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NUCLEAR MOMENTS

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I. INTRODUCTION

The hyperfine interaction refers to deviations from the Coulomb law for interaction between a nucleus and its surrounding electrons or mu-mesons as the case may be. Since a point charge yields the Coulomb force field, the hyperfine interaction measures the deviations of the nucleus from a point charge character. Such deviations are ordinarily expressed in terms of multipole moments which are the subject of this talk.

Since it is nuclear moments being discussed, the electrons or muons will be considered simply to produce an electromagnetic field distribution over the nuclear volume and we consider the interaction of the charge-current distribution of the nucleus with that field. Actually, except in the case of a classically produced external field, the dynamic interaction between nucleus and electron (muon) should be considered and in the case of heavy mu-atoms this becomes a non-trivial complication of the calculations.

For the moment, consider this interaction of the static field on the stationary nucleus (diagonal matrix element). The field and the nuclear charge-current distribution are conventionally expanded in multipoles which interact in pairs

$$W = \sum_{L\pi} (\text{Nucleus})^{L\pi} \times (\text{Field})^{L\pi}, \qquad (1)$$

the multipoles being characterized by their tensor character under rotation and reflection of the coordinates. The multipoles are classed as electric (EL) if the parity, $\pi = (-1)^L$ and as magnetic if $\pi = (-1)^{L+1}$. Since the nuclear states all have definite parity to a very good approximation, only the $\pi = +1$ moments exist for static (diagonal) matrix elements. The multipoles to be considered are thus: Electric Monopole (E0), Magnetic Dipole (M1), Electric Quadrupole (E2), Magnetic Octupole (M3), Electric Hexadecapole (E4), etc. Only those listed have been seriously considered as candidates for observation as static moments.

A dozen or so magnetic octupole moments have been measured[1)] using atomic beams. The complication arises here that the octupole interaction is so small that the electron producing the field in Eq. (1) must be treated in second order in the lower stronger multipoles. There has also been some discussion of E4 moments.[2)] There would seem to be little prospect for the future of measuring higher static moments as the interaction energy drops off rapidly with increasing L for the obtainable "static" fields.

Thus, with the two exceptions above, we are stuck with the monopoles, dipoles, and quadrupoles of olden days. According to conventional terminology, the E0 moment is simply the charge, a single number (the only multipole moment for which we have a fully satisfactory theory at present), the M1 moment is a vector, a single interesting number representing the magnitude and two more representing the direction, and the E2 moment is a set of five numbers, two interesting ones, β and γ, and the other three representing the orientation of the principle axes. If the moment is carried by a quantum state of definite angular momentum J and parity π, only a single number is measurable for each moment, the other 2L numbers being given by the Wigner Echart theorem. Also as is well known, the L pole vanishes unless $J \geq \frac{L}{2}$.

Recent developments might be classed as follows:

a) developments in measurement of moments

b) developments in nuclear structure theory of moments.

Topics a) and b) will be treated in that order in the remainder of this paper.

II. DEVELOPMENTS IN MEASUREMENT

The developments in measurement involve some new techniques and a large increase in the number of cases measured, but before considering these developments, let us broaden the discussion by noting the important fact that the nuclear charge and current distribution is by no means completely described by a charge, a magnetic dipole moment, a quadrupole moment, etc. The classification into multipoles only concerns the angular dependence of the charge-current distribution while for a complete description, the radial dependence must be given as well. Owing to experimental developments, this radial dependence of the multipoles has received renewed attention recently.

A. Monopole Moment

The radial distribution of the monopole moment is well known under the name, finite size effect, volume isotope or isomer shift, nuclear radius effect, etc. That the interaction energy between an electron (or muon) and the nucleus should depend on the radial nuclear charge distribution even in the absence of any $L \neq 0$ multipoles is obvious. For light nuclei, the effect can be calculated non-relativistically by perturbation theory assuming the charge distribution of the nucleus to interact with the electric potential V produced by a Coulomb bound electron (or muon). For the electric interaction, (1) becomes

$$W = \int \rho_{Nuclear} V d\tau . \qquad (2)$$

Expanding V in a Taylor series about the origin we have

$$V = V_o + V_x X + V_y Y + V_z Z + \frac{1}{2}(V_{xx}X^2 + V_{yy}Y^2 + V_{zz}Z^2) + V_{xy}XY + V_{yz}YZ + V_{zx}ZX + \ldots (3)$$

the derivatives to be evaluated at the origin. For a pure monopole form for $\rho_{Nuclear}$ (2) becomes

$$W = V_o \int \rho_{Nuclear}\, d\tau + \frac{1}{6}(V_{xx} + V_{yy} + V_{zz}) \int \rho_{Nuclear} R^2 d\tau + \ldots$$

$$= V_o q_{Nuclear} + \frac{2\pi}{3} \rho_{Electron}(0) \cdot (qR^2_{Average})\ Nuclear + \ldots \qquad (4)$$

The Laplacian combination of field derivatives in (4) vanishes except where the charge producing the field is present. There we have

$$\nabla^2 V = V_{xx} + V_{yy} + V_{zz} = 4\pi\rho_{Electron} , \qquad (5)$$

from which the well known result (4) arises.

For heavy nuclei, much discussed relativistic corrections must be included so that the energy is not exactly dependent on the mean-square (MS) nuclear radius. Particularly for mu-atoms, higher terms in (4) must be included reflecting the fact that the mu wave function is not constant over the nucleus, and for heavy mu-atoms the perturbation scheme is no good at all, and it is necessary to solve the Dirac equation for the mu in the monopole potential of the assumed nuclear charge distribution.

Recent interest in the nuclear electric monopole distribution arises from the greatly increased resolution in mu-spectroscopy[3] due to the development of solid state detectors, and from recent experiments in which the volume effect was observed in atomic x-ray spectra.[4] Both of these techniques have the advantage over the older optical isotope and isomer shift measurements (and also over the Mössbauer measurements) that the calculation of $\rho_{Electron}$ (or ρ_{muon}) can be made with much greater precision. The reason is that the screening of the mu or of the K or L electron is many times smaller than that of the optical or valence electron. That this is a "hot" subject is indicated by the fact that one recent volume of Phys. Rev. Letters 18 had half a dozen articles on such experiments including an isotope shift measurement using a lazer.

The mu and x-ray measurements have by and large shown that no gross errors had been made in the interpretation of the older optical and Mössbauer data, and are also in agreement with electron scattering data on nuclear radii. In addition, a number of new cases have been measured. The isotope shift effect, that nuclear radii generally grow at a slower rate than $A^{1/3}$ when just neutrons are added has been reconfirmed, an extreme case being that of the calcium isotopes for which the electric charge radius actually decreases as neutrons are added. More cases of odd-even staggering have been observed showing quite generally that odd isotopes have smaller charge radii than the average of the neighboring evens. Also radius differences between ground and excited states have been observed both for predominately single particle states in odd nuclei and for collective states in even-even nuclei. Recent measurements on Sm^{152} and Yb^{170} show the first 2+ level to be larger than the ground state.[5] As the muon method gives absolute radius results, it can and has been used to measure isotone shifts, i.e., radius changes on the addition of a proton. The optical method has been extended to include more unstable nuclei.

B. Dipole Moment

The magnetic moment of a nucleus is of obvious interest, the recent experimental developments being the mreasurement of more cases with greater accuracy, particularly a number of excited states. This has been possible owing to bigger and better magnets and improved understanding of internal fields. One of the more interesting developments (see several contributed papers to this meeting) has been the measurement of a number of magnetic moments of 2+ states in even nuclei. The result of these measurements is that the 2+ g factors are mostly not too far from the collective value, Z/A not only for the well deformed nuclei, but for those nearer closed shells as well. This is not too surprising in view of the large quadrupole moments recently observed for some of these states.

There have also been new measurements on nuclei expected to display a more single particle character in order to study core polarization effects.

In addition to this Ml moment itself, its radial distribution has received attention again since this distribution is of paramount importance for the magnetic hyperfine interaction in heavy mu-atoms. The nucleus of an ordinary atom finds itself in a very nearly constant magnetic field due to an unpaired electron while the field due to a muon is far from constant.

For an s-state muon with its spin in the z direction, a non-relativistic calculation of the magnetic field, which gives correctly all its qualitative features, yields

$$\underline{B}(\underline{r}) = (8\pi/3)\mu_{Mu}|\psi_\mu|^2 \underline{k} + 4\pi\mu_{Mu}(|\psi_\mu|^2_{Av} - |\psi_\mu|^2)(r^{-2} z\underline{r} - \tfrac{1}{3}\underline{k}). \qquad (6)$$

The first term is a field in the direction of the μ spin, whose magnitude drops off with radius r like the muon charge density $|\psi_\mu(r)|^2$. The second term has the angular form of a field due to a dipole at the origin, but of strength $(|\psi_\mu|^2_{Av} - |\psi_\mu|^2)$. The quantity $|\psi_\mu|^2_{Av}$ is the volume average of $|\psi|^2$ out to the radius r in question, being, for the 1s muon state, greater than or equal to $|\psi_\mu|^2$, the equality holding at $r = 0$ and out to a radius over which the change in ψ_μ is negligible.

For a point nucleus the energy of magnetic hyperfine interaction is given by

$$W_{Point} = -\underline{\mu}_N \cdot \underline{B} = -(8\pi/3)\mu_N \mu_{Mu} |\psi_\mu(0)|^2, \qquad (7)$$

and only depends on the total nuclear magnetic moment. For an actual nucleus, the interaction with the nonuniform $\underline{B}$ field of Eq. (6) depends on the distribution of the nuclear magnetism. For an ordinary atom the field is very nearly constant over the nucleus and the distributed nuclear magnetism makes only a very small correction to the point result.[7] The result is a slight difference between the ratio of magnetic moments for two isotopes (measured in a uniform field) and the ratio of the magnetic hyperfine interactions for the two isotopes (determined in the nonuniform field due to an unpaired electron). This hyperfine structure anomaly or Bohr Weisshopf effect[6] provides about the only motivation for making precise magnetic moment measurements for complex nuclei since

In (9) and (10) Ψ is the nuclear wave function and S and L g_s and g_ℓ the spin and orbital angular momentum operators and g factors respectively. The quantity μ_o is the nuclear magniton.

The first term of W_S is just like that of W_L except for the replacement of $g_s S_z$ by $g_\ell L_z$ and except that the radial weighting factor is $|\psi_\mu|^2$ in the spin case and $|\psi_\mu|_{Av}$ in the orbital case. Thus a nucleon spin at radius r samples the mu moment just at that radius, while an orbiting proton is sensitive to an average of the mu moment over a volume inside its (the proton's) orbit. This is essentially because the orbital current loop is equivalent to a sheet of dipoles within the loop. In addition there is an extra term for the spin if (as is usual) the nuclear wave function does not have spherical spatial symmetry.

Relativistic calculations of the mu magnetic hyperfine interaction for Bi^{209}, using a configuration admixed wave function chosen to give the correct moment, appears to disagree with the present experimental results. The test can be quite sensitive as simple models yielding the same moment can differ by 50% in magnetic hyperfine interaction.

C. Quadrupole Moment

To round out the discussion of the radial distribution of moments it should be mentioned that there has also been some interest in the distribution of the electric quadrupole moment. In the usual collective picture of the nucleus, both the monopole and quadrupole radial distributions arise from a charge density $\rho(r)$ which is more or less constant out to the surface region at r=c where it drops to zero over a thickness characterized by t. For the usual axially symmetric deformed nucleus the surface region is not a sphere, but an ellipsoid. The conventional density is

$$\rho(r,\theta) = \left[1 + \exp\left(\frac{r - c(1 + \beta Y_{20}(\theta))}{0.228t}\right)\right]^{-1} \rho_0 \qquad (11)$$

For this form of charge distribution, the quadrupole moment is all concentrated in the nuclear surface region. For the oposite extreme model, the single particle model, the quadrupole moment will have the radial spread of the single particle wave function in question. For all but nuclei just at magic numbers, the magnitudes of quadrupole moments are several to many times single particle, and the collective picture is probably more or less correct, though, of course, a microscopic model would not yield exactly the form of Eq. (11), with its implied relation between the monopole, quadrupole, and higher moment distributions.

The experiments with mu atoms are probably the most sensitive to this quadrupole radial distribution, and an attempt was made recently to determine it in more detail. In particular the experiments were analyzed with a charge distribution in which not only c, the half radius parameter, but also t, the thickness parameter depended on angle.[9)]

Inelastic α particle scattering angular distributions also seem to be particularly sensitive to this radial distribution. Higher multipole moments than quadrupole have been included in such calculations,[2)] but a direct connection with the electromagnetic multipole moments discussed here is not possible owing to the fact that the α particle interacts with the nuclear force form factor and not just with the electromagnetic one.

One of the most interesting recent developments is the measurement of the quadrupole moment of a number of excited states (2+ in particular) by means of the reorientation effect in Coulomb-excitation. These measurements have been primarily for non deformed nuclei not too far from closed shells and gave the unexpected result that even these nuclei often have very large quadrupole moments for the 2+ state, comparable, in fact, with their 0+ → 2+ transition matrix elements.

Large 2+ quadrupole moments are expected for deformed nuclei described by the rotational model, and have been reconfirmed by mu atomic experiments which, for heavy nuclei, involve real and virtual nuclear excitation and are thus sensitive to the excited state quadrupole moment. The Mössbauer technique has also been used to determine such quadrupole moments of excited states.

III. DEVELOPMENTS IN THEORY

Recent developments in nuclear structure theory of moments has not been so impressive, and there is still no theory capable of predicting moments to much better than one figure accuracy.

A. Monopole Moment Theory

The nuclear radius is closely connected with the saturation properties of the nucleon-nucleon force and thus difficult to treat from first principles. However, a semi-quantitative understanding of radius changes from level to level or nucleus to nucleus is possible on the basis of independent particle and collective ideas.

Features to be explained are the following: 1) Along the stability line the charge radius goes like $A^{1/3}$. 2) For fixed A, the radius decreases with increasing neutron number. 3) Deviations from the smooth dependences indicated in 1) and 2) are generally small unless a large change in quadrupole deformation is involved, in which case deviations as large as $\Delta R/R \sim A^{-1}$ can occur. 4) Odd nuclei are systematically smaller than the average of the neighboring even nuclei.

Point 1) is the saturation property. Point 2) measured by the isotope shift (size increases less rapidly than $A^{1/3}$ as neutrons are added) has had considerable discussion over the years. There are two reasons why the addition of a proton increases the nuclear charge radius more than the addition of a neutron.

The first reason is that the added proton, being charged and having a mean square (ms) orbit radius larger than that of the protons already present (the added proton is in an outer orbit while those already present in the core will include protons in smaller inner orbits) will directly cause an increase in the m.s. charge radius as well as an increase of Z by one unit. There is no corresponding radius increase on the addition of an uncharged neutron.

The second reason involves the monopole polarization of the core by the added neutron or proton. Most discussions have ignored the first effect and stressed the second. The core size increase is greater for an added proton than for an added neutron both because of the Coulomb and nuclear force. The extra repulsive Coulomb interaction with a proton added gives an extra outward force on the core relative to the neutron case. (If the entire isotope shift effect is attributed to this one cause an unreasonable compressibility parameter corresponding to a very soft nuclear core is required.)

Finally, the nuclear force has the same effect. An added neutron makes the proton nuclear one body potential deeper (this is the well known isospin dependence of the one body potential) so that the core proton wave functions are pulled in a bit, making the core m.s. charge radius smaller for an added neutron than for an added proton.

In both the calculations of Uher and Sorensen[10] and in the theory of interacting quasi-particles of Migdal[11] the average experimental isotope shift is used to determine the parameters of the theory.

Point 3), that large increases in deformation yield large increases in the m.s. radii, is easily understood if the nucleus is assumed to be approximately incompressible under deformation, for then we have for the RMS radius

$$\Delta R/R = (5/8\pi)\Delta\beta^2. \qquad (12)$$

Recent experiments[5] indicating an 0+ - 2+ isomer shift in Sm and Yb may be interpreted as evidence of excess deformation of the excited state. Efforts to relate this increase in deformation to the increased rotational motion have not yet been fully successful. Likewise the peculiarly small or even negative isotope shifts just below closed shells may reflect the especially small m.s. deformation of the magic nuclei.

Point 4, that odd nuclei are systematically smaller than the neighboring even ones has recently been explained on the basis that the m.s. quadrupole deformation of odd nuclei is smaller than that of the neighboring evens on the average.[17] Detailed calculations of this effect using the pairing plus quadrupole force model together with Eq. (12) qualitatively confirms this explanation as a major cause of the odd-even staggering.

Radius effects can be computed with a microscopic model only if both monopole and quadrupole core polarization effects are properly taken into account. The theory of Baranger and Kumar,[13] for example, can yield isomer shifts only under some assumption such as incompressibility under which Eq. (12) was derived.

B. Dipole Moment Theory

Most theories of the dipole moment start from a single particle model so that nuclei just one particle away from double magic have received special attention. Still, only in the case of O^{16} are magnetic properties known for all four neighbors (p and n, particle and hole). Many of these moments are near the expected Schmidt values, but there are some notable exceptions, in particular Bi^{209} whose moment is very far from the single particle value. One tries to understand these deviations in terms of meson effects and core polarization (configuration mixing) effects.

The meson effects are thought to be small ($\simeq$ 0.2 magnitons), but have still not been well calculated. The polarization effects depend on the "residual" interaction. A recent attempt[14)] to explain the Bi moment deviation with "realistic" forces was unsuccessful. Configuration mixing calculations with phenomenological forces in the manner of Arima and Horie,[15)] and Blin-Stoyle,[16)] and including pairing and quadrupole effects[17)] have been reasonably successful for nuclei not too far from closed shells, as have the calculations of Migdal[11)] and collaborators. Some magnetic moment measurements on odd-odd nuclei and excited states of even-even nuclei reported in contributed papers to this conference have been interpreted as arising from two particle or two quasi-particle configurations.

For more deformed or collective nuclei, including, apparently, even the excited 2+ states of nuclei near closed shells, the above description is unsatisfactory. The odd particle must be placed in a deformed potential, and the collective rotational contribution to the moment included. If all particles contribute equally to the collective rotational motion, the rotational g factor is $g_R = Z/A$. For odd deformed nuclei the resulting g factors fall between the Schmidt limits in rough agreement with experiment. Some effort to identify Nilsson levels on this basis has been tried.

For the even 2+ states the motion is all collective and $g = g_R = Z/A$ unless a microscopic calculation of the motion is made. For deformed nuclei Nilsson and Prior[18] calculated that $g < Z/A$ owing primarily to the fact that the proton pairing force is stronger than that of the neutrons so that the neutrons are free to contribute more to the rotational motion than are the protons. This difference in proton and neutron pairing deduced from the odd-even mass differences gave reduced of values in agreement with the observations.

For even nuclei nearer closed shells it had been hoped, until a few years ago, that the lowest few states could be described in terms of harmonic quadrupole vibrations about a spherical equilibrium shape by means of the random phase approximation (RPA). When the expected triplet (0+, 2 +, 4+) failed to appear with complete regularity and was often more complex, it was still hoped that RPA would be satisfactory for the lowest 2+ state. Now even that hope is gone and only the ground state transition matrix element, $B(E2)0+ \rightarrow 2+$, seems reasonably represented by RPA.

In particular, the magnetic moments predicted by RPA have substantial fluctuations near closed shells as seen from Fig. 1. Pd and Cd have predicted $g \gtrsim 1$ since the wave function involves $g_{\frac{9}{2}}$ protons to a large extent, while Sn and Te have small predicted g factors. The experimental values, which include some contributed to this meeting, in this region are not so far from $g_{2+} = Z/A$, the collective value. For the heavier nuclei there is less disagreement between RPA and experiment. Attempts to increase the mixing by extending the RPA to higher orders has not been very convincing to date,[19] although lots of serious work has been done.

A different approach is made by Baranger and Kumar[13] who describe the nuclear motion as completely collective, but use a microscopic theory of the collective parameters. The microscopic part of their calculation utilizes the phenomonological pairing plus $P^{(2)}$ force with parameters chosen to give the best agreement with experiment. Calculations have also been made in which the collective parameters were simply chosen to fit the data.

The collective parameters are a potential energy and inertial parameters which are functions of β and γ, which describe the nuclear shape. The collective motion involves changes of the nuclear shape (β and γ) and also changes of orientation (rotation). The quantum mechanical solution of this motion leads to wave functions for each state which describe a distribution over β and γ values, the different states having different average deformations and asymmetries. A number of nuclei have been successfully described this way.

C. Quadrupole Moment Theory

The failure of RPA to describe "vibrational" 2+ states was most clearly demonstrated by the large quadrupole moments observed by the reorientation effect in Coulomb excitation. The RPA is a microscopic description of harmonic vibrations about a spherical shape. Such oscillations pass from oblate to spherical to prolate and back again, so that the purely harmonic collective picture describes the 2+ as being prolate as often as oblate and thus as having $Q_{2+}=0$. The usual RPA predicts quadrupole moments which are not zero, but which are mostly less than the single particle value, while the observed moments are four to eight times the single particle value and thus in gross disagreement with RPA as seen in Fig. 2.

These large Q_{2+} values, typical for deformed nuclei, were a surprise since they were observed for nuclei with vibrational rather than rotational spectra. Since their observation, theorists have tried very hard to show that it was not so surprising after all.

The microscopic theories still need to describe the motion as some sort of vibration based on RPA, but the vibration is clearly anharmonic. The game is to extend the RPA to include anharmonic effects of various sorts, to determine which are the important ones, and then to do a calculation including all the important effects. Lots of important effects have been suggested (since the desired result was known), but a convincing calculation including all important effects is yet to be seen.

The collective calculations of Baranger and Kumar picture the nucleus as vibrating through various shapes with the rotation of the deformed shapes taken properly into account. They find that it is indeed possible to have a system whose energy spectrum looks roughly harmonic, but whose 2+ wave function has deformations of one sign heavily weighted compared to those of the opposite sign so that a large Q_{2+} results.

IV. CONCLUSIONS

There have been a number of experimental developments over the last few years which have been quite pertinant to the measurement of nuclear moments. In addition, new information concerning excited state moments and other properties has caused a large change in our way of thinking about "so called" spherical nuclei.

Developments in nuclear structure theory of the last few years have been more conservative and less spectacular. Changes in theory have been forced upon

upon us by the interesting new experimental results, and there remains much to be done to bring the theory into accord with the experiments.

At this time in the continuing contest of experimentalist vs theorist, the experimentalist would seem to be in the lead.

Footnotes and References

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Figure Captions

Fig. 1. "Phonon" magnetic dipole g factors. Experimental points are compared with theoretical curves calculated using the random phase approximation for the g factor of the first 2+ state of various "sperical" nuclei.

Fig. 2. "Phonon" quadrupole moments. Experimental points determined by the reorientation effect in Coulomb excitation are compared with theoretical curves calculated using the random phase approximation for the quadrupole moment of the first 2+ state of various "spherical" nuclei.

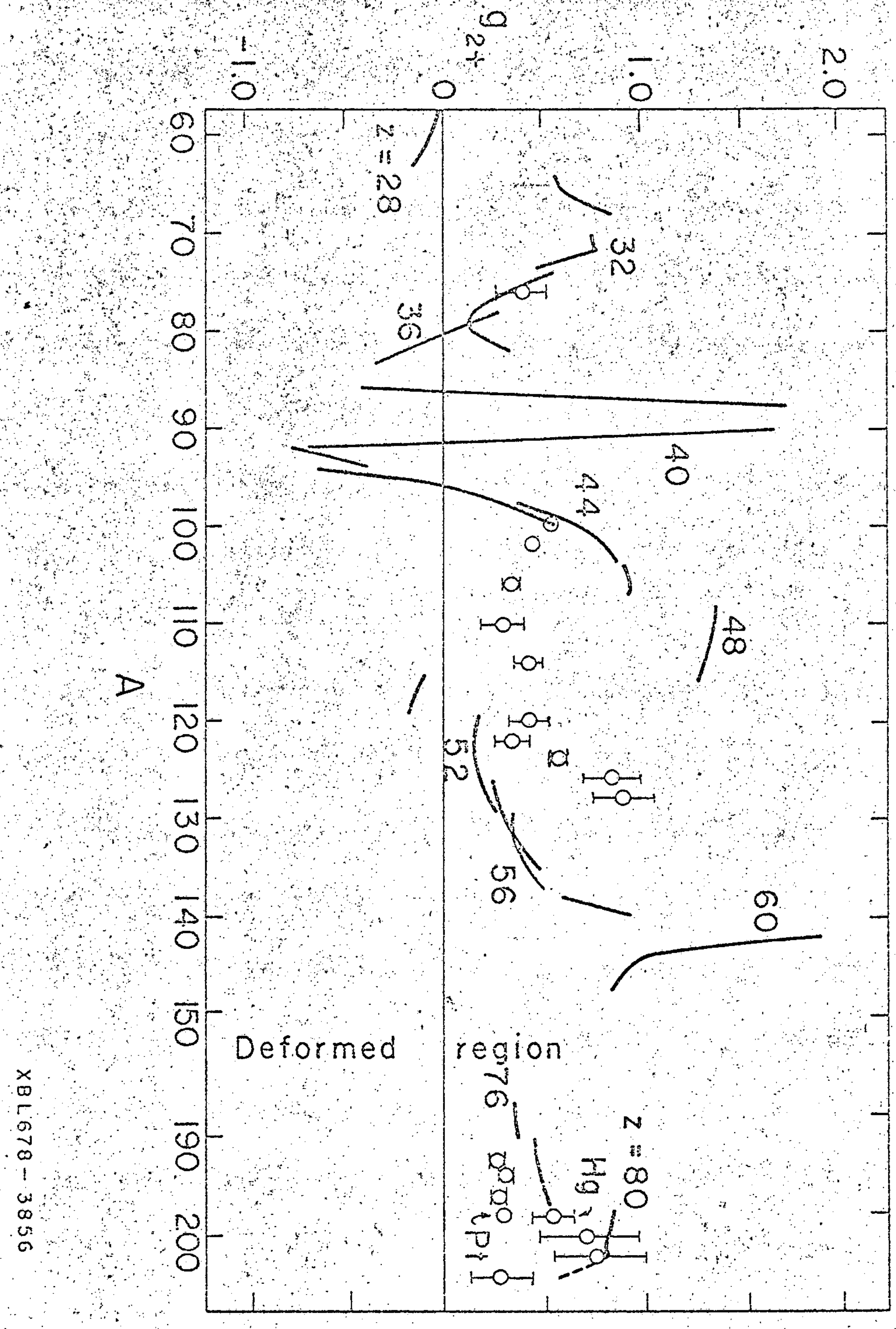
g_{2+}
A
Deformed region
z = 28
32
36
40
44
48
52
56
60
76
z = 80
Hg
Pt
XBL678 - 3856

Fig. 1.

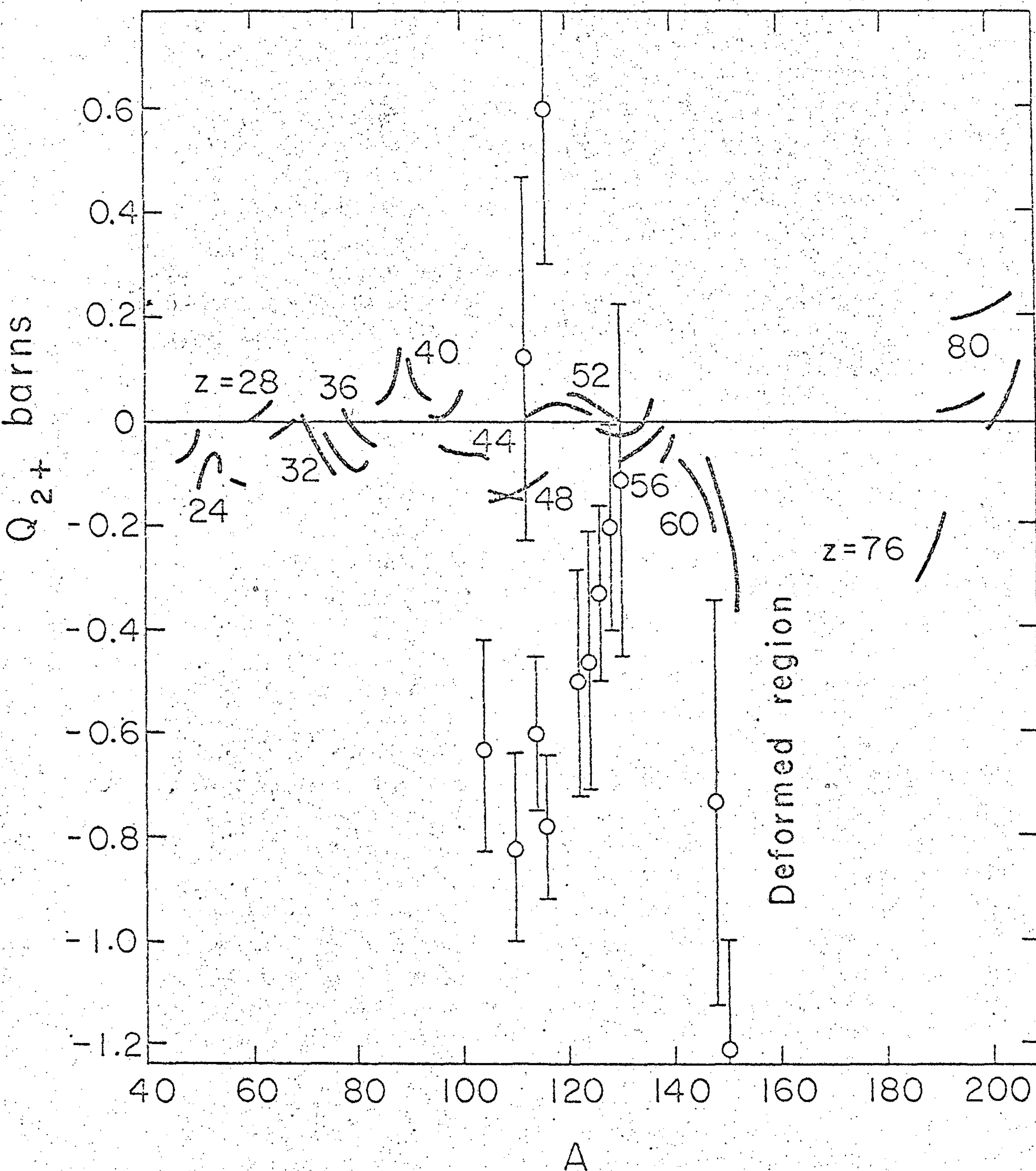

Fig. 2.

XBL678-3855