^{31}Ar examined: New limit on the β-delayed three-proton branch

H. O. U. Fynbo,[1] L. Axelsson,[2] J. Äystö,[3] M. J. G. Borge,[4] L. M. Fraile,[4] A. Honkanen,[3,*] P. Hornshøj,[1] Y. Jading,[5] A. Jokinen,[3] B. Jonson,[2] I. Martel,[5,†] I. Mukha,[1,‡] T. Nilsson,[2,§] G. Nyman,[2] M. Oinonen,[3,§] K. Riisager,[1] T. Siiskonen,[3] M. H. Smedberg,[2] O. Tengblad,[4] F. Wenander,[2] and the ISOLDE Collaboration[5]

[1]*Institut for Fysik og Astronomi, Aarhus Universitet, Denmark*
[2]*Fysiska Institutionen, Chalmers Tekniska Högskola, Göteborg, Sweden*
[3]*Department of Physics, University of Jyväskylä, Finland*
[4]*Instituto de Estructura de la Materia, CSIC, Madrid, Spain*
[5]*EP Division, CERN, Genève, Switzerland*

(Received 17 December 1998)

We have remeasured the decay of ^{31}Ar with a setup sensitive to multiparticle decay branches and obtained a new limit of 1.1×10^{-3} (99% C.L.) on the β-delayed three-proton branch between the isobaric analog state in ^{31}Cl and the ground state of ^{28}Si. This a factor of 17 below the previously reported first observation of β-delayed three-proton emission in ^{31}Ar. The limit on a possible $\beta 3p$ branch to the first excited state in ^{28}Si is 2.9×10^{-4}. [S0556-2813(99)04404-0]

PACS number(s): 23.90.+w, 23.40.Hc, 24.30.Gd, 27.30.+t

β-delayed multiparticle emission becomes increasingly important when approaching the drip lines [1]. On the neutron-rich side of β stability, β-delayed three-neutron emission has been seen from ^{11}Li [2] and in the case of ^{17}B even β-delayed four-neutron emission has been reported [3]. On the proton-rich side the first observation of β-delayed three-proton emission ($\beta 3p$) was reported in the decay of ^{31}Ar in an experiment performed at GANIL eight years ago [4]. The detector used in that experiment consisted of nine segments, enabling events with higher multiplicities to be detected. The events assigned to the $\beta 3p$ branch had a multiplicity of at least 2. In addition the observation was based on energetics, with the proposed $\beta 3p$ branch going through the isobaric analog state (IAS) in ^{31}Cl to the ground state in^{28}Si and with an estimated branching ratio of 2.1(10)%.

In a recent experiment at ISOLDE we have measured the β decay of ^{31}Ar with a setup designed to have a high efficiency for multiparticle decays. The ^{31}Ar beam, with an intensity of 3 atoms/s, entered through the central hole of a hemispherical mount holding 15 silicon (Si) *p-i-n* diode detectors, and was stopped in a carbon foil placed in front of a double-sided (16×16 strips) Si detector. No particle identification is possible with this setup, but with detector thicknesses of about 300 μm, β particles in most cases deposit less than 500 keV. The electronics had a lower limit on the trigger of about 500 keV in the strip detector and about 250 keV in the *p-i-n* diode detectors. With a total solid angle of 25% of 4π divided into 271 segments, this setup combines excellent efficiency with good angular resolution. Both are essential for this type of study, enabling a very stringent test of the existence of the proposed $\beta 3p$ branch. For more details about the setup and the results on the $2p$ branches from the same experiment, see [5].

With the high segmentation of the setup, the analysis of the multiparticle events is in principle straightforward. From the energy and angles of the three detected particles, momentum conservation (assuming they are all protons) is used to derive the recoil energy of the daughter nucleus and thus to reconstruct the full decay energy (Q_{3p}) of the event. The result of this procedure is the Q_{3p} spectrum shown in Fig. 1. The figure shows events with Q_{3p} up to and above 8 MeV with no prominent (narrow) peaks. It is unlikely that all counts in Fig. 1 are $3p$ events as strong feeding is not expected to states above the IAS, which has a Q value of 4.87(5) MeV for the transition to the ground state of ^{28}Si. Since ^{31}Ar has a large branch of β-delayed two-proton emission ($\beta 2p$), the most obvious source of background is $\beta 2p$ events. This hypothesis is easily tested in the following way: For each multiplicity-3 event we assign the signal with the lowest energy to be the β particle and calculate the Q_{2p} value of the remaining two signals (assuming they correspond to protons). The result of this procedure is shown in Fig. 2 where the strongest two-proton transitions from the IAS to the lowest states in ^{29}P can clearly be identified; for comparison see Fig. 3 in [6]. Thus the group of counts around 8 MeV in Fig. 1 stems from β particles in coincidence with the $2p$ transition at 7.6 MeV connecting the IAS with the ground state in ^{29}P. A Kolmogorov test [7] between the spectrum shown in Fig. 2 and the Q_{2p} spectrum from the multiplicity-2 events (to be described in detail separately in [5]) above 2.5 MeV gives a probability of 15% that the two spectra are derived from the same distribution. This means that all counts in Fig. 1 are consistent with being $\beta 2p$ events, excluding any positive identification of $\beta 3p$ branches. The $\beta 2p$ background varies between 0.5 and 2.5 counts/(20 keV) depending on the structure of the Q_{2p} spectrum.

*Present address: Helsinki Institute of Physics, University of Helsinki, P.O. Box 9, FIN-00014, Finland.

†Present address: University of Sevilla, Sevilla, Spain.

‡Permanent address: Kurchatov Institute, 123182 Moscow, Russia.

§Present address: EP Division, CERN, Genève, Switzerland.

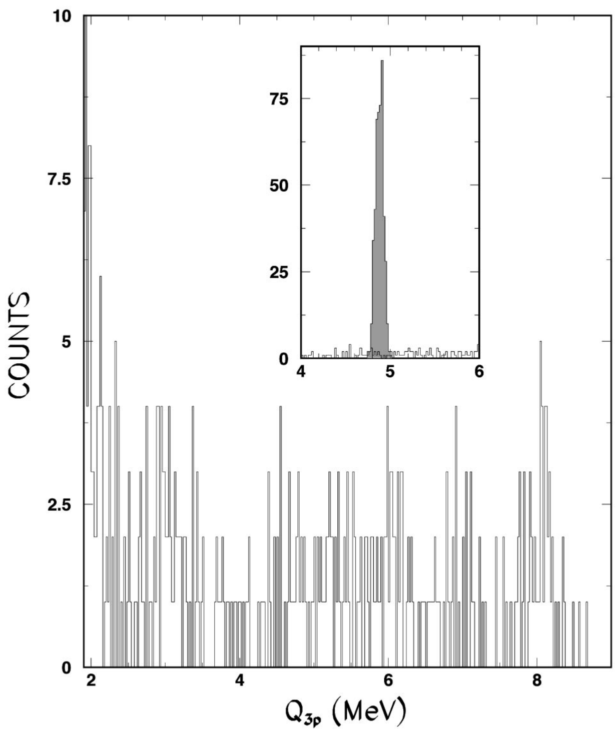

FIG. 1. Q_{3p} spectrum from multiplicity-3 events. The inset shows the data together with the results of a Monte Carlo simulation of the $3p$ emission normalized to a branching ratio of 2.1%.

The inset in Fig. 1 shows the data together with the result of a Monte Carlo simulation of $3p$ emission from the IAS to the ground state of ^{28}Si with a normalization corresponding to the previously reported branching ratio. In this simulation the individual proton energies and angles are distributed according to phase space only. Further, the energy resolution and geometry of the detectors are taken into account, leading to the peak shown in Fig. 1. With the Monte Carlo simulation the $\beta 2p$ peaks from the same experiment are well described. We also simulate $3p$ emission between the IAS and the first excited state in ^{28}Si at 1.779 MeV, whereas the second excited state at 4.617 MeV lies too high to be relevant. In the analysis of the Q_{3p} spectrum we make a conservative estimate of the $\beta 2p$ background of 0.5 counts/(20 keV) in the kinematically allowed regions for the $\beta 3p$ events, which themselves are determined by the width of the peaks from the Monte Carlo simulations. Since our setup does not have a full angular coverage, the efficiency of detection is sensitive to angular correlations between the emitted protons. Convoluting our acceptance with angular correlation functions, we find that in the worst case the acceptance is reduced by 15% compared to the case where the angular distributions between the protons are isotropic. We include this factor in the limits quoted below.

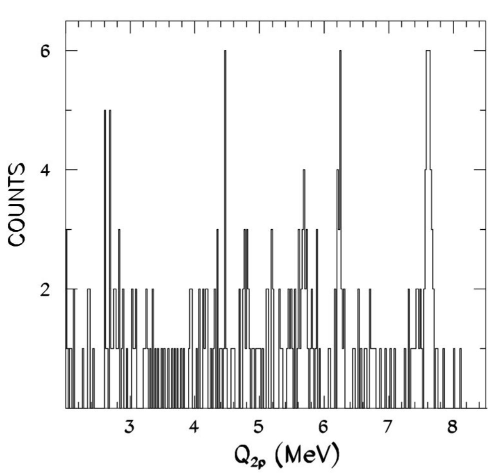

FIG. 2. Q_{2p} spectrum from multiplicity-3 events. We assume that the signal with the lowest energy is a β particle and calculate the Q_{2p} value assuming the remaining two particles are protons.

A point of importance is the threshold used in the detector systems. In general we do not expect to observe protons with energies less than our largest threshold of about 500 keV since the Coulomb barrier hinders emission of protons with low energy, and gamma decay takes over. From the $\beta 2p$ transitions in the same decay, and from other cases of β-delayed two-proton emission, we expect the emission to take place via states in the intermediate nuclei [5]. Since the first two protons have many possible intermediate states available, it is unlikely that they will be emitted with low energies. Hence, we only have to consider the relevant states in ^{29}P, which are well known [8]. The lowest state from which proton emission is observed is the state at 4.954 MeV, with a corresponding proton energy of 2.21 MeV [9]. The only state giving protons below 500 keV is the $5/2^+$ state at 3.106 MeV, but this hypothetical 345 keV proton would have angular momentum 2 and thus be strongly hindered. Furthermore, the detector system is indeed sensitive to events down to proton energy 250 keV if that proton is detected in one of the p-i-n diode detectors. This constraint corresponds to less than a factor of 2 reduction in the solid angle.

The deduction of limits from a Poisson distribution with constant background is a problem treated recently by Feldman and Cousins [10]. From the 2.1 MeV proton group with a known branching ratio of 29(3)% (the weighted mean of the values quoted in [4] and [11]) we arrive at $1.0(1)\times 10^6$ ^{31}Ar atoms collected on the foil. Correcting for the solid angle, this result allows us to derive an upper limit on the branching ratio. The application of this procedure to the $\beta 3p$ branches between the IAS and the ground state and the first excited state in ^{28}Si results in the limits given in Table I. Since the detector system was operated with two different thresholds, we also give limits on the $\beta 3p$ branches corresponding to an off-line lower limit on the individual particle energies of 500 keV, which corresponds to our highest threshold. The limits given are at the 99% confidence level. The presence of the $\beta 2p$ background prevents us from placing any lower limit on the $\beta 3p$ transitions.

The introduction of the low energy cut leads to a reduction in the number of counts, consistent with most of the multiplicity-3 events being $\beta 2p$ events where the β particle is recorded in a p-i-n diode detector with the low threshold. As our final result we adopt the limit corresponding to all particles being above 500 keV. This value is a factor of 17 below the intensity reported by Bazin *et al.* [4].

Turning now to a possible explanation of this discrepancy, we first note that their observation was based partly on

TABLE I. Upper limits for $\beta 3p$ branches in the decay of ^{31}Ar via the IAS in ^{31}Cl. E_{th} is an off-line threshold on the particle energies introduced in the analysis to ensure a consistent threshold. The upper limits are at the 99% confidence level.

	IAS→ground state in ^{28}Si: $Q_{3p}=4.87(5)$ MeV			
E_{th}	Counts	Background	Upper limit	Branching ratio
0 keV	12	5	18.8	1.7×10^{-3}
500 keV	5	1	12.3	1.1×10^{-3}
	IAS →1. exited state in ^{28}Si: $Q_{3p}=3.09(5)$ MeV			
E_{th}	Counts	Background	Upper limit	Branching ratio
0 keV	17	5	25.3	2.2×10^{-3}
500 keV	0	1	3.8	2.9×10^{-4}

the sum energy in the detector system being that expected for a transition to the ^{28}Si ground state and partly on the multiplicity being at least 2. Second, we note that with these criteria it is not possible to distinguish between a $\beta 3p$ branch from the IAS and a $2p$ branch from another state in ^{31}Cl that accidentally gives the same sum energy. Incidentally, in our experiment we observe a $\beta 2p$ peak with a Q value of 4.8 MeV with an intensity of 0.6(1)% [5], and we suggest that the existence of this branch may in part explain the observation of Bazin *et al.* As argued above, it is unlikely that the threshold of maximum 500 keV in our setup will explain the discrepancy.

In conclusion, we have reinvestigated the β decay of the drip line nucleus ^{31}Ar and find that the previous claim of the existence of a strong $\beta 3p$ branch in this decay cannot be verified. We place an upper limit on the $\beta 3p$ branch between the IAS and the ground state in ^{28}Si of 1.1×10^{-3} (99% C.L.).

[1] B. Jonson and G. Nyman, in *Nuclear Decay Modes*, edited by D.N. Poenaru (Institute of Physics, Bristol, 1990), p. 102.

[2] R.E. Azuma, T. Bjǿrnstad, H.Å. Gustafsson, P.G. Hansen, B. Jonson, S. Mattsson, G. Nyman, A.M. Poskanzer, and H.L. Ravn, Phys. Lett. **96B**, 31 (1980).

[3] J.P. Dufour *et al.*, Phys. Lett. B **206**, 195 (1988).

[4] D. Bazin *et al.*, Phys. Rev. C **45**, 69 (1992).

[5] M.J.G. Borge *et al.* (unpublished).

[6] L. Axelsson *et al.*, Nucl. Phys. **A628**, 345 (1998).

[7] W.T. Eadie, D. Drijard, F.E. James, M. Roos, and B. Sadoulet, *Statistical Methods in Experimental Physics* (North-Holland, Amsterdam, 1971), p. 269.

[8] P.M. Endt, Nucl. Phys. **A521**, 1 (1990).

[9] D.J. Viera, R.A. Gough, and J. Cerny, Phys. Rev. C **19**, 177 (1979).

[10] G.J. Feldman and R.D. Cousins, Phys. Rev. D **57**, 3873 (1998).

[11] V. Borrel *et al.*, Nucl. Phys. **A531**, 353 (1991).