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β-decay of ^{13}O

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The β decay of ^{13}O has been studied at the IGISOL facility of the Jyväskylä accelerator centre (Finland). By developing a low-energy isotope-separated beam of ^{13}O and using a modern segmented charged-particle detector array an improved measurement of the delayed proton spectrum was possible. Protons with energy up to more than 12 MeV are measured and the corresponding $\log(ft)$ values extracted. A revised decay scheme is constructed. The connection to molecular states and the shell model is discussed.

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I. INTRODUCTION

Recently the $A = 13$ isobar has attracted interest as part of the discussion of molecular states consisting of neutrons occupying molecular-like orbits around α-particle clusters. This has been most successfully demonstrated in the Be isotopes where rotational bands have been identified and compared to detailed theoretical calculations, see, e.g., Refs. [1,2] and references therein. Similar states are expected to exist in the C isotopes where rotational bands have been suggested in ^{13}C from a survey of existing experimental data [3]. However, this suggestion is based on changing the spin-parity of several states above 9.5 MeV excitation energy in ^{13}C compared to the most recent compilation [4], and experimental verification of this assignment is clearly needed. The cluster structure suggested for these excited states should also influence their decay to the $n + {}^{12}$C or $n + 3\alpha$ final states. These decay properties are not known in detail for the relevant states.

Breaking of isospin symmetry has been suggested as a further indicator for molecular-like states because protons, because of Coulomb repulsion, are expected to be unable to occupy the molecular-like orbits [3]. Hence, in the $A = 13$ isobar one should expect isospin asymmetries between the β decays of ^{13}B and ^{13}O that feed excited states in ^{13}C and ^{13}N respectively. Work on the ^{9}Li/^{9}C pair has recently provided the largest asymmetry between mirror β transitions ever measured [5,6]. Presently no theoretical understanding of this large asymmetry exists, but differences in (cluster) structure of the ^{9}Be/^{9}B daughters could play a role. Because the $A = 13$ system can be thought of as "an α particle added to $A = 9$" independent of whether molecular structure is present, it would clearly be interesting to search for similar asymmetries within this system.

The β decays of ^{13}O and ^{13}B provide a test of the predictions of molecular orbits in ^{13}C: These decays populate $1/2^-$, $3/2^-$, and $5/2^-$ states in the daughters ^{13}N and ^{13}C, and hence spin assignments can be extracted from how the interesting states in the daughters are populated in these decays. Large isospin asymmetries could indicate the presence of molecular orbits in the neutron-rich part of the isobar.

Calculations of the ^{13}O and ^{13}B β decays are presented in Ref. [7] and recently in Ref. [8], where the former calculates transition strengths to the four lowest states in the daughters, and the latter includes estimates of the breaking of mirror symmetry, but includes only transitions to the ground states.

As a first step we present here new data on the β decay of ^{13}O using modern techniques for studying short-lived isotopes. Studies of ^{13}O β decay are reported in three papers prior to this work, all using the reaction ^{14}N$(p, 2n)^{13}$O for producing the activity [9–11]. These works have identified transitions to six states up to an energy of 10 MeV in the daughter ^{13}N. The focus of these earlier studies was on extracting β-decay asymmetries between the β decays of ^{13}O and ^{13}B with the aim of restricting possible induced currents in the weak interactions within these nuclei. The asymmetries were reported to be large in [10], but in the latest study [11] the ^{13}O half-life was remeasured and the asymmetries much reduced.

We outline our experimental approach in Sec. II, present the result of our analysis in Sec. III, and conclude the article with a discussion in Sec. IV.

II. EXPERIMENTAL

The previous experiments on ^{13}O decay all used the reaction ^{14}N$(p, 2n)^{13}$O with a $\simeq$1 mg/cm^2 N_2 gas target and a proton energy of 43–50 MeV (threshold 31.2 MeV). The produced radioactivity was then either directly measured from within

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TABLE I. Experimental values for energy, width, and relative intensities. For each level in ^{13}N information is given on the decay to different final states in ^{12}C after proton emission.

Literature				This work		
^{13}N level[a] (MeV)	E_p (cm)[b] (MeV)	Γ_{cm}[a] (MeV)	Relative intensities[c]	E_p (cm) (MeV)	Γ_{cm}[d] (keV)	Relative intensities
gs.	—	—	—	—	—	—
3.502(2)	1.559(2)	62(4)	100	1.5597(10)	63(4)	100
7.376(9)	0.993(9)	75(5)	1.7(8)[e]	1.006(6)	104(20)	2.4(3)
	5.433(9)		0.17(7)	5.445(6)		0.09(4)
8.918(11)	2.535(11)	230	1.44(25)	2.591(6)	278(16)	4.5(3)
	6.975(11)		4.83(51)	7.030(6)		5.3(4)
9.476(9)	3.092(9)	30	0.61(15)	3.175(6)	143(18)	1.06(11)
	7.532(9)		0.98(14)	7.614(6)		1.40(13)
10.36	3.976	30	0.12(8)	—	—	—
	8.416		0.05(3)	—		—
10.833(9)	4.449(9)	—	—	—	—	—
	8.889(9)		—	—		—
11.70(30)	5.356(30)	115(30)	—		315(112)	0.00(2)
	9.796(30)		— }	9.78(6)		0.15(4)
11.74(50)	5.360(50)	530(80)	—			
	9.800(50)		—			
13.26(10)	?	?	—	—	521(210)	0.00(9)
	?		—	11.32(9)		0.11(9)
15.06457	7.365	0.86(13)	—	7.396(53)	—[e]	0.011(2)[f]
	8.681		—	8.714(53)		0.030(5)[f]
	13.121		—	13.152(53)		0.049(7)
15.3(2)	9.0(2)	350(150)	—	—	—	0.000(4)
	13.4(2)		—	13.5(4)	—	0.04(3)

[a]From Ref. [4] except for the 13.26- and 15.3-MeV levels determined in this work.
[b]Calculated from $E_{\rm thresh} = 1.9435$ MeV, $E_{\rm ex} = 4.439$ MeV.
[c]From Ref. [11].
[d]Not corrected for nuclear recoil broadening from the β decay.
[e]Estimate from ^{12}C+p scattering [11].
[f]The decay branches of the IAS were fixed to values from Ref. [4].

the target or transported with a helium gas flow system to a counting area. The clear disadvantage of this approach is that the detectors see a very extended source, and particles emitted in the β decay have to pass through the gas and possibly windows before being detected.

To ameliorate the detection conditions an Isotope Separated On-Line (ISOL) beam of ^{13}O was developed at the IGISOL facility of the Jyväskylä accelerator centre (Finland). We also use the reaction ^{14}N$(p, 2n)^{13}$O, but use a solid state boron nitride target (1 mg/cm^2), which was placed in front of the IGISOL gas cell. The proton beam energy from the K130 cyclotron was varied between 40 and 50 MeV and the intensity between 10 and 30 μA, resulting in only modest variations in the yield of ^{13}O. The produced ions recoiled out of the target and stopped in the helium buffer gas, and the singly charged ions were then carried out by the helium flow and skimmed from the carrier gas before being injected into the mass separator by a 25-kV voltage, mass separated and stopped in a 30 μg/cm^2 carbon-foil; see Ref. [12] for a full description of this method.

The data presented here were obtained over a 40-h period with an average yield of ^{13}O deposited on the collection foil of 4–5 atoms/s determined from the branching ratios given in Table I.

The experimental setup is shown in Fig. 1. The collection point was viewed by three thin ($\simeq$60 μm) double-sided Si strip detectors (DSSSDs), which were all backed by thick Si pad detectors (two 1.500 μm and one 700 μm). These DSSSD telescopes permitted particle identification of protons of energy more than 2–3 MeV, depending on the angle of incidence on the DSSSD. Toward the beam direction the collection foil was viewed by the new ISOLDE Si ball, which is an array of 36 one-mm-thick segmented Si detectors (144 segments) developed at CERN-ISOLDE [13].

Energy and timing signals from all detector segments were analyzed by VME ADCs and TDCs and were recorded event by event on hard disks. The trigger was defined by a signal in any of the DSSSDs. The Si ball detectors were left out of the trigger because of their large response to the abundant β particles from ^{13}O and its daughter ^{13}N.

The detectors were energy calibrated using the α sources ^{148}Gd, ^{241}Am, and ^{20}Na, where the latter was produced on-line. Corrections were made for the pulse-height defect [14]. For the DSSSDs the special calibration procedure given in

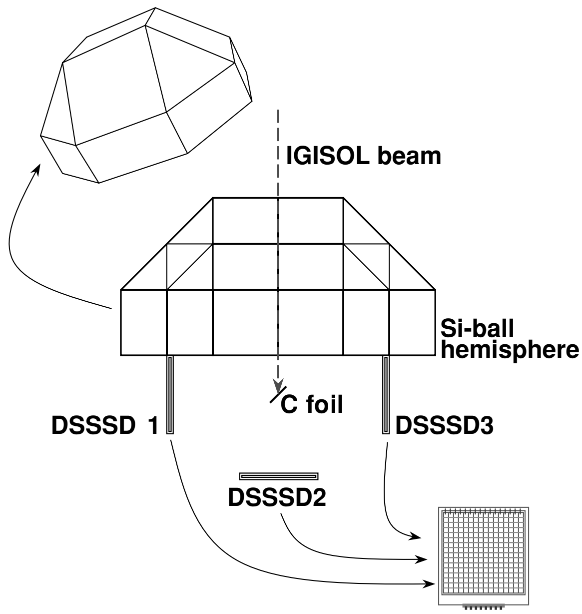

FIG. 1. A schematic drawing of the experimental setup for measuring β-delayed charged particles from ^{13}O.

Ref. [15] to correct for energy loss of α particles in detector deadlayers was applied. Two of the three DSSSDs were of a new design with reduced deadlayer to permit detection of low-energy particles [16].

III. RESULTS AND ANALYSIS

Figure 2 shows the spectrum of charged particles obtained from DSSSD telescopes number 1 and 3 on Fig. 1 (number 2 did not stop the highest energy protons emitted in the β decay of ^{13}O). The spectrum extends to both lower and higher energy and has slightly better statistics than the previous measurements [9–11]. The peak at 1 MeV center-of-mass energy (c.m.) and everything above 9 MeV is seen here for the first time. The full curve is a fit to the proton spectrum, which is explained in the following.

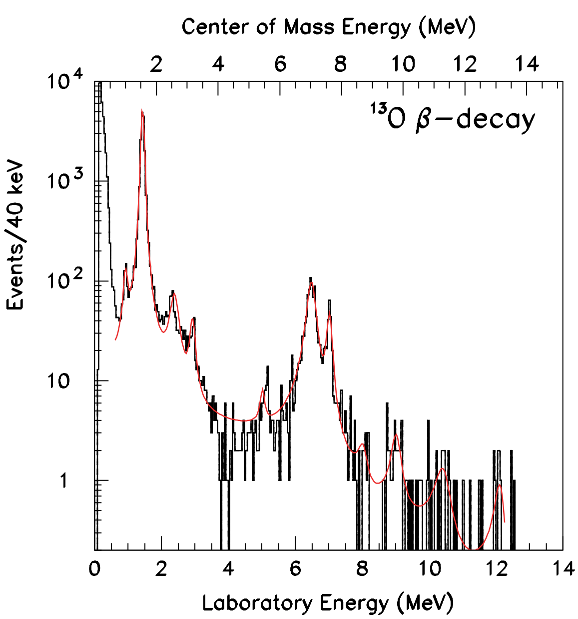

FIG. 2. (Color online) Delayed proton spectrum from the β decay of ^{13}O. The full curve is a fit using Breit-Wigner peak shapes modified by the integrated Fermi function (the f factor). The lower energy scale is the observed proton energy and the upper the center-of-mass energy.

We describe each populated level in the daughter ^{13}N by a Breit-Wigner peak shape multiplied by the integrated Fermi function to take into account that the low-energy sides of (broad) levels populated in β decay are enhanced. For each level we then determine the energy, width, and branching ratio. For levels above the $p + {}^{12}$C(4.439 MeV) threshold at 6.383 MeV we also determine the fraction populating the 4.439-MeV level in ^{12}C. For the Isobaric Analogue State (IAS) at 15.06 MeV the well-known [4] fractional decays to $^{12}C + p$ and $^{9}B + \alpha$ final states were kept fixed in the fit. We do not take into account interference effects between states of identical spin-parity populated in the decay, but estimate that such effects should be small. The fit takes into account detector resolution through a convolution with a Gaussian ($\sigma = 30$ keV). We do not correct for broadening because of nuclear recoil after β decay, and hence our extracted widths will be too large. The recoil broadening is estimated to be of order 20–40 keV. Protons with laboratory energy between 2–2.5 MeV barely penetrate the DSSSDs and enter the thick detectors behind. This energy region is therefore sensitive to deadlayers at the exit of the DSSSDs and entry of the thick detectors, and the energy calibration of the thick detectors at low energies. This is clear from Fig. 2, where the proton peak from the decay of the 7.376-MeV state to the 4.439-MeV state of ^{12}C is not well reproduced by the fit. To determine correctly this branch this region was taken out of the fit and the corresponding intensity extracted separately.

Because we did not determine the number of ^{13}O nuclei produced in our experiment we cannot extract absolute branching ratios, instead we normalize to the branching ratio of 9.2(2.0)% for the 3.502-MeV level determined in Ref. [11]. The branching ratio to the ground state was calculated by subtracting the branching ratios of the observed branches to excited states from 100%.

The best parameters determined from minimizing the Poisson maximum likelihood χ^2 using the MINUIT [17] package are shown in Table I, and the extracted branching ratios and $\log(ft)$ values for the populated levels in ^{13}N are given in Table II.

IV. DISCUSSION AND CONCLUSION

Our results for the transitions to the 3.5-, 7.4-, 8.9-, and 9.5-MeV states are in fair agreement with the latest evaluation [4]. Our observed proton energies from the 8.9- and 9.5-MeV levels are larger by 50 and 80 keV respectively. We do not expect these deviations will affect the conclusions expressed in the rest of this article. Only the ft values depend sensitively on level energies, but the variation caused by energy shifts of this magnitude are well within the error limits quoted in Table II. We have used level energies calculated from our

TABLE II. Experimental log(ft) values.

Literature				This work	
^{13}N level[a] (MeV)	J^π	% of all β decays[a]	log(ft)[a]	% of all β decays[b]	log(ft)[b]
gs.	$\frac{1}{2}^-$	89.2(2.2)	4.08(2)	88.7(2.0)	4.08(2)
3.502(2)	$\frac{3}{2}^-$	9.8(2.0)	4.55(9)	9.8	4.55
7.376(9)	$\frac{5}{2}^-$	0.18(9)	5.56(22)	0.24(2)	5.44(13)
8.918(11)	$\frac{1}{2}^-$	0.61(14)	4.66(10)	0.96(4)	4.45(10)
9.476(9)	$\frac{3}{2}^-$	0.16(4)	5.09(11)	0.24(2)	4.89(11)
10.36	$\frac{5}{2}^-$	0.02(1)	5.7(3)	—	—
10.833(9)	$\frac{1}{2}^-$	—	—	—	—
11.70(30)	$\frac{5}{2}^-$	—	— }	0.015(8)	5.4(3)
11.74(50)	$\frac{3}{2}^-$	—	—	—	—
13.26(10)	?$^-$	—	—	0.011(3)	4.8(3)
15.06457	$\frac{3}{2}^-$	—	3.306[c]	0.019(4)	3.12(17)
15.3(2)	$(\frac{3}{2})^-$	—	—	0.004(2)	3.3(7)

[a]From Ref. [4].
[b]Normalized to the 3.502-MeV state in Ref. [11].
[c]Estimated from the Fermi strength only.

proton energies in the calculation of the ft values given in Table II. Our relative intensities in Table I have in general reduced errors. For the 7.4-MeV state the existing values for the relative decay to the ground state and 4.439-MeV states in ^{12}C, which were estimated from $^{12}\mathrm{C}+p$ scattering data, are in good agreement with our direct measurement. For the 8.9-MeV state we see a higher relative branch to ^{12}C(4.439 MeV). We see no significant evidence for feeding to the 10.36-MeV state previously suggested in Refs. [10,11]. Only the transition to ^{12}C(4.439 MeV) was seen in these experiments and the branch to the ground state again estimated from $^{12}\mathrm{C}+p$ scattering. Hence, the identification of the 10.36-MeV state in this decay rests on a good understanding of the proton spectrum near 4 MeV center-of-mass energy, a region dominated by the high energy tails of the peaks at lower energy. We believe that our Gaussian convoluted Breit-Wigner lineshapes describe these tails well and suggest that the previous observations of this peak were because of insufficient treatment of this effect. The fitted χ^2 is reduced from 680 to 420 for 280 degrees of freedom when we change the lineshape from a simple Gaussian to the more correct one. In addition, our proton spectrum is obtained under significantly improved conditions and should therefore be more reliable.

The analysis of the proton spectrum above 8 MeV is restricted by the low statistics, but nevertheless some conclusions are possible. The isobaric analog state can be safely identified on the basis of its known energy and narrow width, and our extracted log(ft) value is in good agreement with the expected value from the Fermi strength to this level. The proton peak at 10 MeV (c.m.) is consistent with either of the 11.70- and 11.74-MeV states and both could be contributing to the data in that region. The data at 11–13 MeV (c.m.) are here fitted with just one peak; a more detailed analysis is not possible with the present data. It is, however, possible to conclude that significant feeding to this energy region exists. Finally, we have tentatively analyzed the counts above the IAS, which are consistent with the known 15.3-MeV state if its parity is negative instead of the tentatively assigned positive parity.

The decay scheme of ^{13}O based on our new data is shown in Fig. 3 and compared to that of ^{13}B from the latest evaluation [4]. The mirror asymmetries are all consistent with zero within the experimental error, except for the ground-state transitions, where the difference is 2 standard deviations. This asymmetry is in agreement with the estimates of Smirnova and Volpe [8]. Nonzero asymmetries for the excited states of similar size as for the ground state are of course possible. Our slightly reduced log(ft) values bring better agreement with the calculations in Ref. [7].

Although extension of the ^{13}B β-decay data to higher energy together with better statistics for ^{13}O is clearly needed to draw definite conclusions on the existence of molecular orbits in this energy region by this method, some remarks can already be made at the present stage. The observed 9.476 MeV $3/2^-$ state is the mirror of the 9.897 MeV state in ^{13}C, which is suggested to be the band-head of a $K=3/2^-$ band in [3]. As previously mentioned there is no significant asymmetry in the feeding of these levels in β decay. The next member of this band is the 10.818 MeV $5/2^-$ level in ^{13}C, where we should observe the mirror state in ^{13}N at 10.3–11 MeV. There is no evidence for feeding to such a state in our data. In the $K=3/2^+$ band also suggested in Ref. [3] the band head is at 11.08 MeV in ^{13}C and the existing spin assignment of $1/2^-$ for this state is then suggested to be wrong. The corresponding mirror state in ^{13}N should now be at 10.5–11.2 MeV, we do not see feeding to any state in this region that is consistent with the reassignment of Ref. [3] (although, of course, not proving it).

In addition to improved data there is presently a clear need for theoretical understanding of how possible cluster

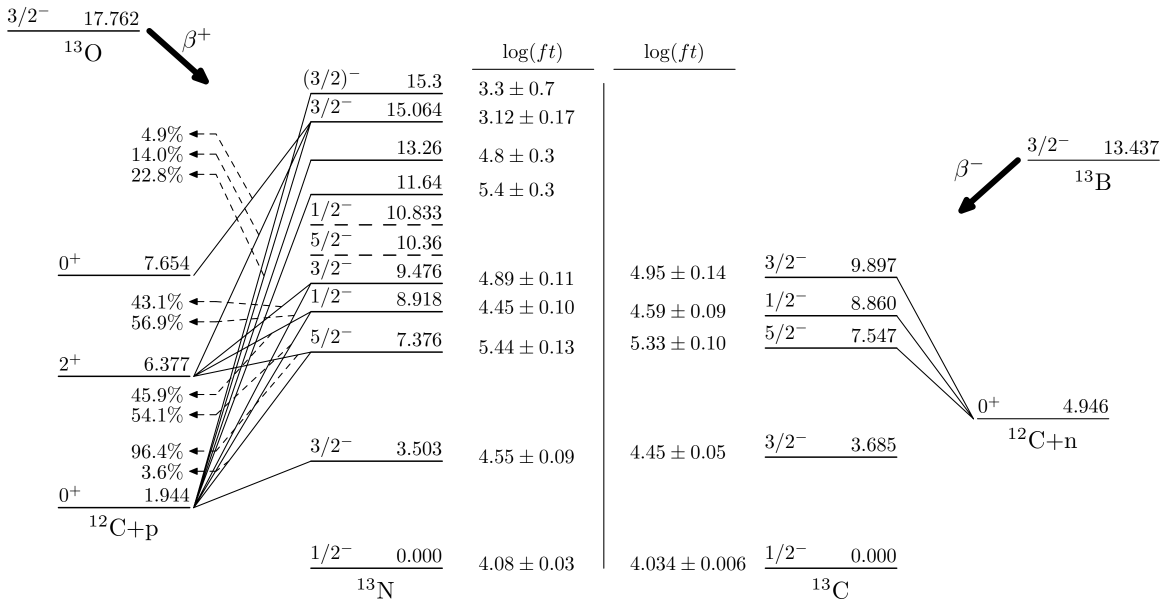

FIG. 3. ^{13}O and ^{13}B decay schemes. The ^{13}N level energies are in mega-electron volts. For ^{13}O the relative feedings to different ^{12}C states is given.

structure in the $A = 13$ system could modify these β decays, for example, using the Antisymmetrized Molecular Dynamics approach recently used for the $A = 12$ system [18,19].

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