Search for short lived neutral particle in the 15.1 MeV isovector transition of ^{12}C

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We report a search for a short lived neutral particle ϕ emitted in the decay of the 15.1 MeV $J^{\pi}(T)=1^{+}(1)$ state in ^{12}C. The experiment is sensitive to $\phi\to e^{+}e^{-}$ decays and finds no evidence for such a particle. We set upper limits on $\Gamma_{\phi}/\Gamma_{\gamma}$ for mean lifetimes between $\sim 10^{-13}$ and $\sim 10^{-8}$ sec and in the mass range 1.02–2.5 MeV.

Recent experiments[1] looking at positron spectra following collisions of heavy ions have revealed some puzzling features, viz., narrow line structures whose energy and excitation probability seem to be roughly independent of the total charge number of the colliding system. In addition, a later experiment[2] has shown that these lines are in coincidence with an electron of the same energy. The various explanations that have been put forward to explain the above observations fall into roughly three categories: (i) resonant $e^{+}e^{-}$ production in strong electromagnetics fields,[3] (ii) decay of composite objects such as $e^{+}e^{-}$ clusters[4] or nontopological solitons formed in strong electromagnetic fields,[5] and (iii) two body decay of a hitherto undetected neutral particle ϕ of mass ~ 1.8 MeV produced almost at rest in the center of mass of the colliding heavy ions.[6,7]

If the third explanation is correct then it is most likely that ϕ is pseudoscalar in nature.[6,7] From existing precision (g_e-2) experiments for the electron and the maximum possible allowed deviation in comparison with theory, a lower limit on the mean lifetime of ϕ can be derived: $\tau_{\phi\to e^{+}e^{-}}>10^{-13}$ sec.[7,8] It is possible that this particle could be the axion[8,9,10] a particle proposed[11] in connection with the strong CP problem. Pseudoscalar particle searches, looking for the axion, have found no evidence for emission in vector meson decays,[12] in beam dump experiments, and in nuclear processes.[13,14,15] All these searches have been sensitive to $\tau_{\phi}>5\times 10^{-11}$ sec (except the J/ψ and Υ decays which are sensitive to $\tau_{\phi}>10^{-11}$ sec). There thus seemed to be a range of allowed lifetimes for ϕ, viz., 10^{-11} to 10^{-13} sec, and it was pointed out that there was a need for a renewed search for such a particle.[7,9] If ϕ has a nonzero coupling to nucleons, because of its pseudoscalar nature, it can compete with photons in all magnetic transitions in nuclei, when energetically allowed. We report here a search for such a neutral particle in the decay of the 15.1 MeV $J^{\pi}(T)=1^{+}(1)$ state in ^{12}C. We find no evidence for ϕ in mass range 1.02–2.5 MeV and lifetime range $\sim 10^{-13}$–$\sim 10^{-8}$ sec.

The experiment consisted of populating the 15.1 MeV state by inelastic proton scattering and looking for a small ϕ branch in the deexcitation of this state through its in flight decay beyond the target into an $e^{+}e^{-}$ pair. Protons of 19.5 MeV delivered by the 13 MV Orsay tandem accelerator were used, the beam energy being chosen to be below the (p,n) threshold of ^{12}C so as not to be troubled by the activity of ^{12}N. A ΔE-E telescope was located at the focus of the magnetic lens spectrometer SOLENO (Ref. 16) in order to detect the $e^{+}e^{-}$ pair from ϕ decay. The mean angle between the e^{+} and e^{-} following the decay of such a particle of mass 1.8 MeV in the laboratory system is about 11° and nicely matched the angular acceptance of SOLENO (7.2°–18.6°). The field was adjusted to focus electrons and positrons with energies of about 7 MeV, and a momentum acceptance $\Delta p/p\simeq 5\%$. A peak in the sum energy spectrum $E_{e^{+}}+E_{e^{-}}$ would signal the presence of the ϕ decay provided other background processes leading to a peak were under control.

In order to eliminate the contribution of the internal pair conversion (IPC) process which could mask the weak peak expected from ϕ decay, since the IPC coefficient is equal to about 3×10^{-3},[17] the thickness of the 99.999% ^{12}C enriched target was chosen equal to 3.2 mm. This thickness was enough to stop the proton beam. However, the excitation of the 15.1 MeV state took place in the first 0.5 mm of the target. The electron and positron from IPC pair lost about 1 MeV each in crossing the target and thus were not focused on the telescope. This method precluded a measurement of short lived particles with mean lifetimes $<10^{-13}$ sec which would mainly decay in the target; therefore, the resulting $e^{+}e^{-}$ pair would not be focused, considering the subsequent loss of energy. However, this lower limit of 10^{-13} sec is not a serious limitation, considering the (g_e-2) limit previously mentioned.

A schematic of the apparatus is shown in Fig. 1. As the details of the superconducting solenoidal spectrometer SOLENO are available elsewhere,[16] only the modification for this experiment will be described. A lead rod of 150 mm length was placed in the long Faraday cup situated on the axis of the SOLENO to attenuate the line of sight 15.1 MeV gamma rays reaching the telescope. The ΔE detector was of the surface barrier type of 300 μm thickness and 20 mm diameter and was placed in vacuum at the exit of SOLENO. A conical lead shield of 20 cm thickness lined on the inside with aluminium was placed in front of the ΔE detector to reduce the scattered gamma ray background entering the

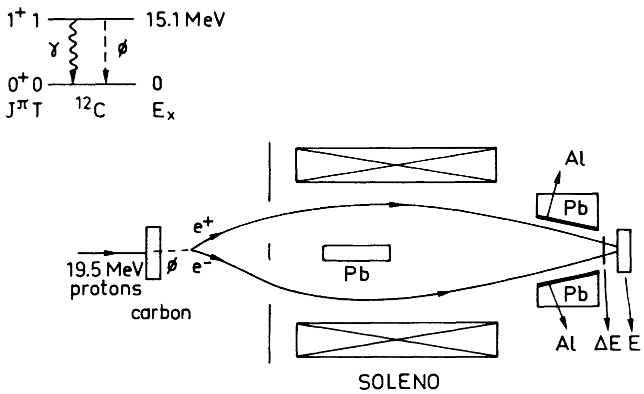

FIG. 1. A schematic diagram of the apparatus used.

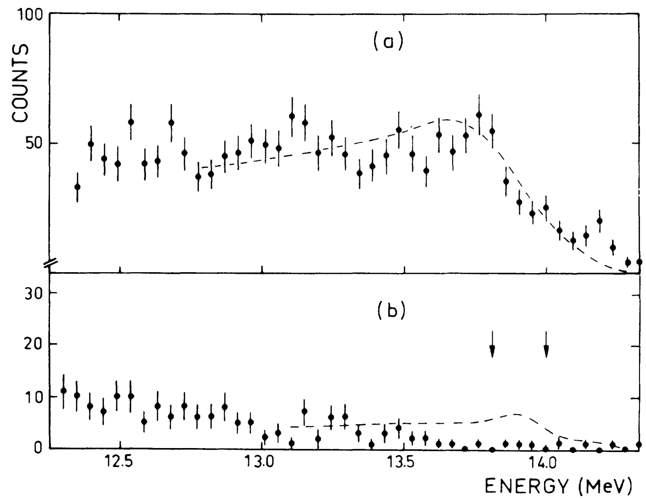

FIG. 2. Sum energy spectra obtained in the E detector gated by the $2e$ window in the ΔE detector for two runs, respectively. (a) external pair conversion spectrum with 50 μm Ta foil behind the thick carbon target. The dashed curve is expected curve (see text) for 5.4 mC. (b) spectrum in ϕ search. The dashed curve is the expected spectrum for $m_\phi = 1.8$ MeV, $\tau_\phi = 5\times 10^{-13}$ sec and $\Gamma_\phi/\Gamma_\gamma = 10^{-3}$. In both plots the bin width is 47 keV.

E detector placed behind. The E detector was a 36 mm diameter 10 mm thick intrinsic germanium device cooled to liquid nitrogen temperature. The e^+e^- pair had to traverse the exit window of ~ 100 μm Mylar and the 250 μm thick Be window of the E detector.

A test run was first performed in conditions identical to that of the ϕ particle search except that a 50 μm tantalum foil was placed behind the thick carbon target to look at the external pair conversion spectrum of the 15.1 MeV gamma ray. Coincident ΔE-E events were recorded on tape. The threshold on the ΔE detector was as low as possible, viz., ~ 80 keV and that on the E detector ~ 1.5 MeV. Typical counting rates were ~ 1 kHz for the ΔE detector, ~ 5 kHz for the E detector and ~ 50 Hz for the ΔE-E coincidences for a beam current of about 300 nA. The ΔE-E spectrum of the coincident events in this run showed a very clear separation between one and two electron events. The E spectrum with a window corresponding to two electrons, for a current setting of the SOLENO maximizing the pair conversion counting rate, is shown in Fig. 2(a).

Subsequently the tantalum foil was removed, the current setting of the SOLENO increased appropriately and events stocked in the ϕ search. The E spectrum gated by the two electron window in the ΔE detector, for 4.1 mC of accumulated charge, is shown in Fig. 2(b). There is no evidence of a peak at ~ 13.9 MeV, the energy of the e^+e^- pair expected from ϕ decay in vacuum after taking into account energy losses in the ΔE detector, the Mylar and beryllium windows. The residual background (in the region of the peak expected from ϕ decay) is mainly from the tail of the external pair production of the 15.1 MeV gamma ray from the back of the carbon target and from areas close to the target. The rising background at lower energies is probably due to electrons and positrons of similar origin[18] hitting the inner walls of SOLENO and rescattering onto the ΔE-E detectors.

The sum spectrum expected from a possible ϕ branch for a given $\Gamma_\phi/\Gamma_\gamma$, τ_ϕ, and m_ϕ was calculated using the following ingredients.

(i) The measured (p,p$'\gamma$) excitation function, (p,p$'$) angular distribution and coefficients of the γ-ray angular distributions[19] from threshold to 19.5 MeV for the 15.1 MeV state in ^{12}C were used to calculate, respectively, the total production rate of γ rays, the Doppler profile of the 15.1 MeV emitted by the recoiling ^{12}C nucleus, and the corresponding angular distribution for a 0^- particle, resulting in an enhancement by a factor of 4 for the forward production, relative to that of a γ ray.

(ii) The transport efficiency of SOLENO for e^+e^-

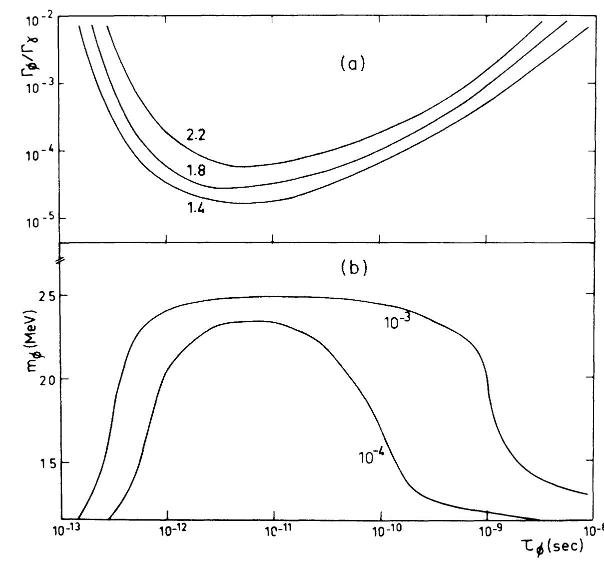

FIG. 3. (a) Plot of the upper limit on $\Gamma_\phi/\Gamma_\gamma$ vs τ_ϕ for three assumed values m_ϕ. The region above the curve is ruled out at 90% C.L. by this experiment. (b) Exclusion plot for the pseudoscalar ϕ in m_ϕ-τ_ϕ space. The region below the curves is excluded at 90% C.L. for the two values of $\Gamma_\phi/\Gamma_\gamma$ given beside each curve.

pairs resulting from ϕ decay outside the carbon target was calculated using the Monte Carlo technique, for the experimental geometry used. For a given current in the SOLENO, it depends on the mass of the particle, through the angular distribution of the e^+e^- pair, and on its lifetime. As can be expected, the efficiency is low both for short lifetimes $<10^{-13}$ sec, when ϕ decays mainly in the target, and for large lifetimes, when it mostly decays outside the object zone of the spectrometer.

(iii) The response of the Ge detector, with the ΔE detector and the Pb shielding in place was measured for 7 MeV electrons, at the secondary electron beam line at the Accélérateur Linéaire de Saclay (ALS) in Saclay. The full energy peak had a width of 100 keV, reconcilable with the energy width of the secondary electron beam, and contained about 20% of the total counts. The response for the e^+e^- pair was deduced by convolution, including a correction for the possibility of a Compton scattering of the annihilation γ rays from the e^+ stopped in the detector. The energy calibration was done using ^{22}Na and ^{60}Co sources, and when extrapolated agreed reasonably well with the sum energy of external pairs from the Ta foil + carbon run.

A similar type of calculation was done for the external pair production in the Ta foil, using the theoretical differential cross sections for e^+e^- creation,[20] and also incorporating energy and angular straggling of the pair in the Ta converter. The calculated spectrum is shown in Fig. 2(a) normalized to the data. This normalization factor could come from some loss of transport efficiency of the SOLENO at the relatively low currents where the residual magnetic fields, not included in the calculations, are not insignificant and also from uncertainties in the absolute (p,p′) cross sections and in the method of determination of response of the Ge detector to the e^+e^- pair. The same factor has also been applied to the expected spectrum from ϕ-particle decay. The sum spectrum expected from a small branch in the 15.1 MeV transition corresponding to $\Gamma_\phi/\Gamma_\gamma=10^{-3}$ and for $m_\phi=1.8$ MeV, $\tau_\phi=5\times10^{-13}$ sec is shown by the dashed curve in Fig. 2(b).

An upper limit of 6.5 counts at 90% C.L. can be derived for the region between the arrows in Fig. 2(b). This was then converted to an upper limit on $\Gamma_\phi/\Gamma_\gamma$ for various assumed values of m_ϕ and τ_ϕ. In deriving these limits it was assumed that the ϕ decay is only through the e^+e^- channel. A plot of the upper limit $\Gamma_\phi/\Gamma_\gamma$ as function of the assumed mean lifetimes of ϕ for some values of m_ϕ is shown in Fig. 3(a). An alternative way of showing the same results is the plot of Fig. 3(b).

As can be seen the mass region 1.02–2.5 MeV is excluded in the lifetime range $\sim10^{-13}-\sim10^{-8}$ sec. For the sake of orientation it might be recalled that the "standard" axion model predicts $\Gamma_\phi/\Gamma_\gamma\sim1.2\times10^{-2}$ for $m_\phi=1.8$ MeV with $\tau_\phi=5\times10^{-12}$ sec.[21] This is definitely ruled out by this experiment.

Following Donnelly *et al.*[22] the limit on $\Gamma_\phi/\Gamma_\gamma$ can be converted to a limit on $g^{(1)}$ the isovector ϕ-nucleon coupling constant using their relation:

$$\frac{\Gamma_\phi}{\Gamma_\gamma}=\frac{1}{2}\left[\frac{k_\phi}{k_\gamma}\right]^3\left[\frac{2g^{(1)}}{e\mu^{(1)}}\right]^2,$$

where k_ϕ,k_γ are the ϕ and γ momenta, $g^{(1)}$ the isovector ϕ-nucleon coupling, and $\mu^{(1)}$ the isovector nucleon magnetic moment.

From the results of this experiment the upper limit on $g^{(1)}$ for an assumed τ_ϕ of 5×10^{-13} sec and $m_\phi=1.8$ MeV is 1.45×10^{-2}. This limit can also be converted into a limit on λ_3, following Bardeen *et al.*,[23] for viable axion models. For the same values of τ_ϕ,m_ϕ the upper limit obtained from this experiment on $|\lambda_3|$ is 3.2. The toy models of Refs. 8 and 10, where ϕ couples to one quark generation ($N=1$), predict $\lambda_3=26.6$ and are thus ruled out. This limit can also be compared with the other possible values of λ_3, deduced from Ref. 20 for an assumed axion mass of 1.8 MeV, and is listed in Table I. The experimental limit on $|\lambda_3|$ is well below theory except for the $[u_R\times\phi_1]$, large X, $N=3$ case. However, this value would correspond to a very short lifetime ($\tau_\phi<10^{-13}$ sec) in conflict with precise g_e-2 measurements, as already mentioned.[7,8]

During the course of this work several ϕ searches have appeared in literature. Savage *et al.*[24] reported a search in the isovector 9.17 MeV transition in ^{14}N with an upper limit for $\tau_\phi<10^{-11}$ sec. de Boer *et al.*[25] report a search in the isoscalar 3.59 MeV transition in ^{10}B. Their upper limit while going against the standard axion model and most of the axion variants is unable to say anything about the model of Krauss-Wilczek[8] since in the latter model $g^{(0)}$ is vanishingly small. Baba *et al.*[26] reported a search in a mixed isospin transition in ^{13}C yielding a limit of

$$|g^{(0)}+g^{(1)}/\sqrt{3}|<3\times10^{-3}.$$

A recent reanalysis of IPC data[27] has shown that the experiment was inconsistent with the existence of a 1.7 MeV axion. Table II presents a summary of all data on experimental searches for ϕ in nuclear transitions. Recent searches for ϕ in beam dump experiments,[28] in π^+ decay,[29] and in Υ decay[30] also find no evidence for its existence.

In summary, therefore, we have searched for light pseudoscalar particle emission in the isovector 15.1 MeV transition in ^{12}C and have not found it in the mass range 1.02–2.5 MeV and the lifetime range $\sim10^{-13}-10^{-8}$ sec. The only region allowed for ϕ is either in conflict with

TABLE I. Theoretical values for λ_3, calculated following Ref. 20 for the various combinations of possible choices: number of quark generations N, coupling of the right-handed quark u_R to the Higgs field ϕ_1 or $\tilde{\phi}_2$, and the two possible values of $X=\langle\phi_2\rangle/\langle\phi_1\rangle$, as determined assuming $m_\phi=1.8$ MeV. The upper limit from this experiment is $|\lambda_3|<3.2$ for the same mass and $\tau_\phi=5\times10^{-13}$ sec.

		$N=1$	$N=2$	$N=3$
$[u_R\times\phi_1]$	Large X	26.6	8.7	2.7
	Small X	−45.4	−27.4	−21.4
$[u_R\times\tilde{\phi}_2]$	Large X	−18.7	−18.7	−18.7
	Small X	−90.7	−54.7	−42.7

TABLE II. Summary of experimental searches for pseudoscalar emission in nuclear transitions with range of experimental sensitivity for m_ϕ, τ_ϕ and derived upper limits on $\Gamma_\phi/\Gamma_\gamma$ and $g^{(0)}, g^{(1)}$ assuming $\phi \rightarrow e^+e^-$ only.

Nucleus	E_{trans} (MeV)	Mass range of ϕ (MeV) explored	τ_ϕ (sec)	$\frac{\Gamma_\phi}{\Gamma_\gamma}$	Upper limits on coupling constant for $m_\phi = 1.7$ MeV	Ref.
^{14}N	9.17	1.02–2.2	$< 10^{-11}$	4×10^{-4}	$g^{(1)} < 1.4\times10^{-2}$	24
^{10}B	3.59	1.7 [a]	$< 10^{-9}$ [b]	7.2×10^{-3}	$g^{(0)} < 1.4\times10^{-2}$ [c]	25
^{13}C	3.68	1.7–2	$< 10^{-11}$	7×10^{-5}	$\left\lvert g^{(0)} + \frac{g^{(1)}}{\sqrt{3}} \right\rvert < 3\times10^{-3}$	26
^{6}Li	3.56	1.7 [a]	$< 2\times10^{-11}$	9.0×10^{-5}	$g^{(1)} < 1.2\times10^{-2}$ [c]	27
^{10}B	3.59			2.6×10^{-3}	$g^{(0)} < 5.1\times10^{-3}$	
^{14}N	7.03			2.7×10^{-3}	$g^{(0)} < 4.1\times10^{-3}$	
^{12}C	15.11	1.02–2.5	$\sim 10^{-13}-10^{-8}$	1.5×10^{-4}	$g^{(1)} < 1.25\times10^{-2}$ [d]	Present work

[a]Do not quote mass range.
[b]This number has been estimated from the experimental geometry of the original paper.
[c]Estimated from $\Gamma_\phi/\Gamma_\gamma$ quoted by the respective authors.
[d]Limit quoted for $\tau_\phi = 5\times10^{-13}$ sec, $m_\phi = 1.7$ MeV.

$g_e - 2$ experiments for the electron or not allowed by other experimental searches in isoscalar nuclear transitions. The experimental evidence is thus strongly against a particle explanation for the e^+e^- peaks found in the GSI experiments.

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[1]J. Schweppe *et al.*, Phys. Rev. Lett. **51**, 2261 (1983); M. Clementi *et al.*, Phys. Lett. **137B**, 41 (1984).
[2]T. Cowan *et al.*, Phys. Rev. Lett. **56**, 444 (1986).
[3]G. Scharf, Phys. Lett. **177B**, 429 (1986).
[4]B. Muller, J. Reinhardt, W. Greiner, and A. Schafer, J. Phys. G **12**, L109 (1986).
[5]L. S. Celenza, V. K. Mishra, C. M. Shakin, and K. F. Lin, Phys. Rev. Lett. **57**, 55 (1986).
[6]A. Schafer, J. Reinhardt, B. Muller, W. Greiner, and G. Soff, J. Phys. G **12**, 169 (1986).
[7]A. B. Balantekin, C. Bottcher, M. R. Strayer, and S. J. Lee, Phys. Rev. Lett. **55**, 461 (1985).
[8]L. M. Krauss and F. Wilczek, Phys. Lett. **173B**, 435 (1986).
[9]N. Mukhopadhyay and A. Zehnder, Phys. Rev. Lett. **56**, 206 (1986).
[10]R. D. Peccei, T. T. Wu, and T. Yanagida, Phys. Lett. **172B**, 435 (1986).
[11]S. Weinberg, Phys. Rev. Lett. **40**, 279 (1978).
[12]C. Edwards *et al.*, Phys. Rev. Lett. **48**, 403 (1982).
[13]F. P. Calaprice *et al.*, Phys. Rev. D **20**, 2706 (1979).
[14]A. Zehnder, K. Gabathuler, and J. L. Vuilleumier, Phys. Lett. **110B**, 419 (1982).
[15]V. M. Datar, C. V. K. Baba, M. G. Betigeri, and P. Singh, Phys. Lett. **114**, 63 (1982).
[16]J. P. Schapira *et al.*, Nucl. Instrum. Methods **224**, 337 (1984).
[17]M. E. Rose, Phys. Rev. **76**, 678 (1949).
[18]On closing the gate valve at the entry to the SOLENO this background reduced drastically implying that it mainly arose from electrons produced by the high γ ray flux in the target area.
[19]D. Berghofer *et al.*, Nucl. Phys. **A263**, 109 (1976); D. K. Scott, P. S. Fischer, and N. S. Chant, Nucl. Phys. **A99**, 177 (1967).
[20]W. Heitler, *Quantum Theory of Radiation* (Oxford University Press, London, 1954).
[21]A. Barrosso and N. C. Mukhopadhyay, Phys. Rev. C **24**, 2382 (1981); S. B. Treiman and F. Wilczek, Phys. Lett. **74B**, 381 (1978).
[22]T. W. Donnelly *et al.*, Phys. Rev. D **18**, 1607 (1978).
[23]W. A. Bardeen, R. D. Peccei, and T. Yanagida, Nucl. Phys. **B279**, 401 (1987). Their λ_3 is related to $g^{(1)}$ defined in the text through the relationship $\lambda_3 = 2.16\times10^2 g^{(1)}$.
[24]M. J. Savage, R. D. McKeown, B. W. Fillipone, and L. W. Mitchell, Phys. Rev. Lett. **57**, 178 (1986).
[25]F. W. N. de Boer *et al.*, Phys. Lett. **180B**, 4 (1986).
[26]C. V. K. Baba, D. Indumathi, A. Roy, and S. C. Vaidya, Phys. Lett. **180B**, 406 (1986).
[27]A. L. Hallin, F. P. Calaprice, R. W. Dunford, and A. B. McDonald, Phys. Rev. Lett. **57**, 2105 (1986).
[28]A. Konaka *et al.*, Phys. Rev. Lett. **57**, 659 (1986).
[29]R. Eichler *et al.*, Phys. Lett. **175B**, 101 (1986).
[30]T. Bowcock *et al.*, Phys. Rev. Lett. **56**, 2676 (1986); G. Mageras *et al.*, *ibid.* **56**, 2672 (1986).