Search for magnetic monopoles with the MoEDAL forward trapping detector in 13 TeV proton-proton collisions at the LHC

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MoEDAL is designed to identify new physics in the form of long-lived highly-ionising particles produced in high-energy LHC collisions. Its arrays of plastic nuclear-track detectors and aluminium trapping volumes provide two independent passive detection techniques. We present here the results of a first search for magnetic monopole production in 13 TeV proton-proton collisions using the trapping technique, extending a previous publication with 8 TeV data during LHC run-1. A total of 222 kg of MoEDAL trapping detector samples was exposed in the forward region and analysed by searching for induced persistent currents after passage through a superconducting magnetometer. Magnetic charges exceeding half the Dirac charge are excluded in all samples and limits are placed for the first time on the production of magnetic monopoles in 13 TeV pp collisions. The search probes mass ranges previously inaccessible to collider experiments for up to five times the Dirac charge.

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The existence of a magnetically charged particle would add symmetry to Maxwell's equations and explain why electric charge is quantised in Nature, as shown by Dirac in 1931 [1]. In addition to providing a consistent quantum theory of magnetic charge and elucidating electric charge quantisation, Dirac predicts the fundamental magnetic charge number (or Dirac charge) to be $g_{\rm D} = \frac{1}{2\alpha_{em}} \simeq 68.5$ where α_{em} is the fine-structure constant. Consequently, in SI units, magnetic charge can be written in terms of the dimensionless quantity $g_{\rm D}$ as $q_m = n g_{\rm D} e c$ where n is an integer number, e is the proton charge, and c is the speed of light in vacuum. Because $g_{\rm D}$ is large, a fast monopole is expected to induce ionisation in matter thousands of times higher than a particle carrying the elementary electric charge. Additionally, the existence of the monopole as a topological soliton is a prediction of theories of the unification of forces [2–5] where the monopole mass is determined by the mass scale of the symmetry breaking that allows nontrivial topology. For a unification scale of 10^{16} GeV such monopoles would have a mass in the range $10^{17} - 10^{18}$ GeV. In unification theories involving a number of symmetry-breaking scales [6–8] monopoles of much lower mass can arise, although still beyond the reach of the LHC. However, an electroweak monopole has been proposed [9–12] that is a hybrid of the Dirac and 't Hooft-Polyakov monopoles [2, 3] with a mass that is potentially accessible at the LHC.

Monopole relics from the early Universe have been extensively searched for in cosmic rays and in materials [13, 14]. In the laboratory, monopole-antimonopole pairs are expected to be produced in particle collisions, provided the collision energy exceeds twice the monopole mass M. Each time an accelerator accessed a new energy scale, dedicated searches were made in new monopole mass regions [15]. The Large Hadron Collider (LHC) is no exception to this strategy as a comprehensive monopole search programme using various techniques has been devised to probe TeV-scale monopole masses for the first time [16, 17]. The results obtained by MoEDAL using 8 TeV pp collisions allowed the existing LHC constraints on monopole pair production [18] to be improved to provide limits on monopoles with $|g| \leq 3g_{\rm D}$ and $M \leq$ 3500 GeV [19].

In 2015, an increase in the LHC pp collision energy from 8 TeV to 13 TeV was achieved, opening a significant discovery opportunity window. This paper presents the first monopole search results in this new energy regime, using the forward monopole trapping detector of the MoEDAL experiment exposed to 0.371 ± 0.004 fb^{-1} of 13 TeV pp collisions in 2015. The trapping volume used here is an upgrade of the prototype which was exposed in 2012 [19]. It consists of 672 squared aluminium rods with dimension $19{\times}2.5{\times}2.5$ cm^3 for a total mass of 222 kg in 14 stacked boxes which were placed 1.62 m from the IP8 LHC interaction point under the beam pipe on the side opposite to the LHCb detector. A crucial underlying assumption for the effectiveness of the trapping technique using aluminium elements is that there is a strong binding of a magnetic monopole to the $^{27}_{13}$Al nucleus, due to the large magnetic dipole moment of the latter [20]. We also note that aluminium does not present a problem with respect to activation, while its non-magnetic nature favours the stability of the SQUID magnetometer measurements. A description of the geometry of the experimental area and a discussion of the assumptions relevant to this search are given in Ref. [19].

The samples were individually scanned with DC SQUID long-core magnetometer (2G Enterprises Model 755) newly installed at the Laboratory for Natural Magnetism at ETH Zurich. Conveniently, the new instrument features a conveyor tray for transporting samples through the sensing coils. It is calibrated using both the convolution method and a long solenoid with equivalent pole strength of 32.4 $g_{\rm D}/\mu A$, as described in Ref. [21]. The two independent methods give a calibration that is consistent to within 10%. The linearity of the magnetometer response is directly demonstrated for magnetic poles in the range $0.3 - 10^6 g_{\rm D}$.

After calibration, the magnetic charge con-

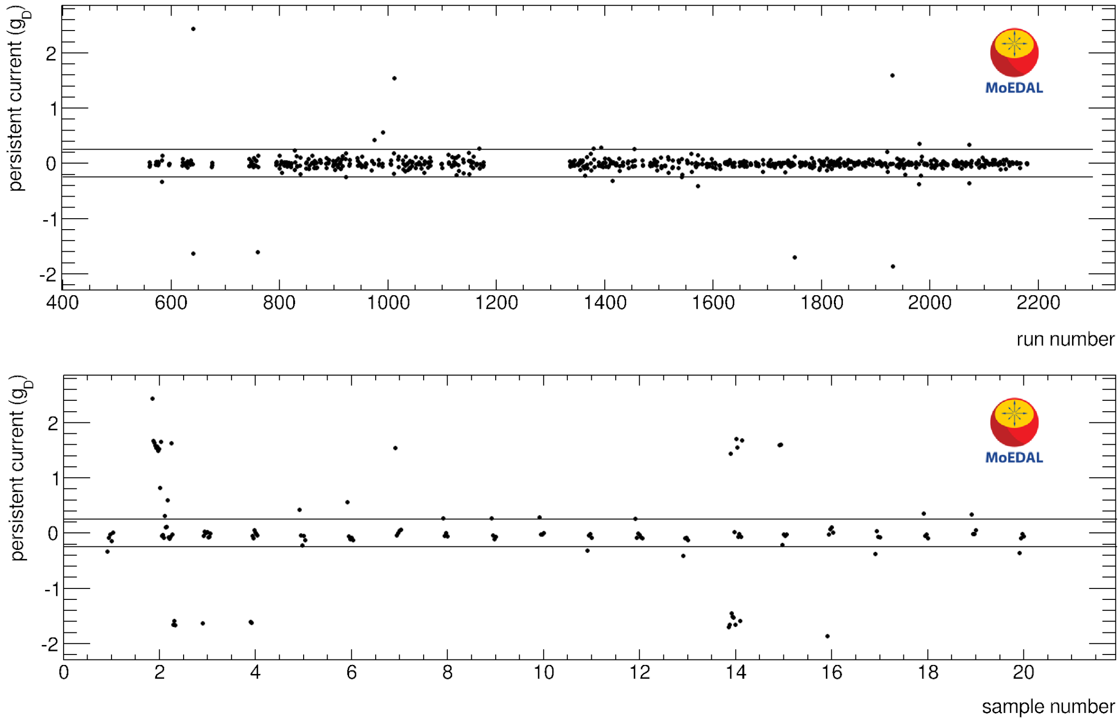

FIG. 1. Top: persistent current after first passage through the magnetometer for all samples. Bottom: results of repeated measurements of candidate samples with absolute measured values in excess of $0.25g_{\rm D}$.

tained in a sample is obtained from the measurement of the persistent current – defined as the difference between the current in the SQUID measured after and before the passage of the sample through the sensing coil – after the contribution of the conveyor tray has been subtracted. Persistent currents measured during the first passage of the 672 forward trapping detector samples through the SQUID magnetometer are shown in the top panel of Fig. 1. The 20 samples which yielded an absolute value corresponding to a magnetic charge larger than $0.25g_{\rm D}$ were set aside and remeasured at least 3 more times.

The bottom panel of Fig. 1 shows the results of the multiple measurements for these candidates. Samples with a total magnetic dipole moment exceeding $1.5 \cdot 10^{-7}$ Am^2 (whose measured value corresponds to $> 500g_{\rm D}$) sometimes cause the flux-locked loop of the SQUID to be lost and recovered at a different quantum level. This can then leave a signal similar to what is expected from a monopole, as can be seen for samples 2 and 14 in Fig. 1 (bottom). Similar effects were found in measurements with non-exposed samples of similar or greater magnetisation (see also Refs. [21, 22]). In these samples, the fake signal can cluster around a given value (here $\pm 1.6g_{\rm D}$, a characteristic of the instrument) as would be the case for a monopole. However its polarity depends on which end is introduced first through the magnetometer, and a fraction of the measurements still yield zero persistent current. Neither of these two features would be present in the case of a genuine magnetic monopole. Samples of weaker magnetic dipole moments do not exhibit this behaviour and consistently yield persistent currents around zero. From these results, the presence of a monopole with absolute magnetic charge exceeding $0.5g_{\rm D}$ is excluded at more than 99% confidence level in all samples.

The trapping detector acceptance is defined as the probability that a monopole of given mass, charge, energy and direction would end its trajectory inside the trapping volume. It is determined from the knowledge of the material traversed by the monopole [19] and the ionisation energy loss of monopoles when they go through matter [23–26] implemented in a simulation based on GEANT4 [27]. Simulations with uniform monopole energy distributions allow to identify, for various charge and mass combinations, ranges of kinetic energy and polar angle for which the acceptance is relatively uniform, called fiducial regions. The fiducial regions given in Ref. [19] can conservatively be used to provide an interpretation which does not depend on the monopole production model.

As a realistic model of monopole pair production, a Drell-Yan (DY) mechanism is employed for its simplicity and for ease of comparison with previous LHC results [18, 19]. It should be noted, though, that the DY model does not constitute a reliable tool for calculating the monopole production cross section as a consequence of the fact that it is perturbative, and thus not strictly applicable to the non-perturbative regime of strong magnetic charges. Two scenarios for monopole spin are adopted, namely spin-0 and spin-1/2. Monopole trapping acceptances in the range 0.1% to 4% are are obtained from full GEANT4 simulations of DY events in 13 TeV pp collisions generated with MADGRAPH5 [28] in the intervals $1-6g_{\mathrm{D}}$ and $200 \leq M \leq 6000$ GeV, with 100000 events for each mass-charge combination.

Acceptance loss is a combination of monopoles punching through the trapping volume (mostly for $|g| = g_{\mathrm{D}}$) and monopoles ranging out before reaching the trapping volume (for the higher charges). The latter effect decreases the acceptance for DY monopoles with increasing charge and reaches below 0.1% for a charge of $6g_{\mathrm{D}}$, in which case the DY interpretation ceases to be meaningful. The behaviour of the acceptance as a function of mass has two contributions: the mass dependence of the DY kinematic distributions (more central and less energetic monopoles at high mass), and the velocity dependence of the energy loss (lower at lower velocity for monopoles). The spin dependence is solely due to the different event kinematics (more central and more energetic monopoles for spin-0). Uncertainties in the acceptance include event statistics as well as the effects of uncertainties in energy loss calculations, detector position, and material budget. The latter represents the main contribution to the acceptance uncertainty and is estimated using full simulations of monopole propagation through the setup with two additional geometries covering conservative uncertainties on the material placed upstream of the trapping detector, as described in Ref. [19].

Cross-section limits for spin-1/2 and spin-0 monopole production are shown in Fig. 2. They are extracted from the following inputs: the acceptance estimates and their uncertainties, assuming DY kinematics; the luminosity of 0.371 ± 0.004 fb^{-1} obtained during the 2015 exposure to 13 TeV pp collisions; the expectation of strong binding to aluminium nuclei [20] of monopoles with velocity $\beta = \frac{v}{c} \leq 10^{-3}$, where v is the velocity of the monopole; and the non-observation of magnetic charge inside the trapping detector samples.

mass limits [GeV]	$1g_{\mathrm{D}}$	$2g_{\mathrm{D}}$	$3g_{\mathrm{D}}$	$4g_{\mathrm{D}}$
MoEDAL 13 TeV (this result)				
DY spin-1/2	890	1250	1260	1100
DY spin-0	460	760	800	650
MoEDAL 8 TeV				
DY spin-1/2	700	920	840	–
DY spin-0	420	600	560	–
ATLAS 8 TeV				
DY spin-1/2	1340	–	–	–
DY spin-0	1050	–	–	–

TABLE I. Monopole lower mass limits (95% confidence level) in models of spin-1/2 and spin-0 DY pair production in LHC pp collisions for monopole charges $|g|$ up to $4g_{\mathrm{D}}$. These limits are based upon cross sections computed at leading order. These cross sections are only indicative since the monopole coupling to the photon is too large to allow for perturbative calculations. Previous results obtained in 8 TeV collisions are from Ref. [19] (MoEDAL prototype trapping detector) and Ref. [18] (ATLAS).

The DY cross sections computed at leading order are shown as solid lines in Fig. 2, with the caveat, as already mentioned, that the coupling of the monopole to the photon is so large that perturbative calculations are not expected to be reliable. Using these cross sections and the limits set by the search, indicative mass limits are extracted and reported in Table I for magnetic charges up to $4g_{\mathrm{D}}$. For $5g_{\mathrm{D}}$ (pink stars in Fig. 2), the trapping acceptance for masses below 1000 GeV is not good enough to set a mass limit.

In summary, the aluminium elements of the MoEDAL trapping detector exposed to 13 TeV LHC collisions in 2015 were scanned using a SQUID-based magnetometer for the presence of trapped magnetic charge, and none were found. Consequently, monopole-pair production cross-section limits in the range $200-10000$ fb were set for magnetic charges up to $5g_{\mathrm{D}}$ and masses up to 6 TeV. In a DY model with spin-1/2 monopoles, this translates into monopole mass limits exceeding 1 TeV – the strongest to date at a collider experiment – for charges between two and four times the Dirac charge.

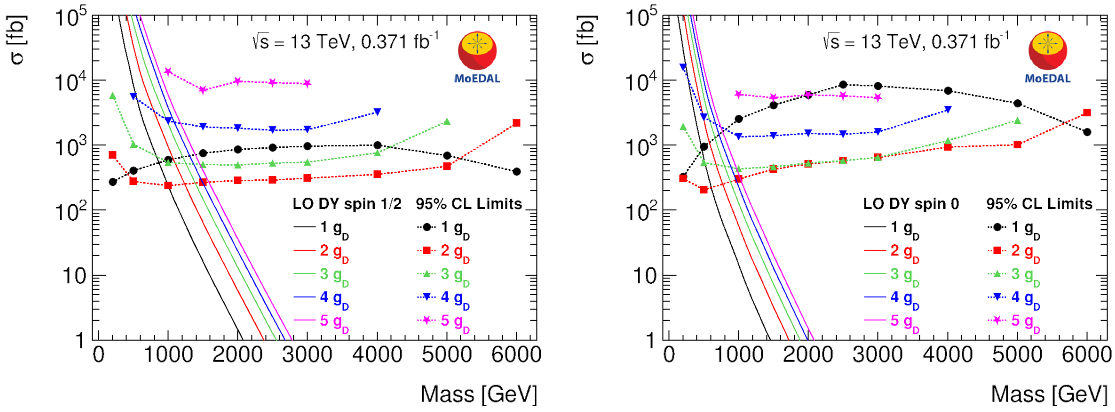

FIG. 2. Cross-section upper limits at 95% confidence level for DY monopole production in 13 TeV *pp* collisions as a function of mass for spin-1/2 (left) and spin-0 (right) monopoles. The colours correspond to different monopole charges. The solid lines are DY cross-section calculations at leading order.

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