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EXOTIC ATOMS AND HYPERNUCLEI*

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We review recent progress in hypernuclear and exotic atom physics. We include a discussion of quasiatomic and very energetic γ rays from the $\bar{p}p$ atom, and their possible relevance to the multiquark baryonium states. We also summarize the most recent results on the study of Λ and Σ hypernuclei, in particular the proposals for the central and spin-orbit components of the single particle potentials and the spin-spin term in the ΛN residual interaction, as revealed by hypernuclear spectra and γ ray transitions.

Very recently[1,2,3], experimental information has become available on the γ-ray emission from the antiproton-proton ($\bar{p}p$) system, i.e., "protonium". Evidence for both quasiatomic[1,2] and quasinuclear[3] (γ-rays to very deeply bound states) transitions exists. In ref. (2), the preliminary results for K X-rays indicate a repulsive shift of the $\bar{p}p$ 1S atomic level of $\Delta E \approx 3$ keV, with a corresponding upper limit on the width of $\Gamma \leq 0.2$ keV. In the work of Auld et al[1], the L X-rays from the $\bar{p}p$ atom were seen at a level of $6\pm3\%$ per stopped $\bar{p}$, and an upper limit of 0.6% was quoted for K X-rays. This indicates that annihilation from the 2P level is more prevalent than γ emission by a ratio of 10:1 or more. This group also has preliminary indications[4] of a few 2P→1S transitions detected in coincidence with the 3D→2P line, with no indication of a shift as large as $\Delta E \approx 3$ keV for the 1S level. This uncertainty in the value of ΔE is only likely to be resolved when more intense $\bar{p}$ beams are available at the LEAR facility[5] at CERN.

Several theoretical predictions exist for ΔE and Γ, based on $\bar{p}p$ potential models[6,7,8,9]. Older models[6,7] give values $(\Delta E, \Gamma) = (0.8, 1.3)$ keV in ref. (6) or $(0.6, 0.3)$ keV in ref. (7). Recent calculations[8] based on the more realistic Paris potential[10] yield values of ΔE from 0.8 - 1keV. Finally, coupled channel calculations of Kaufmann[9] yield values ΔE also less than 1keV; these include tensor coupling and isospin mixing. Although the $\bar{p}p$ potential models studied thus far do not produce a shift as large as $\Delta E \approx 3$keV, this value can always be fitted by ad hoc adjustments of the short range part of the potential, about which we know very little.

The Backenstoss group[3] has also reported evidence for very energetic γ rays emitted from the $\bar{p}p$ system. Energies of about 180, 220 and 410 MeV are quoted in ref. (3); a second run also showed the 180 and 220 MeV lines, but the 410 MeV line disappeared in favor of another possible candidate at 330 MeV. Possible mechanisms for sharp background γ lines have been suggested[4], involving $\bar{p}$ annihilation into kaons followed by kaon-induced γ rays, but the rates for these processes may be much smaller than the observed γ intensities of $6\text{-}8\times10^{-3}$ per stopped antiproton. Another search[11] for γ rays at Brookhaven obtained no monoenergetic lines at the level of 3×10^{-2}. This limit is not inconsistent with the results of ref. (3).

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Although the experimental evidence for energetic γ rays from the $\bar{p}p$ atom is somewhat shaky, a positive result, if confirmed, would be extremely significant, as it points to the existence of low-lying "baryonium" states. Such new mesons have been discussed both in potential models[12,13] ("nuclear quasimolecules") and as multiquark complexes[14,15] of diquark-antiquark ($Q^2\bar{Q}^2$) type. Recently, the relative coupling strengths of various $Q^2\bar{Q}^2$ trajectories to the $\bar{N}N$ system, via γ or π emission, have been estimated[8,16]. For this purpose, the model used by Jaffe[14] to estimate the direct $\bar{N}N \to Q^2\bar{Q}^2$ coupling was generalized. The qualitative conclusions[8] are as follows: i) relatively few of the numerous predicted $Q^2\bar{Q}^2$ states are likely to be seen in γ or π emission; ii) if the transition proceeds from quasiatomic S-states, the dominant γ and π transitions populate <u>different</u> final $Q^2\bar{Q}^2$ states. In principle, this offers a way of distinguishing $Q^2\bar{Q}^2$ mesons from "quasimolecules" produced in potential models[12,13] for which γ and π emission usually goes to the <u>same</u> final states; iii) the γ transitions populate some of the $\ell=1$ states on the $Q^2\bar{Q}^2$ $B^{\pm}$ trajectories, in the notation at Jaffe[14], which have binding energies of the order of 150 MeV. Two strong lines are predicted. This is in the energy range of the 180 and 220 MeV γ's claimed in ref. (2); iv) the $\ell=0$ $Q^2\bar{Q}^2$ states are populated by π rather than γ emission in this model[8]. The strong γ and π transitions are sufficiently few so that essentially unique quantum number assignments can be made in the $Q^2\bar{Q}^2$ model, if sharp lines indeed exist. No reliable calculation exists for the widths of "baryonium" states. Since the $Q^2\bar{Q}^2$ states below the $\bar{N}N$ threshold which could be seen in γ or π emission correspond to low orbital angular momentum $\ell=0$ or 1, there is a significant chance that these states may be broad. In this case, one has to concentrate attention on the high ℓ $Q^2\bar{Q}^2$ mesons predicted well above the $\bar{N}N$ threshold[14,15].

We now turn to another elementary two-body system, the K^-p atom. Recently, the 1S complex level shift of this system was measured by Davies et al[17], who obtained $\Delta E \approx 40 \pm 60$eV and $\Gamma \approx 0^{+230}_{-0}$ eV. If this is converted to a complex scattering length a_s via the usual formula $\Delta E + i\,\Gamma/2 \approx 2\mu^2\alpha^3 a_s$, where μ is the reduced mass and α is the fine structure constant, we obtain $a_s = 0.1 \pm 0.15 + i0^{+0.28}_{-0.0}$ fm. A recent analysis[18] of low energy K^-N scattering data suggests a much larger value $a_s \approx 0.66 + 0.71i$ (fm). Large complex scattering lengths for K^-N are also obtained in many other analyses. There is as yet no convincing explanation for this large discrepancy. Two contributions[19] to this conference bear on this question: Deloff and Law point out an ambiguity in Coulomb corrections, while Kumar and Nagami obtain singular behavior of the K^-N amplitude near threshold in a particular model.

We now consider the problem of more complex exotic atoms. There exists a recent compilation of all data on the complex energy shifts $\Delta E + i\,\Gamma/2$ in π^-, K^-, $\bar{p}$ and Σ^- atoms[20]. One standard method of analyzing the shifts is in terms of a complex effective amplitude A, using an optical potential given by $V_{opt} = A\rho(r)$. Recent analyses of this type for Σ^- atoms have been performed by Johnstone and Law[21]. There are also some attempts to calculate Vopt from many-body theory[22]. For complex atoms, a first principles analysis has eluded us. In the case of $\bar{p}$ and K^- atoms, the situation is particularly difficult because of the existence of two-body resonances close to threshold. This causes strong density dependent modifications of the effective amplitude A in the nuclear medium. In view of the uncertainties in reaction mechanism, the K^- and $\bar{p}$ atoms have not yet proven useful for an extraction of nuclear properties such as neutron densities. These have generally been used as input into the calculation.

In the last several years, there has been considerable progress in our understanding of hypernuclear properties. The (K,π) reaction has proved to be an especially powerful tool for the production of single Λ and Σ hypernuclei. With available kaon beams in the momentum regime of 700-900 MeV/c, one is able to work near the ideal recoilless limit of zero momentum transfer for the (K,π) reaction. The CERN[23-25] and Brookhaven[26] groups have reported new data on Λ and Σ hypernuclei at this conference. We report only the main conclusions here.

The CERN group[23-25] has explored the systematics of Λ single particle states in hypernuclei. They offer an appealingly simple picture of the Λ effective interaction. The level spacing between s, p, d and f Λ-shell model states is observed to be approximately constant at 9 MeV. The Λ well depth is about 30 MeV, consistent with older determinations from emulsion data. The most interesting aspect of this work is the claim that the Λ-nucleus spin-orbit potential is much weaker than that for nucleons[23,24]. It is also suggested that the residual Λ-nucleon spin-spin interaction $V_{\sigma\sigma}$ is weak, so the Λ acts roughly as a "spinless neutron". The most recent Λ shell model calculations incorporating these features are due to Bouyssy[27]. A good description of the coarse resolution experimental data is obtained using only simple Λ particle-neutron hole configurations; the agreement is good both for energy splittings and relative intensities.

Experiments with higher energy resolution are required before the Λ spin-orbit and spin-spin forces can be probed further. The detailed fine structure of the hypernuclear spectrum can provide additional constraints on the spin dependence. Such fine structure corresponds, for instance, to splittings between states of different J but the same p-h configuration, e.g. $(\Lambda P_{3/2}, nP_{3/2}^{-1})\ 0^+, 2^+$. Another example is the splitting of ground state doublets, e.g. $(\Lambda S_{1/2}\ nP_{3/2}^{-1})\ 1^-, 2^-$; these register directly the effect of the ΛN spin-spin potential. Note that the unnatural parity member of the doublet will be very difficult to excite in the (K^-,π^-) reaction. Spin-flip transitions are predicted to be several orders of magnitude smaller than transitions to natural parity states[29] (comparing peak cross sections for 2^+ and 2^-, say). Another source of information on $V_{\sigma\sigma}$ is the observation of hypernuclear γ rays from particle stable excited states; we return to this point later.

There are several theoretical estimates of the strength $V_{LS}^{\Lambda N}$ of the two-body ΛN spin-orbit interaction[29,30,31]. The estimated strengths range from $V_{LS}^{\Lambda N} = 0$ in a particular approximation to quark-gluon dynamics[31], to about $V_{LS}^{\Lambda N}/V_{LS}^{NN} \approx 1/3$ using phenomenological one boson exchange potentials[29] which simultaneously describe NN, ΛN and ΣN scattering processes[32]. The value of $V_{LS}^{\Lambda N}$ is of considerable interest for the meson exchange model of baryon-baryon forces, since the Λ and Σ hypernuclear systems probe the SU(3) structure of these interactions.

Recently, angular distributions for the (K^-,π^-) reaction were obtained by the Brookhaven group[26]. They studied the $^{12}C(K^-,\pi^-)^{12}_{\Lambda}C$ reaction at 800 MeV/c. Their main conclusions are as follows: The (K^-,π^-) reaction on ^{12}C, with coarse resolution of 2.5 MeV, exhibits two prominent peaks whose relative intensity varies with angle. The lower mass peak corresponds to a binding energy of 10.79 ± 0.1 MeV, in excellent agreement with the ground state binding energy of 10.76 MeV obtained from the older emulsion data. The angular distribution for the lower peak displays a maximum at about 10^o. This is consistent with theoretical expectations[29] for the $(\Lambda S_{1/2}, nP_{3/2}^{-1})\ 1^-$ member of the ground state doublet. The position of the peak in the angular distribution is not very sensitive to the choice of distorting potentials[29]. The "analog" peak at 11 MeV excitation is thought to correspond to a clumping of the $(\Lambda P_{3/2}, nP_{3/2}^{-1})\ 0^+, 2^+$ and $(\Lambda P_{1/2}\ nP_{3/2}^{-1})\ 2^+$ p-h configurations. Because of the small momentum transfer, the CERN experiments at $\Theta_{LAB} = 0^o$ are sensitive mostly to the 0^+ component. The presence of the 2^+ states is revealed in the BNL data as a shoulder in the angular distribution around $\Theta_{LAB} = 15^o$. In this region, the 0^+ cross section is predicted to be much smaller than the observed value, while 2^+ states should have their maximum near 15^o. The triplet of $0^+, 2^+, 2^+$ states were not resolved in the Brookhaven experiment[26]. If one assumes that only one 2^+ is appreciably excited, the 0^+-2^+ energy splitting is less than 420 keV (95% confidence); if both 2^+'s are excited with the same intensity, the data[26] indicate a splitting for the 2^+'s of less than 820 keV. These limits may already yield some constraints on the spin dependence of the Λ interaction.

No evidence for core excited states in $^{12}_{\Lambda}C$ was seen in the Brookhaven data[26]. Theoretical calculations of Dalitz and Gal[33], based on Cohen-Kurath wave functions, predicted two additional 1^- states between the ground state and the analog peak, with a summed intensity of about 40% relative to the ground state. The use of Soper wave functions[34] reduces this to about 20%. The observed event excess[26] in the 2-7 MeV region of excitation energy gives an upper limit of 6±5% for the relative intensity of core excited states in ${}^{12}_{\Lambda}C$. The cause of this discrepancy is not yet understood. The search for core excited states in hypernuclei is an important area for future research, although higher intensity kaon beams will be required. The intensities of such states provide a very sensitive test of the correlation structure of "closed shell" nuclei, for instance, 2p-2h correlations in the ground state of ^{12}C.

The CERN group has recently found evidence for Σ^0 and Σ^- hypernuclei[23-25], via the (K^-, π^-) and (K^-, π^+) reactions at 720 MeV/c, respectively. From their data, they are able to extract a preliminary value of about 20 MeV for the Σ well depth in the nucleus. The data do not indicate any sizable difference between the Σ^0 and Σ^- wells (a Lane potential for Σ's). In ${}^{9}_{\Lambda}Be$, they find evidence for a rather narrow Σ_0 peak with $\Gamma \leq 6$ MeV. This is perhaps the most interesting feature of the data. In heavy nuclei, naive width estimates based on the known Σ-Λ conversion cross sections ($\Sigma^- p \rightarrow \Lambda n$ or $\Sigma^0 p \rightarrow \Lambda p$) give values in the range $\Gamma \approx 20$-40 MeV. For light "discrete" systems, which are not spin and isospin saturated, these crude estimates do not suffice, and one must consider more detailed models. Attention must be paid to the possibility of additional selection rules (overall isospin conservation, for instance).

There is also some new data on hypernuclear γ rays[35,36]. The γ rays in ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$ have been remeasured[35], with resulting energies of 1.04 and 1.15 MeV, respectively. These correspond to the transition between the 1^+ and 0^+ members of the $(\Lambda S_{1/2}\ N\ S_{1/2}^{-1})$ configuration. These and other data have been analyzed[35] in terms of a spin dependent ΛN interaction containing a charge symmetry breaking term V_{CSB} proportional to τ_3^N. The conclusion is that $V_{\sigma\sigma}$ is rather strong and V_{CSB} is weak. This is the reverse of the conclusion of Bamberger et al[37], which is based, however, on an erroneous value of 1.42 MeV for the ${}^{4}_{\Lambda}He$ γ-ray. These new data do not seem to be consistent with the idea[23,24] of the Λ as a "spinless neutron". However, note that the conclusions of refs. (23,24) are much stronger for the spin-orbit force than for the spin-spin part; $V_{\sigma\sigma}$ is, in fact, not well determined from the observation of unresolved p-h states[23,24] alone.

There is another candidate[36] in ${}^{8}_{\Lambda}Li$ for a γ ray of energy 1.22 MeV. The low-lying states in ${}^{8}_{\Lambda}Li$ are obtained by coupling a Λ in the $S_{1/2}$ orbit to the $3/2^-$ ground state and $1/2^-$ first excited state of the ^7Li core. Dalitz and Gal[33] have calculated the resulting spectrum and γ ray intensities. They predict a strong $1^- \rightarrow 1^-$ transition with energy 1.28 MeV, which may correspond to the γ line seen[36]. Two other lines which are predicted to be fairly strong lie in an energy region (0.5-0.9 MeV) where background γ lines from ordinary nuclei are seen. It is thus difficult to isolate the contribution from the hypernuclear transitions. If the interpretation of the 1.22 MeV γ ray is correct, a sizable spin-spin ΛN potential is indicated. The weak spin dependence used in ref. (27) would lead to a significantly smaller γ ray energy[34]. It is very important to pursue the studies of hypernuclear γ rays. They are potentially very revealing of hypernuclear structure and residual ΛN interactions.

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