NUCLEON KNOCKOUT BY KAONS

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ABSTRACT

The $(K^+, K^+ p)$ reaction is considered as a probe of the deep hole states in nuclei. DWIA calculations are presented for the knockout of a $1s_{1/2}$ proton from ^{40}Ca . We conclude that the experiment should be valuable.

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The knockout of nucleons from nuclei by protons¹ and electrons² has proved to be a very useful tool in demonstrating the shell-model structure of both light nuclei and the surface of medium weight nuclei. Binding energies, hole state widths, form factors, and spectroscopic strengths have all been extracted with varying degrees of success using these reactions.

The deep hole states of medium weight nuclei are particularly interesting³ as they give us a direct view into the single particle structure of nuclei. Theories of the lifetimes of these states can also give us insight into the dynamics of the interaction of quasi-particles with nuclear matter. Unfortunately, there are serious difficulties in studying deep hole states reliably using either the electron or proton probe. In knockout by electrons the difficulty arises from the weakness and long range of the electron-nuclear interaction. The resulting cross sections are small and fall off rapidly with increasing momentum transfer or energy loss. Background extractions and statistics (as well as what appears to be the broad natural width of the states) make extraction of clean information very difficult. In knockout by nucleons the difficulty arises from the strength of the proton-nucleon interaction. The distorting potentials for the projectile modify its wave function considerably and in a manner which is uncertain in the nuclear interior, exactly in the region where the deep hole wave functions are concentrated.

What is needed is a probe which has a stronger interaction with nucleons than the electron does, yet one which interacts weakly enough so that distortion effects can be handled unambiguously. It has been suggested⁴ that low energy K^+ mesons ($0 < p \leq 800$ MeV/c) satisfy these requirements.

This suggestion is attractive on a number of counts. The $K^+ - N$ interaction leads to total cross sections⁴ in this energy range of about 10 mb; which is about one quarter of the relevant nucleon-nucleon cross sections. The cross section is almost constant in energy, there being no resonances at all in the low energy region. The lightest mass which can be exchanged is a ρ meson so the range of the force is about 0.25 fm. This means that only S- and P- waves in the $K^+ - N$ system are relevant at the indicated energies and that the off-shell variation of the amplitude will be small⁵. The weakness of the interaction means that K^+ distortion effects should be reasonably small and should be calculable from first principles⁶, reducing the interior uncertainty of the probe wave function.

In order to see whether this suggestion is reasonable, given the current state of kaon beams, in this letter we calculate the absolute angular correlation for the reaction $^{40}\text{Ca}(K^+, K^+ p)^{39}\text{K}$ leading to the $1s_{1/2}$ proton hole state. The energy of the incident K^+ is taken to be 300 MeV ($p \approx 620$ MeV/c). Calculations of the Distorted Wave Impulse Approximation (DWIA) for the knockout are performed using the code AAB described in Ref. 7.

The K^- nucleus distorted waves are found by solving a Klein-Gordon equation. Since S- and P- waves suffice to describe the $K^+ - N$ interaction and since the force range is small we take the optical potential to be of Kisslinger type^{4,8}. This gives an optical potential of the form

$$-2 EV(r) = b_0 \rho(r) - b_1 \vec{\nabla} \cdot \rho(r) \vec{\nabla} \quad (1)$$

where b_0 and b_1 are $K^+ - N$ amplitudes⁴ and ρ is the nuclear density. The density is taken to be a Fermi shape⁹ with a radius of 3.51 fm and a diffuseness of 0.563 fm. It is normalized so that the volume integral of ρ is equal to the total number of nucleons. The $K - N$ amplitudes are taken from the phase shift analysis of Martin¹⁰. The proton optical potential is taken from the study of van Oers¹¹.

The calculations are performed for the angular correlation in the coplanar geometry with the outgoing K^+ and p making equal angles with the beam in the lab. The proton energy is kept constant at 89 MeV.

The $K^+ - N$ transition amplitude appearing inside the DWIA integral should in principle be a fully-off-shell T matrix^{7,12}. Since the force is so short ranged, the variation of the amplitude as a function of its momenta should be slow. This justifies factoring the amplitude out of the integral and using the on-shell T matrix at the final relative energy¹². This gives an amplitude at a relative $K - N$ energy of

$$T_{\text{rel}} = 0.65 T_{\text{lab}} - Q \quad (2)$$

where T_{lab} is the lab kinetic energy of the K^+ and Q is the separation energy of the proton. The factor 0.65 arises from the kinematic transformations.

The near symmetry of the kinematics used implies that the $K - N$ amplitude appearing will be for a scattering angle in the CM near 90° . This means that the P-wave amplitude will contribute little to the transition amplitude for our particular kinematic final states. Therefore, only the S-wave amplitude is retained. Again, the Martin amplitudes are used.

The $1s_{1/2}$ proton bound state is taken to have a binding energy² of 58.5 MeV. The wave function is taken to be the one found in a Woods-Saxon well whose depth is adjusted to give the right separation energy. The geometric parameters of the well are those of Nakamura, et al.²

Three calculations are performed in order to see the effects of the various distortions. The full distorted wave calculation includes distortions on all three external legs. A second calculation sets the K^+ optical potentials equal to zero but retains the distortion of the external proton leg. Finally, a plane wave calculation is done. Here all the distortions are turned off. In all of the calculations the spectroscopic strength C^2S is set equal to unity. Here C is the usual isospin-conserving Clebsch-Gordon coefficient and S is the spectroscopic factor⁷. (For the closed $1s_{1/2}$ proton shell C^2S should actually have a value around 2).

The results are shown in Fig. 1. The peak cross section for the full DWIA calculation occurs near 45° and has a value of $1.4 \mu\text{b}/\text{sr}^2 \cdot \text{MeV}$. If the kaon distortions are turned off, the peak value is only increased by a factor of 1.9. If the proton distortion is also turned off the peak value increases further by a factor of 3.2 giving a plane to distorted wave ratio of 6.0. This shows that the major distortion is due to the escaping proton and that the overall reduction from distortions is not sufficient to cast doubt on the validity of the assumed reaction mechanism. The corresponding reduction factor¹³ for a $(p,2p)$ reaction at a comparable incident momentum ($E \sim 200 \text{ MeV}$) at the co-planar symmetric quasi-free peak is about 28. The absolute magnitude of this $(p,2p)$ cross section is about 10 times larger than that for the $(K^+, K^+ p)$ reaction. Thus the larger

cross section is obtained at the cost of a large increase in distortion effects and a corresponding increase in the uncertainty of the extraction of structure information.

The measured $(e, e'p)$ cross section for knockout of the 1s proton in ^{40}Ca by 500 MeV electrons is about $2 \cdot 10 \text{ nb/sr}^2 \cdot \text{MeV}$. The distortion of the electron wave is not expected to produce any significant modifications while the proton distortion reduces the cross section by a factor² of 4.4. The distortion effects are comparable to that for the (K^+, K_p^+) reaction but the cross section is 100 times smaller.

It thus appears that on theoretical grounds, the K^+ would be an excellent probe for the study of deep lying hole states. We must however consider whether the experiment is feasible with existing accelerators. We may obtain an estimate of the counting rate as

$$N = N_0 \frac{L}{\lambda} \quad (3)$$

where N_0 is the available flux, L the target thickness, and $\lambda = 1/\rho\sigma$ the mean free path; ρ is the density and σ the cross section to the desired slice of phase space. In order to keep the energy loss of the outgoing proton less than 1 MeV, we restrict our target thickness¹⁴ to less than $1/5 \text{ gm/cm}^2$. We use our peak DW cross section and angular acceptance of 10 msr for each final particle and an energy acceptance of 10 MeV. For a ^{40}Ca target this gives

$$N = N_0 \times 10^{-11} \quad (4)$$

Current beams¹⁵, e.g. at the AGS at Brookhaven, deliver on the order of 10^5 kaons/sec. This would yield a count rate of about 3 counts a month in our angle-energy bin. This is certainly much too small a cross section to

do realistic experiments. If, however, the K^+ production of the AGS is upgraded by a factor of 100 as has been proposed¹⁵, one would obtain on the order of one count an hour. This is close to being reasonable, since much of the desired phase space could be collected simultaneously.

We conclude that the K^+ meson would theoretically provide an excellent probe of the deep hole states via knockout. The effects of distortion should be much less than in (p,2p) reactions. The cross sections are larger than those observed in (e,e'p) reactions, but the availability of high flux electron beams tends to give the electron reaction the advantage at the present time. Fluxes of K^+ mesons of the order of $10^7 - 10^8$ /sec would make this experiment possible and would add a valuable tool to our current collection of probes of the nucleus.

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FIGURE CAPTION

Fig. 1: Absolute cross sections for knockout of a $1s_{1/2}$ proton from ^{40}Ca by a 300 MeV Kaon. — = full DWIA; - · - = only proton distorted, - - - = PWIA (no distortions). C^2S is taken to be 1.