Search for Dark Forces at KLOE and KLOE-2

Fabio Bossi for the KLOE-2 Collaboration
Laboratori Nazionali di Frascati INFN, via Enrico Fermi 40, 00044 Frascati, Italy
E-mail: fabio.bossi@lnf.infn.it

Abstract. Following recent puzzling astrophysical results, searches for a relatively low mass (~1 GeV) new vector boson (the $U$), weakly coupled with SM particles, are being pursued in several different laboratories in the world. In particular the KLOE-2 Collaboration has searched for this new particle in the decays of the $\phi$ meson into an $\eta$ and an $e^+e^-$ pair, with null result. An upper limit on the existence of the $U$ has been set, in the mass range $50 < M_U < 420$ MeV.

1. Introduction
The lagrangian of the Standard Model (SM) of particle physics is built to obey the $\text{SU}(2)_L \otimes \text{U}(1)_Y \otimes \text{SU}(3)_C$ gauge symmetry. Massless matter fermions are charged under at least one of the above symmetries, which are mediated by the proper set of massless vector bosons. Spontaneous symmetry breaking induced by the Higgs potential provides then mass to both the matter fields and to the vector bosons. This theory perfectly describes all of the known reactions of elementary particles observed to date.

On the other hand, in the context of newtonian gravity, there is compelling astrophysical evidence of the existence of Dark Matter (DM), whose nature is still undiscovered. The only thing we know about DM is that it is not composed of SM particles, and that is sensitive to gravitation. Actually, there is no fundamental reason not to assume that matter fields different from the SM ones are sensitive to different types of gauge symmetries, and thus sensitive to different types of vector bosons. If (at least some of) these new matter fields are also coupled to SM gauge bosons (for instance they have electric charge), higher order loop diagrams can allow SM particles to couple the new symmetries, even if they are not charged under them.

The above ideas were already developed in the early 80’s in the framework of supersymmetric extensions of the SM [1] [2], but have in recent years become particularly popular since they might allow explaining some intriguing and thus far unexplained experimental astrophysical results. A further reason for these models to be particularly attractive is that they can induce observable effects in present day collider experiments, also at energies of order 0.1 - 10 GeV.

In this paper I will firstly briefly present some of the most interesting astrophysical puzzles of the recent years, and their possible explanation in terms of the existence of a new hidden gauge symmetry. I will then discuss some of the possible collider signatures of this new symmetry, finally concentrating on the recent KLOE-2 limit on the existence of a “dark photon” using $\phi$ meson Dalitz decays.
2. Experimental results and their possible explanation

Several recent experiments, as for instance PAMELA [3], FERMI [4], and ATIC [5] have observed in cosmic ray data a large excess of electrons and positrons with energies between approximately 10 and 100 GeV, with respect to what can be accounted by supernova shocks and interactions of cosmic ray protons with the interstellar medium.

The INTEGRAL satellite [6] observes a 511 keV signal from the galactic core, which suggests the existence of an abundant positron annihilation source, far exceeding what expected from supernovae only.

Another long standing puzzle is the annual modulation signal reported by the DAMA/LIBRA experiment in the Gran Sasso laboratory [7], that is consistent with what expected by nuclear scattering of WIMP dark matter. The CoGent Collaboration observes an excess of events in their lowest energy electrons bins, with a possible annual modulation in the signal [8]. However, other experiments [9] using different detection techniques contradict both DAMA and CoGent.

All in all, these observations do not have easy interpretations in terms of standard astrophysical and/or particle physics processes, which makes their study an intriguing task per se. More interestingly, however, there have appeared in literature papers [10], [11], [12] [13], [14] arguing that they can all be interpreted by some common physical process, i.e. by the same model of DM production and annihilation. Although these papers differ between each other by some specific detail, all of them in general postulate the existence of relatively heavy (\(\sim 1 \text{ TeV}\)) WIMP DM states together with at least one relatively light (\(\sim 1 \text{ GeV}\)) vector boson, mediator of a new hidden gauge symmetry. SM particles are not charged under this new symmetry, however they can still couple with the “dark photon” (baptized under different names in the literature: \(A'\), \(U\), \(\phi\ldots\)) through the kinetic mixing mechanism with ordinary SM bosons, and specifically with the photon. Typically, the mixing strength is parametrized by a single parameter \(\epsilon\), whose value has to be determined experimentally. In order to better accommodate the above mentioned experimental results, however, preferred values of \(\epsilon\) are in the ball-park of \(10^{-3}\). As a consequence of that, the \(U\) can be produced and observed at present day colliders depending on its mass and on the value of \(\epsilon\), as discussed in the following section.

Before discussing the collider signatures of the \(U\) boson, it is important to underline that another intriguing aspect of the models discussed above, is the role that they can play in explaining the observed \(3\sigma\) discrepancy between the measured and calculated values of the muon g-2 (see for instance [15]). Actually, the presence of diagrams of \(U\) boson exchange can increase the theoretical prediction towards the measured value, for properly chosen \(M_U\) and \(\epsilon\).

3. \(U\) boson production mechanisms

The \(U\) boson can be produced in \(e^+e^-\) collisions via the radiative reaction \(e^+e^- \rightarrow U\gamma\), with subsequent decay of the \(U\) into a lepton pair. If the two leptons are charged, it can be observed as a resonant peak of the lepton pair invariant mass distribution over the standard continuous QED background. An estimate based on a BaBar measurement of \(T(2S,3S)\) decays into \(\mu^+\mu^-\gamma\), gives null result. The analysis was actually motivated by the search for a light scalar particle [16], which should have in fact a different acceptance with respect to a vector one. With some caveat one can still translate the BaBar null result into a limit of \(\sim 10^{-3}\) on the mixing parameter in the range \(2m_\mu - 9.3 \text{ GeV}\).

\(U\) bosons can be produced in electron collisions on a fixed target in a process analogous to ordinary bremsstrahlung. In this case, production cross sections are much higher with respect to \(e^+e^-\) processes. However backgrounds, both from ordinary QED reactions and from possible beam related sources are also higher. A comprehensive discussion of the possible detection strategies for this kind of experiments can be found in [17]. Schematically, beam dump experiments are useful to probe the region of low masses and very low couplings, a condition which favours relatively long \(U\) lifetimes, while for higher masses and couplings forward
spectrometers with the best possible vertex resolution are required.

Some old beam dump experiments is actually being data-mined, while new experimental activities have started in several laboratories all over the world. In particular, during the last year two papers have been published by the MAMI A1 experiment in Mainz (Germany) [18], and by the APEX experiment at JLAB (USA) [19], setting limits on the existence of the $U$ boson with mass between approximately 200 and 300 MeV, for $\epsilon$ down to $\sim 10^{-3}$.

A further line of reasearch also available at $e^+e^-$ colliders is the study of the decays of a vector meson into a pseudoscalar and a $U$, as suggested by Reece and Wang [20]. This decays should occur at a rate suppressed by a factor $\epsilon$ with respect to the standard radiative ones, which have typical branching ratios of $\sim 1\%$. In particular Reece and Wang have focussed their attention on the channel $\phi(1020) \rightarrow \eta U$. With the statistics acquired so far by the KLOE experiment at the DAΦNE facility in Frascati, they have argued that one could probe mixing parameters down to $\sim 10^{-3}$, for $U$ masses below $m_{\phi} - m_{\eta} \sim 470$ MeV. This search has actually been performed by the KLOE-2 Collaboration, as described in the rest of the paper.

4. The KLOE experiment

The KLOE experiment operated from 2000 to 2006 at DAΦNE, the Frascati $\phi$-factory. DAΦNE is an $e^+e^-$ collider running at a center-of-mass energy of $\sim 1020$ MeV, the mass of the $\phi$ meson. Equal energy positron and electron beams collide at an angle of $\pi$-25 mrad, producing $\phi$ mesons nearly at rest. The detector consists of a large cylindrical Drift Chamber (DC), surrounded by a lead-scintillating fiber electromagnetic calorimeter (EMC). A superconducting coil around the EMC provides a 0.52 T field. The beam pipe at the interaction region is spherical in shape with 10 cm radius, it is made of a Beryllium-Aluminum alloy of 0.5 mm thickness. Low beta quadrupoles are located at about $\pm 50$ cm distance from the interaction region. The drift chamber [21], 4 m in diameter and 3.3 m long, has 12,582 all-stereo tungsten sense wires and 37,746 aluminum field wires. The chamber shell is made of carbon fiber-epoxy composite with an internal wall of $\sim 1$ mm thickness, the gas used is a 90% helium, 10% isobutane mixture. The spatial resolutions are $\sigma_{xy} \sim 150$ $\mu$m and $\sigma_z \sim 2$ mm. The momentum resolution is $\sigma(p) / p \approx 0.4\%$. Vertexes are reconstructed with a spatial resolution of $\sim 3$ mm. The calorimeter [22] is divided into a barrel and two endcaps, for a total of 88 modules, and covers 98% of the solid angle. The modules are read out at both ends by photomultipliers, both in amplitude and time. The readout granularity is $\sim (4.4 \times 4.4)$ cm$^2$, for a total of 2440 cells arranged in five layers. The energy deposits are obtained from the signal amplitude while the arrival times and the particles positions are obtained from the time differences. Cells close in time and space are grouped into energy clusters. The cluster energy $E$ is the sum of the cell energies. The cluster time $T$ and position $\vec{R}$ are energy-weighted averages. Energy and time resolutions are $\sigma_E / E = 5.7\% / \sqrt{E}$ (GeV) and $\sigma_T = 57$ ps/$\sqrt{E}$ (GeV) $\pm 100$ ps, respectively.

The physics program of KLOE covers a wide range of topics, including tests of discrete symmetries conservation/violation, precision measurement of SM parameters, studies on low energy QCD. A good review can be found in [23].

5. $U$ boson production in $\phi$ decays

We have studied the process $\phi \rightarrow \eta U$, using a sample of 1.5 fb$^{-1}$ of data collected in 2004-2005. The $U$ boson is searched for looking at its decay into an electron-positron pair, since $e^\pm$ are easily identified in KLOE using time-of-flight (ToF), while the $\eta$ meson is tagged by its $\pi^+\pi^-\gamma$ decay channel, which provides a clean final state with four charged particles and two photons.

Radiative decays of the $\phi$ into $\eta \gamma$ have a branching ratio of about 1.2%, which translates in a cross section of approximately 40 nb. The photon can convert into an electron-positron pair while traversing some detector material with probability of $\sim 1\%$, resulting in a final state that mimicks our signal. An irreducible background due to the Dalitz decay of the $\phi$ meson,
is also present, with branching ratio of order $10^{-4}$. Differently from our signal, however, it is not resonant. In order to study the effect of these events on our analysis, they have been simulated by the Monte Carlo, using a Vector Meson Dominance model [24], using the form factor parametrization from the SND experiment [25]. Signal production and decay has been simulated according to [20].

Events are preselected requiring the presence of four charged tracks from the interaction point (IP) and two photons. The best match to the $\eta$ mass of the two photons and two oppositely charged tracks (assumed to be pions) is found, the remaining two tracks are assumed to be an $e^{\pm}$ pair. The recoil mass to the $e^{\pm}$ pair is then computed and only events with $535 < M_{\text{recoil}}(e^+e^-) < 560$ MeV are retained.

Although a large part of the backgrounds are already rejected at this level, some contamination from photon conversions and from misreconstructed $\phi$ decay channels still remains. The former are rejected thanks to a specific photon-conversion recognition alghoritm, the latter by identifying fake $e^{\pm}$ by time-of-flight to the calorimeter. In fact this last category of backgrounds is dominated by multi-pionic events.

The analysis efficiency, estimated by MC, ranges between 10 and 20%, depending on the invariant mass value of the $e^{\pm}$ pair.

About 14,000 $\phi \rightarrow \eta e^+e^-$ events survive the cuts, with a negligible background contamination. No evident peak is seen in the invariant mass distribution of the lepton pair, as shown in fig. 1. In order to extract the correct upper limit on the $U$ boson production, an accurate description of the Dalitz decay background is needed. For the purpose a fit is performed on the $M_{ee}$ distribution, with a function taken from [24]. The binning of the fit is of 5 MeV. When estimating the background of a given bin, the fit is performed removing the five bins centered around it. Details of the procedure are found in [26].

![Figure 1](image.png)

**Figure 1.** Fit to the corrected $M_{ee}$ spectrum for the Dalitz decays $\phi \rightarrow \eta e^+e^-$.  

In fig. 2 the exclusion plot at 90% C.L. on the number of events for the decay chain $\phi \rightarrow \eta U$, $\eta \rightarrow \pi^+\pi^-\pi^0$, $U \rightarrow e^+e^-$, is shown. Taking into account the analysis efficiency this result is then reported in terms of the parameter $\alpha'/\alpha = \epsilon^2$, where $\alpha'$ is the coupling of the $U$ boson to electrons and $\alpha$ is the fine structure constant. The opening of the $U \rightarrow \mu^+\mu^-$ threshold, in the hypothesis that the $U$ boson decays only to lepton pairs and assuming equal coupling to $e^+e^-$ and $\mu^+\mu^-$, has been included. In fig. 3 the smoothed exclusion plot at 90% C.L. on $\alpha'/\alpha$ is compared with existing limits from the muon anomalous magnetic moment $a_\mu$ and from recent measurements of the MAMI/A1 [18] and APEX [19] experiments. The gray line is where the
U boson parameters should lay to account for the observed discrepancy between measured and calculated $a_\mu$ values.

**Figure 2.** Upper limit at 90% C.L. on the number of events for the decay chain $\phi \rightarrow \eta U$, $\eta \rightarrow \pi^+\pi^-\pi^0$, $U \rightarrow e^+e^-$.  

**Figure 3.** Exclusion plot at 90% C.L. for the parameter $\alpha'/\alpha = \epsilon^2$, compared with existing limits in our region of interest.

Our result greatly improves existing limits in a wide mass range, resulting in an upper limit on the $\alpha'/\alpha$ parameter of $\leq 2 \times 10^{-5}$ @ 90% C.L. for $50 < M_U < 420$ MeV, thus covering part of the expected $\epsilon$ range. We exclude that the existing $a_\mu$ discrepancy is due to a U boson with mass ranging between 90 and 450 MeV.

6. Future plans

In the described analysis, only the $\pi^+\pi^-\pi^0$ decay channel has been used to tag the presence of the $\eta$ meson. We are presently studying the possibility to use also other $\eta$ dominant decay channels, as the $2\gamma$ and the $3\pi^0$ ones. Moreover, a new data taking campaign with a slightly modified detector has started with the aim of increasing the acquired luminosity by about an order of magnitude [27]. This will allow us increasing our sensitivity to lower $\epsilon$ values in the same mass range.

We are also studying the possibility of using the $e^+e^- \rightarrow e^+e^-\gamma$ reaction, which will allow us to test the very low mass region.
References
[1] P. Fayet, 1980 Phys. Lett. B 95 285
[2] P. Fayet, 1981 Phys. Lett. B 187 184
[3] O. Adriani et al 2009 Nature 458 607
[4] A.A. Abdo et al 2009 Phys. Rev. Lett. 102 181101
[5] J. Chang et al 2008 Nature 456 362
[6] P. Jean et al 2003 Astron. Astrophys. 407 L55
[7] R. Bernabei et al 2008 Eur. Phys. J. C 56 333
[8] C.E. Aalseth et al 2011 Phys. Rev. Lett 107 141301
[9] E. Aprile et al 2011 Phys. Rev. Lett 107 131302
[10] M. Pospelov, A. Ritz, M.B. Voloshin 2008 Phys. Lett. B 662 53
[11] N. Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer, N. Weiner, 2009 Phys. Rev. D 79 015014
[12] D.S.M. Alves, S.R. Behbahani, P. Schuster, J.G. Wacker, 2010 Phys. Lett. B 692 323
[13] R. Essig, P. Schuster, N. Toro 2009 Phys. Rev. D 80 015003
[14] J.M. Cline and A.R. Frey 2011 Phys. Rev. D 84 075003
[15] F. Jegerlehner and A. Nyffeler 2009 Phys. Rept. 477 1
[16] B Aubert et al 2009 Phys. Rev. Lett. 103 081803
[17] J.D. Bjorken, R. Essig, P. Schuster, N. Toro, 2009 Phys. Rev. D 80 075018
[18] H. Merkel et al., 2011 Phys. Rev. Lett. 106 251802
[19] S. Abrahamyan et al., 2011 Phys. Rev. Lett 107 191804
[20] M. Reece, L.T. Wang, 2009 JHEP 07 051
[21] M. Adinolfi et al 2002 Nucl Inst.and Meth. A 488 51
[22] M. Adinolfi et al 2002 Nucl.Inst.and Meth. A 482 364
[23] F. Bossi et al 2008 Riv. Nuovo Cim. 31 531
[24] L.G. Landsberg 1985 Phys. Rep. 128 301
[25] M. N. Achasov et al 2001 Phys. Lett. B 504 275
[26] F Archilli et al. 2012 Phys. Lett. B 706 251
[27] G. Amelino Camelia et al 2010 Eur. Phys. J. C 68 619