Such a theory may at present be based tentatively on the group SU(5) (the Georgi-Glashow model) or on some other group embodying the different subgroups associated with the SU(3) colour symmetry of strong interactions and the SU(2) $\times$ U(1) symmetry of the electroweak interaction. In such a framework, three interactions are unified in one stroke, and one can then calculate $\sin^2\Theta_w$.

A key point of such a unified approach is that quarks and leptons appear as members of the same multiplet, and the postulated symmetry thus implies transitions transforming quarks and leptons into one another.

The decay of the proton is then an inescapable consequence. The energy at which the symmetry would become manifestly realized is however so high ($\sim 10^{15}$ GeV) that its manifestation through virtual quantum effects are extremely improbable. The expected mean life of the proton is of the order of 10^{30} years while the age of our expanding Universe is only about 2×10^{10} years. While the decay probability is extremely small, it appears nevertheless to be within experimental possibilities, provided adequate detectors are built. The stability of the proton, long considered dogma, has now become a subject for debate.

Summary

While basic constituents are numerous and nothing yet even limits quarks and leptons to three doublets, a great unity appears to emerge among basic interactions. A unified theory of weak and electromagnetic processes has already scored many impressive successes and there is little doubt that the two hitherto different basic interactions share many common features and are but two facets of a unique mode of interaction. While still speculative, the understanding of strong interactions at the quark level raises the possibility of a grand unified theory of all three interactions with a prominent consequence : proton decay.

While we do not meet simplicity in the sense of an economy of particles, the new unified approach to basic interactions opens great perspectives through an economy of principle.

Further Reading

"Gauge Theory and Neutrino Physics", Phys. Reprint Book Series 2, 78.

Copies of the Plenary Lecture given at the closing session of the 4th EPS General Conference in York, by A. Zichichi entitled "New Developments in Elementary Particle Physics" are available at the EPS Secretariat on request.

Alchemy in 20th Century Atomic Physics

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The study of heavy ion-atom collisions has grown out of the field of plasma physics and gas discharges, where ionisation processes in electronic and atomic collisions were found to obey the so-called adiabatic criterion (Massey and Burhop, 1952). The impact of electrons or protons on atoms will be adiabatic (projectile velocity small compared with orbiting velocity of the electron concerned in the ionisation) and ionisation will be absent, if $\Delta E.b/h.v > 1$ where ΔE is the electron binding energy, b the impact parameter and v the collision velocity. However, in the early 1960's, in pioneering work with heavy ion beams, the groups of Fedorenko and of Everhart showed that the ionisation processes occurring in heavy ion-atom collisions did not obey the above criterion. Then Fano and Lichten in 1965 suggested that inner shell ionisation could be understood assuming that under adiabatic conditions the colliding atom and ion form a quasi-molecule.

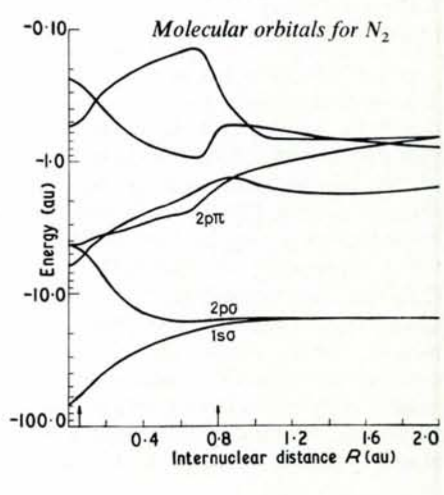
In slow collisions, the atomic electrons can adjust adiabatically to the changing Coulomb field of projectile and target. As the two nuclei approach each other, the atomic states merge into molecular states and in the limit of zero internuclear distance, even into the united atom state. This is the well-known Born-Oppenheimer approximation, according to which the electronic states only depend on the internuclear distance, not on the nuclear motion. At some internuclear distances, however, quasi-molecular levels may come so close, that this approximation is no longer valid and coupling of electronic levels may result from nuclear motion. In terms of the Massey criterion one might say that for some inner electrons in a quasi-molecular state, the energy gap ΔE to a vacant state is reduced so much that excitation is possible. This occurs for impact parameters for which the inner shells start to overlap. Cross-sections for inner shell ionisation in heavy ion-atom collisions are in consequence, large.

This interpretation in terms of a molecular model became very popular among theorists and experimentalists immediately upon its formulation. Large cross sections for inner shell ionisation could be easily verified experimentally by measuring X-ray emission cross-sections in a variety of collision systems and energy regions. At the same time, developments in computer technology made possible the evolution of a better theoretical description of the transiently formed quasi-molecular states. Especially appealing was the predicted formation of united atom states in these ion-atom collisions, which in principle opened the possibility of studying super-heavy quasi-atoms long before the nuclear physicists had reached the islands of stability expected in the region of atomic numbers larger than 100.

Inner Shell Ionisation

Figure 1 shows the calculated molecular orbitals (MO) of two nitrogen atoms as a function of internuclear distance. The MOs correlate the levels of the separated atoms to those of the united atom. At large internuclear distance there are four nitrogen K-shell electrons, so that only two can correlate to the silicon K-shell via 1sσ. The other two have to correlate to the silicon L-shell via 2pσ. This effect is called electron promotion and was recognized by Fano and Lichten as the prime mechanism for K-shell ionisation in heavy ion-atom collisions. As

Fig. 1 — Calculated molecular orbits of two nitrogen atoms as a function of nuclear distance.



In 1972 one of the founders of Molecular Physics, professor Mulliken, did a computer experiment. Using the code ALCHEMY he calculated the electronic energy levels in two nitrogen atoms as a function of internuclear distance. He found that the molecular orbital energies at small internuclear distance converge to those of the silicon atom. At the same time, but independent from Mulliken, atomic physicists showed that a similar kind of alchemy can be done in an ion accelerator laboratory. They have put much effort into observing these short-lived united atoms. By in-beam spectroscopy of collisions of very heavy atoms of the periodic system one even hoped to observe superheavy quasi-atoms. 20th century alchemists have improved our understanding of emission of continuum X-rays, electrons or positrons in ion-atom collisions, the results of which are now being applied to the description of hot plasmas and the development of short wavelength lasers.

Units employed :

1 a.u. of energy	=	27.2 eV
1 a.u. of length	=	0.53 Å
1 a.u. of velocity	=	2.18×10^6m/s
1 a.u. of time	=	2.42×10^{-17}s

is seen in Fig. 1, two more MO's correlate to the silicon L-shell : $2p\pi$ and $2s\sigma$. K-shell vacancies may be produced in a $N^+ + N$ collision since vacancies are likely to be present in the $2p\pi$ level and promoted K-shell electrons following the $2p\sigma$ orbital may be excited to the $2p\pi$ level via rotational coupling in or near the united atom. Subsequent decay of these vacancies will lead to N-K, X-ray or Auger-electron emission. Evidence for this model for K-shell ionisation has been obtained by comparing calculated cross-sections for rotational-coupling excitation of K-electrons to measured cross-sections for X-ray and Auger-emission, not only for $N^+ + N$ collisions but for a large variety of combinations of atoms from the first row of the periodic system.

Ab-initio calculations of K-shell ionisation by rotational coupling have been performed and show good agreement, with experiment for projectile and target atomic number $\leqslant 10$. However, K-shell ionisation in collision systems where atoms heavier than Ne are involved, is still a matter of dispute. The difficulty lies in the $2p\pi$ MO which in heavy systems is normally filled, thus the rotational coupling channel is blocked. Nevertheless, K-shell ionisation does occur as is evidenced by the emission of characteristic X-rays or Auger electrons. Non-adiabatic effects may account for this, either because the $2p\pi$ MO acquires the necessary vacancies during the incoming part of the collision, or the $2p\sigma$ MO couples directly to higher vacant orbitals near or inside the continuum.

MO X-Rays

The success of the molecular model in explaining at least qualitatively a large variety of inner shell ionisation effects in ion-atom collisions, has stimulated investigations to observe the transient molecule directly. The quasi-molecule may radiate during the collision if the lifetime of excited molecular states is not too different from the collision time. Inner shell vacancy lifetimes are of the order of 10^{-15} s, only a factor ten or hundred longer than collision times in the case of, say, 100 keV heavy ions. It is to be expected therefore, that in some cases, vacancies present in the inner molecular levels, decay during the collision, giving rise to X-ray or Auger-electron spectra characteristic of the MOs involved. Since the internuclear distance during a collision changes continuously, the transition energy will vary also resulting in continuous X-ray or electron spectra instead of characteristic lines.

Fig. 2 shows an example of X-ray continuum emission during collisions of 50 keV N^+ and N_2. The continuum extends from 500 eV to almost 1700 eV and can be identified as MO X-rays due to a $N^+ + N$ collision. If $1s\sigma$ vacancies decay at large internuclear distance, the transition energy almost equals that of $N - K_\alpha$ ($\sim$ 450 eV not shown in Fig. 2). During a head-on collision, the vacancy may decay at an internuclear distance smaller than 0.1 a.u., i.e. inside the united atom K-shell and the X-ray energy emitted will be equal to $\sim$ 1750 eV. Radiative transitions to the $1s\sigma$ vacancy at intermediate internuclear distances are responsible for the continuum spectrum in between these two extremes.

Since the discovery of MO X-rays in 1972, these X-ray spectra have been investigated in a large variety of collision systems using nuclear physics accelerator facilities. It is important to note that the ratio of collision velocity to the orbiting velocity of the K-shell electrons, is small and almost identical for 50 keV N + N, 17 MeV

Ni + Ni, 30 MeV Br + Br, 67 MeV Nb + Nb, 115 MeV La + La or 0.5 GeV U + U. All these collisions are, therefore adiabatic as far as the inner shells are concerned and in many cases, valuable information on the shape of the transient MOs has been obtained from measured MO X-ray spectra.

In an attempt to penetrate more deeply into the united atom, experiments with higher beam energy have been performed. Unfortunately, the famous uncertainty principle of Heisenberg prevents us from doing accurate spectroscopy of these transient united atom states. At a collision velocity of 1 a.u. the time to cross the united atom K-shell is at the most 0.1 a.u., hence the energy uncertainty becomes $\geq$ 10 a.u. (which is $\sim$ 270 eV).

MO Auger Transitions

As in atoms, inner shell vacancies in molecules cannot decay via X-ray emission only ; Auger transitions are also possible. MO Auger transitions in quasi-molecules have been observed during Kr^+ + Kr collisions. These continuum electron spectra could be identified as originating from a MO connected with the outer-shell of Kr, which contains vacancies not only because the projectile is ionised, but also besause of electron promotion and level crossing effects. Indeed it is from the MO Auger electron spectra that the shape of the MO has been determined. Apparently the 4pπ MO is involved which correlates to the united atom 4p level. The experiment almost makes it into the united atom but again dynamic effects at high collision energies (> 200 keV Kr^+ + Kr) prevents us from an accurate spectroscopic observation.

Superheavy Quasi-Atoms

With the availability of lead and uranium beams at the new heavy ion accelerator in Darmstadt, it has become possible to study very deep quasi-molecular states. Quantum electrodynamic calculations show that if a nucleus of charge Z exists in free space, without any surrounding electrons, the system is stable provide Z is less than Z_{cr} which is about 173. When Z is greater than Z_{cr}, which can occur in principle when two uranium atoms are brought sufficiently close together to form a quasi super heavy atom with Z = 184, theory indicates that a positron would be created spontaneously. In this process, an electron would fill the empty innermost bound resonant state, the 1sσ MO, associated with the K-shell of the subcritical system, and the positron would be emitted with a kinetic energy of $E_b - 2m_ec^2$ where E_b is the binding energy of the 1sσ state, Z_{cr} is that value of Z that causes
$E_b = 2m_ec^2 = 1.02$ MeV.

In a series of experiments, a group at GSI bombarding lead and uranium with beams of the same species at energies of $\sim$ 1.2 GeV, has been searching for this fundamentally new phenomenon. Positrons have indeed been detected and after proper background subtraction, and measurements of impact parameter dependence, of beam energy and of projectile and target Z, it can be concluded that these positrons are of atomic rather than nuclear origin. However, the process involved does not appear to be due to 1sσ vacancies with a binding energy larger than 1.02 MeV. As in the case of united atom X-ray or Auger emission, the dynamic effects dominate. Positrons are produced by direct pair production by the time variation in the strong electric field of two nuclear charges passing close to each other.

Conclusion

The success of the adiabatic molecular model for heavy ion-atom collisions has stimulated atomic and nuclear physicists to become inquisitive modern alchemists. By taking the molecular model to its extreme, new mechanisms for ionisation and emission were discovered, the importance of which is not only academic. In quantitative descriptions of physical processes in hot plasmas, such as in Tokamak nuclear fusion devices or in astrophysical conditions, a knowledge of heavy ion-atom collision phenomena has to be applied. Further, in the development of short-wavelength laser systems the concepts of heavy ion-atom collisions appear to be essential.

Further Reading

For further reading on the subjects discussed here, reference can be made to the invited talks and progress reports of the International Conference on the Physics of Electronic and Atomic Collisions.

Fig. 2 — X-ray continuum emission during collisions of nitrogen ions on nitrogen.