

Nuclear medium effects on the \bar{K}^* meson

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Abstract

The \bar{K}^* meson in dense matter is analyzed by means of a unitary approach in coupled channels based on the local hidden gauge formalism. The \bar{K}^* self-energy and the corresponding \bar{K}^* spectral function in the nuclear medium are obtained. We observe that the \bar{K}^* develops a width in matter up to five times bigger than in free space. We also estimate the transparency ratio of the $\gamma A \rightarrow K^+ K^{*-} A'$ reaction. This ratio is an excellent tool to detect experimentally modifications of the \bar{K}^* meson in dense matter.

Keywords: \bar{K}^* meson, hidden-gauge formalism, \bar{K}^* spectral function, transparency ratio

1. Introduction

For years vector mesons in nuclear matter have been a matter of interest tied to fundamental aspects of QCD [1, 2, 3]. The ρ , ω and ϕ mesons in dense matter have been the focus of many theoretical and experimental analysis. The latest experiments conclude that there is no mass shift for the ϕ and ρ in [4, 5]. With regard to the ω meson, the debate started in [6] concerning the background subtraction and was finally decided by explicitly determining the sources of background that there is no evidence of a mass shift [7].

Nevertheless, up to our knowledge, the properties of vector mesons with strangeness in matter have not been discussed in the literature. The fact that the \bar{K}^* cannot be detected with dileptons might be a reason for the

experimental neglect. From the theoretical point of view, recently the \bar{K}^*N interaction in free space has been studied in Ref. [8] using SU(6) spin-flavour symmetry, and within the hidden local gauge formalism for the interaction of vector mesons with baryons of the octet [9] and the decuplet [10].

In this paper we study the \bar{K}^* self-energy in dense matter [11] following the work of Ref. [9] and in a similar way as done in Ref. [12, 13, 14]. We observe a spectacular enhancement of the \bar{K}^* width in the medium, up to five times the free value of 50 MeV. In order to test this scenario experimentally, we also estimate the transparency ratio for \bar{K}^* production in the $\gamma A \rightarrow K^+ \bar{K}^{*-} A'$ reaction.

2. The \bar{K}^*N interaction

The interaction of the \bar{K}^* mesons with nucleons is obtained from t -channel vector-meson exchange mechanisms. The needed interactions among vector mesons in these processes are derived within the hidden-gauge formalism [15, 16, 17, 18], which leads to the following three-vector vertex Lagrangian

$$\mathcal{L}_{III}^{(3V)} = ig \langle (V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu) V^\nu \rangle, \quad (1)$$

where V_μ is the SU(3) matrix of the vectors of the octet of the ρ plus the SU(3) singlet. On the other hand, we also need the Lagrangian for the coupling of vector mesons to the baryons [19, 20]:

$$\mathcal{L}_{BBV} = g \left(\langle \bar{B} \gamma_\mu [V^\mu, B] \rangle + \langle \bar{B} \gamma_\mu B \rangle \langle V^\mu \rangle \right), \quad (2)$$

where B is the SU(3) matrix of the baryon octet. Then, we can construct the Feynman diagrams that lead to the vector-baryon (VB) transitions, $VB \rightarrow V'B'$.

We proceed as in Ref. [9] by neglecting the three momentum of the external vectors versus the vector mass, as similarly done for chiral Lagrangians in the low energy approximation. Thus, one obtains the transition potential:

$$V_{ij} = -C_{ij} \frac{1}{4f^2} (k^0 + k'^0) \vec{\epsilon} \vec{\epsilon}', \quad (3)$$

where f is the pion decay constant; k^0, k'^0 are the energies of the incoming and outgoing vector mesons, respectively; $\vec{\epsilon} \vec{\epsilon}'$ is the product of their polarization vectors; and C_{ij} are the channel coupling coefficients [9].

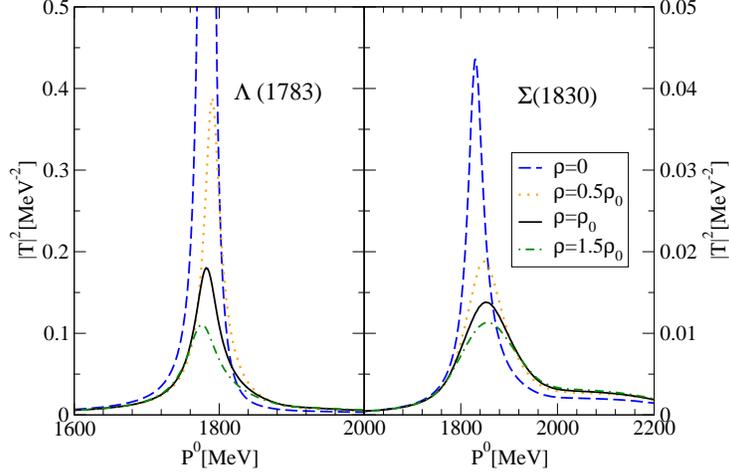


Figure 1: ($I = 0$) $\Lambda(1783)$ and ($I = 1$) $\Sigma(1830)$ states for various densities, where $\rho_0 = 0.17 \text{ fm}^{-3}$ is the nuclear matter saturation density.

In order to obtain the meson-baryon scattering amplitude, we solve the on-shell Bethe-Salpeter equation in coupled channels [13, 24]

$$T = [1 - V G]^{-1} V , \quad (4)$$

with G being the vector-baryon loop function. The loop is regularized taking a natural value of -2 for the subtraction constants at a regularization scale $\mu = 630 \text{ MeV}$ [9, 24]. We also incorporate the relatively large decay width of the ρ and \bar{K}^* vector mesons (into $\pi\pi$ or $\bar{K}\pi$ pairs, respectively) in the loop functions via the convolution of the G function [25].

We analyze the vector meson-baryon $S = -1$ sector with isospin $I = 0$ (\bar{K}^*N , $\omega\Lambda$, $\rho\Sigma$, $\phi\Lambda$ and $K^*\Xi$) and $I = 1$ (\bar{K}^*N , $\rho\Lambda$, $\rho\Sigma$, $\omega\Sigma$, $K^*\Xi$ and $\phi\Sigma$). Two resonances in the $I = 0$ and $I = 1$ sectors are generated, $\Lambda(1783)$ and $\Sigma(1830)$ [9], as displayed by the dashed lines in Fig. 1. These can be identified with the experimentally observed states $J^P = 1/2^-$ $\Lambda(1800)$ and $\Sigma(1750)$, respectively, although the calculated widths are smaller than the ones measured experimentally due to the absence, in the present approach, of the pseudoscalar-baryon decays in free space. Note that the factorization of the factor $\vec{\epsilon}\vec{\epsilon}'$ for the external vector mesons appearing in the potential and also in the T matrix [9] provides degenerate pairs of dynamically generated resonances which have $J^P = 1/2^-, 3/2^-$.

Medium modifications on the \bar{K}^*N scattering amplitude, which are incorporated in the \bar{K}^*N loop function, come from the Pauli blocking effects acting on the nucleons and from the change in the properties of mesons and baryons in nuclear matter. Specifically, we consider the self-consistent \bar{K}^* self-energy in the \bar{K}^*N intermediate states, as explained below. The modulus squared of the medium-modified \bar{K}^*N amplitudes in the isospin basis, which are obtained from the solution of the on-shell Bethe-Salpeter coupled-channels equations in nuclear matter, $T^{\rho,I} = [1 - V^I G^\rho]^{-1} V^I$, are displayed in Fig. 1, for $I = 0$ and $I = 1$, as functions of the center-of-mass energy P^0 for a total momentum $\vec{P} = 0$ and various densities. Nuclear matter effects result in a substantial increase of their free widths due to the opening of new decay channels in matter, such as $\bar{K}^*N \rightarrow \pi\bar{K}N$, $\bar{K}^*N \rightarrow \bar{\pi}\pi Y$, or $\bar{K}^*NN \rightarrow \bar{K}NN$.

3. Contributions to the \bar{K}^* self-energy

The K^{*-} width in vacuum is determined by the imaginary part of the free \bar{K}^* self-energy at rest, $\text{Im}\Pi_{\bar{K}^*}^0$, due to the decay of the \bar{K}^* meson into $\bar{K}\pi$ pairs: $\Gamma_{K^{*-}} = -\text{Im}\Pi_{\bar{K}^*}^0/m_{\bar{K}^*} = 42$ MeV [11]. Note that this value is quite close to the experimental value $\Gamma_{K^{*-}}^{\text{exp}} = 50.8 \pm 0.9$ MeV.

The \bar{K}^* self-energy in matter, on one hand, results from its decay into $\bar{K}\pi$, $\Pi_{\bar{K}^*}^{\rho,(a)}$, including both the self-energy of the antikaon [14] and the pion [26, 27] (see first diagram on the left hand side of Fig. 2 and some specific contributions in diagrams (a1) and (a2) of Fig. 3). Moreover, vertex corrections required by gauge invariance are also incorporated, which are associated to the last three diagrams in the l.h.s. of Fig. 2.

We show the imaginary part of the \bar{K}^* self-energy for $\vec{q} = 0$ coming from $\bar{K}\pi$ decay in the right panel of Fig. 2: free space calculation (dotted line), adding the π self-energy (dot-dashed line) and including both π and \bar{K} self-energy contributions (dashed line) at normal nuclear matter saturation density ($\rho_0 = 0.17$ fm $^{-3}$). We observe that the main contribution to the \bar{K}^* self-energy comes from the pion self-energy in dense matter. The reason is that the $\bar{K}^* \rightarrow \bar{K}\pi$ decay process leaves the pion with energy right in the region of ΔN^{-1} excitations, where there is considerable pionic strength. The inclusion of vertex corrections (solid line) reduces the effect of the pion dressing on the \bar{K}^* self-energy, giving a \bar{K}^* width of $\Gamma_{\bar{K}^*}(\rho = \rho_0) = 105$ MeV at the \bar{K}^* mass. This turns out to be about twice the value of the width in vacuum.

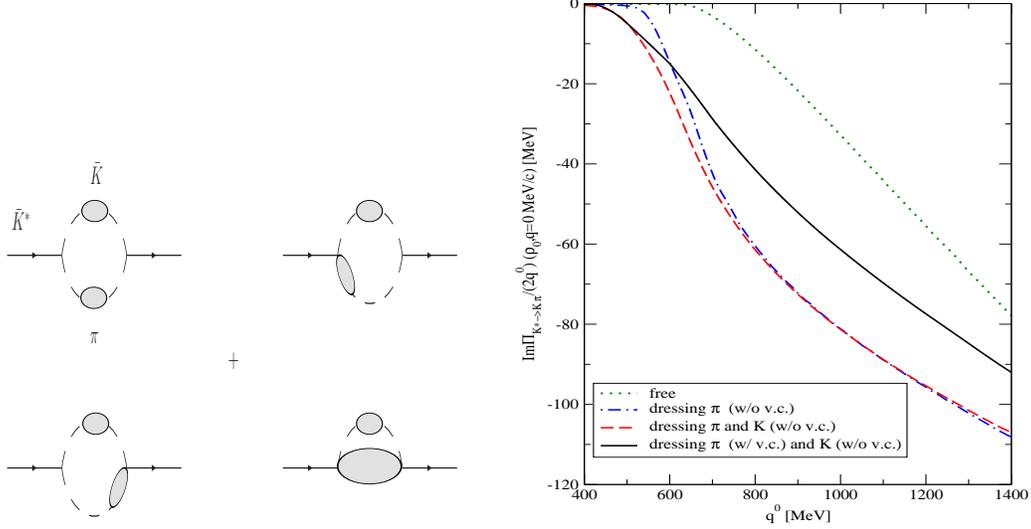


Figure 2: Left figure: Self-energy diagrams from the decay of the \bar{K}^* meson in the medium. Right figure: Imaginary part of the \bar{K}^* self-energy at $\vec{q} = 0 \text{ MeV}/c$, resulting from the $\bar{K}^* \pi$ decay in dense matter at ρ_0 .

The second contribution to the \bar{K}^* self-energy comes from its interaction with the nucleons in the Fermi sea, as displayed in diagram (b) of Fig. 3. This accounts for the direct quasi-elastic process $\bar{K}^* N \rightarrow \bar{K}^* N$ as well as other absorption channels $\bar{K}^* N \rightarrow \rho Y, \omega Y, \phi Y, \dots$ with $Y = \Lambda, \Sigma$. This contribution is determined by integrating the medium-modified $\bar{K}^* N$ amplitudes, $T_{\bar{K}^* N}^{\rho, I}$, over the Fermi sea of nucleons,

$$\Pi_{\bar{K}^*}^{\rho, (b)}(q^0, \vec{q}) = \int \frac{d^3 p}{(2\pi)^3} n(\vec{p}) \left[T_{\bar{K}^* N}^{\rho, (I=0)}(P^0, \vec{P}) + 3T_{\bar{K}^* N}^{\rho, (I=1)}(P^0, \vec{P}) \right], \quad (5)$$

where $P^0 = q^0 + E_N(\vec{p})$ and $\vec{P} = \vec{q} + \vec{p}$ are the total energy and momentum of the $\bar{K}^* N$ pair in the nuclear matter rest frame, and the values (q^0, \vec{q}) stand for the energy and momentum of the \bar{K}^* meson also in this frame. The self-energy $\Pi_{\bar{K}^*}^{\rho, (b)}$ has to be determined self-consistently since it is obtained from the in-medium amplitude $T_{\bar{K}^* N}^{\rho}$ which contains the $\bar{K}^* N$ loop function $G_{\bar{K}^* N}^{\rho}$, and this last quantity itself is a function of the complete self-energy $\Pi_{\bar{K}^*}^{\rho} = \Pi_{\bar{K}^*}^{\rho, (a)} + \Pi_{\bar{K}^*}^{\rho, (b)}$.

We note that the two contributions to the \bar{K}^* self-energy, coming from the decay of $\bar{K}^* \pi$ pairs in the medium [Figs. 3(a1) and 3(a2)] or from the $\bar{K}^* N$

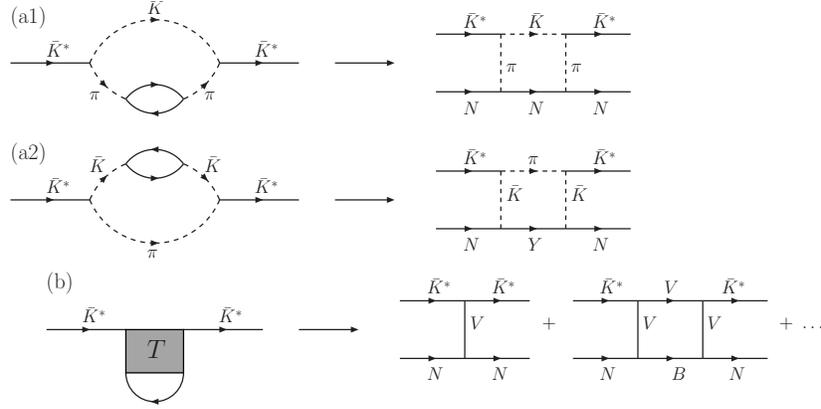


Figure 3: Contributions to the \bar{K}^* self-energy, depicting their different inelastic sources.

interaction [Fig. 3(b)] provide different sources of inelastic \bar{K}^*N scattering, which add incoherently in the \bar{K}^* width. As seen in the upper two rows of Fig. 3, the \bar{K}^*N amplitudes mediated by intermediate $\bar{K}N$ or πY states are not unitarized. Ideally, one would like to treat the vector meson-baryon (VB) and pseudoscalar meson-baryon (PB) states on the same footing. However, at the energies of interest, transitions of the type $\bar{K}^*N \rightarrow \bar{K}N$ mediated by pion exchange may place this pion on its mass shell, forcing one to keep track of the proper analytical cuts contributing to the imaginary part of the amplitude and making the iterative process more complicated. A technical solution can be found by calculating the box diagrams of Figs. 3(a1) and 3(a2), taking all the cuts into account properly, and adding the resulting $\bar{K}^*N \rightarrow \bar{K}^*N$ terms to the $VB \rightarrow V'B'$ potential coming from vector-meson exchange, in a similar way as done for the study of the vector-vector interaction in Refs. [21, 22]. Preliminary results of this procedure in free space indicate that the generated resonances barely change their position for spin 3/2 and only by a moderate amount in some cases for spin 1/2. Their widths are somewhat enhanced due to the opening of the newly allowed PB decay channels [23].

4. The \bar{K}^* meson properties in dense matter

In this section we show results for the \bar{K}^* self-energy and the corresponding \bar{K}^* spectral density in dense matter, which is obtained from the imaginary

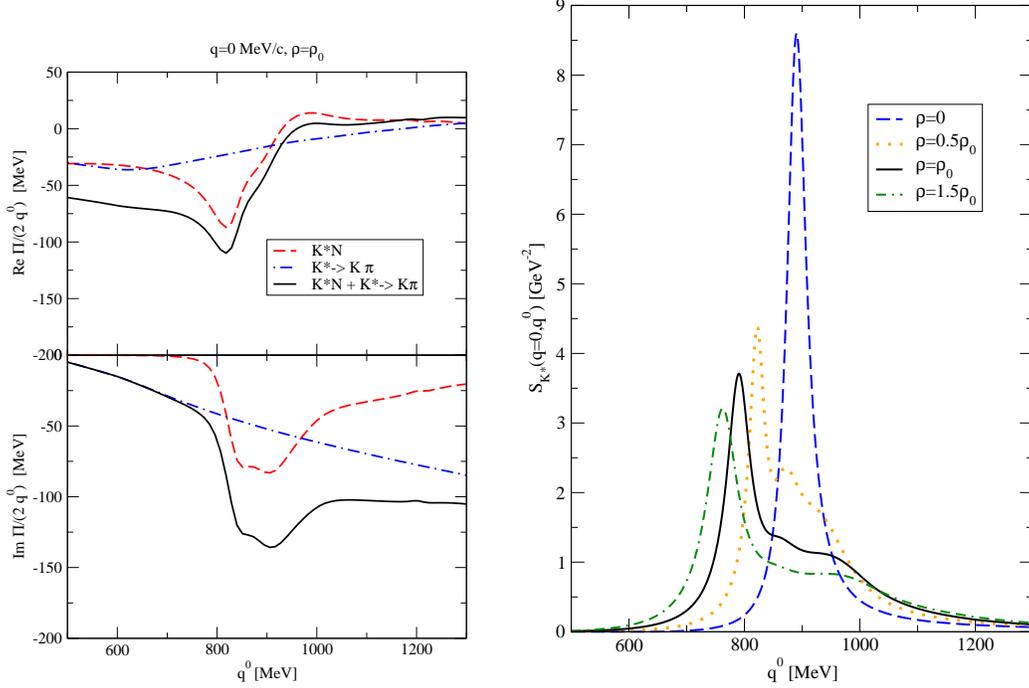


Figure 4: Left figure: \bar{K}^* self-energy for $\vec{q} = 0$ MeV/c and ρ_0 . Right figure: \bar{K}^* spectral function for $\vec{q} = 0$ MeV/c and different densities.

part of the in-medium \bar{K}^* propagator, and is given by

$$S_{\bar{K}^*}(q^0, \vec{q}) = -\frac{1}{\pi} \text{Im} \left[\frac{1}{(q^0)^2 - (\vec{q})^2 - m_{\bar{K}^*}^2 - \Pi_{\bar{K}^*}^\rho(q^0, \vec{q})} \right]. \quad (6)$$

The full \bar{K}^* self-energy as a function of the \bar{K}^* energy for zero momentum at normal nuclear matter density is shown in the left hand side of Fig. 4. We explicitly indicate the contribution to the self-energy coming from the self-consistent calculation of the \bar{K}^*N effective interaction (dashed lines) and the self-energy from the $\bar{K}^* \rightarrow \bar{K}\pi$ decay mechanism (dot-dashed lines), as well as the combined result from both sources (solid lines).

Around $q^0 = 800 - 900$ MeV we observe an enhancement of the width as well as some structures in the real part of the \bar{K}^* self-energy. The origin of these structures can be traced back to the coupling of the \bar{K}^* to the in-medium $\Lambda(1783)N^{-1}$ and $\Sigma(1830)N^{-1}$ excitations, which dominate the \bar{K}^* self-energy in this energy region. However, at lower energies where the

$\bar{K}^*N \rightarrow VB$ channels are closed, or at large energies beyond the resonance-hole excitations, the width of the \bar{K}^* is governed by the $\bar{K}\pi$ decay mechanism in dense matter.

The \bar{K}^* meson spectral function is displayed in the right panel of Fig. 4 as a function of the \bar{K}^* meson energy, for zero momentum and different densities up to $1.5 \rho_0$. The calculation in free space, where only the $\bar{K}\pi$ decay channel contributes, is given by the dashed lines while the other three lines correspond to fully self-consistent calculations, which also incorporate the process $\bar{K}^* \rightarrow \bar{K}\pi$ in the medium.

The $\Lambda(1783)N^{-1}$ and $\Sigma(1830)N^{-1}$ excitations are present at the right-hand side of the quasiparticle peak, which is given by

$$\omega_{qp}(\vec{q}=0)^2 = m^2 + \text{Re}\Pi_{\bar{K}^*}(\omega_{qp}(\vec{q}=0, \vec{q}=0)) . \quad (7)$$

Nuclear matter effects result in a dilution and merging of those resonant-hole states as well as a general broadening of the spectral function due to the increase of collisional and absorption processes. Thus, the \bar{K}^* feels a moderately attractive optical potential and acquires a width of 260 MeV, which is about five times its width in vacuum.

5. Transparency ratio for $\gamma A \rightarrow K^+ K^{*-} A'$

The width of the \bar{K}^* meson in nuclear matter can be analyzed experimentally by means of the nuclear transparency ratio. The aim is to compare the cross sections of the photoproduction reaction $\gamma A \rightarrow K^+ K^{*-} A'$ in different nuclei, and tracing the differences to the in medium K^{*-} width.

The normalized nuclear transparency ratio is defined as

$$T_A = \frac{\tilde{T}_A}{\tilde{T}_{^{12}\text{C}}} , \text{ with } \tilde{T}_A = \frac{\sigma_{\gamma A \rightarrow K^+ K^{*-} A'}}{A \sigma_{\gamma N \rightarrow K^+ K^{*-} N}} . \quad (8)$$

The quantity \tilde{T}_A is the ratio of the nuclear K^{*-} -photoproduction cross section divided by A times the same quantity on a free nucleon. This describes the loss of flux of K^{*-} mesons in the nucleus and is related to the absorptive part of the K^{*-} -nucleus optical potential and, therefore, to the K^{*-} width in the nuclear medium. In order to remove other nuclear effects not related to the absorption of the K^{*-} , we evaluate this ratio with respect to ^{12}C , T_A .

In Fig. 5 we show the transparency ratio for different nuclei and for two energies in the center of mass reference system, $\sqrt{s} = 3 \text{ GeV}$ and 3.5 GeV ,

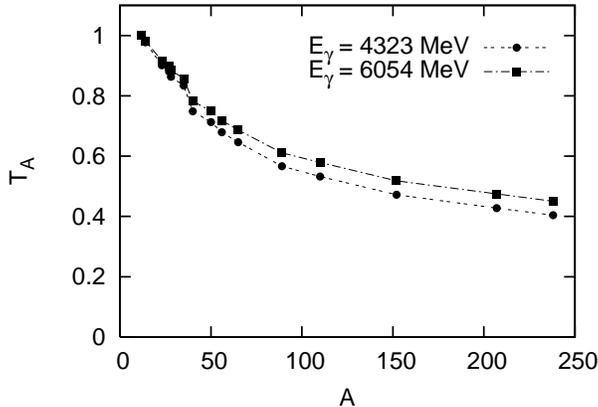


Figure 5: Nuclear transparency ratio for $\gamma A \rightarrow K^+ K^{*-} A'$ for different nuclei

or, equivalently, two energies of the photon in the lab frame of 4.3 GeV and 6 GeV respectively. There is a very strong attenuation of the \bar{K}^* survival probability coming from the decay or absorption channels $\bar{K}^* \rightarrow \bar{K}\pi$ and $\bar{K}^* N \rightarrow \bar{K}^* N, \rho Y, \omega Y, \phi Y, \dots$, with increasing nuclear-mass number A . The reason is the larger path that the \bar{K}^* has to follow before it leaves the nucleus, having then more chances of decaying or being absorbed.

6. Conclusions

The properties of \bar{K}^* mesons in symmetric nuclear matter are studied within a self-consistent coupled-channel unitary approach based on hidden-gauge local symmetry. We obtain the self-energy and, hence, the spectral function of the \bar{K}^* meson. The corresponding in-medium solution incorporates Pauli blocking effects and the \bar{K}^* meson self-energy in a self-consistent manner, the latter one including the $\bar{K}^* \rightarrow \bar{K}\pi$ decay in dense matter.

We have observed an important change in the \bar{K}^* width in nuclear matter as compared to free space. At normal nuclear matter density the \bar{K}^* width is found to be about 260 MeV, five times larger than its free width. We have also made an estimate of the transparency ratio for different nuclei in the $\gamma A \rightarrow K^+ \bar{K}^* A'$ reaction. We have found a substantial reduction from unity of that magnitude due to decay and absorptive new mechanisms in matter.

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