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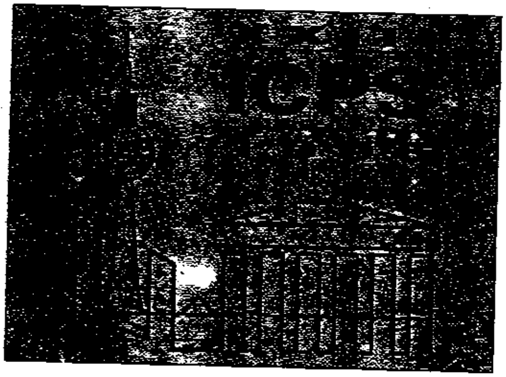

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QUANTUM CHAOS IN THE MAGNETO-EXCITONIC SPECTRUM OF GaAs QUANTUM WELLS ?

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ABSTRACT

We have found signs of Wigner statistics in the excitonic level distribution of a high-quality GaAs quantum well in the presence of a magnetic field. The appearance of this statistics is usually associated with quantum chaos. The statistical properties of the eigenvalues of the system are tuned by the field, which reduces the exciton radii, increases the oscillator strengths and favors the resolution of the excitonic excited states. An analysis of the energy spacing distribution can be satisfactorily fitted with a Brody distribution, which interpolates between the Poisson and Wigner distributions.

Statistical correlations in the spectra are widely regarded as the hallmark of quantum chaos. This seems to happen in some complex systems in different domains: nuclear physics, atomic and molecular physics, chemical physics and solid state physics.[1] The real quantum systems need to be both complex (in the sense that their classical dynamics is chaotic) and simple (the dynamics can be analyzed and simulated numerically). The hydrogen atom in a static magnetic field fulfills both requirements.[2] Since, classically, chaotic motion takes place in situations where the Lorentz force is comparable to the Coulomb force, huge magnetic fields would be necessary to attain this condition for the hydrogen atom. Thus, usually, Rydberg states, with principal quantum number $n \approx 50$, where the Coulomb force of the nucleus is greatly decreased, are the object of the studies. Furthermore, to obtain the simplest systems, their dimensionality is usually reduced using a field with cylindrical symmetry around the z-axis, which gives rise to a two-dimensional (2D) Hamiltonian.[3] A quantum-mechanical equivalent to hydrogenic-like atoms is obtained in solid state physics considering the Wannier excitons in a semiconductor.[4] The dimensionality of this system can be easily reduced using quantum wells (QW's) and, moreover, the fields attainable in the laboratory are enough to observe the fine structure of the spectra without the need to prepare highly excited states.[5] We present in this work a magneto-optical study of the exciton spectrum in GaAs QW's.

We used a p-i-n heterostructure, consisting of 5, 160 Å wide, GaAs QW's sandwiched between n^+ and p^+ GaAs layers. The high quality of the sample (peaks FWHM ~0.3 meV) was a key factor for the success of the experiments. Highly resolved photoluminescence excitation (PLE) spectra were obtained in a polyhelix resistive magnet with

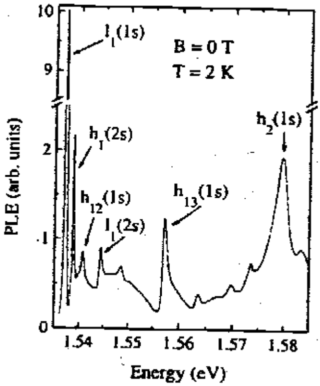

Fig. 1. Zero field, low temperature, PLE spectrum of the 160 Å wide GaAs QW.

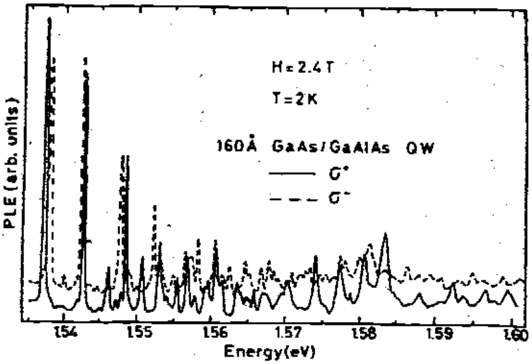

Fig. 2. PLE spectra for excitation with σ^+ (solid) and σ^- (dashed) polarized light at 2.4 T. The lowest peak corresponds to the ground state of the light-hole exciton, l_1(1s).

fields, up to 17 T, applied in the Faraday configuration. Spectra were recorded at 2K with circularly polarized light from a LD700 dye laser, pumped by a Kr^+-ion laser. The sample was biased to flat band conditions.

Figure 1 depicts the low-temperature PLE spectrum at zero magnetic field, which consist of "allowed" and "forbidden" excitonic transitions, superimposed on a steplike background typical of 2D systems. The forbidden transitions are seen due to the presence of a residual electric field of ~5kV/cm. The peaks are labeled using the following notation: *h* (*l*) means heavy (light) hole; a subindex indicates the same confined subband for electrons and holes; in the case of two subindices the former (latter) corresponds to electrons (holes); a nydrogenic notation *nm* is used for the exciton envelope function, where *n* is the principal quantum number and *m* the angular momentum quantum number. The number of states increases remarkably in the presence of an external magnetic field, as can be noticed in Fig. 2, which presents PLE spectra recorded with σ^+ (solid lines) and σ^- (dashed lines) polarized light at a field of 2.4 T. The lowest measured peak in all the spectra corresponds to l_1(1s), since it was not possible to observe in PLE the $h_1(1s)$ because of the vanishing Stokes shift of the sample. The energy of $h_1(1s)$ was obtained from PL experiments. In a previous work,[5] we have identified the structures in the spectra in an energy range of ~35 meV above $h_1(1s)$. The complexity of the spectra of this QW is clearly demonstrated in the figure.

The fan diagram of the excitonic transitions obtained from σ^--PLE is shown in Fig. 3. The intensities of the peaks are color coded (light-grey: minimum; black maximum). Numerous level repulsions can be observed in this diagram when it is inspected in close detail. Figure 4 illustrates one of the anticrossings between states of the same symmetry for fields between 1.5 and 6 T. Both states belong to the same irreducible representation, Γ_7, and therefore can interact. Increasing the field $l_1(3d^-)$ comes closer to

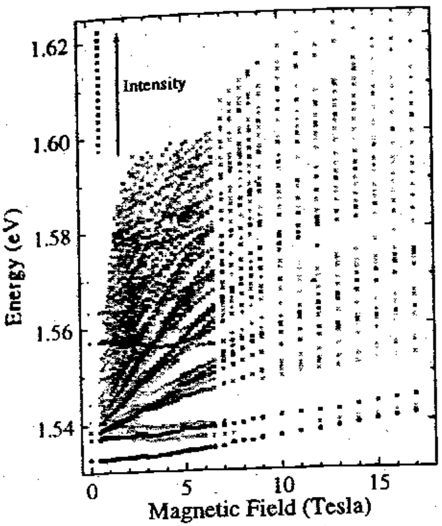

Fig. 3. Energies versus magnetic field of the structures observed in the PLE spectra (squares). The dots correspond to $h_1(1s)$ measured with PL.

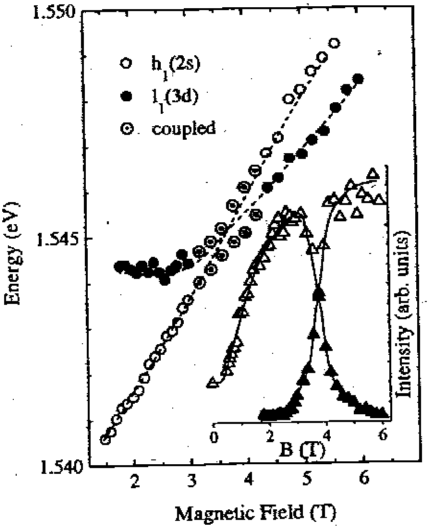

Fig. 4. Energies of $h_1(2s)$ and $l_1(3d^-)$ versus magnetic field. The inset shows the oscillator strengths normalized to those of $l_1(1s)$.

$h_1(2s)$ and gains intensity. The points are shown as ⊙ in the region of strong interaction, when they repel each other and share their oscillator strengths as demonstrated in the inset. Many couplings of this type are observed in the fan diagrams, specially in σ^- configuration. This can lead to stochastic processes, which are known to play an important role in atomic spectra.[3]

The histogram of the energy distribution of the excitonic levels is presented in Fig. 5 for a magnetic field of 2.5 T. The bars correspond to the experimental results and the symbols to the best fit with different statistical distributions. A completely random sequence of energy levels is described by a Poisson distribution, given by:

$$P(\omega) = \frac{1}{D} e^{-\frac{\omega}{D}} \tag{1}$$

where ω is the energy difference between two transitions and D is the mean local distance between the levels.[6] For this distribution small energy spacings predominate, and it presents a maximum at $\omega=0$. However, if repulsions between energy levels take place, they dominate all the spectral fluctuations and the energy spacings between the levels is described by a Wigner distribution given by:

$$P(\omega) = \frac{\pi\omega}{2D^2} e^{-\frac{\pi\omega^2}{4D^2}} \tag{2}$$

which assumes a linear repulsion among the levels.[6] The Wigner distribution applies only for a pure sequence of levels, which have all the same values of the quantum numbers. In a case of mixed sequences, the repulsions are moderated by the vanishing matrix elements of the interaction connecting different symmetries, the spectral distribution moves towards a random distribution: the spacing distribution becomes Poisson like. Brody has introduced a level distribution which interpolates between the Wigner and Poisson distributions:[7]

$$P_\beta(\omega) = A\left(\frac{\omega}{D}\right)^{\beta} e^{-\alpha\left(\frac{\omega}{D}\right)^{1+\beta}} \qquad (3)$$

with A= (1+β) α, $\alpha = \left[\frac{1}{D}\Gamma\left(\frac{2+\beta}{1+\beta}\right)\right]^{1+\beta}$, Γ(x) is the Gamma function, and β is the Brody parameter. When the Brody parameter β=0 (β=1), the Brody distribution reduces to the Poisson (Wigner) distribution. This distribution is only heuristic and does not have a theoretical basis as a measure of underlying chaos in the system. However, in the absence of a distribution which does have a theoretical basis, it is useful since it depends only on one parameter. We obtain the best fit of our data at 2.5 T with β=0.24 and D=150 meV. Both β and D increase with field up to ~5 T and then saturate.

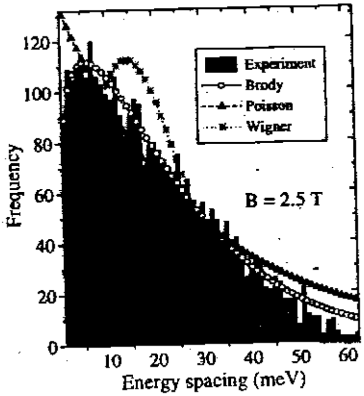

Fig. 5. Histogram of energy distribution of the excitonic. Bars: experiments. Symbols best fits to Brody (open circles), Poisson (triangles) and Wigner (stars) distributions.

In summary, we have found statistical correlations in the magnetoexcitonic spectra of GaAs QW's which can be regarded as a hallmark of quantum chaos. The departure from a Wigner distribution is due to the existence of excitonic levels which belong to different irreducible representations. They can be energetically degenerate, thus the probability of zero energy spacing grows, introducing a Poisson contribution to the distribution.

Acknowledgments

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