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Three-particle breakup of the isobaric analog state in ^{17}F

J. C. Chow,[1] A. C. Morton,[1] R. E. Azuma,[1] N. Bateman,[1,2,4] R. N. Boyd,[3] L. Buchmann,[2] J. M. D'Auria,[4] T. Davinson,[5] M. Dombsky,[2] W. Galster,[6] E. Gete,[2] U. Giesen,[2,4] C. Iliadis,[1,2,*] K. P. Jackson,[2] J. D. King,[1] G. Roy,[7] T. Shoppa,[2] and A. Shotter[5]

[1]*Physics Department, University of Toronto, Toronto, Ontario, Canada M5S 1A7*
[2]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*
[3]*Departments of Physics and Astronomy, Ohio State University, Columbus, Ohio 43210*
[4]*Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6*
[5]*Department of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom EH9 3JZ*
[6]*Département de Physique, Université Catholique de Louvain, Louvain-la-Neuve, Belgium 1348*
[7]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2J1*

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We have studied the β-delayed particle decay of ^{17}Ne to test the feasibility of determining both the $E1$ and $E2$ components of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ cross section at energies relevant to helium burning in stars. In this context we have observed the breakup of the isobaric analog state in ^{17}F at 11.193 MeV into three particles via three channels: proton decay to the 9.59 MeV state in ^{16}O; and α decay to the 2.365 and 3.502/3.547 MeV states in ^{13}N. This is the first reported observation of the decay of the IAS to the 1^- state in ^{16}O at 9.59 MeV and the first reported β-delayed proton-α decay. With straightforward improvements to our detection apparatus to improve angular resolution, β suppression, and solid angle coverage, we should be able to proceed to the measurement of the effect of the tail of the subthreshold state at 7.117 MeV in ^{16}O on the α spectrum from the breakup of the 9.59 MeV state. [S0556-2813(98)50602-4]

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The β-delayed particle decay of ^{17}Ne has been the subject of two major experimental studies [1,2]. However, there are significant differences between the results of these studies, and the energetically allowed proton decay into unbound states of ^{16}O was not observed in either work. The decay into unbound states in ^{16}O also offers, in principle, the possibility of determining the reduced α width of the $J^\pi=2^+$ bound state at $E_x=6.917$ MeV in ^{16}O. This reduced α width is intimately related to the strength of the $E2$ component in the astrophysically important $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ radiative capture reaction [3–5]. This component has been shown to be poorly constrained by present data and difficult to determine by future direct measurements [5].

Recently, we have used the β-delayed α-particle spectrum from ^{16}N ($t_{1/2}=7.13$ s) to constrain the $E1$ cross section at low energies. Simultaneous fits were made to the ^{16}N β-delayed α spectrum, to the four sets of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ $E1$ cross-section data, and to the $^{12}\mathrm{C}(\alpha,\alpha)^{12}\mathrm{C}$ phase shifts. From the fits we were able to determine the α width of the subthreshold 1^- state at 7.117 MeV, and thereby much reduce the uncertainty in the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ $E1$ cross section at 300 keV [6,7]. However, 2^+ states are not significantly populated in the decay of ^{16}N and our knowledge of the $E2$ component was not improved by that experiment. However, in the β-delayed proton decay of ^{17}Ne, both 1^- and 2^+ states in ^{16}O are populated. Therefore, we are investigating the decay of ^{17}Ne to see if we can determine the strengths of the tails of both the 6.917 and 7.117 MeV subthreshold states in the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction. Here we report the first observation of the decay of the isobaric analog state (IAS) in ^{17}F to the 1^- state of ^{16}O at 9.59 MeV. A detailed study of this decay mode should provide an independent check on the $E1$ strength in $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$. We also give corrected branching ratios for the decay of the IAS.

The energy available for the β^+ decay of ^{17}Ne is 13.51 MeV [8]. Since ^{17}F is bound by only 0.6005 MeV against proton decay to ^{16}O, most states populated in the β decay of ^{17}Ne will decay by proton emission [1,2,8]. States in ^{17}F with energy greater than 7.762 MeV may decay into α-unbound states in ^{16}O, including the tails of the subthreshold 6.917 and 7.117 MeV states. The partial level scheme for ^{17}Ne decay [2,8] shown in Fig. 1 indicates that all states in ^{17}F above 5.819 MeV may also decay into ^{13}N plus an α particle.

The TISOL facility [9] at the TRIUMF laboratory has been used to investigate the β-delayed proton decay of ^{17}Ne to excited states of ^{16}O. A ^{17}Ne beam was produced by bombarding a MgO target with 500 MeV protons and extracting a mass 17 beam from an on-line ECR source. The branching ratios for the decay to bound excited states in ^{16}O were determined by measuring proton–γ-ray coincidences. Transitions were observed to the 2^+ state at 6.917 MeV in ^{16}O from states in ^{17}F at 11.193, 10.0, 9.45, 8.83, and 8.44 MeV. Many new transitions to the 1^- state at 7.117 MeV and to the 3^- state at 6.130 MeV were also observed, and the decay of the IAS to the 2^- state in ^{16}O at 8.872 MeV was seen for the first time [10,11].

To collect a low-background α-particle spectrum with a component from the tail of the subthreshold state in ^{16}O at

*Present address: Department of Physics and Astronomy, The University of North Carolina at Chapel Hill, Chapel Hill, N.C. 27599-3255.

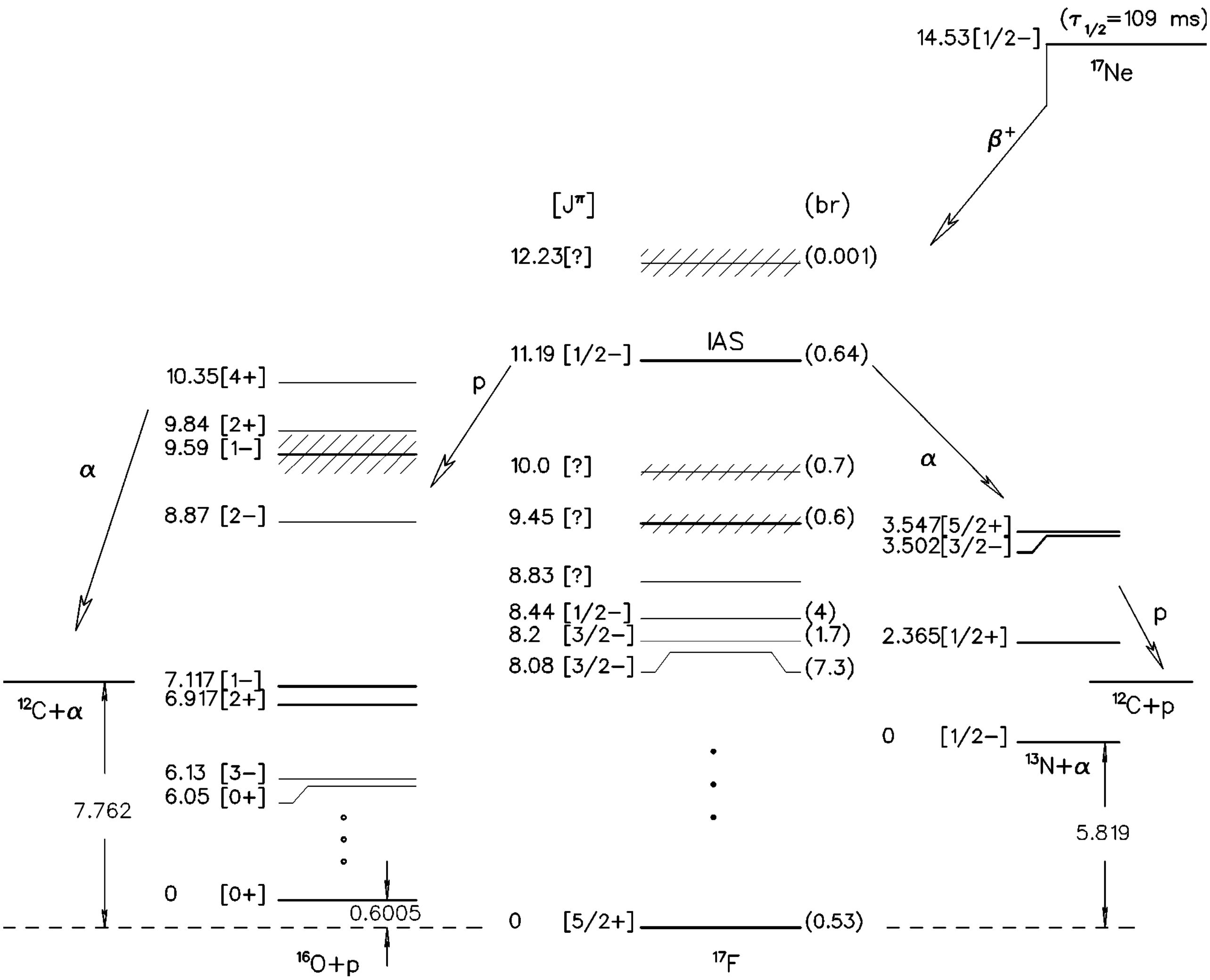

FIG. 1. Partial decay scheme of ^{17}Ne [2,8]. States below 8 MeV in ^{17}F are omitted since they cannot populate the 2^+ state at 6.917 MeV in ^{16}O via proton decay.

6.917 or 7.117 MeV will require a triple coincidence between the α particle, the recoiling ^{12}C nucleus, and the proton emitted from the parent ^{17}F state. The IAS in ^{17}F at 11.193 MeV has a width of only 0.18 keV [8] and is populated in $\approx$0.7% of the ^{17}Ne decays. It decays by proton emission to all states in ^{16}O up to the 9.59 MeV state (first reported here) and by α emission to the ground and first excited states of ^{13}N. Thus, the IAS seems a good candidate state in ^{17}F for the observation of p-α-^{12}C triple coincidences.

A Monte Carlo simulation was used to define an optimum detector arrangement for observing triple coincidences. The experimental arrangement (see Fig. 2) consisted of two 900 mm^2 ion-implanted Si detectors at right angles, and two 450 mm^2 ion-implanted Si detectors placed at 110^o to one of the larger detectors. The detector plane was inclined at 45^o to the incoming ^{17}Ne beam in order to provide access for the beam to a 10 μg cm^{-2} carbon collector foil at the center of the array. The beam intensity was typically 1–2$\times 10^4$ s^{-1}.

In order to reduce the event rate, the master trigger was set to require coincidences between any adjacent pair of detectors. Triple coincidence spectra were combined into the triple-energy-sum spectrum of Fig. 3. The breakup of the recoiling ^{16}O and ^{13}N nuclei produces a back-to-back α-^{12}C or proton-^{12}C pair, respectively, in the center-of-mass system. Since the decay of excited states in ^{17}F is predominantly by proton emission [1,2,10,11], and each proton decay is accompanied by an ^{16}O recoil, an accidental event in the

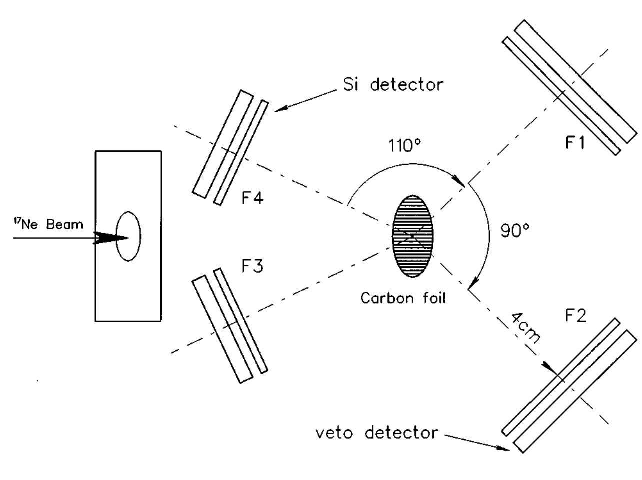

FIG. 2. Detector arrangement for the detection of p-α-^{12}C triple coincidences from the decay of the IAS in ^{17}F.

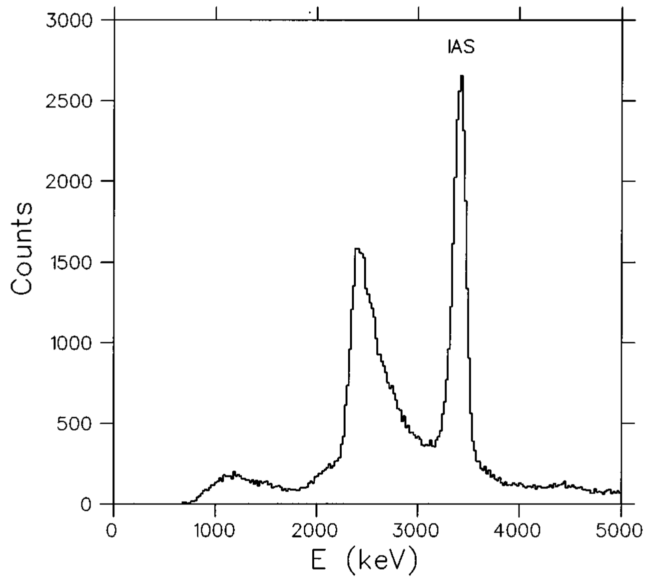

FIG. 3. Triple sum spectrum for the β-delayed particle decay of ^{17}Ne. See text for details.

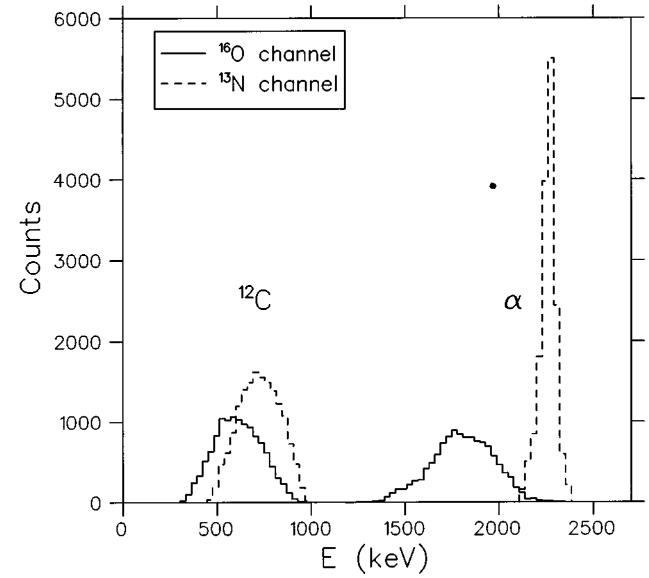

FIG. 5. Spectrum of α particles and ^{12}C recoil nuclei in triple coincidence with protons resulting from the breakup of the IAS of ^{17}F. The full curve is the spectrum for proton decay to the 9.59 MeV state of ^{16}O followed by breakup into $\alpha+{}^{12}$C. The dashed curve is the spectrum for α decay to the 2.365 MeV state in ^{13}N followed by breakup into p$+{}^{12}$C. The spectra were obtained by setting conditions on proton-^{12}C coincidences as indicated in Fig. 4.

third counter (at 90°) will provide a triple coincidence. If all triple coincidences are assumed to be p-α-^{12}C events then, from the measured energies and conservation of mometum, the angles between the particles can be calculated. Rejection of events with angles outside the ranges covered by the detectors eliminated most of the background in the spectrum due to two-body decays.

The energy difference between the IAS in ^{17}F and the threshold for breakup into α + ^{12}C in ^{16}O is 3.43 MeV [8]. A narrow peak at about 3.4 MeV is apparent in Fig. 3. The peak near 2.4 MeV is due primarily to the strong α decay of the 8.08 MeV state to the ground state of ^{13}N, which has not been removed completely by the kinematic cut. The width of the peak associated with the IAS decay is compounded from the inherent resolution of the system and the inaccuracy of energy calibration of lower-energy α particles and ^{12}C recoils, plus a possible contribution from misidentified low-energy particles.

Single and double coincidence spectra were then obtained with a gate set on the 3.4 MeV peak of Fig. 3. A plot of ^{12}C

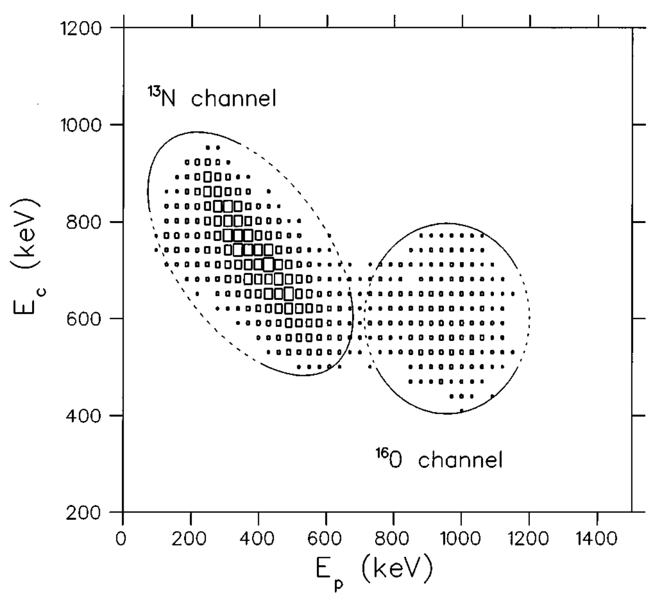

FIG. 4. Two-dimensional plot of protons versus ^{12}C recoil nuclei emitted during the breakup of ^{17}F in its IAS. The ellipses show the gates used to obtain the particle spectra of Fig. 5.

TABLE I. Branching ratios for the decay of the IAS of ^{17}F.

Particle	E_x (MeV)	$J^\pi;T$	B.R. (%) [1]	B.R. (%) [2]	Present (%)
	(^{16}O)				
	0	$0^+;0$	10±2	10.7±0.6	7.8±0.4
p	6.049	0^+	<3	11±3	9.6±0.8
	6.130	3^-	22±2	25±2	17.6±0.6
	6.917	2^+	24±6	<4	0.5±0.1
	7.117	1^-	44±4	18±3	13.4±0.3
	8.872	2^-	–	–	8.6±1.2
	9.59	1^-	–	–	22.7±11.3
	(^{13}N)				
α	0	$\frac{1}{2}^-;\frac{1}{2}$	–	1.1±0.5	0.8±0.2
	2.365	$\frac{1}{2}^+$	–	29±9	14.6±1.1
	3.50/3.55	$\frac{3}{2}^-/\frac{5}{2}^+$	–	–	1.0±0.5
	(^{17}F)				
γ	0.495	$\frac{1}{2}^+;\frac{1}{2}$		3.4±1.5 [a]	

[a]Branching ratio for γ decay taken as given in Ref. [2].

recoil energy versus proton energy summed over the F1F2F3 and F1F2F4 detector configurations (see Fig. 2) is shown in Fig. 4. Protons from the IAS to the 9.59 MeV state in ^{16}O should peak at about 1 MeV in the laboratory frame of reference, while α particles from the breakup of the 9.59 MeV state should appear at about 1.8 MeV, with the ^{12}C recoils at about 0.6 MeV. If the IAS decays by emission of an α particle to the excited state in ^{13}N at 2.365 MeV, the proton, α, and ^{12}C energies are near 0.4, 2.3, and 0.7 MeV, respectively, in our choice of detector geometry. The two coincidence peaks outlined in Fig. 4 show that these two decay modes are fairly well separated; this separation arises only because the α energies of the two modes are themselves well separated. Figure 5 shows the α and ^{12}C spectra obtained by setting gates on the two ellipsoidal areas outlined in Fig. 4. This observation of βp-delayed α particles from ^{17}Ne through the IAS of ^{17}F adds another branch to the proton decay of the IAS reported in Ref. [11] and represents the first reported β-delayed pα decay.

In Table I we summarize the branching ratios for the decay of the IAS in ^{17}F [1,2,10,11]. New proton branches to the 8.872 and 9.59 MeV states in ^{16}O have been observed. The proton branch to the 9.59 MeV state in ^{16}O and the α-particle branch to the 2.365 MeV state in ^{13}N have both been observed (in true triple coincidence) to lead to breakup of the recoiling unbound residual nucleus.

The detection of 14,000 triple-coincidence decay events at 0.15% coincidence efficiency into the 9.59 MeV state of ^{16}O corresponds to approximately 2×10^{-6} of the total observed ^{17}Ne decays. This is about a factor of 10^4 more than the number of β-delayed proton decays through the IAS estimated to populate the tail of the 7.117 MeV state in ^{16}O and to have been detected in this experiment. While it would be straightforward with the ^{17}Ne yields recently achieved with TISOL ($\geqslant 2\times10^5$ s$^{-1}\mu$A^{-1}), with improved angular resolution, and with much larger solid angle coverage, to achieve the count rate required to detect the tail of this subthreshold state in ^{16}O, further detector improvements have to be made to suppress false triple coincidences resulting primarily from coincidences with β particles.

In the next phase of our study, with improved β suppression and much better statistical accuracy, it should be feasible to determine the influence of the tail of the subthreshold 7.117 MeV state on the α spectrum from the decay of the IAS into the 9.59 MeV state of ^{16}O. This will provide an independent determination of the effect of this subthreshold state on the ^{12}C$(\alpha,\gamma)^{16}$O cross section for comparison with the result obtained from ^{16}N decay [6,7].

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[1] J.C. Hardy, J.E. Esterl, R.G. Sextro, and J. Cerny, Phys. Rev. C **3**, 700 (1971).
[2] M.J.G. Borge *et al.*, Nucl. Phys. **A490**, 287 (1988).
[3] W.A. Fowler, Rev. Mod. Phys. **56**, 149 (1984).
[4] T.A. Weaver and S.E. Woosley, Phys. Rep. **227**, 65 (1993).
[5] L. Buchmann, R.E. Azuma, C.A. Barnes, J. Humblet, and K. Langanke, Phys. Rev. C **54**, 393 (1996).
[6] L. Buchmann *et al.*, Phys. Rev. Lett. **70**, 726 (1993).
[7] R.E. Azuma *et al.*, Phys. Rev. C **50**, 1194 (1994).
[8] D.R. Tilley, H.R. Weller, and C.M. Ceves, Nucl. Phys. **A564**, 1 (1993).
[9] J.M. D'Auria, L. Buchmann, M. Dombsky, P. McNeely, G. Roy, H. Sprenger, and J. Vincent, Nucl. Instrum. Methods Phys. Res. B **70**, 75 (1992).
[10] J.D. King *et al.*, in *Proceedings of the Fourth International Symposium on Nuclear Astrophysics: Nuclei in the Cosmos*, Notre Dame, IN, 1996 [Nucl. Phys. **A621**, 169c (1997)].
[11] J.D. King *et al.*, in *Proceedings of the International Workshop on the Physics of Unstable Nuclear Beams*, Serra Negra, São Paulo, Brazil, 1996, edited by C.A. Bertulani, L. Felipe Canto, and M.S. Hussein (World Scientific, New Jersey, 1997), p. 15.