Search for axion emission in the decay of excited states of ^{12}C

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We report on a search for axion emission in the ground-state decay of the $T = 1$, $J^P = 1^+$ (15.1 MeV) and the $T = 0$, $J^P = 1^+$ (12.7 MeV) states of ^{12}C. The experiment is sensitive to axions decaying by emission of e^+e^- pairs. We see no evidence for the existence of the axion and our results rule out a range of possible axion masses and mixing angles in the mass region between 1 and 15 MeV.

I. INTRODUCTION

The axion particle was proposed by Weinberg and by Wilczek as one mechanism for preserving *CP* invariance of strong interactions in the presence of instantons.[1] Several discussions of this proposal appeared in the literature,[2] but it quickly became clear that existing experiments already cast considerable doubt on the existence of the axion. The main evidence ruling out low-mass axions ($m_a \lesssim 2.5$ MeV) derives from certain reactor-based experiments[3,4] which were originally designed to detect neutrino events. For higher masses, limits are obtained from a reanalysis of a SLAC beam-dump[4] experiment and even more stringent limits from CERN neutrino experiments.[5]

The reactor and beam-dump experiments set stringent limits for a wide range of axion masses and the unknown coupling parameter λ, using order-of-magnitude estimates for the production rate of axions. As emphasized by Treiman and Wilczek,[6] the uncertainty in axion emission can be eliminated, in certain cases, by relating the axion emission from excited nuclear states with isospin $T = 1$ to the β decay of the isospin-analog states. Their procedure enables the strong and nuclear complications to be absorbed in the measured β-decay rates.

Our motivation for the work described below was to carry out a search for axions in a system such as that proposed by Treiman and Wilczek. In particular, we investigated the possibility of axion emission from the 15.1-MeV $T = 1$, $J^P = 1^+$ state in ^{12}C. A partial level scheme for the $A = 12$ system is shown in Fig. 1. The three $T = 1$ states and their principal decay modes are shown by bold lines, as is the principal decay mode of the $J^P = 1^+$, $T = 0$ state in ^{12}C at 12.7 MeV. Weaker decay branches are shown by light lines, and the main axion decay modes are shown by dashed lines. The primary decay of the 15.1-MeV state is by an isovector $M1$ γ-decay to the ground state, with a transition width of $\Gamma_\gamma = 37.0 \pm 1.1$ eV.[7] The other γ branches shown in the figure and the isospin-forbidden α branch contribute to give a total width of 42 ± 7 eV.[7] The 12.7-MeV state decays primarily to $\alpha + {}^8Be$ with a small width of 14.2 ± 2.5 eV. The total width, including γ decay, is 14.6 ± 2.6 eV.[7] The β decays of ^{12}B and ^{12}N are primarily to the ^{12}C ground state, with respective $\log ft$ values 4.07 and 4.12.[8] The experimentally determined decay rates of the $T = 1$ states were used by Treiman and Wilczek to calculate the branching ratio for axion emission from the ^{12}C state.

As shown in Fig. 1, the $T = 1$ states also decay to excited states of ^{12}C, and axion emission rates to

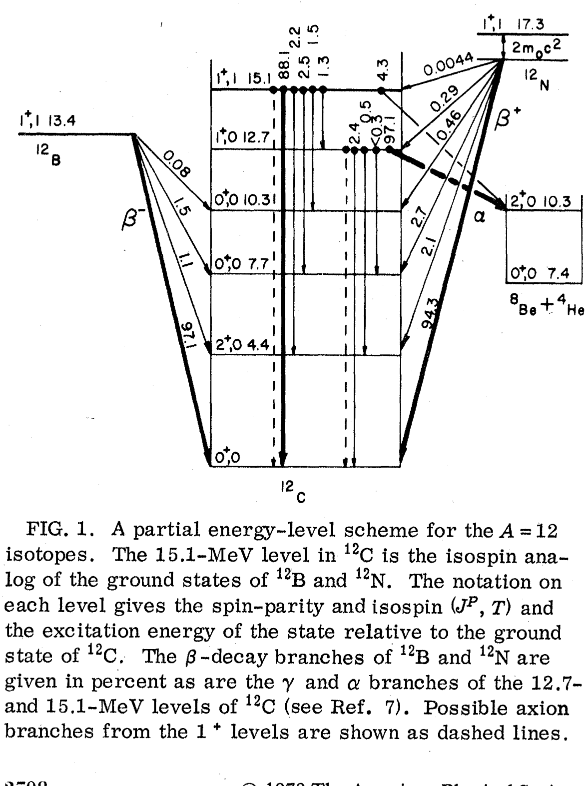

FIG. 1. A partial energy-level scheme for the $A = 12$ isotopes. The 15.1-MeV level in ^{12}C is the isospin analog of the ground states of ^{12}B and ^{12}N. The notation on each level gives the spin-parity and isospin (J^P, T) and the excitation energy of the state relative to the ground state of ^{12}C. The β-decay branches of ^{12}B and ^{12}N are given in percent as are the γ and α branches of the 12.7- and 15.1-MeV levels of ^{12}C (see Ref. 7). Possible axion branches from the 1^+ levels are shown as dashed lines.

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these states can be predicted from known data. However, these rates are small and affect our conclusions negligibly.

We are also sensitive to axions emitted from the 12.7-MeV $T=0$, $J^P=1^+$ state. In this case there are no analog β decays, and one must rely on a theoretical calculation of the axion decay branch. Other states are excited which might decay by axion emission. However, most of these have large particle decay widths and thus very weak axion branches. There are narrow states at 4.4 and 7.7 MeV, but axion decay of these states is forbidden by angular momentum and parity conservation.

Finally we note that the relatively large transition energy available in the decay of the 1^+ states enables axions with rather large masses to be emitted, and thus this experiment provides a useful overlap with both the reactor and high-energy neutrino experiments.

II. DISCUSSION OF THE EXPERIMENT

The plan of the experiment is to detect axions by their in-flight decays into e^+e^- pairs. A schematic illustration of the apparatus is shown in Fig. 2. The 15.1-MeV and 12.7-MeV levels of ^{12}C are excited by inelastic scattering of 22-MeV protons impinging on a thick natural carbon target. The figure shows a hypothetical axion which is emitted from the target, passes through the lead, and then

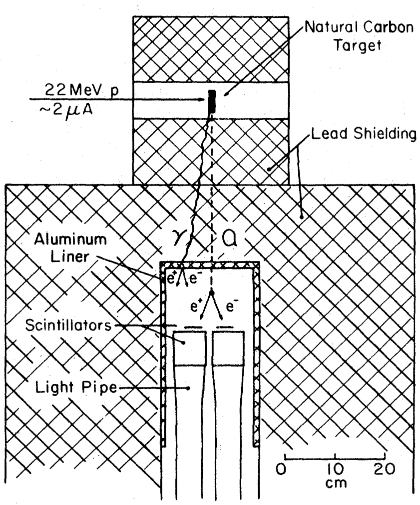

FIG. 2. Schematic of experimental apparatus. ^{12}C excited states are produced by inelastic scattering of 22-MeV protons produced by the Princeton University cyclotron. Lead shielding attenuates γ rays (γ) while axions (a), which interact only semiweakly with matter, are not significantly attenuated. The cavity housing the detectors is lined with aluminum to reduce the probability that γ rays will produce e^+e^- pairs on these surfaces and simulate axion events.

decays in air into an e^+e^- pair. The pair travels a short distance in air before each particle is detected with a ΔE-E Pilot B plastic scintillator telescope. The detectors were placed at 45 cm from the target. In a separate run, they were moved out to 60 cm for enhanced sensitivity to events with small opening angles.

The ΔE detectors are 1.6 mm thick with a cross section of 3.8 cm $\times$ 3.8 cm. The E detectors are 7 cm thick and 6.35 cm $\times$ 6.35 cm in cross section. The E detectors were made as thin as possible to minimize neutron and γ-ray background while also providing a reliable measurement of a large percentage of the variable energies of the e^+e^- pairs. Each scintillator is coupled through a light pipe to an RCA 8575 photomultiplier tube. Each of the E detectors is gain stabilized with a signal created by a light emitting diode attached to the scintillator. The detectors were calibrated using the internal conversion electrons from a ^{207}Bi source and the Compton edge of the 4.4-MeV γ ray of ^{12}C.

The detectors were placed inside a lead "house" to shield them from the intense flux of γ rays emanating from the target. The most intense γ ray is that from the decay of the 4.4-MeV state of ^{12}C. The 15.1-MeV γ rays, though less intense, are more problematic since these are capable of generating e^+e^- pairs which may be detected with the correct energy to simulate axion decays. Such an event would have to originate near the inner surface of the shielding to avoid significant energy loss.

A background event of this type is shown in Fig. 2. The 29 cm of lead shielding between the target and the detector attenuates the γ rays by more than 10^{-8}, greatly reducing this background. To further reduce this background, we lined the inner surface of the detector housing with aluminum, which, because of its lower atomic number, generates fewer pairs than lead. For this configuration, Monte Carlo calculations predict that we should detect less than one such background event in the course of the experiment.

A typical e^+e^- event is identified as a fourfold coincidence of the four detectors making up the two telescopes. The data were recorded on magnetic tape event-by-event with eight analog parameters characterizing each event. The eight parameters consist of four $\Delta E, E$ energy signals and four time-to-amplitude (TAC) signals. Two of the TAC's are started by a ΔE detector and stopped by its associated E detector. A third TAC is started by one ΔE detector and stopped by the other. These three TAC's provide the means for requiring a fourfold coincidence while also allowing for analysis of accidental coincidences. Timing resolution was typically 2 nsec. The fourth

TAC is started by either ΔE signal and stopped by a signal from the cyclotron rf so that it provides a measure of the time of flight (TOF) of a particle from the target to the detector.

Figure 3 shows the energy spectrum of the sum of the energies deposited in the four scintillators for events satisfying the requirements of a fourfold coincidence and having the proper time of flight. Events which fall within region b are accepted as possible candidates for axions decaying from the 15.1-MeV state, while events in region a are candidates for axions decaying from the 12.7-MeV state. Table I gives the number of counts observed in each of these windows and the breakdown in terms of the two target to detector distances. The total integrated beam currents for the data runs with the detectors at 45 and 60 cm were 0.29 and 0.17 C, respectively. In the analysis of accidental events, the TOF spectrum proved to be the most important. With all of the lead shielding in place, the TOF spectrum does not show a prompt peak since the prompt γ rays are thoroughly attenuated. The inset in Fig. 3 shows a TOF spectrum taken with much of the lead removed so as to indicate clearly the location of the prompt peak due to γ rays. Very light axions, which would travel near the speed of light, would arrive at the same time as the prompt γ rays. Heavy axions would arrive later, and the TOF window around the prompt peak (Region C) was sufficiently wide to include axions with rest mass up to 14.5 MeV from the 15.1-MeV state and up to 12.2 MeV from the 12.7-MeV state.

By analyzing fourfold coincidence events which lie in regions B and D, the number of accidental coincidence counts for the time-of-flight condition was determined. Combining this with the accidentals similarly determined from the other three TAC spectra yields the total accidental counts shown in Table I. Also shown are the final experimental results after subtraction of accidentals;

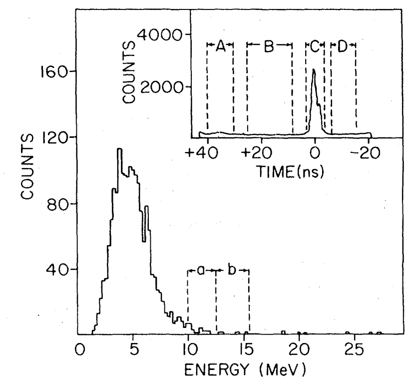

FIG. 3. Total energy spectrum for coincidence events with the proper time of flight. Data for the two detector distances used in the experiment are combined. Most of the events are accidental coincidences. Regions a and b were analyzed for axions from the 15.1-MeV and 12.7-MeV levels of ^{12}C. The inset is a typical time-of-flight spectrum for detectors at 60 cm. Some lead shielding was removed to show a prompt peak (region C). The stop signal from the cyclotron rf was delayed to offset the prompt peak. Fast neutrons appear in region A. Regions B and D were used to estimate background.

these results show no evidence for the existence of the axion.

III. ANALYSIS AND CONCLUSIONS

To assess the significance of these data, we need to predict the number of events we should have seen if the axion exists. The calculation by Treiman and Wilczek[6] gives the ratio of the axion width to the γ width for the isovector transition from the 15.1-MeV state to the ground state of ^{12}C. Their result is

$$\frac{\Gamma_a}{\Gamma_\gamma}=2\times 10^{-5}\beta^2\left(1-\frac{m_a^2}{\Delta^2}\right)^{3/2},$$

TABLE I. Experimental results.

^{12}C level	Detector distance	Observed counts	Accidental counts	Counts −accidentals
15.1 MeV	45 cm	3	5 ± 2	-2 ± 3
	60 cm	2	2 ± 1	0 ± 2
	Combined	5	7 ± 2	-2 ± 3
12.7 MeV	45 cm	13	13 ± 2	0 ± 4
	60 cm	5	4 ± 1	1 ± 2
	Combined	18	17 ± 3	1 ± 5

where $\Delta = 15.1$ MeV and $\beta = \frac{1}{2}(\tan\lambda - \cot\lambda)$ gives the dependence on the parameter λ. The only unknowns in this branching ratio are the axion mass and λ.

As noted above, the ^{12}C state at 12.7 MeV decays predominantly by α emission to ^8Be. For the isoscalar transition from this state to the ground state of ^{12}C, the matrix element for axion decay cannot be determined from experimental β-decay rates. For definiteness, we take the ratio of the axion width to the total width of this state to be

$$\frac{\Gamma_a}{\Gamma} = 1.1\times 10^{-5}\beta'^2\left(1 - \frac{m_a^{\,2}}{\Delta'^2}\right),$$

where $\beta' = \frac{1}{2}(\tan\lambda + \cot\lambda)$ and $\Delta' = 12.7$ MeV. To obtain this result, we replace the parameter C of Ref. 6 by C', which is the equivalent isoscalar parameter. We note $C \approx g_a M_{\rm GT}$ and $C' \approx g_a' M_{\rm GT}'$, where g_a is the isovector weak coupling constant and $M_{\rm GT}$ is the isovector Gamow-Teller matrix element. The primes denote the corresponding isoscalar quantities. The value of g_a' is highly uncertain; we have used the quark-model estimate $g_a' = \frac{3}{5} g_a$.[4] Millener has estimated $M_{\rm GT}' = M_{\rm GT}$ using an SU_3 shell-model code.[9] From these considerations, we obtain $C' \approx \frac{3}{5} C$ which is used to obtain the axion width (Γ_a) of this state. We compare this with the known total width $\Gamma = 14.6 \pm 2.6$ eV.[6]

Axions with $m_a > 2m_e$ can decay either into two photons or into an electron-positron pair with the rates[1]

$$\Gamma_{\gamma\gamma} = \frac{2^{1/2} G\alpha^2 m_a^{\,3}}{9\pi^3}\,\frac{N^2}{\sin^2 2\lambda},$$

$$\Gamma_{e^+e^-} = \frac{2^{1/2} G\, m_a m_e^{\,2}}{8\pi}\cot^2\lambda\left(1 - \frac{4m_e^{\,2}}{m_a^{\,2}}\right)^{1/2},$$

where N is the number of quark/lepton doublets (we use $N=3$).

Prediction of the axion yield requires knowledge of cross sections for the (p,p') scattering to the 15.1- and 12.7-MeV states. The relevant cross sections were taken from the data of Berghofer *et al.*,[10] who measured the yield of 12.7- and 15.1-MeV γ rays produced by inelastic scattering of protons from ^{12}C for proton energies from threshold to 24 MeV. Their data also included γ-ray angular distributions which we used to determine the nuclear spin alignment parameters of the excited carbon levels which in turn were used to predict the angular distribution of axions. The anisotropy of axion emission from aligned nuclei results in a downward correction of 23% in the expected axion intensity from the 15.1-MeV state, and a downward correction of 14% for the 12.7-MeV state. Since the target is thick enough to stop the beam, cross sections and nuclear alignments are averaged over the energy range of the protons, from threshold to the beam energy.

Using these cross-section data and the above expressions for the axion decay branches and lifetimes, a Monte Carlo calculation was performed to determine the number of axion events that should have been seen in our experiment as a function of m_a and λ. For each of the two detector positions, predictions were made for the axion yield expected from the 15.1-MeV state and from the 12.7-MeV state. The results are presented in Fig. 4. The uncertainty in the predictions is 35%, with the largest contribution coming from the uncertainty in the cross sections. It is seen that the data rule out axions for a wide range of possible values of m_a and λ, but that other values are not ruled out. In particular, the data do not rule out the heavier axion masses for small λ. The dip in the number of expected counts at $\lambda = \pi/4$ radians in the predictions for the 15.1-MeV state is a result of the form of β which is zero for this value of λ. No zero occurs in β', so that consideration of the 12.7-MeV level serves to

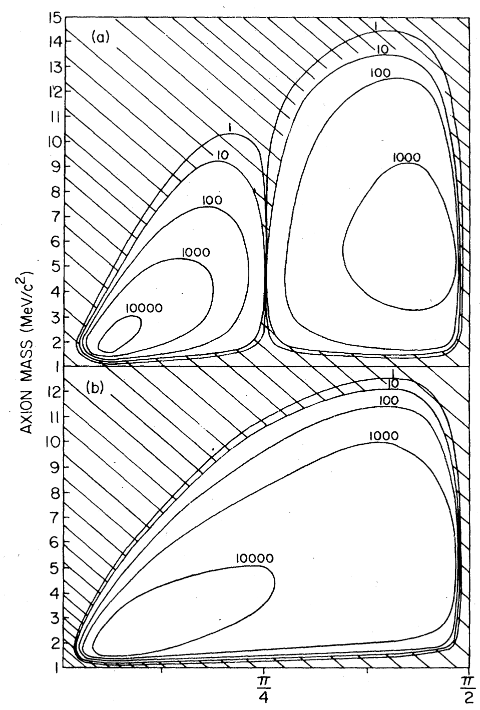

FIG. 4. Contour plots showing Monte Carlo predictions for the number of events expected from decay of the ^{12}C states at 15.1 MeV (a) and 12.7 MeV (b). The shaded regions indicate the values of the axion mass and the parameter λ which are not ruled out by the present experiment at the level of three times the uncertainties given in Table I. The contours are labeled with the numbers of expected axion events.

rule out axions for the case of λ near $\pi/4$ radians, provided our estimate for the branching ratio is not too far off.

To check that our apparatus had the predicted sensitivity to electron-positron pairs, a separate experiment was performed to observe pairs intentionally produced by γ rays. With the detectors located 60 cm from the target, the lead shielding between the target and the detectors was reduced to 13 cm, thus allowing γ rays to produce pairs in a 1-mm-thick lead sheet which was placed 12 cm in front of the detector (Fig. 5 inset).

Figure 5 shows the energy spectrum of pairs produced in the lead sheet; background measured without the lead sheet has already been subtracted. The broad peak around 12 MeV is due to the pairs from 15.1-MeV γ rays. As expected, the peak is shifted downward and broadened, owing to energy loss and straggling in the lead sheet. The peak contains 166 counts, which is in satisfactory agreement with a Monte Carlo prediction of 260 $\pm$ 130. The uncertainty in this calculation is largely associated with the strong dependence of the γ attenuation factor on the thickness of the lead shielding.

Our results agree with other studies in finding no evidence for the existence of the axion. Each experiment is sensitive to axions only over a limited range of axion mass and coupling parameter λ. The order-of-magnitude analyses of reactor experiments rule out axions for masses up to ~2–3 MeV,[3,4] while CERN neutrino experiments[5] and others[2,4,11] additionally rule out higher-mass axions. The recent experiment of Bechis *et al.*[12] and our experiment can both be analyzed without recourse to model-dependent approximations. In both of these experiments, the sensitivity extends to axion masses of ~12 MeV but with slightly different ranges of λ.

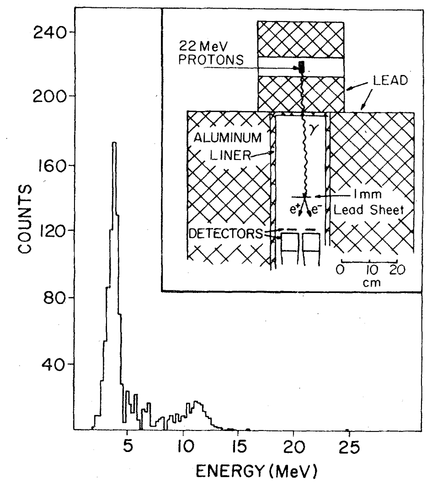

FIG. 5. Energy spectrum of e^+e^- pairs generated in a separate experiment by γ rays pair producing in a lead sheet placed in front of the detectors. The broad peak near 12 MeV arises from pairs generated by 15.11-MeV γ rays. The inset shows the experimental arrangement used in obtaining these data.

It should be noted that the sensitivities of all of the experiments break down for small enough λ. This is because the axion decay length becomes so short that axions do not reach the detection region. Further experimental data are needed to rule out the possibility that λ is small.[13]

ACKNOWLEDGMENTS

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