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An experimental limit on the coupling of a light neutral pseudoscalar particle to hadrons

D INDUMATHI*, C V K BABA, A ROY and S C VAIDYA

Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India

*Present address: The Institute of Mathematical Sciences, Madras 600 113, India

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Abstract. Detailed results of an experiment, looking for a short-lived neutral particle decaying by an e^+e^- pair in the decay of the 3·68 MeV (3/2) state in ^{13}C, whose decay is predominantly M1, are presented. An upper limit of 7×10^{-5} has been placed on the branching ratio for decay through such a particle with a mass in the range 1·7 to 1·9 MeV/c^2. This leads to an upper limit of 10^{-6} for the coupling of such a particle to nucleons. Such a limit rules out the explanation of the e^+ and e^- peaks recently observed in heavy ion collisions, as due to the decay of a neutral particle.

Keywords. Pseudoscalar neutral particle; axion; axion-nucleon coupling costant.

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1. Introduction

The existence of a light neutral pseudoscalar particle, the axion, was proposed in connection with the strong CP problem in quantum chromodynamics (QCD). The instanton solutions for the QCD, which is a non-abelian gauge theory, give rise to strong P, T and CP violating terms in the Lagrangian. Peccei and Quinn (1977) introduced a global chiral U(1) symmetry in order to restore these symmetries. Weinberg (1978) and Wilczek (1978) pointed out that due to the spontaneous breaking of this symmetry, a light pseudoscalar particle, the axion, would result. In the 'standard' axion model (Donnelly *et al* 1978), the mass and the lifetime of the axion are determined in terms of a free parameter, X, which is the ratio of the vacuum expectation values of two Higg's fields f_1 and f_2 (Peccei and Quinn 1977). These are:

$$f_1=\frac{\sin\lambda}{(\sqrt{2}\,G_F)^{1/2}} \quad \text{and} \quad f_2=\frac{\cos\lambda}{(\sqrt{2}\,G_F)^{1/2}} \tag{1}$$

and
$$f_\phi=(f_1^2+f_2^2)^{1/2}\simeq 250\ \text{GeV} \tag{2}$$

where G_F is the fermi coupling constant. The axion would be expected to decay into two photons and to a e^+e^- pair if its mass exceeds $2\,m_ec^2$. The mass m_ϕ and the lifetime τ_ϕ are given in terms of X as (Donnelly *et al* 1978):

$$m_\phi c^2\simeq 25\ \text{N}\left(X+\frac{1}{X}\right)\text{keV} \tag{3}$$

$$\tau_{\phi \to 2\gamma} \simeq 0{\cdot}7\left(\frac{100\ \text{keV}}{m_\phi c^2}\right)^5 \text{sec} \tag{4}$$

$$\tau_{\phi \to e^+e^-} = \frac{8\pi\hbar X^2 f_\phi^2}{(m_\phi c^2)[m_\phi^2 c^4 - 4m_e^2 c^4]^{1/2}}. \tag{5}$$

There has been several searches for such a particle in the past. Calaprice *et al* (1979) ruled out an axion of $m_\phi > 2m_e$ and lifetime $> 10^{-11}$ sec. Radioactive decay experiments (Zehnder 1981) and reactor experiments (Datar *et al* 1982; Cavaignac *et al* 1983) rule out a lighter particle decaying into 2γ's with lifetime between 10^{-2} and 10^{-9} sec. However, a particle of a lifetime shorter than 10^{-11} sec would have escaped detection in the existing experiments.

The interest in axions revived following the recent observation of narrow positron and electron peaks (width <70 keV) of energy ~ 350 keV in the collision of heavy ions (Schweppe *et al* 1983; Clemente *et al* 1984; Cowan *et al* 1985; Tsertos *et al* 1985). Such peaks were observed with the same energy in several collision systems with a combined charge of $(Z_1+Z_2) \geqslant 163$, in addition to the broad continuum expected due to the spontaneous creation of positrons in supercritical systems. In a later experiment (Cowan *et al* 1986), the electron and positron peaks were found to be coincident and the sum of the kinetic energies of the two peaked at 0·7 MeV and had a narrow width. Balantekin *et al* (1985) and Schafer *et al* (1985) investigated the possibility that the e^+ and e^- peaks are due to the decay of a neutral particle produced at rest in the centre of mass system of the two colliding ions. From the production cross-section for these monoenergetic positrons, of $\sim 200\ \mu$b and from the existing limits on the coupling of any boson other than photon to the leptons, obtained from $(g-2)$ experiments on electrons, Schafer *et al* (1985) concluded that the only possibility is a pseudoscalar particle and that it should have a coupling to proton/neutron of $\alpha = g^2/4\pi \geqslant 10^{-4}$. If this particle were to be identified as the axion, one obtains a value of $X=22$ or $X=0{\cdot}045$, which leads to a value of $\sim 10^{-7}$ sec or $\sim 10^{-12}$ sec for its lifetime, respectively. The earlier experiments rule out the longer halflife (Calaprice *et al* 1979), but the shorter lived axion is a possible explanation for the observed e^+e^- peaks. However, the above values of X give predictions for the branching ratios of $(J/\Psi) \to \gamma\phi$ and $\Psi \to \gamma\phi$ which do not agree with the observed limits (Yamada 1983). In this context Peccei *et al* (1986) and Krauss and Wilczek (1986) pointed out that the 'standard' model can be modified to accommodate the observed limits. Subsequent experiments (Bowcock *et al* 1986; Mageras *et al* 1986), however, conclusively rule out an axion with $X=22$ or $0{\cdot}045$.

Irrespective of whether the particle decaying into e^+e^- pairs observed in the heavy ion collision experiment is an axion or not, it is necessary to establish whether the particle interpretation of the observed e^+e^- peaks is tenable. There are alternative explanations, though exotic, that attempt to explain these peaks as due to the creation of a multi electron-positron system (Muller *et al* 1986) of dimensions of ~ 100 fm or as due to non-topological soliton solutions in the strong fields produced in the vicinity of the colliding nuclei (Celenza *et al* 1986). If the particle decay interpretation is the correct one, one should look for other situations where such a particle is produced. Since the particle (called ϕ throughout this paper, whether it is the axion or any other particle) should couple to hadrons with $\alpha > 10^{-4}$ (Schafer *et al* 1985), it could compete with an electromagnetic decay of a nuclear excited state, if the transition energy is larger than the rest mass of ϕ (Mukhopadhyay and Zehnder 1986). If the particle has a pseudoscalar nature, it can compete with magnetic multipole radiation. In this paper, we shall describe an experiment to search for the formation of such a particle and its decay by $e^+ e^-$ pair from the 3·68 MeV ($3/2^-$) excited state in ^{13}C**. The result of the experiment showed that if such a particle exists, its coupling to neutron/proton is $<10^{-6}$, which is inconsistent with the value $>10^{-4}$ required, on the basis of the analysis of the heavy ion collision experiments, to interpret the $e^+ e^-$ pairs as the decay products, of a particle. A brief account of these results has been published (Baba *et al* 1986). In this paper, the details of the experiment and its interpretation are presented.

2. Experimental Details

2.1 *Experimental set-up*

The axion was looked for in the decay of the 3·68 MeV state in ^{13}C which has $J^\pi = 3/2^-$, $T = 1/2$ and decays to the ground state ($J^\pi = 1/2^-$, $T = 1/2$) by a predominantly magnetic ($M1 + 0{\cdot}9\%$ $E2$) transition. The γ-transition has both isoscalar and isovector components. However, the isoscalar component is expected to be small (Morpurgo 1958). This state in ^{13}C was populated by the ^{10}B(α, p)^{13}C* reaction using the alpha particle beam from the 5·5 MV Van de Graaff accelerator at BARC, Trombay. The experimental configuration is shown in figure 1. The target of thickness ~ 20 μg/cm^2 was prepared by vacuum deposition of isotopically enriched (>99%) ^{10}B on ^{12}C backing (~ 10 μg/cm^2). The α-particle beam current was ~ 1 μA and was collected in a Faraday Cup and measured by a current integrator. The electrons (positrons) were detected by liquid nitrogen cooled Si(Li) detectors placed coplanar with the target and beam direction. One detector, det 1, was 5 mm thick with a diameter of 6 mm while det 2 was 5 mm thick with a diameter of 16 mm. The third detector, det 3, was 4 mm thick but had the same diameter as det 2 but was covered with 2 mm thick copper plate to stop the electrons, so that only γ-rays would be detected by det 3. Detectors 1 and 2 were covered by 0·3 mm Al so as to prevent the protons and the scattered alpha particles from reaching the detectors. The energy loss of electrons in the Al foil was $\simeq 100$ keV which was taken into account for the determination of electron (positron) energy. Det 2 had a curved copper slit of width 2 mm which subtended an angle of $\pm 3°$ in θ (polar angle) at the target but allowed the maximum possible opening in the azimuthal direction ϕ. The target was continuously monitored by a Si surface barrier detector placed at 150° to the beam direction and checking the yield of the proton groups. A $12{\cdot}5 \times 12{\cdot}5$ cm dia NaI(Tl) detector was mounted outside the vacuum chamber to monitor the γ-rays produced in the reaction. A 120 cm^3 Ge(Li) detector was also used to record the γ-ray spectra. The chamber was maintained at a pressure of $\sim 4 \times 10^{-6}$ Torr. Two collimators separated by about 30 cm maintained the size of the beam spot to ~ 2 mm dia on the target. The detector pairs 1,2 and 1,3 subtend an angle of 50° at the target, detector 1 being at 90° from the beam direction.

**The state at 3·68 MeV in ^{13}C is chosen for the investigation for the following reasons: (i) the energy of the excited state is convenient to study the $e^+ e^-$ decay of a particle of mass $\sim 1{\cdot}7$ MeV/c^2; (ii) this state decays predominantly through M1 (99·1%) transition; (iii) the easy availability of the target and the beam to produce this reaction; (iv) the possibility of investigating isovector coupling (see § 3).

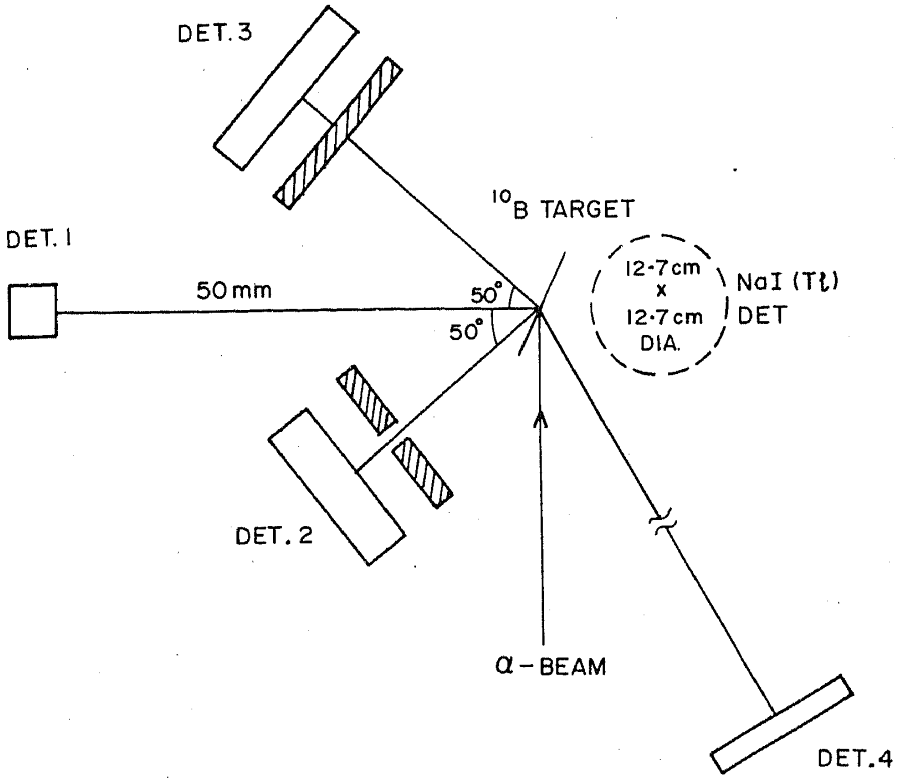

Figure 1. Schematic diagram of the experimental configuration. Detectors 1, 2 and 3 are liquid nitrogen cooled Si(Li) detectors. Detector 4 is a Si surface barrier detector. In addition to the NaI(Tl) detector, a 120 cm^3 Ge(Li) detector was also used for detecting gamma rays.

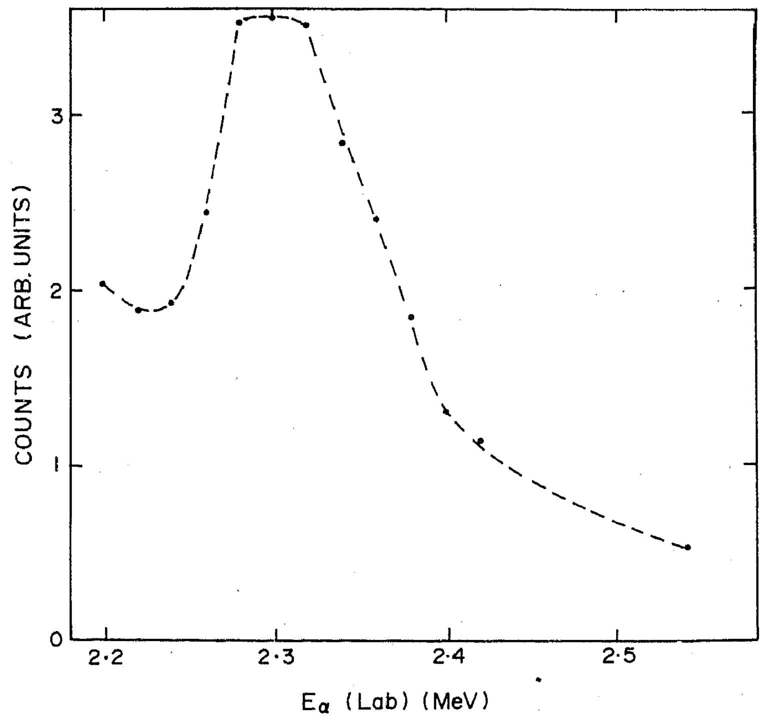

Figure 2. Yield of (3·68 + 3·85) MeV gamma rays in the vicinity of the resonance at $E_\alpha = 2{\cdot}26$ MeV.

The energy, E_α, of the α-particles incident on the ^{10}B target was varied in steps of 20 keV and the yield to the (3·68 + 3·85) MeV γ-rays was measured in the NaI(Tl) detector to locate the resonance at $E_\alpha = 2{\cdot}26$ MeV (Gallmann *et al* 1969). The yield of the proton groups was also measured in the surface barrier detector. The excitation function of the γ-rays is presented in figure 2. It is seen that at the energy $E_\alpha = 2{\cdot}26$ MeV, the reaction shows a resonance which preferentially populates the 3·68 MeV state. The γ spectra in both the NaI(Tl) and Ge(Li) detectors at $E_\alpha = 2{\cdot}31$ MeV presented in figures 3 and 4, respectively, show no γ-rays other than those produced in the reaction under study. The surface barrier spectrum (figure 5) also shows that other states in ^{10}B are populated only to a level of ~10% of that for the 3·68 MeV state. The α-particle energy was maintained at this value ($E_\alpha = 2{\cdot}31$ MeV) thereafter, ensuring maximum population of the ^{13}C excited state of interest.

2.2 *Detector configuration and Monte Carlo simulation*

The 50° angle between the pairs of detectors (1,2) and (1,3) was chosen considering the fact that should axions be produced in the reaction, their decay into e^+e^- pairs would have a strong angular correlation. The value of this particular angle and the efficiency of detection for the detector configuration was obtained for different values of the axion mass, m_ϕ between 1·7–1·9 MeV/c^2 using a Monte Carlo simulation described below.

An event starts with the direction of emission of the axion (θ_ϕ, ϕ_ϕ) being chosen at random assuming an isotropic distribution in the laboratory system. The departure from isotropy due to nuclear recoil in this case is less than 0·5° and thus can be neglected. The direction of emission $(\theta_e^{cm}, \phi_e^{cm})$ of e^- in the cm system of ϕ was then chosen at random considering the decay to be isotropic. The e^+ is emitted in the opposite direction to e^- in the cm system. The direction of emission of the e^- and e^+

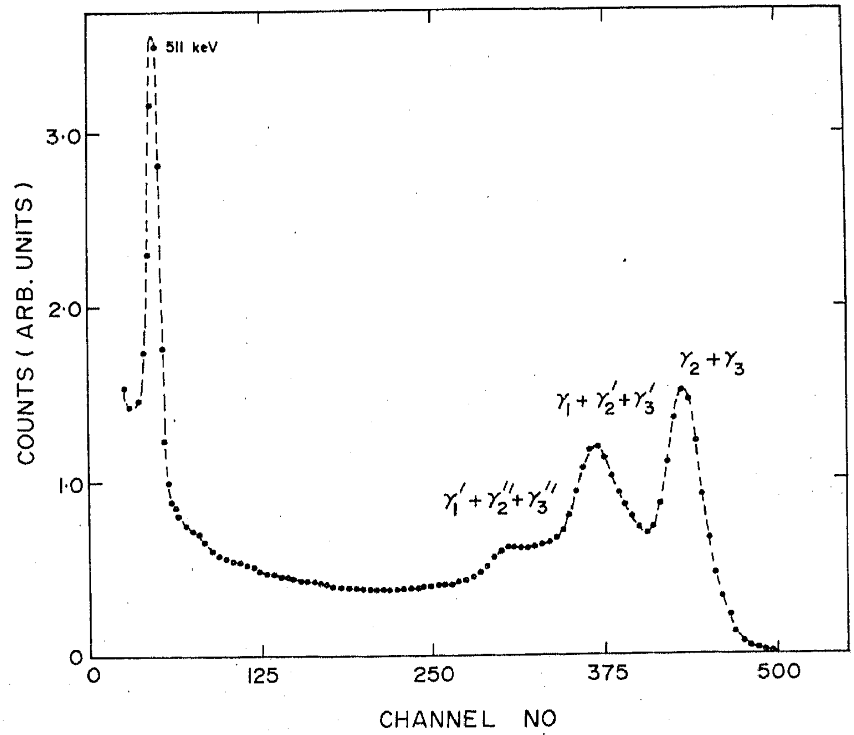

Figure 3. Gamma spectrum obtained with a NaI(Tl) detector at $E_\alpha = 2{\cdot}31$ MeV.

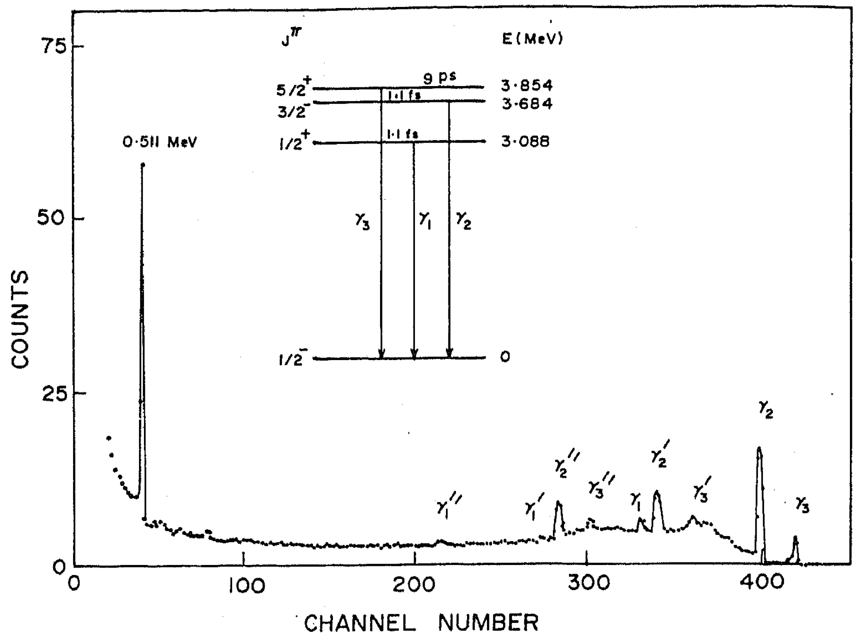

Figure 4. Gamma spectrum obtained with a Ge(Li) detector at $E_\alpha = 2{\cdot}31$ MeV. The observed peaks all correspond to the reaction under study.

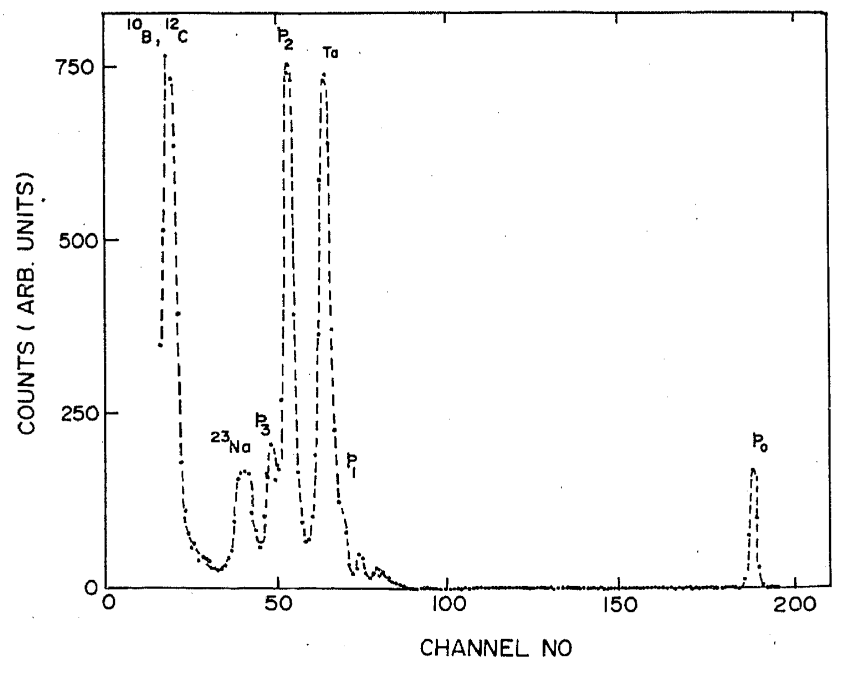

Figure 5. Proton and alpha spectrum obtained with a Si surface barrier detector at $E_\alpha = 2{\cdot}31$ MeV.

and their energies in the laboratory frame were obtained by usual relativistic transformations. At this stage the values of the laboratory angles of e^- and e^+ were checked to see if they fall within the directions defined by the detectors. To eliminate the effect of noise and low energy background in the detectors a lower threshold of 0·8 MeV was put on the energy of the e^- (e^+) to be considered. This automatically puts an upper threshold on the energy of the accompanying e^+ (e^-) since they share the total energy. The fact that the detectors did not distinguish between e^- and e^+ was taken into account. The above process was repeated for 10^7 events and the number of events recorded by both the detectors satisfying the thresholds was determined giving the efficiency of detection. The values obtained for $1{\cdot}7\ \mathrm{MeV/c^2} < m_\phi < 1{\cdot}9\ \mathrm{MeV/c^2}$ are presented in table 1.

2.3 *Data acquisition and calibration of detectors*

The energy output from each of the three detector preamplifier combinations was amplified and the bipolar outputs of the amplifiers were fed to three single channel analysers (SCA). The SCA outputs were given to a multiple coincidence circuit with the requirement of at least two of the pulses to be in coincidence within a resolving time of 1 μsec. The delayed unipolar pulses from the amplifiers were gated by the coincidence output in three different linear gate modules. The outputs from the linear gates were fed to three analog to digital converters and data were recorded in list mode on tape with the help of a PDP 11/23 computer. The energy calibration of the detectors were performed using the γ-rays from ^{60}Co, ^{207}Bi as well as the double escape peak of the 3·68 MeV γ-ray from the reaction under study. The total detection cum recording system was checked using the $^{19}F(p, \alpha)\,^{16}O^*$ reaction with a CaF_2 target populating the 6·06 MeV O^+ state in ^{16}O which decays almost entirely by $e^- e^+$ emission. Since the detectors were not thick enough to stop the higher energy electron and positrons from this reaction, the sum energy spectrum did not show a clear peak. However, the number of coincidences recorded agreed well with the number expected from the $e^- e^+$ decay of the 6·06 MeV state in ^{16}O.

2.4 *Data analysis*

From the binary list mode data collected on tape, two sets of coincidences, between the detector pairs (1,2) and (1,3) were sorted out. The set (1,3) contained events generated due to the γ-background alone since det 3 could not detect electrons. Two dimensional plots of energies E_{e^-} (E_{e^+}) and E_{e^+} (E_{e^-}) were generated by projecting the coincidence data energywise into 100 keV wide energy bins. The numbers thus obtained for set (1,3) after normalization for the solid angles were subtracted from those for set (1,2). From the resultant data, sum energy spectrum ($E_{e^+} + E_{e^-}$) was generated. The sum spectrum thus obtained contained contributions from the following sources:

Table 1. Efficiency of detection for decay of $\phi \to e^- e^+$ and the width for the decay of ^{13}C through ϕ.

m_ϕ (MeV/c^2)	ε	$\frac{\Gamma_\phi}{\Gamma_\gamma}$	Γ_ϕ (eV)
1·7	6×10^{-5}	$<6\times10^{-5}$	$<2{\cdot}2\times10^{-4}$
1·8	$3{\cdot}5\times10^{-5}$	$<10^{-4}$	$<4{\cdot}1\times10^{-4}$
1·9	$5{\cdot}2\times10^{-6}$	$<6{\cdot}7\times10^{-4}$	$<29\times10^{-4}$

(i) Internal pair production from the decay of the 3·68 MeV and other excited states of ^{13}C produced in the reaction, and

(ii) $e^+ e^-$ decay of a neutral particle, ϕ. The energies of the e^- and e^+ produced in the internal pair creation and their angular distribution has been given by Rose (1949) for different electric and magnetic multipole transitions. Using these equations and the solid angles subtended by the detectors, the contribution from internal pair creation for the transitions of 3·68 MeV, 3·08 and 3·85 MeV were determined.

3. Results and discussion

The e^+ and e^- sum energy spectrum obtained from the coincidence data for 10^{10} photons produced at the target is presented in figure 6. We see the most prominent peak centred around 3·68 MeV with full width at half maximum (FWHM) of 200 keV which is the effective resolution of the detection system considering the straggling in the absorbers. The solid lines give the contributions to this spectrum from the internal pair creation for the transitions at 3·68, 3·08 and 3·85 MeV. The total number of counts under the peak at 3·68 MeV from this process is estimated to be 70. We see that the data can be completely accounted for by this contribution alone. The dotted line shows the expected number of counts at 3·68 MeV if in addition to the internal pair creation a contribution at the $2\sigma(\sigma \sim 17)$ level (i.e. at a 95% confidence level) from a neutral particle decay is considered.

Thus $\varepsilon_\phi \Gamma_\phi / \Gamma_\gamma < 35 \times 10^{-10}$ where ε_ϕ is the efficiency of detection for ϕ; Γ_ϕ and Γ_γ are the partial widths for the decay of the 3·68 MeV state through the particle ϕ and γ, respectively. The limits on the values of $\Gamma_\phi/\Gamma_\gamma$ for different values of m_ϕ, and thus on Γ_ϕ using $\Gamma_\gamma = (0{\cdot}43 \pm 0{\cdot}04)$ eV (Lederer and Shirley 1978) are presented in table 1.

The limit on the coupling constant $\alpha_{\phi \mathrm{NN}}$ of the particle, ϕ, with nucleons can be obtained by two independent methods. Ignoring isospin, the decay width of 3·68 MeV state $(3/2^-)$ to the g.s. $(1/2^-)$ of ^{13}C through ϕ, Γ_ϕ can be compared to the decay width, Γ_Δ for the $\Delta(3/2^+)$ resonance decaying by emitting a π to the nucleon $(1/2^+)$. The ratios

$$\frac{\Gamma_\phi}{\Gamma_\Delta} = \frac{\alpha_{\phi\mathrm{NN}}}{\alpha_{\pi\mathrm{NN}}} \frac{p_\phi^3}{p_\pi^3}$$

where p_ϕ and p_π are the associated momenta of the ϕ and π and $\alpha_{\pi\mathrm{NN}}$ is the coupling constant of the π with nucleons. The limits on $\alpha_{\phi\mathrm{NN}}$ thus obtained are given in column 2 of table 2.

The second method is due to Donnelly *et al* (1978) who have given an expression for the ratio $\Gamma_\phi/\Gamma_\gamma$ as

$$\frac{\Gamma_\phi}{\Gamma_\gamma} = \frac{1}{2} \frac{p_\phi^3}{p_\gamma^3} \left[\frac{g^{(1),(0)}}{e\mu^{(1),(0)}} \right]^2$$

where (1) and (0) stand for iso-vector and iso-scalar couplings respectively and $\mu^{(1),(0)}$ the magnetic moments:

$$\mu^{(0)} = \mu^p + \mu^n - \tfrac{1}{2} = 0{\cdot}38 \text{ nm} \quad \text{and}$$

$$\mu^{(1)} = \mu^p - \mu^n = 4{\cdot}71 \text{ nm}.$$

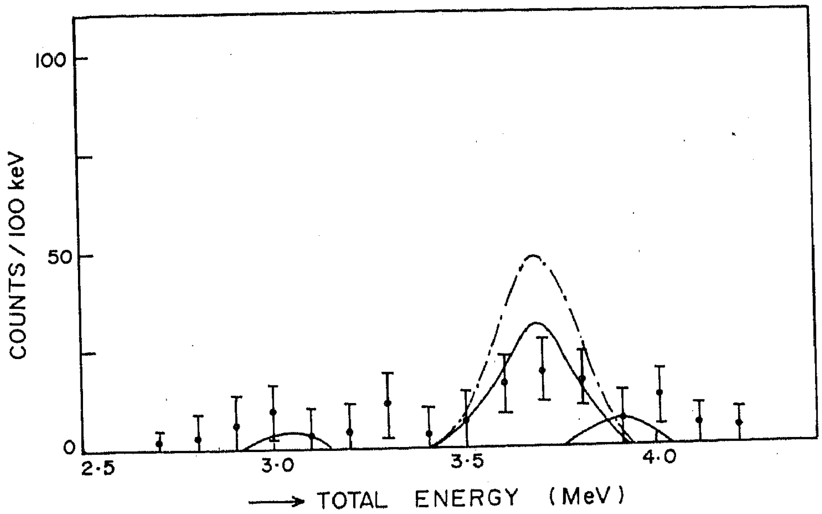

Figure 6. The energy sum spectrum obtained from the coincidence data. See text for explanations.

Table 2. Upper limits on the coupling of ϕ with nucleon. α and g with superscript (a) are calculated by comparison with decay of Δ resonance and those denoted by (b) are those obtained from the formula of Donnelly *et al* (1978).

m_ϕ (MeV/c^2)	$\alpha^{(a)}_{\phi NN}$	$g^{(a)}_{\phi NN}$	$\alpha^{(b)}_{\phi NN}$	$g^{(b)}_{\phi NN}$
1·7	$0{\cdot}65\times10^{-7}$	$0{\cdot}9\times10^{-3}$	$0{\cdot}7\times10^{-6}$	3×10^{-3}
1·8	$1{\cdot}32\times10^{-7}$	$1{\cdot}3\times10^{-3}$	7×10^{-5}	3×10^{-2}
1·9	$9{\cdot}43\times10^{7}$	$3{\cdot}4\times10^{-3}$	$1{\cdot}7\times10^{-4}$	7×10^{-2}

In the present case of ^{13}C the transition is a mixture of isoscalar and isovector components and thus limits can be put on the combination $|g^{(0)}+(1/\sqrt{3})\,g^{(1)}|$ which are shown in column 3 of table 2.

Recently, Savage *et al* (1986) also looked for such a particle in the decay of the 9·17 MeV state in ^{14}N via an M1 isovector transition and give an upper limit of $g^{(1)}\leqslant 1{\cdot}4\times10^{-2}$ for the coupling strength. In another experiment de Boer *et al* (1986) have searched for such a particle in the isoscalar decay of 3·59 MeV state in ^{10}B and give an upper limit of $g^{(0)}\leqslant 10^{-2}$. Thus the present experiment gives the most stringent limit for the coupling of an axion to nucleons obtained from a nuclear decay.

Since a coupling strength of $g\geqslant 3\times10^{-2}$ is required for explaining the e^+e^- peaks in the GSI experiment, as arising from the decay of axions, this explanation can be ruled out on the basis of the present experiment. In conclusion, this experiment gives upper limits on the possibility of a pseudoscalar neutral particle, ϕ (which itself decay by e^+e^- emission) mediating in the decay of an excited nuclear state as a function of its mass, m_ϕ. The upper limit of 10^{-6} is placed on the coupling of such a particle to the nucleon.

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