ray for neutron decay to the ^{70}Ge ground state. High-energy gamma rays would be the experimental signature for decay to lower states in ^{71}Ge.

The ^{71}Ge IAS gamma coincidence spectrum clearly shows a 1.04 MeV gamma ray. Using the efficiency determined from the aluminum data, and correcting for backgrounds, the branching ratio of the ^{71}Ge IAS to a state producing a 1.04 MeV gamma is found to be 53(9)%.

From a pileup analysis, an upper limit can be set on the number of high-energy (>2.5 MeV) gammas. Assuming the dependence of pileup on photopeak energy is linear, using the peak shapes determined from the aluminum data, and including a 20% systematic uncertainty for the relative rates in the NaI for the gallium and aluminum measurements, the branching ratio for decay of the ^{71}Ge IAS by emission of a single high-energy gamma ray is found to be 3(4)% or less than 11% for a 95% confidence

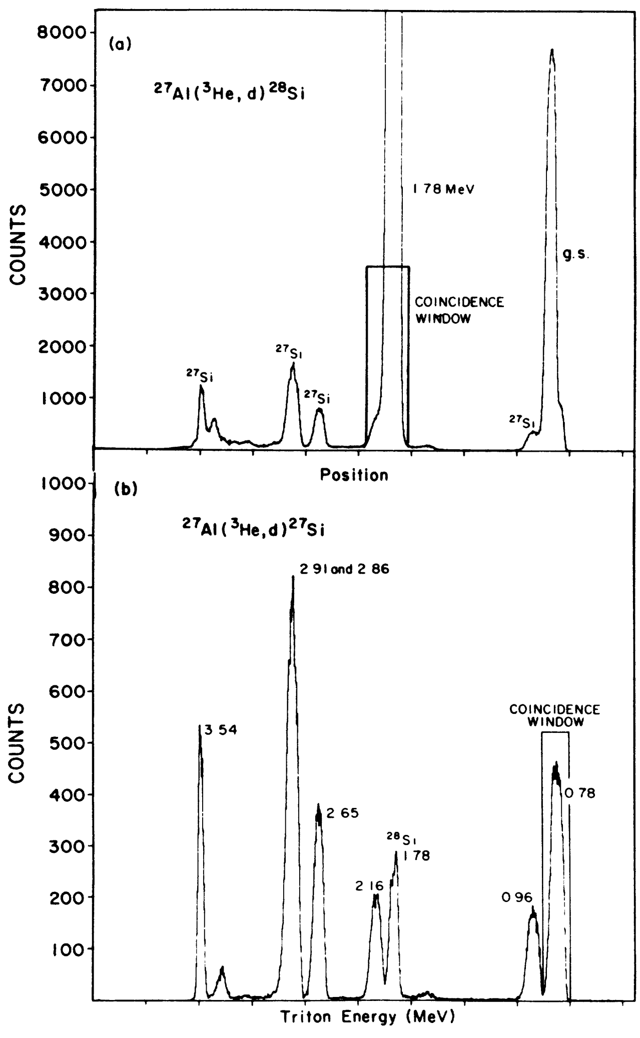

FIG. 4. Spectra at 30 MeV and 0°, indicating the coincidence window, for (a) ^{27}Al(^{3}He,d)^{28}Si showing the 1.78 MeV state and (b) ^{27}Al(^{3}He,t)^{27}Si showing the 0.78 MeV state.

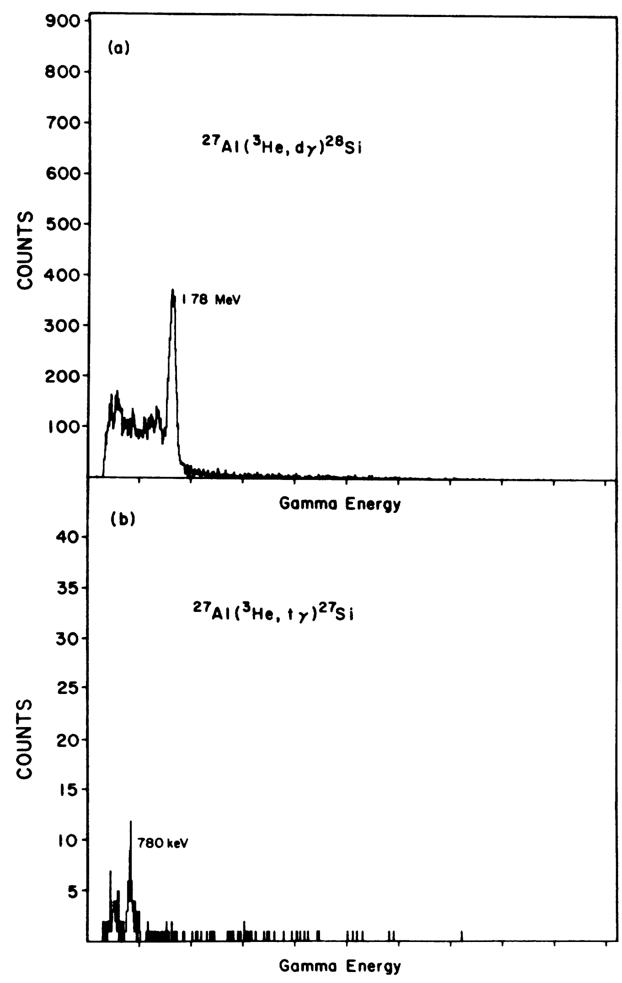

FIG. 5. Spectra of gamma rays, with randoms subtracted, in coincidence with the (a) ^{27}Al(^{3}He,d)^{28}Si 1.78 MeV state and (b) ^{27}Al(^{3}He,t)^{27}Si 0.78 MeV state.

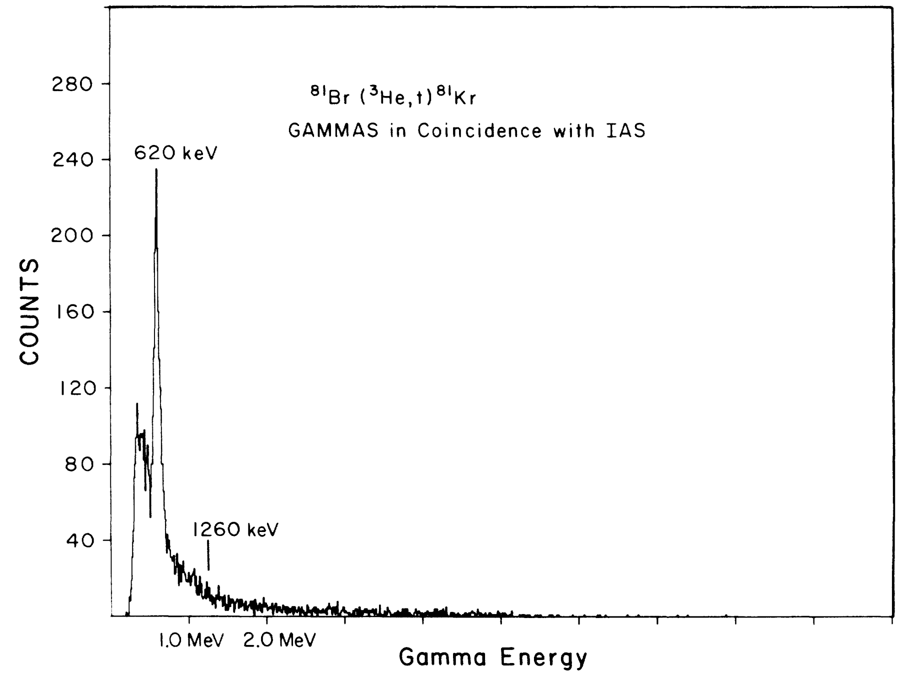

FIG. 6. Spectrum of gamma rays in coincidence with the IAS in ^{81}Kr and the reals in the TAC's. The position where a 1.26 MeV gamma would appear is indicated.

level. For emission of two 4.9 MeV gammas, the limit would be 8% for a 95% confidence level.

This result implies that the ^{71}Ge IAS does not decay by emission of high-energy gamma rays, but most likely decays completely by neutron emission.

^{81}Kr

The measurement of the decay of the ^{81}Kr IAS, seen in Fig. 2(b), used the same technique as that described for the ^{71}Ge IAS. The ^{81}Br(^{3}He,t)^{81}Kr reaction was observed at zero degrees with a 29.8 MeV ^{3}He beam on a 300 μg/cm^2 thick target of NaBr enriched to 97.8% in ^{81}Br.

The calibration of the system was again carried out with the ^{27}Al(^{3}He,d)^{28}Si and ^{27}Al(^{3}He,t)^{27}Si reactions. The ^{81}Kr IAS is energetically allowed to neutron decay to the ground, 0.617, 1.257, 1.320, 1.437, and 1.789 MeV states of ^{80}Kr. The gamma ray cascades of the excited states yield gamma rays with energies of 0.617 and 1.257 MeV (22% of the decay of the 1.257 MeV state), and others attributed to the unknown decay properties of the 1.320 MeV state. Again, high-energy gamma rays would indicate direct gamma decay of the IAS to lower states in ^{81}Kr.

The ^{81}Kr IAS gamma coincidence spectrum seen in Fig. 6, shows a strong 0.62 MeV gamma ray and no indication of a 1.26 MeV gamma ray (less than 1% as strong as the 0.62 MeV state). Using the efficiency (0.18), geometric factor (2.06), and peak to totals (0.57) determined from theory[16] and confirmed by the aluminum data, and correcting for backgrounds, the branching ratio of the ^{81}Kr state producing a 0.62 MeV gamma ray is found to be 1.1(2). From a pileup analysis, an upper limit can be set on the number of high-energy ($>$ 1.5 MeV) gamma rays. The branching ratio for the ^{81}Kr IAS to decay by emission of a single high-energy gamma ray is found to be 0(5)% or less than 10% for a 95% confidence level. For the emission of two 4.9 MeV gammas, the limit is 6.4% for a 95% confidence level.

This measurement implies that the ^{81}Kr IAS does not decay by emission of high-energy gamma rays, but most likely decays completely by neutron emission.

SUMMARY

The isobaric analog states in ^{71}Ge and ^{81}Br are cleanly produced using the (^{3}He,t) reaction. The gamma ray detection efficiency and pileup fraction were determined by measurements of the ^{27}Al(^{3}He,d)^{28}Si (1.78 MeV) and ^{27}Al(^{3}He,t)^{27}Si (0.78 MeV) reactions. By examining the high-energy portion of the gamma ray spectrum we were able to set an upper limit of 11% for the gamma decay branching ratio of the IAS in ^{71}Ge and 10% for the IAS in ^{81}Kr.

Therefore, the Fermi transitions to isobaric analog states in ^{71}Ge and ^{81}Kr will contribute less than 0.3 SNU (11% limit $\times$2% contribution $\times$133.7 SNU) and 0.2 SNU (10% limit $\times$6% contribution $\times$27.8 SNU), respectively, in gallium and bromine solar neutrino detectors for rates calculated from the standard solar model. A measurement of the decay of the IAS in ^{69}Ge is in progress.

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