**Φ-meson–nucleus bound states**

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(Dated: September 4, 2017)

The properties of light vector mesons at finite baryon density, such as their masses and decay widths, have attracted considerable experimental and theoretical interest over the last few decades; see Refs. [1–3] for recent reviews. In part this has been related to their imputed potential to carry information on the partial restoration of chiral symmetry. In 2007 the KEK-E325 collaboration reported a 3.4% mass reduction of the φ-meson [4] and an in-medium decay width of ≈14.5 MeV at normal nuclear matter density. These conclusions were based on the measurement of the invariant mass spectra of e+e− pairs in 12 GeV p+A reactions, with copper and carbon being used as targets [4].

Even though this result may indicate a signal for partial restoration of chiral symmetry in nuclear matter, it is not possible to draw a definite conclusion solely from this. In fact, recently, a large in-medium φ-meson decay width (>30 MeV) has been extracted at various experimental facilities [5,6], without observing any mass shift. It is therefore evident that the search for evidence of a light vector meson mass shift in nuclear matter is indeed a complicated issue and further experimental efforts are required in order to understand the phenomenon better. Indeed, the J-PARC E16 collaboration [7,8] intends to perform a more systematic study for the mass shift of vector mesons with higher statistics than the above-mentioned experiment at KEK-E325.

However, either complementary or alternative experimental methods are desired. The study of the φ-meson–nucleus bound states is complementary to the invariant mass measurements, where only a small fraction of the produced φ-mesons decay inside the nucleus and may be expected to provide extra information on the φ-meson properties at finite baryon density. Along these lines and motivated by the 3.4% mass reduction reported by the KEK-E325 experiment, the E29 collaboration at J-PARC has recently put forward a proposal [9,10] to study the in-medium mass modification of the φ-meson via the possible formation of φ-nucleus bound states [11,12]. Furthermore, there is also a proposal at the Thomas Jefferson National Accelerator Facility (JLab), following the 12 GeV upgrade, to study the binding of φ (and η) to 4He [13]. This new experimental approach [11,14,15] for the measurement of the φ meson mass shift in nuclei, will produce a slowly moving φ-meson [11,14,15], where the maximum nuclear matter effect can be probed. In this way, one may indeed anticipate the formation of a φ-nucleus bound state, where the φ-meson is trapped inside the nucleus.

Meson-nucleus systems bound by attractive strong interactions are very interesting objects; see Refs. [17,18] for recent reviews on the subject. First, they are strongly interacting exotic many-body systems and to study them serves, for example, to understand better the multiple-gluon exchange interactions, including QCD “van der Waals” forces [18], which are believed to play a role in the binding of the J/Ψ and other exotic heavy-quarkonia to
matter (a nucleus) \[11\] \[13\] \[20\] \[29\]. Second, they provide unique laboratories for the study of hadron properties at finite density, which may not only lead to a deeper understanding of the strong interaction \[1\] \[3\] \[17\] \[18\] but of the structure of finite nuclei as well \[30\] \[31\].

A downward mass shift of the \(\phi\)-meson in a nucleus is directly connected with the possible existence of an attractive potential between the \(\phi\)-meson and the nucleus, the strength of which is expected to be of the same order as that of the mass shift. Along these lines, various authors predict a downward shift of the in-medium \(\phi\) meson mass and a broadening of the decay width, many of them focusing on the self-energy of the \(\phi\) meson due to the kaon-antikaon loop. Ko et al. \[32\] used a density-dependent kaon mass determined from chiral perturbation theory and found that at normal nuclear matter density, \(\rho_0\), the \(\phi\) mass decreases very little, by at most 2\%, and the width \(\Gamma_\phi \approx 25\) MeV and broadens drastically for large densities. Hatsuda and Lee calculated the in-medium \(\phi\) mass based on the QCD sum rule approach \[33\] \[34\], and predicted a decrease of 1.5\%-3\% at \(\rho_0\). Other investigations also predict a small downward mass shift and a large broadening of the \(\phi\) width at \(\rho_0\): Ref. \[35\] reports a negative mass shift of < 1\% and a decay width of 45 MeV; Ref. \[36\] predicts a decay width of 22 MeV but does not report a result on the mass shift; and Ref. \[37\] gives a rather small negative mass shift of \(\approx 0.81\%\) and a decay width of 30 MeV. More recently, Ref. \[38\] reported a downward mass shift of < 2\% and a large broadening width of 45 MeV at \(\rho_0\); and finally, in Ref. \[39\], extending the work of Refs. \[36\] \[37\], the authors reported a negative mass shift of 3.4\% and a large decay width of 70 MeV at \(\rho_0\). The reason for these differences may lie in the different approaches used to estimate the kaon-antikaon loop contributions to the \(\phi\)-meson self-energy and this might have consequences for the formation of \(\phi\)-meson–nucleus bound states.

From a practical point of view, the important question is whether this attraction, if it exists, is sufficient to bind the \(\phi\) to a nucleus. A simple argument can be given as follows. One knows that for an attractive spherical well of radius \(R\) and depth \(V_0\), the condition for the existence of a nonrelativistic \(s\)-wave bound state of a particle of mass \(m\) is \(V_0 > \frac{\pi^2\hbar^2}{8mR^2}\). Using \(m = m_\phi^*\), where \(m_\phi^*\) is the \(\phi\)-meson mass at normal nuclear matter density found in Ref. \[4\] and \(R = 5\) fm (the radius of a heavy nucleus), one obtains \(V_0 > 2\) MeV. Therefore, the prospects of capturing a \(\phi\)-meson seem quite favorable, provided that the \(\phi\)-meson can be produced almost at rest in the nucleus.

An initial calculation of possible \(\phi\)-nucleus bound states was carried out in Ref. \[40\] for a few nuclei. However, the theoretical potential on which this study was based \[32\] was too weak, with only two bound states being found. In order to remedy this, the real part of the potential was scaled, without any theoretical basis, so as to simulate a 3\% mass reduction of the \(\phi\)-meson, that is, approximately equal to that reported in Ref. \[32\]. This (scaled) potential was mainly used to study the sensitivity of the formation spectra to the potential strength \[37\]. Here, it was found that, as expected, whether or not the formation of the \(\phi\)-meson bound state is possible depends on the strength of the attractive potential between the \(\phi\)-meson and the nucleus.

In previous work \[41\] we studied the \(\phi\)-meson mass shift and decay width in nuclear matter, based on an effective Lagrangian approach, by evaluating the \(KK\) loop contribution in the \(\phi\) self-energy, with the in-medium \(K\) and \(\bar{K}\) masses explicitly calculated by the quark-meson coupling (QMC) model \[42\]. Here we extend our previous initial study \[41\] to seven selected nuclei, showing details of the calculated nuclear potential and computing the \(\phi\)-nucleus bound state energies and absorption widths by solving the Klein-Gordon equation. The nuclear density distributions for heavy nuclei studied (except for \(^4\)He), as well as the medium modification of the \(K\) and \(\bar{K}\) masses, are explicitly calculated using the QMC model \[43\].

This paper is organized as follows. In Sec. II we briefly discuss the computation and present results for the mass shift and decay width of the \(\phi\)-meson in infinite (symmetric) nuclear matter. Using the results of Sec. II together with the density profiles of the nuclei to be studied, in Sec. III we present results for the real and imaginary parts of the scalar \(\phi\)-nucleus potentials, as well as the corresponding bound state energies and absorption widths. Finally, Sec. IV is devoted to a summary and discussion.

II. \(\phi\)-MESON SELF-ENERGY IN INFINITE NUCLEAR MATTER

The \(\phi\)-meson property modifications in nuclear matter, such as its mass and decay width, are strongly correlated to its coupling to the \(KK\) channel, which is the dominant decay channel in vacuum. Therefore, one expects that a significant fraction of the density dependence of the \(\phi\)-meson self-energy in nuclear matter might arise from the in-medium modification of the \(KK\)-loop in the \(\phi\)-self-energy intermediate state.

Here we use the effective Lagrangian approach of Ref. \[44\] and briefly review the computation of the \(\phi\)-meson self-energy in vacuum and in nuclear matter made in Ref. \[41\]. The interaction Lagrangian \(\mathcal{L}_{\text{int}}\) involves \(\phi K\bar{K}\) and \(\phi\phi K\bar{K}\) couplings dictated by a local gauge symmetry principle:

\[
\mathcal{L}_{\text{int}} = \mathcal{L}_{\phi K\bar{K}} + \mathcal{L}_{\phi\phi K\bar{K}},
\]

where

\[
\mathcal{L}_{\phi K\bar{K}} = ig_\phi \phi \mu \left[K(\partial_\mu K) - (\partial_\mu \bar{K})K\right],
\]

and

\[
\mathcal{L}_{\phi\phi K\bar{K}} = g_\phi^2 \phi \mu \phi_\nu K\bar{K}.
\]
We use the convention for the isospin doublets:
\[ K = \left( \begin{array}{c} K^+ \\ K^0 \end{array} \right), \quad \bar{K} = \left( \begin{array}{c} K^- \\ K^0 \end{array} \right) \tag{4} \]

We note that the use of the effective interaction Lagrangian of Eq. (1) without the term given in Eq. (3) may be considered as being motivated by the hidden gauge approach in which there are no four-point vertices, such as Eq. (3), that involve two pseudoscalar mesons and two vector mesons \( \pi \pi \). This is in contrast to the approach of using the minimal substitution to introduce vector mesons as gauge particles where such four-point vertices do appear. However, these two methods have been shown to be consistent if both the vector and axial vector mesons are included \[47–50\]. Therefore, we present results with and without such an interaction. We consider first the contribution from the \( \phi K \bar{K} \) coupling given by Eq. (2) to the scalar part of the \( \phi \) self-energy, \( \Pi_\phi(p) \), by evaluating the diagram of FIG. 1.

For a \( \phi \)-meson at rest the scalar self-energy is given by
\[ i \Pi_\phi(p) = -\frac{8}{3} g_\phi^2 \int \frac{d^4q}{(2\pi)^4} q^2 D_K(q) D_K(q-p) \tag{5} \]
where \( D_K(q) = (q^2 - m_K^2 + i\epsilon)^{-1} \) is the kaon propagator; \( p = (p^0 = m_\phi, 0) \) is the \( \phi \)-meson four-momentum vector at rest, with \( m_\phi \) the \( \phi \)-meson mass; \( m_K = m_\bar{K} \) is the kaon mass; and \( g_\phi \) is the coupling constant.

The integral in Eq. (5) is divergent but it will be regulated using a phenomenological form factor, with cutoff parameter \( \Lambda_K \), as in Refs. \[41\]. The sensitivity of the results to the cutoff value is analyzed below.

The coupling constant \( g_\phi \) is determined in Ref. \[41\] from the experimental value for the \( \phi \to K \bar{K} \) decay width in vacuum, corresponding to the branching ratio of 83.1% of the total decay width \( (4.266 \text{ MeV}) \) \[52\]. For the \( \phi \) mass in vacuum, \( m_\phi \), we use its experimental value \( m_\phi^{\text{expt}} = 1019.461 \text{ MeV} \) \[52\]; while for the kaon mass \( m_K \) we use the average of the experimental values \( 938.877 \) MeV and \( m_\bar{K}^{\text{expt}} = 497.611 \), respectively. We note that the effect of this tiny mass ambiguity on the in-medium kaon (antikaon) properties is negligible. Then, we obtain the coupling \( g_\phi = 4.539 \). The \( \Lambda_K \)-dependent \( \phi \)-meson bare mass \( m_\phi^{\text{b}} \) is fixed by fitting the physical \( \phi \)-meson mass \( m_\phi^{\text{expt}} \), and the values obtained are given in the caption to TABLE II.

The mass and decay width of the \( \phi \)-meson in vacuum \( (m_\phi \) and \( \Gamma_\phi \), as well as in nuclear matter \( (m_\phi^* \) and \( \Gamma_\phi^* \), are determined self-consistently in Ref. \[41\] from
\[ m_\phi^2 = (m_\phi^0)^2 + 3\Pi_\phi(m_\phi^2), \tag{6} \]
\[ \Gamma_\phi = -\frac{1}{m_\phi} 3\Pi_\phi(m_\phi^2). \tag{7} \]

The nuclear density dependence of the \( \phi \)-meson mass and decay width is driven by the intermediate-state kaon and antikaon interactions with the nuclear medium. This effect enters through \( m_K^* \) in the kaon propagators in Eq. (5). The in-medium mass, \( m_K^* \), is calculated within the QMC model \[41\], which has proven to be very successful in studying the properties of hadrons in nuclear matter and finite nuclei. For a more complete discussion of the model see Refs. \[42, 53, 54\]. Here we just make a few necessary comments. In order to calculate the in-medium properties of \( K \) and \( \bar{K} \), we consider infinitely large, uniformly symmetric, spin-isospin-saturated nuclear matter in its rest frame, where all the scalar and vector mean field potentials, which are responsible for the nuclear many-body interactions, become constant in the Hartree approximation \[41\]. In FIG. 2 we present the resulting in-medium kaon Lorentz scalar mass \( (\text{=antikaon Lorentz scalar mass}) \), calculated using the QMC model, as a function of the baryon density. The kaon effective mass at normal nuclear matter density \( \rho_0 = 0.15 \text{ fm}^{-3} \) has decreased by about 13%. We also recall, in connection with the calculation of the in-medium \( KK \)-loop contributions to the \( \phi \)-meson self-energy, that the isoscalar-vector \( \omega \) mean field potentials arise both for the kaon and antikaon. However, they have opposite signs and cancel each other. Equivalently, they can be eliminated by a variable shift in the loop calculation \[42, 53, 54\] of the \( \phi \)-self-energy, and therefore we do not show them here.

In FIG. 3 we present the \( \phi \)-meson mass shift (upper panel) and decay width (lower panel) as a function of the nuclear matter density. \( \rho_B \), for three values of the cutoff parameter \( \Lambda_K \). As can be seen, the effect of the in-medium kaon and antikaon mass change yields a negative
mass shift for the $\phi$-meson. This is because the reduction in the kaon and antikaon masses enhances the $K\bar{K}$-loop contribution in nuclear matter relative to that in vacuum. For the largest value of the nuclear matter density, the downward mass shift turns out to be a few percent at most for all values of $\Lambda_K$. On the other hand, we see that $\Gamma_{\phi}^*$ is very sensitive to the change in the kaon and antikaon masses: it increases rapidly with increasing nuclear matter density, up to a factor of $\sim 20$ enhancement for the largest value of $\rho_B$. At normal nuclear matter density, $\rho_0$, we see that the negative kaon and antikaon mass shift of 13% [41] induces a downward mass shift of the $\phi$-meson of just $\approx 2\%$, while the broadening of the $\phi$-meson decay width is an order of magnitude larger than its vacuum value.

For completeness, and in connection with the paragraph just after Eq. (4), we show in FIG. 4 the impact of adding the $\phi\phi\bar{K}K$ interaction of Eq. (3) on the in-medium $\phi$ mass and decay width. We have used the notation that $\xi = 1(0)$ means that this interaction is (not) included in the calculation of the $\phi$ self-energy. As can be seen, one still gets a downward shift of the in-medium $\phi$ mass when $\xi = 1$ as well as a significant broadening of the decay width. In both cases, though, the absolute values are slightly different from the $\xi = 0$ case. In TABLE I we present the values for $m_\phi^*$ and $\Gamma_{\phi}^*$ at normal nuclear matter density $\rho_0$ with and without the gauged Lagrangian of Eq. (3). In both cases, the effect of adding Eq. (3) can be compensated by the use of a larger cutoff $\Lambda_K$ (compare the first and the last columns of TABLE I).

| $\Lambda_K$ | $m_\phi^*$ (MeV) | $\Gamma_{\phi}^*$ (MeV) |
|------------|----------------|-----------------------|
| 2000 MeV   | 1000.9 (1009.5) | 34.8 (37.8)           |
| 3000 MeV   | 994.9 (1004.3) | 32.8 (36.0)           |
| 4000 MeV   | 990.4 (1000.6) | 31.3 (34.7)           |

TABLE I: $\phi$ mass and width at normal nuclear matter density $\rho_0$ with and without the gauged Lagrangian of Eq. (3). All quantities are given in MeV. For the cutoff values of $\Lambda_K = 2000, 3000, \text{ and } 4000$ MeV we find the $\phi$-meson bare mass $m_\phi^0$ values of 1074.0 (1023.4) MeV, 1132.9 (1024.6) MeV, and 1213.6 (1025.6) MeV, respectively.

FIG. 3: $\phi$-meson mass shift (upper panel) and decay width (lower panel) in symmetric nuclear matter for three values of the cutoff parameter $\Lambda_K$.

FIG. 4: Effect of adding ($\xi = 1$) the $\phi\phi\bar{K}K$ interaction of Eq. (3) on the in-medium $\phi$ mass (upper panel) and width (lower panel) for two values of the cutoff parameter $\Lambda_K$.

The results described above support a small downward mass shift and a large broadening of the decay width of the $\phi$-meson in a nuclear medium. Furthermore, they open experimental possibilities for studying the binding and absorption of $\phi$-mesons in nuclei. Although the mass shift found in this study may be large enough to bind the $\phi$-meson to a nucleus, the broadening of its decay width will make it difficult to observe a signal for the $\phi$-nucleus bound state formation experimentally. We explore this further in the following section.
FIG. 5: Real $[U_\phi(r)]$ and imaginary $[W_\phi(r)]$ parts of the $\phi$-meson-nucleus potentials in seven nuclei selected, for three values of the cutoff parameter $\Lambda_K$. 
III. \(\phi\)-NUCLEAR BOUND STATES

In this section we discuss the situation where the \(\phi\)-meson is placed in a nucleus. The nuclear density distributions for \(^{12}\text{C}\), \(^{16}\text{O}\), \(^{40}\text{Ca}\), \(^{48}\text{Ca}\), \(^{90}\text{Zr}\), and \(^{208}\text{Pb}\) are obtained using the QMC model \([52]\). For \(^4\text{He}\) we use the parametrization for the density distribution obtained in Ref. \([55]\). Then, using a local density approximation we calculate the \(\phi\)-meson complex potentials for a nucleus \(A\), which can be written as

\[
V_{\phi A}(r) = U_{\phi}(r) - \frac{i}{2} W_{\phi}(r),
\]

where \(r\) is the distance from the center of the nucleus and \(U_{\phi}(r) = \Delta m_{\phi}(\rho_B(r)) = m_{\phi}^2(\rho_B(r)) - m_{\phi}^2\) and \(W_{\phi}(r) = \Gamma_{\phi}(\rho_B(r))\) are, respectively, the \(\phi\)-meson mass shift and decay width in a nucleus \(A\). As usual, \(\rho_B(r)\) is the baryon density distribution for the particular nucleus.

In Figure \(5\) we present the \(\phi\)-meson potentials calculated for the seven nuclei selected, for three values of the cutoff parameter \(\Lambda_K\). One can see that the depth of the real part of the potential, \(U_{\phi}(r)\), is sensitive to the cutoff parameter, varying from -20 MeV to -35 MeV for \(^4\text{He}\) and from -20 MeV to -30 MeV for \(^{208}\text{Pb}\). In addition, one can see that the imaginary part does not vary much with different values of \(\Lambda_K\). These observations may well have consequences for the feasibility of experimental observation of the expected bound states.

Using the \(\phi\)-meson potentials obtained in this manner, we next calculate the \(\phi\)-meson-nuclear bound state energies and absorption widths for the seven nuclei selected. Before proceeding, a few comments on the use of Eq. \([3]\) are in order. In this study we consider the situation where the \(\phi\)-meson is produced nearly at rest. Then, it should be a very good approximation to neglect the possible energy difference between the longitudinal and transverse components of the \(\phi\)-meson wave function \(\psi_{\phi0}^\mu\). After imposing the Lorentz condition, \(\partial_{\mu}\psi_{\phi0}^\mu = 0\), to solve the Proca equation becomes equivalent to solving the Klein-Gordon equation

\[
\left(-\nabla^2 + \mu^2 + 2\mu V(\vec{r})\right)\phi(\vec{r}) = \mathcal{E}^2 \phi(\vec{r}),
\]

where \(\mu = m_{\phi}m_A/(m_{\phi} + m_A)\) is the reduced mass of the \(\phi\)-meson-nucleus system with \(m_{\phi}\) the mass of the \(\phi\)-meson (nucleus \(A\)) in vacuum, and \(V(\vec{r})\) is the complex \(\phi\)-meson-nucleus potential of Eq. \([8]\). We solve the Klein-Gordon equation using the momentum space methods developed in Ref. \([56]\). Here, Eq. \([9]\) is first converted to momentum space representation via a Fourier transform, followed by a partial wave-decomposition of the Fourier-transformed potential. Then, for a given value of angular momentum, the eigenvalues of the resulting equation are found by the inverse iteration eigenvalue algorithm. The calculated bound state energies \((E)\) and widths \((\Gamma)\), which are related to the complex energy eigenvalue \(\mathcal{E}\) by \(E = \Re\mathcal{E} - \mu\) and \(\Gamma = -2\Im\mathcal{E}\), are listed in TABLE II

| \(\Lambda_K\) | \(E\) | \(\Gamma\) |
|---------|------|------|
| 2000    | -2.4 | -4.7 |
| 3000    | -3.2 | -5.5 |
| 4000    | -3.6 | -5.8 |

for three values of the cutoff parameter \(\Lambda_K\), with and without the imaginary part of the potential, \(W_{\phi}(r)\).

We first discuss the case in which the imaginary part of the \(\phi\)-nuclear potential, \(W_{\phi}(r)\), is set to zero. The results are listed inside brackets in TABLE II. From the values shown in brackets, we see that the \(\phi\)-meson is expected to form bound states with all the seven nuclei selected, for all values of the cutoff parameter \(\Lambda_K\). When only the real part is included, where the corresponding single-particle energy \(E\) is given inside brackets, \(\Gamma = 0\) for all nuclei. “n” indicates that no bound state is found. All quantities are given in MeV.

Next, we discuss the results obtained when the imaginary part of the potential is included. Adding the absorptive part of the potential, the situation changes appreciably. From the results presented in TABLE II we note that for the largest value of the cutoff parameter \(\Lambda_K = 4000\) MeV, which yields the deepest attractive potentials, the \(\phi\)-meson is expected to form bound states in all the nuclei selected, including the lightest \(^4\text{He}\) nucleus. However, in this case, whether or not the bound states can be observed experimentally is sensitive to the value of the cutoff parameter \(\Lambda_K\). One also observes that the width of the bound state is insensitive to the values of
for all nuclei. Furthermore, since the so-called dispersive effect of the absorptive potentials is repulsive, the bound states disappear completely in some cases, even though they were found when the absorptive part was set to zero. This feature is obvious for the ⁴He nucleus, making it especially relevant to the future experiments, planned at J-PARC and JLab using light and medium-heavy nuclei [11][14][15].

We here comment that we have also solved the Schrödinger equation with the potential Eq. [5] with and without its imaginary part for the single-particle energies and widths, and compared with those given in TABLE II. The results found in both cases are essentially the same.

IV. SUMMARY AND DISCUSSION

We have calculated the φ–meson–nucleus bound state energies and absorption widths for various nuclei. The φ–meson–nuclear potentials were calculated using a local density approximation, with the inclusion of the K̅K meson loop in the φ–meson self-energy. The nuclear density distributions, as well as the in-medium K and K̅ meson masses, were consistently calculated by employing the quark-meson coupling model. Using the φ–meson–nuclear complex potentials, we have solved the Klein-Gordon equation in momentum space, and obtained φ–meson–nucleus bound state energies and absorption widths. Furthermore, we have studied the sensitivity of the results to the cutoff parameter ΛK in the form factor at the φ – K̅K vertex appearing in the φ–meson self-energy. We expect that the φ–meson should form bound states for all seven nuclei selected, provided that the φ–meson is produced in (nearly) recoilless kinematics. This feature, is even more obvious in the (artificial) case where the absorptive part of the potential is ignored. Given the similarity of the binding energies and widths reported here, the signal for the formation of the φ–nucleus bound states may be difficult to identify experimentally. Therefore, the feasibility of observation of the φ–meson–nucleus bound states needs further investigation, including explicit reaction cross section estimates.

Acknowledgements

This work was partially supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq, Grant Nos. 152348/2016-6 (J.J.C-M.), 400826/2014-3 and 308088/2015-8 (K.T.), 305894/2009-9 (G.K.), and 313800/2014-6 (A.W.T.), and Fundação de Amparo à Pesquisa do Estado de São Paulo-FAPESP, Grant Nos. 2015/17234-0 (K.T.) and 2013/01907-0 (G.K.). This research was also supported by the University of Adelaide and by the Australian Research Council through the ARC Centre of Excellence for Particle Physics at the Terascale (CE110001104), and through Grant No. DP151103101 (A.W.T.).

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