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Abstract: Recent progress in exotic atom physics, kaon-nucleus scattering, and hypernuclear physics is reviewed. Specific problems discussed include searches for muon-nucleon interactions beyond QED, a comparison of data and recent calculations of $K^\pm + {}^{12}\text{C}$ elastic and inelastic scattering, as well as recent studies of Σ and Λ hypernuclei including new data on the level structure of ${}^{13}\text{C}^*_\Lambda$.

1. Introduction

The physical phenomenon discussed in this session consist of exotic atomic and nuclear systems containing bound hadrons and muons as well as the unbound kaon nucleus scattering problem. These topics are both old and new. Whereas exotic atom systems have been discussed for some thirty years, evidence for Σ hypernuclei, first seen at CERN and now confirmed at BNL, have only become available in the last three years. In this short introductory talk it will not be possible to comment on all the recent developments in these areas. I choose to discuss therefore some selected problems in each of the three areas: a) exotic atoms, b) kaon nucleus scattering and c) lambda and sigma hypernuclei.

2. Exotic Atoms

In this section we consider both mesonic and hadronic atoms. It is useful to classify the systems studied as being in the nuclear regime, the hydrogen-like regime, or the electronic regime according to whether the average size of the atomic orbit is comparable to the nuclear radius, intermediate, or comparable to the electronic orbit.

A quite interesting branch of muon spectroscopy deals with high precision x-ray measurements of hydrogen-like systems in order to check the extent to which the muon obeys the relative QED corrections, and to look for the existence of new types of interactions, μ -e universality, and possibly properties of the weak interaction. For a recent review of this subject see Zavattini¹). Aas et al.²) have recently reported precision measurements of the $3d_{5/2} - 2p_{3/2}$ and $3d_{3/2} - 2p_{1/2}$ x-ray transitions in μ ${}^{24}\text{Mg}$, ${}^{28}\text{Si}$, and ${}^{31}\text{P}$ with a bent crystal spectrometer. The measured wave lengths, λ_{exp} , are compared with theoretical values, λ_{th} , obtained from QED calculations. The relative difference averaged over six cases gives:

$$\left\langle \frac{\lambda_{\text{exp}} - \lambda_{\text{th}}}{\lambda_{\text{th}}} \right\rangle = (2 \pm 8) \times 10^{-6}$$

This is a test of the vacuum polarization effect in QED to $(0.6 \pm 2.4) \times 10^{-3}$. Or, assuming that QED is correct, this puts a limit on the presence of any additional muon-nucleon interaction of long range and weak coupling. If such an interaction were mediated by a scalar, isoscalar boson of mass < 1 MeV then the

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coupling constant would be:

$$\frac{g_N g_M}{4\pi} = (-4 \pm 17) \times 10^{-9}$$

Other precise tests of QED vacuum polarization corrections come from $(\mu^- {}^4\text{He})^+$ (see reference 3) and recently⁴⁾ $(\mu^- {}^3\text{He})^+$. Tests of the μ -e interaction are proceeding through studies of the neutral muonic helium atom⁵⁾ and of muonium $(\mu^+ e^-)$ which has recently been observed in vacuum for the first time⁶⁾.

In the electronic regime great interest now centers on the processes involved in forming mesonic molecules. The only case where it is clear that a muon can have a molecular orbit is in hydrogen isotope mixtures. Current measurements and calculations center on determining the formation mechanism, temperature dependence and resonance formation rate of systems like $\mu p p$, $\mu p d$, $\mu d d$ and $\mu d t$ as reported in this session by Bystritsky⁷⁾, Breunlich⁸⁾, and Bakalov⁹⁾. An intriguing possibility is to use the muon as a catalyst in forming the $\mu d t$ system in a energy production process since it ultimately decays through the fusion reaction:

Rates for this process have been discussed by Bogdanova et al.¹⁰⁾.

Spectra obtained in hadronic atoms have been compiled by Poth¹¹⁾ and reviewed by Batty¹²⁾ where they report complex energy shifts, $\Delta E + i \Gamma/2$, for π^- , K^- , P^- , and Σ^- atoms. Although these lead to effective optical potentials, V_{opt} , attempts to calculate V_{opt} from first principles have had mixed results.

In recent reviews, Seki¹³⁾ and Friedman and Gal¹⁴⁾ have made systematic studies of pionic atom data. They are generally able to fit the data except for the recently reported widths¹⁵⁾ of 3d levels in ${}^{181}\text{Ta}$, Re and ${}^{209}\text{Bi}$. Ericson and Tauscher¹⁶⁾ have proposed an explanation for this problem in terms of the energy dependence of the real part of the π nucleus potential due to the strong coulomb field.

In the area of kaonic atoms analysis of the $K^- p$ atom continues to be poorly understood. No consistent picture arises when the different measurements are compared to each other and to low energy $K^- p$ scattering data. The first measurement at Nimrod (Davies et al.¹⁷⁾ gave a shift and width for the 1s level of $\Delta E_{1s} \approx 40 \pm 60$ eV and $\Gamma_{1s} \approx 0^{+230}_{-0}$ eV corresponding to an s wave scattering length of

$$a_s = 0.10 \pm 0.15 + i 0^{+0.28}_{-0.0} \text{ fm.}$$

Izycki et al.¹⁸⁾, in a CERN experiment on kaonic hydrogen, obtained the values: $\Delta E_{1s} = +270 \pm 80$ eV and $\Gamma_{1s} = 560 \pm 260$ eV. Furthermore in a phase shift analysis of low energy $K^- p$ scattering Martin¹⁹⁾ obtains a scattering length of $a_{K^- p} = -0.66 + i 0.70$ fm. This would lead to a repulsive shift of the 1s level in $K^- H$ of $\Delta E_{1s}^{\text{calc}} = -270$ eV and to a width of $\Gamma_{1s}^{\text{calc}} = 580$ eV in disagreement with both the above measurements. A new experiment²⁰⁾ has now been completed at CERN. The results however were not ready in time for reporting at this conference. It is well known that the theoretical analysis of this low energy interaction is complicated by the presence of the subthreshold resonance, $Y^*(1405)$. This has been recently discussed by Borie and Leon²¹⁾.

We now turn to Σ^- atoms. In view of the recent observation of Σ -hypernuclei (see below) there is renewed interest in the Σ -nucleus optical potential. Batty's analysis²²⁾ of Σ x-ray data suggests a real central potential of $V_{\Sigma}^C = 26$ MeV in reasonable agreement with the hypernuclear value²³⁾ or $V_{\Sigma}^C = 21$ MeV.

In the hydrogen-like region the fine structure splitting of an atomic level is proportional to the magnetic moment of the particle in orbit. This has been used by Roberts²⁴⁾ and Hu²⁵⁾ to make a 1% measurement of the antiproton magnetic moment in good agreement with the magnitude of the proton moment. In atomic fine structure measurements of the Σ^- moment, Roberts et al.²⁶⁾ obtain $\mu(\Sigma^-) = -1.48 \pm 0.37$ nm while Dugan et al.²⁷⁾ obtain -1.40 ± 0.41 nm which agree rather well. The simple quark model estimate with equal mass u, d and s quarks gives $\mu(\Sigma^-) = -0.88$ nm while a model in which the s quark is heavier gives $\mu(\Sigma^-) = -1.04$ nm²⁸⁾. In a recent paper Brown et al.²⁹⁾ report a calculation in the chiral bag model in which they obtain $\mu(\Sigma^-) = -0.54$ nm. This problem is being further studied in an Σ^- atom experiment proposed at BNL³⁰⁾ and a polarized Σ^- hyperon beam experiment at FNAL³¹⁾ and is clearly an important test of the quark model.

3. Kaon Nucleus Interactions

The use of kaons as a nuclear probe has been widely discussed in recent years both as a test of reaction dynamics and of nuclear structure. The K^+ meson has spin zero, a very weak K^+N interaction strength with a relatively smooth energy dependence and little absorption (for a recent KN analysis see reference 32). Thus in nuclear scattering it has the advantage of high nuclear penetrability ($\lambda \approx 6$ fm) and a multiple scattering description that should be reliable even in first order since the kaon nucleon interaction is dominated by s-wave scattering even at high momentum transfer and absorption is small. Interest in K^- nucleus scattering comes primarily from the role it plays in the formation of hypernuclei and for the contrast it provides for the K^+ probe. The strength and resonance character of the K^-N interaction are more reminiscent of the pion than of the K^+ probe.

Detailed calculations of K-nucleus multiple scattering have been reported by many authors. Recently Sakamoto³³⁾ has reported on a Glauber description of $K^\pm$ elastic and inelastic scattering on ^{12}C . Elastic scattering of positive kaons on ^{12}C , ^3H , ^3He and ^4He have been calculated with a momentum space optical potential by Paez and Landau³⁴⁾. The latter calculations include effects due to nuclear spin, recoil and binding, the finite size of the nucleons, the nucleon-nucleus angle transfer, as well as neutron and spin distributions in a separable potential model. A dispersion approach to K^+ scattering on light nuclei is reported in this session by Blokhintsev³⁵⁾.

As a specific example of the success of this program it is useful to look at data and calculations of $K^\pm + ^{12}\text{C}$ elastic and inelastic scattering reported by the CMU-BNL-Houston collaboration³⁶⁾.

Differential cross sections for elastic and inelastic scattering of K^- and K^+ mesons from ^{12}C and ^{40}Ca were measured at 800 MeV/c lab momentum. The data covers the angular range from four to thirty four degrees in the laboratory. The measurements were made using the hypernuclear spectrometer at the BNL AGS with a typical energy spectrum shown in Fig. 1 for a ^{12}C target; the resolution is about 2 MeV. The absolute cross section scale for $K-^{12}\text{C}$ scattering was confirmed by measuring the scattering from hydrogen in a CH_2 target. Analysis of the hydrogen data is shown in Fig. 2 together with differential cross sections obtained by other researchers³⁷⁾.

Fig. 1 Excitation spectrum³⁶⁾ for the reaction $^{12}\text{C}(K^-, K^-)^{12}\text{C}^*$ at an 18.5 degree scattering angle where the yields from the ground state and the 4.43 MeV peaks are comparable. The energy resolution is about 2 MeV (FWHM). The kaon momentum is 800 MeV/c in the lab.

The elastic $K^\pm$ data on ^{12}C and ^{40}Ca , shown in Fig. 3, fall rather sharply with angle and display minima which are characteristic of the nuclear sizes involved. The K^+ minima are about 3 degrees further out than for K^- scattering suggesting that the K^+ meson "sees a smaller nucleus". The curves in Fig. 3 show coordinate space optical potential calculations³⁶⁾ using the Kisslinger form and the parameters b_0 and b_1 calculated by Rosenthal and Tabakin³⁸⁾ based on the kaon nucleon amplitudes of Martin³⁹⁾ for K^+ and Gopal/Alston-Garnjost³⁹⁾ for K^- . The potential parameters used are shown in Table 1.

Table 1

Parameters used in the Kisslinger Potential

		Re(b_0)	Im(b_0)	Re(b_1)	Im(b_1)
K^-	Gopal	0.61	0.84	-	-
	Best Fit	0.32	0.88	-	-
K^+	Martin	-0.335	0.241	0.084	0.161
	Best Fit	-0.445	0.010	0.035	0.082

Fig. 2 Center of mass cross sections for a) K^- and b) K^+ scattering on hydrogen at 800 MeV/c kaon lab momentum. The results of the CMU-BNL-Houston measurements³⁶⁾ are compared with previously published experiments³⁷⁾.

The agreement between the coordinate space calculations and the data is moderately good except for the case of $K^+ + {}^{12}\text{C}$. The observed disagreement may be related to shortcomings in the calculation e.g. a) the Kisslinger potential has several known deficiencies including a zero-range fundamental KN amplitude with unphysical off shell behavior, and b) the so-called "angle transformation" was omitted. In addition the nucleon finite size must be unfolded from the nuclear density as taken from electron scattering data since it is included in the elementary t matrix. The effect of this last correction is shown by the dashed and solid lines in Fig. 3.

Fig. 3 Comparison of measured³⁶⁾ differential cross sections for $K^\pm$ elastic scattering on ^{12}C and ^{40}Ca to coordinate space optical potential calculations. The upper curves use electron scattering nuclear densities corrected for the finite nucleon size; the lower curves are uncorrected.

For all of these effects, there are considerably more precise models available in momentum space. The data were compared to momentum space calculations (see Fig. 4) by using a version of the program PIPIT⁴⁰⁾ which was suitably modified for kaons. Here the questions raised regarding KN range, nucleon size and inclusion of higher partial waves in the elementary t matrix are correctly resolved in the context of a first order optical potential. Good agreement is obtained for K^- scattering when the nuclear finite size correction is included however the difficulty in fitting the $K^+ + ^{12}\text{C}$ data persists. The results are not very sensitive to the off shell form factor. Thus we are left with a discrepancy in the K^+ case of as much as a factor of five which we are not able to explain since the full calculation gives results rather close to a simple Born approximation calculation. A "best fit" analysis of this data gives $b_0 = -0.445 + i 0.010$ and $b_1 = +0.035 + i 0.082$ i.e. less absorption than the K^+N interaction values.

Fig. 4 Comparison of measured a) K^- and b) K^+ elastic scattering cross sections for ${}^{12}\text{C}$ with momentum space calculations⁴⁰⁾ in which the correction for finite nucleon size is included.

Analysis of the inelastic scattering data for the 2^+ and 3^- states of ${}^{12}\text{C}$ provide an interesting illustration of the sensitivity of the K^+ probe to the nuclear interior. Data for the 4.4 MeV 2^+ state of ${}^{12}\text{C}$ are shown in Fig. 5 and compared to calculations using a coordinate space distorted wave impulse approximation program using best fit optical potential parameters for the elastic channel (see Table 1). The transition densities were taken from a) a collective dV/dR model (dashed curve) and b) electron scattering data on ${}^{12}\text{C}$ as presented by Gustaffson and Lambert⁴¹⁾ (solid curve) and are compared in Fig. 6 with the

Fig. 5 Comparison of measured³⁶⁾ differential cross sections for a) K^- and b) K^+ inelastic scattering on ^{12}C to the 4.43 MeV 2^+ state to distorted wave impulse approximation calculations (see text). The transition densities were taken from a) a collective, dV/dR model (dashed curve) and b) electron scattering data on ^{12}C as presented by Gustaffson and Lambert⁴¹⁾ (solid curve).

Gillet-Vinh Mau particle hole model⁴²⁾. Although these two transition densities differ, primarily in the nuclear interior where the electron form factor is larger (see Fig. 6), they fit the K^- data equally well. On the other hand the K^+ probe is much more sensitive to this difference and the electron scattering form factor is clearly to be preferred (see Fig. 5). This lends qualitative support to the statement that the K^+ meson is a strongly interacting highly penetrating "electron-like" nuclear probe.

In a separate discussion of this reaction Abgrall⁴³⁾ describes, in terms of a coupled channel Glauber calculation, the contribution of dispersive effects to the process i.e. the virtual excitations and de-excitations of the nucleus during the scattering event. This has been applied successfully to proton scattering on deformed nuclei⁴³⁾.

Fig. 6 Comparison of ^{12}C transition densities (multiplied by $4\pi r^2$) as generated by a) Gillet-Vinh Mau - long dashed curve, b) electron scattering data - solid curve and c) a collective model using a dV/dR interaction - short dashed curve.

4. Λ and Σ Hypernuclei

Although discovery of hypernuclear resonances began in 1969 the development of high quality data has been slow. However over the last several years the high intensity kaon beams at CERN and BNL have produced a number of cases where the level structure has been observed in sufficient detail that theoretical models can be carefully tested. A case in point is the ${}^{16}_{\Lambda}\text{O}$ spectrum which seems to indicate that the Λ -nucleon spin-orbit force for a p orbit is only 5% of the equivalent nucleon case. For the purpose of this review we discuss the following three problems: a) the mass four lambda systems: ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$; b) the level structure of ${}^{13}_{\Lambda}\text{C}$; and c) the formation of Σ hypernuclei.

The low energy states of ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ are isospin doublets arising from the $[(1s_{1/2}) \otimes (1s_{1/2})^{-1}]_{J=0,1}$ particle hole couplings. These four states are now known as a result of gamma decay work of the Cern-Lyon-Warsaw collaboration⁴⁴⁾ and are displayed in Fig. 7. Here we see that the singlet interaction is more attractive than the triplet by about 1 MeV. Furthermore the isospin doublets for the ground state and also for the 1 MeV state are split in energy by about 300 keV when corrected for the Coulomb energy difference. These have been calculated by Wu Hui-fang et al.⁴⁵⁾ from a Λ -N interaction potential constructed from meson exchange terms. Good agreement with the data was obtained. Recently Gibson and Lehman⁴⁶⁾ have argued that the 300 keV isospin splitting is consistent with the small charge symmetry breaking contribution expected from the Nijmegen hyperon-nucleon potential as long as the $\Lambda\text{N}-\Sigma\text{N}$ coupling is not neglected and a so-called "exact" four body calculation is performed. Wang Wei-wei et al.⁴⁷⁾ point out that in a SU(6) classification system one can derive masses for ${}^4_{\Lambda\Lambda}\text{H}$ and ${}^4_{\Lambda\Lambda}\text{He}$ from this data. They find that these exotic systems are not likely to be bound.

Fig. 7 Comparison of ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ level spectra. The measured binding energies are indicated.

In experiments at the Brookhaven AGS⁴⁸⁾, levels of the hypernuclei $^{13}_{\Lambda}\text{C}$, $^{14}_{\Lambda}\text{N}$ and $^{18}_{\Lambda}\text{O}$ have been observed for the first time. The spectrum of $^{13}_{\Lambda}\text{C}$ has been measured in the $^{13}\text{C}(K^-, \pi^-)^{13}_{\Lambda}\text{C}$ reaction in the angular range 0–25 degrees. A typical spectrum is shown in Fig. 8 in which five peaks dominate the strength distribution. This structure has its origin in the coupling of a Λ particle in either the 1s or 1p orbit ($\epsilon_p^{\Lambda} - \epsilon_s^{\Lambda} = 10.8$ MeV) to neutron holes in either the $1p_{1/2}$ or $1p_{3/2}$ orbits. The energy distribution of the neutron hole strength can be obtained either by looking at the $^{13}\text{C}(p, d)^{12}\text{C}$ reaction or the calculations of Cohen and Kurath⁴⁹⁾. The p strength lies primarily in states at 0.0, 4.4, 12.7, 15.1 and 16.1 MeV in $^{12}\text{C}^*$ as shown in Fig. 9. The composite spectrum generated by shifting the Λ from the s orbit to the p orbit (see Fig. 9) is in qualitative agreement with the observed spectrum.

Fig. 8 Measured energy spectrum⁴⁸⁾ of the $^{13}\text{C}(K^-, \pi^-)^{13}_{\Lambda}\text{C}^*$ reaction near zero degrees. The five peaks arise from states excited in $^{13}\text{C}^*$. The experimental energy resolution is about 2.5 MeV.

Fig. 9 Schematic level scheme for $^{13}\Lambda\text{C}$ based on a Λ in either the s or p orbit coupling to states observed in the $^{13}\Lambda\text{C}(p,d)^{12}\text{C}^*$ reaction. The observed strength distribution in $^{13}\Lambda\text{C}^*$ is shown at the right.

E. H. Auerbach et al.⁵⁰⁾ have recently reported a detailed shell model treatment of this hypernuclear system. The pickup strength is calculated directly using a p shell effective interaction due to Cohen-Kurath⁴⁹⁾ and to Millener⁵⁰⁾ and a ΛN interaction which includes central and two body spin orbit components. The resulting wave functions are used in distorted wave calculations that reproduce the observed angular distributions. Fitting the data restricts the central part of the ΛN interaction and constrains the one and two body spin orbit forces to be small. The spectra observed for $^{14}\Lambda\text{N}$ and $^{18}\Lambda\text{O}$ are shown in Fig. 10 for which an analysis similar to Fig. 9 is a good starting point. An analysis of $^{13}\Lambda\text{C}$ in terms of a SU_3 classification is reported by Zhang Zong-ye⁵¹⁾ where candidates for the supersymmetric and strangeness analog states are identified.

Fig. 10 Measured energy spectrum⁴⁸⁾ of a) the $^{14}\text{N}(\text{K}^-, \pi^-)^{14}\text{N}_{\Lambda}$ and b) the $^{18}\text{O}(\text{K}^-, \pi^-)^{18}\text{O}_{\Lambda}$ reactions near zero degrees. For case a) we assume $B_{\Lambda} = 12.2$ MeV. For case b) the energy scale is $-B_{\Lambda}$.

A convincing demonstration of the existence of Σ hypernuclei was first provided by Bertini et al.⁵²⁾ for ${}^9\text{Be}$ and ${}^{12}\text{C}$ targets. Recent studies at BNL⁵³⁾ of the (K^-, π^+) reaction on targets of ${}^6\text{Li}$ and H_2O confirm the existence of narrow states. In ${}_\Sigma^6\text{He}$ at 0° (Fig. 11b) an indication is seen of a narrow peak and a somewhat broader structure at lower excitation energies (higher B_Σ). Because of the relatively high momentum transfer there is a strong contribution from the quasifree continuum. These structures in ${}_\Sigma^6\text{He}$ are interpreted as primarily substitutional states in the 1s and 1p shell respectively, based on the comparison with ${}_\Lambda^6\text{Li}$ (Fig. 11a).

Fig. 11 Comparison of the measured energy spectrum⁴⁸⁾ of the ${}^6\text{Li}(K^-, \pi^+) {}_\Sigma^6\text{He}$ reaction to the ${}^6\text{Li}(K^-, \pi^-) {}_\Lambda^6\text{Li}$ reaction.

Much discussion has centered on why these Σ states are observed with widths of only 8-10 MeV. Since these ΣN^{-1} particle hole states lie 80 MeV up in the ΛN^{-1} spectrum and because the ΣN to ΛN coupling is not small, one should expect large spreading widths. For example Batty's analysis²²⁾ of Σ^- atomic x-ray data suggests widths of ~ 22 MeV for a Σ in a 1s orbit in $^{12}_\Sigma\text{C}$. Several mechanisms to generate narrow widths have been suggested by Kisslinger⁵⁴⁾, Dover⁵⁵⁾, Wycech⁵⁶⁾ and Dabrowski⁵⁷⁾. Kisslinger emphasizes short range repulsion at high momentum transfer. On the other hand, since the $\Sigma N \rightarrow \Lambda N$ conversion is dominated by the $I = 1/2$, 3S_1 channel at low momentum, Dover and Gal emphasize narrow widths for ΣN^{-1} states in which the $I = 3/2$ and 1S_0 channel is dominant. Stopien-Ruddka and Wycech⁵⁶⁾ have recently shown that a nuclear optical potential can be developed that is consistent with the hypernuclear data, Σ -atom x-ray data, and Σ production in stopping K^- experiments. Dabrowski and Rozynek⁵⁷⁾ have recently used the Brueckner reaction matrix method to estimate the ground state energy of a Σ in nuclear matter. They find that the exclusion principle and dispersive effects suppress the $\Sigma N \rightarrow \Lambda N$ conversion process sufficiently to give the observed widths. Better quality data away from the p shell would be very helpful in resolving these various mechanisms.

A problem of great interest in hypernuclear physics deals with the magnitude of the hyperon nucleus spin orbit interaction. Bouyssy⁵⁸⁾ reviews the present status of calculations for various probes in a paper presented in this session. Several experiments now suggest a small Λ spin orbit force (i.e. $^{16}_\Lambda\text{O}$ and $^{13}_\Lambda\text{C}$). Of special interest is the Σ case which is predicted to be similar to that of a nucleon, in the calculations of Bouyssy⁵⁸⁾ and Pirner⁵⁹⁾ while Dillig⁶⁰⁾ obtains a fraction of the nucleon value. Experiments to measure this in $^{16}_\Sigma\text{O}$ are in progress at BNL⁵³⁾ and CERN.

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