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Higher momentum positive kaon-nucleon interactions

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Abstract Cross sections for elastic and inelastic scattering of K^+ from ^{6}Li and ^{12}C are computed in a first order distorted wave impulse approximation (DWIA) code and compared successfuly with recent data The DWIA code is also used to estimate quadrupole noncentral contributions to elastic K^+ scattering from the 1^+ ground state of ^{6}Li, and these are found to be very small

Keywords Kaon-nucleon interaction, elastic and inelastic scattering, distorted wave impulse approximation

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1 Introduction

he K^+-nucleus cross sections should be fairly weak and the amplitudes reasonably simple because of the simple K^+-nucleon system In fact, we expect the K^+-nucleus interaction to be the weakest of any strongly interacting probe, and the resulting mean free path to be large (in the order of 7 fm) [1]. We note that there is not true absorption of the K^+ to complicate the teraction. Resonance are not permissible as 'compound states' the K^+N system, because of strangeness conservation; the first resonance occurs at high momentum $P_{lab} \geq 800$ MeV/ The lack of resonance structure is due to the absence of any hadrons with strangeness + 1. In the quark picture, a K^+N resonance requires formation of five-quark objects, which have never been observed.

Conventional nuclear physics pictures the nucleus as a system of nucleons interacting by the exchange of mesons. The physical characteristics of the nucleons when they are in the nucleus are taken to be identical to that of the free nucleon. Comparisons between theoretical models and experimental values have indicated that the K^+- nucleon cross section, need to be increased by 20% [3] or more in order to obtain agreement with K^+-nucleus elastic data, although the shapes of the angular distributions are in reasonable agreement with the data. This discrepancy between the theory and the data was interpreted [4, 5] as an indication that the nucleons within the nuclear medium do not behave as they do in free space.

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A recently-developed DWIA code allows a scale factor to multiply the amplitudes for each K^+-nucleon collision within the nucleus, as described in Ref. [1], representing a medium enhancement factor for the K^+-N interaction, as suggested by previous elastic and total cross section data. This scale factor also changes the inelastic scattering cross sections computed by the code.

We also used our DWIA code to evaluate part of the noncentral elastic scattering from ^{6}Li. The 1^+ ground state of ^{6}Li permits electric quadrupole and magnetic dipole elastic scattering, which are not treated by central optical model calculations. Our calculations estimate the quadrupole corrections to the observed elastic scattering data to determine the scattering which is to be compared to calculations that include only central scattering, as appropriate to spin zero target nuclei. The magnetic dipole elastic scattering has been neglected because spin-flip scattering by K^+ mesons is weak at small angles.

2. Methods

The DWIA code defines the K^+–N amplitudes as follows :

$$f_{KN} = b_0 + b_1(\boldsymbol{t}\cdot\boldsymbol{\phi}) + (c_0 + c_1(\boldsymbol{t}\ \boldsymbol{\phi}))\boldsymbol{k}\cdot\boldsymbol{k}\ ,$$

where the parameters b_0, b_1, c_0 and c_1 are related to the free kaon-nucleon phase shifts. We define the isospin coupling for the KN system from the following equations :

$$\boldsymbol{I} = \boldsymbol{t} + \boldsymbol{\phi}\ ,$$

where I is the total isospin operator for KN system; its magnitude equals 1 or 0, t is the isospin operator for the kaon of magnitude 1/2, and ϕ is the isospin operator for the nucleon.

$$I^2 = t^2 + \phi + t\ \phi .$$

The isospin coupling for the KN system is :

$$t \cdot \phi = \begin{cases} 1 & \text{for } I = 1, \\ -3 & \text{for } I = 0 . \end{cases}$$

The idea of increasing the elementary amplitudes by a multiplying scale factor SF, adds a considerable improvement to the agreement of our calculations with the experimental data, as shown in the next section.

3. Results

Recent K$^+$ elastic and inelastic scattering data on ^{12}C at 635 and 715 MeV/c and on ^{6}Li at 715 MeV/c kaon lab momentum elastic scattering on ^{6}Li have been considered to compare to our calculations. The geometrical distributions of these nucleons used for our calculations on ^{6}Li and ^{12}C are taken from Ref. [1]. Our calculations were found to match the data shape but the magnitudes of the data are above the calculations using free-space amplitudes. Increasing all KN amplitudes by a scale factor improves the agreement.

New K$^+$ elastic scattering angular distributions from ^{12}C at 715 MeV/c kaon lab momentum are shown in Figure 1. Calculations in our first-order optical potential have been done and compared with these data [6]. These calculations correspond to different choices of K$^+$N amplitude scale factors. The K + – ^{12}C elastic scattering data are in better agreement with the

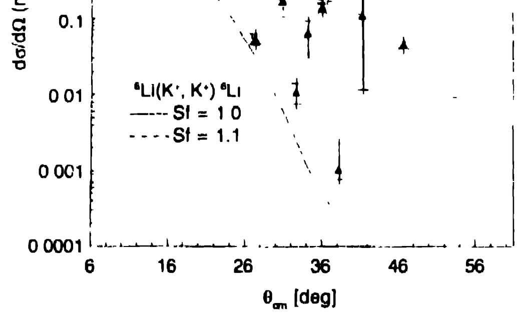

Figure 1. Differential elastic cross sections for K$^+$–^{12}C scattering as the upper set of curves, at 715 MeV/c kaon momentum The lower set of curves show K$^+$–^{6}Li elastic scattering at the same momentum, after division by 10 The data are from Ref [3].

theoretical predictions with real and imaginary KN amplitude increased by 10%. For ^{6}Li, a 10% increase in the amplitudes gives predictions above the data.

In Figure 2, we show the ratios, ^{12}C to ^{6}Li, for calculated differential elastic cross sections, and compare them to the measured values of [6]. This ratio cancels the largest experimental uncertainties shown in Figure 1. This figure shows a pronounced difference at forward angles between the calculated ratios and experimental values by about 20% for calculations with scale factor 1 for both targets, and this deviation persists with increasing equal KN ampitudes applied to both nuclei. Also, curves with different scaling factors are added in Figure 2 to show the dependence of the scaling factor with the density where ^{6}Li has larger RMS charge radius than ^{12}C. The cross point curve used a scale factor 1.1 with ^{6}Li and 1.2 with ^{12}C The fitting looks good at forward angles, while the dot-dashed curve used scaling factor 1.1 with ^{6}Li and 1.15 with ^{12}C is less satisfactory.

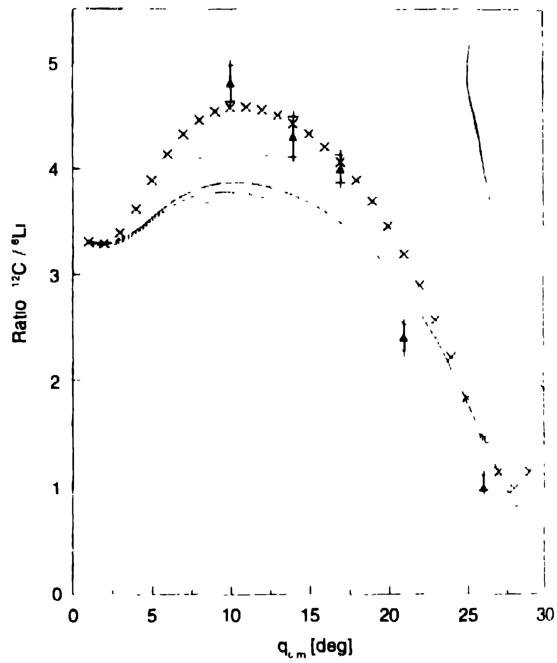

Figure 2. Ratios for the carbon and lithium cross sections of Figure 1 are shown The solid curve shows the results using scale factor 1. the dashed and dotted curves used scale factor 1.1 and 1 2, respectively for both nuclei The dot-dashed curve used scaling factor 1 1 for ^{6}Li and 1 1 for ^{12}C, and the cross curve used 1 1 and ^{6}Li and 1.2 for ^{12}C are shown

At 635 MeV/c, kaon lab momentum elastic scattering calculations on ^{12}C are compared with experimental data [6] in Figure 3. Also included are curves for the theoretical prediction with the KN amplitudes increased by 15 and 20%; this increase gives improvement for the fitting. Calculations for the electric quadrupole elastic scattering will be described below. Its effects are negligible, and these possible complications are not the source of the difference we note between ^{6}Li and ^{12}C.

K$^+$ elastic scattering angular distribution from ^{12}C at 8 MeV/c kaon lab momentum are shown in Figure 4. Calculation in our first – order optical potential have been done and compared with Marlow *et al* [7], also examining the effects of large meson-nucleon coupling. The K^+–^{12}C elastic scattering data are almost

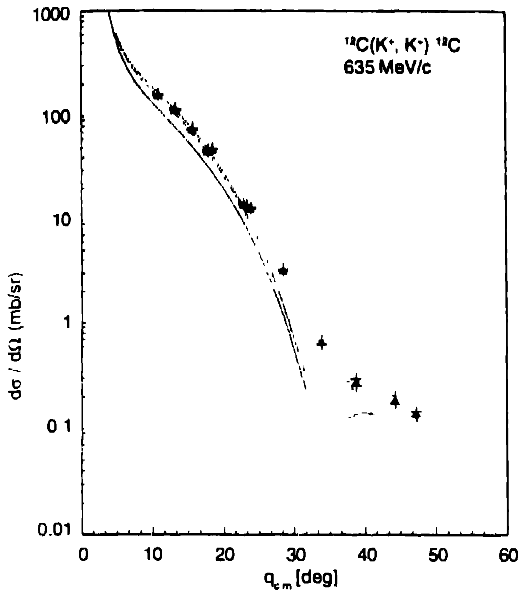

Figure 3. Differential elastic cross sections for K^+–^{12}C scattering at 635 MeV/c kaon momentum. The solid curve is the theoretical prediction, the dashed and dotted curves show the effects of increasing the kaon-nucleon amplitudes by 20 and 15%, respectively The data from Ref [5] are shown

in better agreement with the theoretical predictions with real and imaginary KN amplitude increased by 15%. It must be remarked here that the previous calculations of Chen and co-workers [8] and Clark *et al* [9], which are based on the impulse approximation, fall well below the 800 Mev/c data by about 30-50%

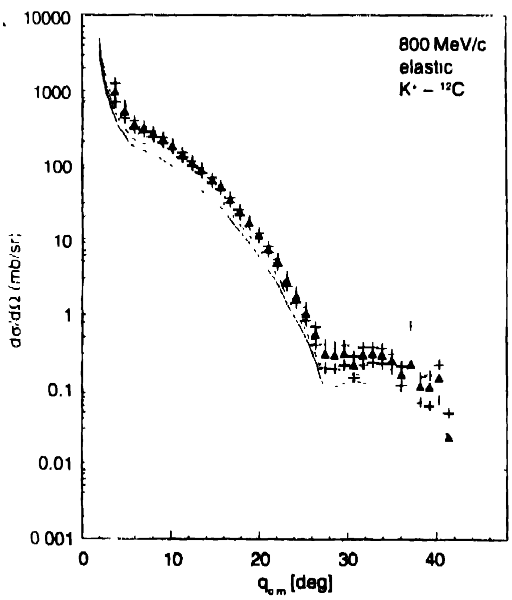

Figure 4. Differential inelastic cross sections for K^+–^{12}C scattering at 800 MeV/c kaon momentum The solid curves are the theoretical prediction; the dashed and dotted curves show the effects of increasing the kaon-nucleon amplitudes by 15 and 20%, respectively The Data from Refs [7,9] are shown

Our first-order optical potential code DOKAY can also be used to predict non-spin inelastic cross sections. We use only derivative transition densities. Recent data for K^+ inelastic scattering from ^{12}C to its strong 2^+ and 3^- excited states have been considered to compare the present calculations. The geometrical distributions of the nucleons on ^{12}C were taken from Ref. [5]. Proton and neutron matrix elements have been used for these calculations were $M_p = 7.5$ fm^2 and $M_n = 7.2$ fm^2 with deformations $\beta_p = 0.61$ and $\beta_n = 0.58$, for the 2^+state and $M_p = 22.7$ fm^3 and $M_n = 26.7$ fm^3, with deformations $\beta_p = 0.57$ and $\beta_n = 0.67$, for the 3^- state [10]. Shapes of computed angular distribution at 635 and 715 MeV/c are found to be similar to the experimental data.

In Figure 5, are shown calculated differential inelastic cross sections along with the recent data of Michael [11] at 635 MeV/c. Increasing all KN amplitudes by 20% for the strong

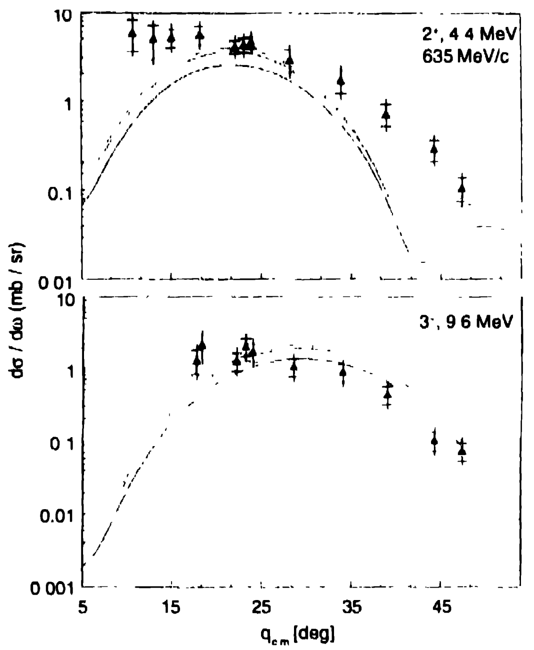

Figure 5. Differential inelastic cross sections for K^+–^{12}C scattering at 635 MeV/c kaon momentum The solid curves are the theoretical prediction, the dashed and dotted curves show the effects of increasing the kaon-nucleon amplitudes by 15 and 20%, respectively The data from Ref. [11] are shown.

coupling of the ground state to the 2^+ excited state, gives close agreement with the data. The theoretical predictions for the 3^- excited state are found to be in better agreement with the data on the average, but increasing the amplitudes by about 20% gives improvement for the fitting at the forward angles. The same results were found with differential inelastic cross sections of K^+ from ^{12}C at 715 MeV/c for the 2^+ and 3^- excited states, as shown in Figure 6. Also in Figure 7 we show the differential inelastic scattering at 800 MeV/c of K^+ from ^{12}C to its strong 2^+ and 3^- excited states. The agreement between the present calculations with increasing KN amplitudes by 15% and the data [10] is good. We used the same β for 2^+ and 3^- states on ^{12}C at 635, 715 and 800 MeV/c, because this depends only on the nucleus and not on the reaction energy.

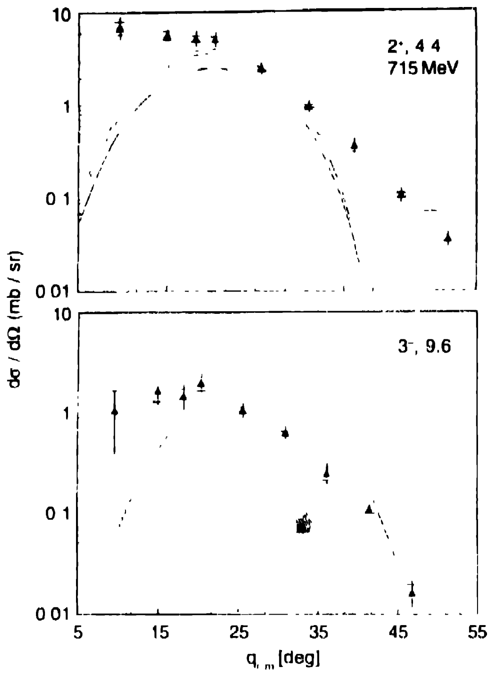

Figure 6. Differential elastic cross sections for K+ ^{12}C scattering at 715 MeV/c kaon momentum The solid curve calculation with the central optical model prediction The dashed curve is the electric quadrupole scattering, and the sum is shown by the curve of crosses The data are from Ref [3]

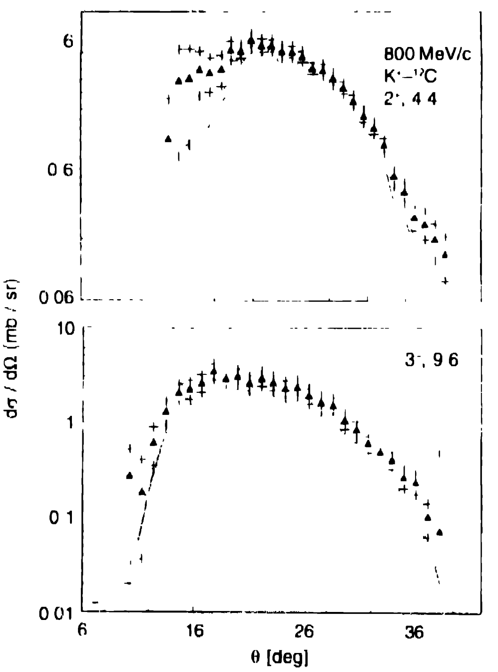

Figure 7. Same as Figure 6 but at 800 Mev/c The data from Ref. [10] are shown

Figure 8 shows the differential elastic cross section for K^+ from the new fits for ^6Li at 715 MeV/c, compared to the data from Ref. [6]. The differential elastic cross sections for ^6Li can be calculated from the following equation, including quadrupole scattering for the 1^+ ground state :

$$\frac{d\sigma}{d\Omega}=\frac{d\sigma}{d\Omega}\left(0^+\rightarrow 0^+\right)+\frac{d\sigma}{d\Omega}\left(1^+\rightarrow 1^+\right).$$

The second term of this equation is computed with β = 0.017 for both neutrons and protons, as known from electric quadrupole moment of ^6Li, with an excitation energy of 0.1 MeV Figure 8 shows three curves, the solid curve is the central optical model prediction for ($0^+ \rightarrow 0^+$). The dashed curve indicates the expected electric quadrupole scattering. The sum is shown by the curve of crosses. It is entirely safe to apply only the standard central optical model to elastic scattering of ^6Li. A scale factor SF = 1.0 was used for these calculations.

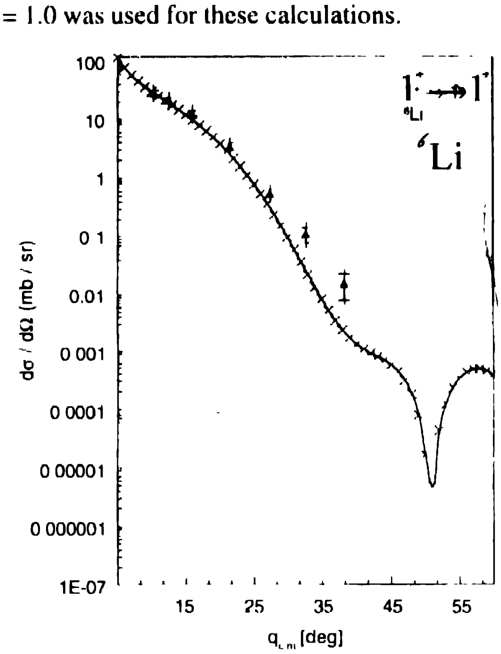

Figure 8. Differential inelastic cross sections for K+ ^6Li scattering at 715 MeV/c kaon momentum A scale factor 1 was used for these calculations The data are from Ref [8]

In Figure 9, the differential inelastic scattering from the 1+ to the 3^+ excited state at 2.1 MeV for ^6Li at 715 MeV/c using β = 0.82 for both neutrons and protons is shown. This $1^+ \rightarrow 3^+$ cross section is the strongest inelastic scattering in $^6Li(p,p')^6Li$ [12], and corresponds to a deformation β = 0.82, if treated as a $0^+ \rightarrow 2^+$ L = 2 cross sections. This β ($1^+ \rightarrow 3^+$) was used as a $0^+ \rightarrow 2^+$ calculation in our code to predict the curves shown in Figure 7, and compared to the data from Ref. [13, 14].

Scaling the K^+–N amplitudes is not the only way in which medium effects might occur. If all *S*- and *P*- wave phase shifts were to be changed by the medium, both real and imaginary amplitudes would change. We have added extra negative phase shifts to those from SAID [15] to compute new K^+–N *t*-matrices for calculations of cross sections. Results are shown in Figure 10 for comparisons of computed σ_R and differential elastic scattering with the data for ^{12}C at 715 Mev/c. Extra shifts

Figure 10(a) can give agreement with elastic data, while other values Figure 10(b) are needed to match the reaction cross sections. Experimental uncertainties are not large enough to

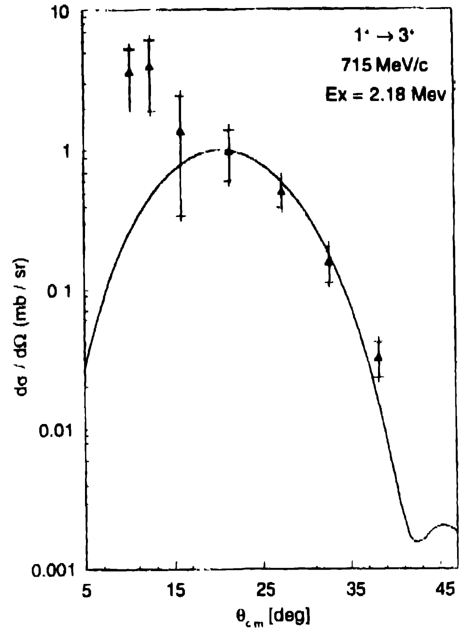

Figure 9. Differential inelastic cross sections for p–^{6}Li scattering from 1^+ to 3^+ excited state at 715 MeV/c. The data of ref. [13] are shown

find agreement for both observables with a single extra shift, so this simple process is not the answer. Varying each phase shift separately would not be fruitful, since the variables would outnumber the data being fitted.

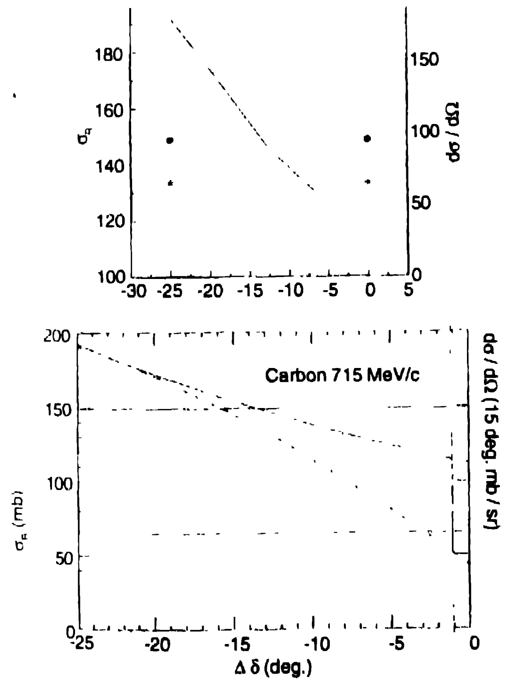

Figure 10. Differential elastic cross sections for K^+–^{6}Li scattering at 715 MeV/c kaon momentum. The extra negative phase shifts are applied · (a) to give agreement with elastic data and (b) to match the reaction cross section. The data are from Refs. [3, 10].

4. Conclusions

The differential elastic cross sections for K^+ from ^{6}Li and ^{12}C were calculated at 715 MeV/c. The K^+–^{12}C elastic scattering data were found to be in better agreement with the theoretical predictions with KN amplitudes increased by 10%. For ^{6}Li, a 10% increase in the amplitudes gave predictions above the data. Since the scale factor for ^{12}C and heavy nuclei was found to be greater than that for ^{6}Li, with its lower density, we conclude that there is indeed some evidence for a density dependence of these medium modifications.

We studied inelastic cross sections of K^+ on ^{12}C to its strong 2^+ and 3^- excited states, as an example of the inelastic process. Shapes of computed angular distributions were found to be similar to the experimental data [10]. If standard matrix elements are used and the KN amplitudes are increased by 20%, the calculations for the 2^+ excited state were found to be in good agreement with the data on the average, at the momenta 635, 715 and 800 MeV/c [see Figure 9]. For the calculations to the 3^- state, we found that the theoretical calculations gave a good fitting with the data at the back angles, and increasing all K^+N amplitudes by 20%, made the calculations nearer to the data at forward angles. In Figure 6, the electric quadrupole scattering makes no difference to the differential elastic cross sections for K^+ from ^{6}Li. The differential inelastic cross sections for protons from ^{6}Li between the states 1^+ and 3+ corresponds to a deformation $\beta = 0.82$, treated as a $0^+ \rightarrow 2^+$ to predict the inelastic cross sections for K^+ from ^{6}Li, and compared to the data [13] [see Figure 7].

The modification of K^+-nucleon amplitudes have been used in meson-nucleus reaction codes to predict observables that match elastic and inelastic data quite well, and gave us a means to investigate the important and modern question of the density dependence of medium modifications sensed by K^+ meson.

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