NUCLEAR MASSES AND THEIR DETERMINATION

EDITED BY
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Nuclear Masses and their Determination

Proceedings of the Conference held in the "Max-Planck-Institut für Chemie" Mainz, 10–12 July 1956

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PREFACE

Up to the present time, the determination of atomic nuclear masses has always been discussed by mass spectroscopists at mass spectroscope conferences and by Q-value experts at nuclear physics conferences. No conference has so far been held bringing together scientists working on nuclear masses, but engaged in different spheres of work. It is therefore especially pleasing that it has been possible to assemble such a conference now, in which the mass spectroscopists and Q-value-, beta decay-, and microwave-experts, all dealing with the determination of atomic masses, can meet together. Unfortunately, we have not been successful in arousing the interest of a greater number of theoretical physicists in this symposium. We hope this may be achieved should such a conference be held again somewhere, for the exceptionally laborious work involved in the determination of nuclear masses, will only prove fruitful through a closer collaboration with the theorists.

The question of errors in measurement plays an important part in this book, as is always the case when people who deal with precision measurement come together. This has already given some more remote observers the impression that the measurement of nuclear masses is an unusually badly developed field. Therefore it may perhaps not be superfluous, at least in one place in this book, to give expression to a matter which is held as self-evident by experts working in this field, namely that in many cases nuclear masses are determined with an accuracy of 1 in 10 millions and that a thorough discussion of error involved or eventually possible in a measurement constitutes an essential criterion of true precision determination.

The discussion has not been reproduced in full. Partly it was possible to shorten it, whilst some questions and remarks had to be omitted as no written version from those who took part in the discussion was available, neither was the tape recording always satisfactory. Individual articles have been revised by their authors as well as the ensuing discussion. As we wished to avoid too great a delay in publication, it was not possible to let every one taking part in the discussion have the proof-sheets for all remarks made by them during the discussion. In these circumstances it will have hardly been possible to exclude all mistakes which crept into the records of the discussion.

To conclude, I would like to thank everybody who has helped with this symposium. Our special thanks to our generous sponsors have been expressed by Professor Hahn in his opening address. I

would, however, like to thank Professor HAHN himself for the effective help he has given in making this symposium possible. Furthermore, I express our most cordial thanks to Professor MATTAUCH for his assistance in making use of the tape recordings and to Dr. MÜLLER-WARMUTH for making them.

H. HINTENBERGER

Max-Planck-Institute for Chemistry,
Mainz.

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OPENING REMARKS

Ladies and gentlemen!

May I extend a warm welcome to you and thank you for taking the trouble to come here to Mainz to take part in this symposium on the precision determination of atomic nuclear masses.

As is natural for this limited theme, the circle of participants and those interested is none too large. But as a compensation, it may be observed with satisfaction that every mass spectroscopic group dealing with the measurement of packing fraction is represented here. Another fact which perhaps makes this symposium of special value, is the presence here, in addition to the mass spectroscope experts, of physicists working on the determination of nuclear masses, who are concerned with other aspects. There has long been a deficiency in the field of nuclear masses, for though numerical values with claims to high precision have been published by various research groups, yet the numerical values much beyond the margins of error of the various groups do not tally. Therefore a comprehensive discussion among those working in this field seemed to be urgently needed. It appears of late to have become increasingly clear that a wholly systematic discrepancy exists between nuclear masses determined by mass spectroscopy and those derived from nuclear reactions. The main objective of this symposium must indeed be to make some contribution to the solution of this discrepancy.

Perhaps I may be allowed to say a few words on how this symposium came about. Last year, Herr MATTAUCH celebrated his sixtieth birthday and as it had long been his wish that a symposium of this kind on nuclear masses should be held, his colleagues wished to afford him that pleasure for his birthday. But it was not possible to implement the original plan as speedily as the calendar and his birth-certificate required, without sacrificing the attendance of some essential participants in the symposium. It therefore seemed preferable not to adhere too strictly to dates and to leave time for the plan to mature for convening the symposium. An especially favourable opportunity was afforded by the Amsterdam conference on nuclear reactions, which brought many international visitors to Europe from all over the world. Practical and economic considerations counselled the holding of this symposium as a sequence to such a conference, in order to save both time and travelling expenses for those participants coming from a great distance, although the date

selected is not very convenient for German University lecturers, as the end of term falls in this week.

Before concluding this address of welcome, I would like to express my special thanks to those who have helped in overcoming the financial difficulties, above all the Federal Ministry in Bonn, Professor K. WINNACKER of the "Farbwerke Höchst" and the "Max-Planck-Gesellschaft" in Göttingen.

In conclusion, I wish you every success in the symposium and I wish all participants a pleasant stay in Mainz.

O. HAHN,

President of the Max-Planck-Gesellschaft, Göttingen.

SESSION I

INTRODUCTION

[1]

THE PRESENT STATUS OF THE DETERMINATION OF NUCLEAR MASSES†

K. T. BAINBRIDGE

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IT IS a pleasure to convene, to make and to renew acquaintances and to exchange ideas within the field of the precise determination of atomic masses in association with President OTTO HAHN, director emeritus of the Max-Planck-Institut für Chemie, and with Prof. JOSEF MATTAUCH, the present director.

Many of us met nearly five years ago at a symposium on Mass Spectroscopy in Physics Research held in Washington in September 1951. The meeting, one of a series of twelve symposia held to commemorate the semicentennial of the U.S. National Bureau of Standards, was supported by the U.S. Department of Commerce and the U.S. Office of Naval Research. That conference was unique to my knowledge as the first international conference in the field of mass spectroscopy, a field which has done so much to advance the sciences of physics, chemistry, and medicine, and which has spread into every engineering and technological field.

Considering one phase of physics only, a large part of our knowledge of nuclear forces of the most fundamental kind has come from empirical knowledge of the masses of nuclei and the systematics of nuclei.

Although there have been many theoretical calculations of the binding energies of helium and lighter nuclei, no satisfactory detailed theory of heavier nuclei has been developed. The isotopic weight M, or mass of an atom, is of fundamental interest. While the mass number A, the atomic number Z, and the neutron number $N = A-Z$ are known for the hundreds of stable and unstable nuclei, M is in many cases not available, and in other cases increased accuracy in the determination of M would be desirable.

The available M values, together with a huge amount of data on radioactive decay schemes, have been correlated within the semi-empirical drop model formula.[1–7]

An entirely acceptable theory of the masses of atomic nuclei must be able to predict the actual values. At this time, the semi-empirical

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formulation of an energy surface permits interpolations and extrapolations which are and have been of great value, but which are recognized as the coarse generalization of more precise information won by experiment. They supply no final substitute for measurements and more complete knowledge derived from experiment. The very nature of a liquid drop model excludes such structural details, with their external manifestations, as appear in the shell theory developed by MAYER, JENSEN, SUESS, HAXEL and others. [8–12]

ELSASSER first pointed out that there must be some sort of shell structure in nuclei for which, at certain values of Z and $N = A - Z$, specially stable configurations resulted.[8] A large field of interest for precise mass measurements lies in the comparison of semi-empirical mass equations with such precise mass data, a comparison which is the subject of WAPSTRA'S talk for this symposium. [13–17] Not only are shell structure effects on binding energy uncovered, but also the general detailed basic foundations of the formulas can be examined.

The four fields of physics primarily concerned with the precise measurement of mass data are all represented in this meeting. The uses of precise mass data and associated information extend far into physics, chemistry, astrophysics, and geophysics. We all share the responsibility of contributing to the erection of a stable and periodically improved structure.

There were available in April 1951 two new mass scales, independently measured, for the light elements. One was that of LI, WHALING, FOWLER, and LAURITSEN, derived from nuclear disintegration energies.[18, 19] The other was the less extensive mass-spectrographic scale measured by H. EWALD who at that time was at this institute.[20] I mention this particularly because the excellence of EWALD'S doublet measurements of 1950 and 1951 has become even more apparent with the passage of time. These measurements and equivalent doublets constructed from LI's table agreed statistically with only one exception among 16 doublets. In other words, the errors in both reports behaved very nearly according to the distribution to be expected for random errors of the magnitude reported.

There were two gross differences occurring at the ^{32}S and the ^{21}Ne doublets, where statistically only one would be expected. EWALD'S 1951 results[20] are in even better agreement with WAPSTRA'S 1955 tabulation[21] based on recent Q values, and with the doublets measured by SCOLMAN, QUISENBERRY, and NIER.[22, 23]

There were at that time (1951) other recently published mass data which did not agree either with those of LI *et al.* or with those of EWALD. These disagreements doubtless played a part generally in stimulating new and continued studies of possible sources of error

in mass-spectroscopic mass measurements, and in the initiation of more extensive studies of the energy standards to which Q values were referred.

The masses of atoms are determined from the results obtained in four fields of experimental physics: mass spectroscopy, microwave spectroscopy, measurements of the ground-state energy transitions in nuclear reactions involving heavy particles, and of ground-state transitions or their equivalent in the decay of radioactive isotopes.

Essentially new methods of attack in all these fields, and the development of improved instruments and techniques, largely account for the great increase in the amount of precise data available for the determination of atomic masses. Some of these advances took place in the few years prior to the 1951 meeting mentioned earlier, but many have been made since that time.

MASS SPECTROSCOPY

The most recently developed apparatus for mass determinations is the mass synchrometer of L. G. SMITH and his associates.[24] Results obtained by its use are promised for this symposium. Those already published or in process of publication are impressive: a half-width resolution which is adjustable between 10,000 and 25,000 is attained for all masses below 250.[24, 25] Experience with their superposition technique of matching peaks shows that the probable error of single measurements of the separation of two peaks is about 10^{-3} of their width at half amplitude. This corresponds to random errors of less than 1 part in 10^7 in M in the comparison of masses, where the mass number of a doublet component $A \approx M$.

The first report on the mass synchrometer prototype of the present model was made at the 1951 conference, just a few days after the first tests of the introduction of radiofrequency modulation at the 180° region of the ion orbits.[24, 25]

The superposition technique for the measurement of doublet separations is also utilized in the most recent mass spectrometer developed by A. O. NIER and his associates. Resolving power values of 30,000 to 60,000 have been used generally, although in certain unspecified cases 75,000 to 100,000 have been attained.

While not specifically stated, the accuracy of the peak matching attained can be calculated to lie in the range of 5×10^{-3} to 10^{-3} of the peak widths or 1 part in 50,000 in the doublet measurements. Accordingly the assigned errors are in the same range of 10^{-7} or better reported by SMITH.[24]

Efforts have naturally been concentrated on three essential factors, resolving power, accurate measurement of line position, and accurate

measurement of dispersion, which enter into the precise determination of masses. Increased resolving power helps to eliminate superimposed satellite lines which can ruin results, and also simplifies the improvement in accuracy of measurement of the separation of the lines. The recently reported values for resolving power are about an order of magnitude greater than those of 20 years ago. The width of a doublet line, however, is of the order of 10^6 electron volts of binding energy. Hence there has always been great necessity for getting inside the line width, that is, for measuring to a fraction of a line width in order to achieve higher accuracy in the comparison of masses. Where photographic recording is used, the grain size of the emulsion imposes a natural statistical limit on the accuracy of the determination of the centre of a line. EWALD has remarked on this and also on the statistical improvement, desirable on other grounds, which is obtained by increasing the number of doublets measured. EWALD's paper was a very concise and comprehensive summary of the problems of precise mass measurements, and of some of the studies which he and MATTAUCH have completed.[31]

Of course, electric recording carries its own natural statistical limitation on accuracy of the determination of the centre of an ion beam. This has limited accuracy.

The natural or assumed limits on slit size, focusing aberrations, ion currents, current densities, etc., together with the above-mentioned considerations on resolving power, have led NIER, DUCKWORTH, HINTENBERGER, MATTAUCH and associates, OGATA and MATSUDA, COLLINS and me to go to larger instruments with greater radii of curvature in the analyser.[32] All hope thereby to attain even higher resolution and higher accuracy as well.

The dispersion constant for all types of instruments was analysed five years ago in a definitive paper by MATTAUCH.[33] The accuracy of the dispersion constant is a prime factor in the precise determination of masses. It appears that this constant is more easily measured to the required accuracy for a fixed-radius spectrometer with electrical recording than for a photo-recording mass spectrograph. The mean dispersion, however, can be and is determined over the whole of the doublet region for mass-spectrograph plates, while what has been published on fixed-radius spectrometers indicates that the dispersion constant usually must be interpolated at the doublet region.[23] The validity of this procedure may be based on the fact that these are effectively linear-scale instruments; and also on the agreement, for the same mass differences, when doublets of different mass numbers are used.

In addition to NIER's new spectrometer[23] and SMITH's synchrometer[34] already mentioned, other new instruments and

improvements to existing ones have been completed in the laboratories DUCKWORTH, ENGLER, EWALD, MATTAUCH, NIER, and OGATA. This list is probably not complete to date.

A most valuable part of any new development or improvement is found in the reports on the tremendous amount of background work which goes into the effort to detect and eliminate systematic errors. The list of references given includes not only the description of many of the current instruments but also research results specifically aimed at uncovering and tracing the source of systematic errors.[23, 24, 31, 34–44] The work of MATTAUCH and EWALD has been particularly valuable for problems connected with photo-recording spectrographs and instruments which use high-voltage gas discharge ion sources.[31, 35–39]

The provisional programme lists seven papers from four laboratories on recent mass determinations. Prof. DUCKWORTH, who has done a major share of the exploration of the heavier nuclei, will speak on his work. Dr. EWALD, whose earlier work I have mentioned in some detail, will discuss mass determinations obtained by means of his stigmatic-focusing spectrograph. Prof. K. OGATA, who recently completed a new instrument at Osaka University, will describe his most recent results. Prof. A. O. NIER and associates have scheduled a series of three reports on the atomic masses of the isotopes of the lighter elements. Dr. L. G. SMITH, whose mass synchrometer represents quite a new approach, will speak on some results of measurements with that instrument.

Some of these results have appeared in part, and some will be presented for the first time at this symposium. Errors in M of 1 part in 10^7, 5 parts in 10^8, and 3 parts in 10^8 are attached to some of the measurements already published.

It is clear from the work already published that it is possible today to obtain and process data at a much faster rate than ever before possible. This is a tremendous accomplishment by Prof. NIER and the Minnesota group, to which Dr. T. L. COLLINS also contributed greatly at the start of the work.

Under these new conditions the standard deviation of a particular measurement can be lowered to a fraction of the systematic error produced by known factors. Data in this category should no longer be handled as if the errors were random errors, although this has been done in a few cases.

In the field of mass spectroscopy, the work of many people is continually improving the precision and reliability of mass determinations. More detailed comment must wait until later in this talk when, in considering mass tables, mass measurements from all sources can be viewed in perspective.