PHYSICAL REVIEW C VOLUME 18, NUMBER 1 JULY 1978

Comment on a search for a $0^- \rightarrow 0^+$ pair transition in ^{16}O†

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(Received 9 February 1978)

The possible $0^- \rightarrow 0^+$ ground-state pair decay of the ^{16}O 10.95- MeV 0^- state was reinvestigated using the ^{19}F$(p,\alpha)^{16}$O reaction at E_p = 5.4–5.7 MeV and a magnetic pair spectrometer. A previously reported pair peak of 3.84 MeV due to the 10.952→7.117-MeV transition was not observed. The data indicate a much smaller relative population of the 10.95-MeV state in this reaction than reported previously and this places doubt on the upper limit derived earlier for the $0^- \rightarrow 0^+$ ground-state pair decay. In a test of the ^{14}N(^{3}He,p)^{16}O reaction at $E_{^3\text{He}}$ = 4 MeV the yield was too low to study the 10.95-MeV state. Using the ^{13}C$(d,p)^{14}$C reaction at E_d = 4.5 MeV the $0^- \rightarrow 0^+$ ground-state branch from the 6.90-MeV 0^- state of ^{14}C was found to be $<1.1 \times 10^{-4}$ via pair decay. The corresponding lifetime limit, $\tau(0^- \rightarrow 0^+)_{e^+e^-} > 3 \times 10^{-10}$ sec, is not considered significant. It is concluded that a sensitive search for M0 pair transitions remains to be made.

[NUCLEAR STRUCTURE ^{16}O, ^{14}C: measured ^{19}F(p,α) and ^{13}C(d,p) pair spectra; previous results on ^{16}O 10.95-MeV $\tau(M0)_{e^+e^-}$ not confirmed; deduced lower limit on ^{14}C 6.90-MeV $\tau(M0)_{e^+e^-}$.]

Nuclear transitions between states of spin-parities 0^- and 0^+ are not expected to occur by positron-electron pair emission or K-electron conversion unless there is a parity admixture in the initial and/or final states or a nonelectromagnetic coupling of the nucleus to the atomic electrons.[1-3] Presumably a $0^- \rightarrow 0^+$ decay could proceed by two-photon emission, i.e., $E1$ plus $M1$ transitions, with an expected probability somewhat less than in the case of $0^+ \rightarrow 0^+$ decay, i.e., two $E1$ transitions. As an example the $0^+ \rightarrow 0^+$ two-photon branch for the 6.05-MeV state of ^{16}O has been found[4] to be only 2.5×10^{-4} as strong as the corresponding $E0$ pair decay and was very difficult to detect.

There appears to have been only one search reported in the literature for a $0^- \rightarrow 0^+$ ($M0$) transition proceeding by positron-electron pair decay. Eklund and Bent[5] (EB) used the ^{19}F$(p,\alpha)^{16}$O reaction at E_p = 5.43 MeV in order to populate the known[6] 0^- state of ^{16}O at 10.95 MeV and they measured the positron-electron pairs with a magnetic spectrometer. As evidence that the 10.95-MeV state was being formed they found a peak corresponding to a 3.84-MeV transition which was attributed to the known[6,7] 10.952→7.117-MeV 100% γ-ray branching ($0^- \rightarrow 1^-$) of the 10.95-MeV state. The upper limit on the intensity of a possible 10.95-MeV pair line together with the 3.84-MeV peak intensity, after corrections for efficiencies, led to an upper limit on the 10.95-MeV ground-state pair branch of 2×10^{-5}. Since the lifetime of the 10.95-MeV state was not known an estimate of 4×10^{-13} sec was assumed from which a lower limit of $\tau > 2 \times 10^{-8}$ sec was derived for the partial lifetime of the 10.95-MeV $0^- \rightarrow 0^+$ pair transition. However, the lifetime of the ^{16}O 10.95-MeV state has now been measured[8] as $(8 \pm 5) \times 10^{-15}$ sec, a factor of 50 shorter than the estimate of EB.

From Fig. 1 of EB the relative (p,α) populations of the various ^{16}O states can be calculated since the pair spectrometer efficiencies are known accurately,[9] as are the γ-ray branching ratios of the ^{16}O states. Thus, the intensity of the 3.84-MeV pair peak in EB would require the 10.95-MeV state to be populated more strongly than the 6.05-, 6.9–7.1-, or 8.88-MeV states by factors ranging from 2 to 15. This seems to be inconsistent with the previous work[6] of Bent and Kruse in which the 10.95-MeV state was first found and studied using the ^{19}F$(p,\alpha)^{16}$O reaction. Thus, at E_p = 5.5 MeV (see Fig. 9 of Ref. 6) the various peaks in the three-crystal pair spectrum, when corrected for detector efficiencies and γ-ray branches, correspond to a population of the 10.95-MeV state less intense by factors of 4 or more relative to any of the other states. Also it may be mentioned that the α-particle spectrum from the ^{19}F$(p,\alpha)^{16}$O reaction at E_p = 7.31 MeV had been measured by Squires, Bockelman, and Buechner[10] in a magnetic spectrograph. No evidence was found for population of the 10.95-MeV state of ^{16}O although the next higher state at 11.095 MeV gave a peak of moderate amplitude.

In view of the uncertainty as to the intensity of the 3.84-MeV pair peak in EB a new measurement was made of the pair spectrum using the same type iron-free intermediate-image spectrometer and closely similar conditions, i.e., a 2-mg/cm^2

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thick BaF_2 target on a 6.7-mg/cm^2 thick Ni backing and a proton beam from a tandem Van de Graaff accelerator. In the first test at $E_p = 6.0$ MeV the beam struck the target material after passing through the Ni backing at which point its energy was 5.7 MeV. Figure 1 shows the results. The peaks due to the 6.05-, 6.92+7.12-, and 8.88-MeV transitions in ^{16}O are in approximately the same intensity ratios as in EB, there is a weak 4.44-MeV peak due to inelastic scattering from carbon contamination, but there is no visible peak of 3.84 MeV. Comparing these data with Fig. 1 of EB the 3.84-MeV peak here (at three standard deviations above background) is at least 10 times less intense relative to the 6.05-MeV peak.

Another difference between the present and previous results is the strong 4.44-MeV peak in EB presumably due to a much greater amount of carbon, perhaps a carbon target backing. A possibility could be that the 3.84-MeV peak in EB (about 20% as intense as the 4.44-MeV peak) was due to $^{13}C(p,p')^{13}C$ excitation of the 3.85-MeV state of ^{13}C. To test this a carbon foil target 3.5-mg/cm^2 thick was inserted with the result shown in the inset in Fig. 1. No peak of 3.85 MeV is observable and it must be <1% as strong as the 4.44-MeV peak. Therefore the 3.84-MeV line in EB cannot be due to natural carbon contaminants.

Allowing for the possibility of resonant excitation of the 10.95-MeV state the experiment on $BaF_2 + p$ was repeated at exactly the same proton energy of 5.43 MeV used previously.[5] There was still no evidence for the 3.84-MeV peak and the upper limit was comparable to that quoted above.

Further tests were made by measuring the γ-ray spectrum from the $^{19}F(p,\alpha)^{16}O$ reaction at $E_p = 5.5$–7 MeV using a 2.0-mg/cm^2 thick BaF_2 target and a Ge(Li) γ-ray detector. In addition to the higher energy γ rays a relatively strong 2.75-MeV line from the 8.88-MeV state of ^{16}O was observed but the 3.84-MeV peak could not be seen above the background. The upper limit on the 3.84-MeV γ-ray intensity was consistent with the relative intensities found in Ref. 6 but not with the pair spectrum in EB.

Thus the relatively large intensity of the 3.84-MeV peak in EB seems to be at variance with the present work as well as with the results of Refs. 6 and 10. Due to the absence of the 3.84-MeV pair peak in Fig. 1 no search was made for a possible 10.95-MeV line.

Since the 10.95-MeV state is known[7] to be excited in the $^{14}N(^3He,p)^{16}O$ reaction, a test was made with the pair spectrometer using a ZrN target made from 0.0025-cm thick Zr foil. The beam intensity was 0.5 μA of $^3He^+$ at 4 MeV. Unfortunately, the counting rates were only ~40/min at the 6.05-MeV $E0$ peak and <0.2/min for the 3.84-MeV peak, a yield too low to continue the study.

A previous investigation[11] of some pair lines in the $^{13}C(d,p)^{14}C$ reaction was carried out but a specific search was not made for the $0^- \to 0^+$ ground-state pair decay of the 6.90-MeV 0^- state of ^{14}C. This state was found[11] to be populated about equally compared with the 6.73-MeV level of ^{14}C for $E_d = 2.8$–4.5 MeV. A measurement was therefore made at $E_d = 4.5$ MeV using a carbon foil target of 90% enriched ^{13}C 0.85-mg/cm^2 thick. From

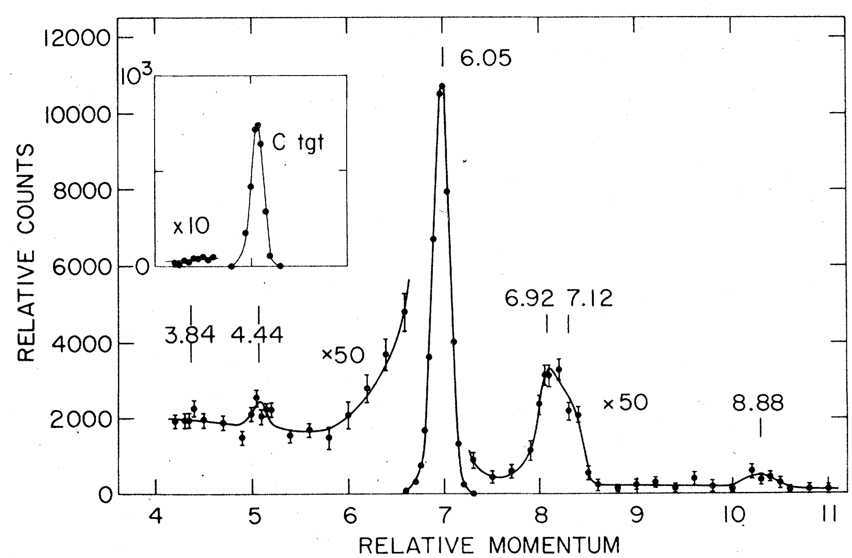

FIG. 1. Pair spectrum from the 5.7-MeV proton bombardment of a 2-mg/cm^2 thick BaF_2 target. The inset shows the spectrum from a 3.5-mg/cm^2 thick carbon target for the same integrated charge per point.

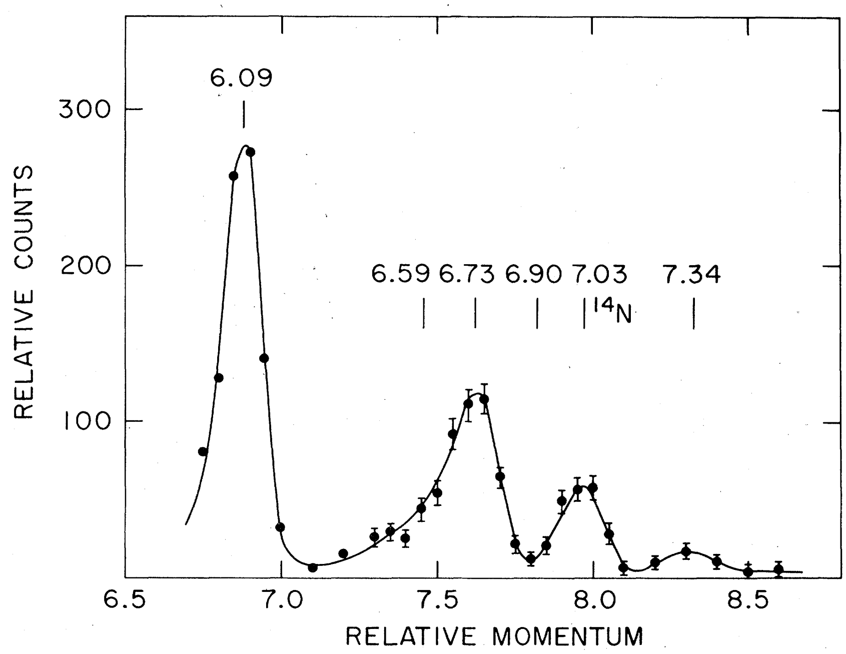

FIG. 2. Pair spectrum from the 4.5-MeV deuteron bombardment of a 90% enriched ^{13}C target. The vertical lines show the expected positions of the ^{14}C peaks at 6.59, 6.73, 6.90, and 7.34 MeV and the ^{14}N peak at 7.03 MeV [from the $^{13}C(d,n)^{14}N$ reaction] using the ^{14}C 6.09-MeV peak for calibration.

the resulting positron-electron pair spectrum shown in Fig. 2 the limit on a 6.90-MeV peak is estimated as <0.05 times the intensity of the 6.73-MeV peak. The latter is an $E3$ transition and thus the ratio of spectrometer efficiencies[9] is $\epsilon_{6.90}/\epsilon_{6.73} = 416$ assuming, for present purposes, the simplistic approximation $\epsilon_{M0} = \epsilon_{E0}$ for the 6.90-MeV transition. From the populations $p_{6.90} \simeq p_{6.73}$ it follows that the 6.90-MeV ground-state pair branch is $<1.1 \times 10^{-4}$. The lifetime[12] of this state, $(3.6 \pm 0.4) \times 10^{-14}$ sec, leads to a lower limit of $\tau > 3 \times 10^{-10}$ sec for the $M0$ pair decay. However, a comparable $E0$ pair transition such as that of 6.05 MeV in ^{16}O, has a lifetime of about 10^{-10} sec, so the experimental lifetime lower limit for the ^{14}C $M0$ pair transition cannot be considered as significant.

It is concluded that a really sensitive search for $0^- \rightarrow 0^+$ pair transitions remains to be made.

The author would like to thank E. K. Warburton and D. H. Wilkinson for helpful comments and suggestions.

†Research supported by the Division of Basic Energy Sciences, Department of Energy, under Contract No. EY-76-C-02-0016.

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