Isobaric quartets in nuclei

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The present experimental evidence on $T = 3/2$ states in nuclei is presented with particular attention to quartets in which the properties of all four members are known. A relation between the masses of the quartet, the isobaric multiplet mass equation, is shown to hold extremely well. The significance of the coefficients of the equation is discussed, and a brief review of the present status of quintets is also presented.

CONTENTS

I. INTRODUCTION

The concept of isobaric spin has now been in existence for more than forty years. Although first used to put charge independence explicitly into descriptions of the nucleon–nucleon force, it has grown to be a quantum number of prime importance in nuclear and particle physics. Although technically not a good quantum number, it is conserved sufficiently to permit first-order perturbation theory calculations to work well. In this article we are mainly restricting our attention to the shifting and mixing of nuclear levels due to the breaking of isobaric spin conservation by charge-dependent forces for the particular case of isobaric spin $T = 3/2$ levels.

The splitting of otherwise degenerate levels by a force which destroys that degeneracy has been an important source of information on quantum levels in all fields of physics. The Zeeman effect and prediction of the Ω particle are two very important examples. The first case just involves the projection of J, the angular momentum, on the magnetic field axis, whereas the second involves the projections of strangeness and isobaric spin. For cases like this it is only necessary to know the form of the perturbing force (or in fact the rank of its representation) to predict the energy or mass dependence of the splitting, provided the splitting is small compared to the total energy. A beautiful example occurs in nuclear physics for $T = 3/2$ levels. These levels have four possible electric charges which correspond to the $2T+1$ projections on the z axis. These four levels would have identical energies were it not for isobaric spin violation. They are easily distinguished from each other because they occur in four different nuclei, and in fact the most difficult experimental problem is often distinguishing them from levels of lower isobaric spin in the same nucleus. In this review article we will attempt to cover all of the available experimental information on isobaric quartets in nuclei and the relevant properties of the individual levels with $T = 3/2$. The last reviews of this subject were published ten years ago (Cerny, 1968, Jänecke, 1969). Particular attention will be paid to the mass of the levels and a relation between the masses, known as the isobaric multiplet mass equation (IMME). The astonishing success of the IMME will be shown in 22 cases, and some discussion will be given on possible reasons for this success. No details of the method of measurement of the quantities presented in the tables will be given; these can be found in the references.

II. ISOBARIC QUARTETS

In principle every nuclear state with isobaric spin T is a member of a $2T+1$ multiplet of levels with very similar wave functions but different charge, as measured by the z component of the isobaric spin T_z. Levels with $T = 1/2$ form doublets which are usually referred to as mirror levels. A state with T greater than the T_z of the nucleus is usually called an analog state. The reason for this nomenclature is that the state in question has an almost identical structure to that of a state in the nearby $|T_z| = T$ nucleus, and therefore is analogous to it. Examination of the schematic representation of the $A = 9$ system shown in Fig. 1 reveals that the $T_z = \pm 1/2$ nuclei ^{9}Be and ^{9}B both have well defined $T = 3/2$ levels which bear a striking similarity to the level structure of the $T_z = \pm 3/2$ nuclei, ^{9}C and ^{9}Li. For the purposes of showing the correspondence between the nuclei, the level schemes for each nucleus have been shifted by the Coulomb energy and neutron–proton mass difference to line up the $T = 1/2$ and $T = 3/2$ levels.

In this article we are mainly studying how much shift is actually caused by Coulomb and other charge-dependent forces, and as a consequence we shall discuss the extent to which $T = 3/2$ levels contain $T = 1/2$ components. The total energy of a level, as measured by its mass, will actually be represented for convenience by its mass excess, and this will mask the fact that the shifts between levels are really quite small compared to the total mass or the total binding energy. Also, there is no requirement that the levels in question be bound. In fact, most $T = 3/2$ levels in $T_z = \pm 1/2$ nuclei

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Inst. Phys. Conf. Ser. No. 49: Chapter 1

Systematics of deep hole states observed in one- and two-particle transfer reactions

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Abstract. One-hole states in orbits below the valence orbits have been observed in a variety of isotope chains using (p,d), (d,t) and (^{3}He,α) reactions. Broad enhanced structure has also been observed by means of (p,t) reactions at 42 and 88 MeV on many isotope chains including tin, samarium and zirconium. The excitation energies, widths and angular distributions of these structures will be discussed.

1. Introduction

In this paper, I shall outline some of the systematic features of hole states observed both in one- and two-particle transfer reactions. Much of the early work on the one-neutron transfer reactions has been done by groups in Tokyo (Sakai and Kubo 1972, Sekiguchi *et al* 1973a, b), Gronningen (Van der Werf *et al* 1974, 1977) and Orsay (Berrier-Ronsin *et al* 1977, Gerlic *et al* 1975) using a variety of reactions. I propose only briefly to summarise this work since it has been very well presented in the appropriate publications. I shall concentrate on the new data on different isotope chains and on higher-energy data taken using the 90 MeV proton beam from the Indiana University Cyclotron. In addition, I shall discuss the two-neutron scattering data which has so far only been reported by the Michigan State University (MSU) group (Crawley *et al* 1977).

The study of simple structures embedded in a large background of other states is an example of the fundamental line-broadening problem in quantum mechanics. The spreading of a simple hole state among the many one-particle–two-hole or even more complex configurations is a good example of this problem. Theoretically, one would like to investigate the response function of single-hole states to high excitation energy. Another motivation is to test the usefulness of the shell model as one probes deeper into the nucleus.

At present there has been little theoretical work carried out in these problems, partly I suspect because until fairly recently there have been comparatively few experiments which have examined the nucleus for more than the first few MeV. For example, many extensive studies have been made of (p,t) reactions on the tin isotopes. However, the broad structures which appear to be such a dominant feature of the spectra above 6 MeV were not reported before 1977. As the level density increases, it is obviously no longer possible to make a microscopic theory of all the states of the nucleus. However, one may be able to predict the behaviour of the overall properties of any structure observed, such

PROCEEDINGS OF THE SYMPOSIUM ON HEAVY ION PHYSICS
FROM 10 TO 200 MeV/AMU

HELD AT
BROOKHAVEN NATIONAL LABORATORY
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Heavy Ion Reactions at Intermediate Energy: Observations, Extrapolations, Speculations

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Let me start out by defining the term "intermediate energy heavy ions" for the purpose of this talk. As "heavy ions" I will accept nuclei heavier than alpha particles and "intermediate energies" shall be the energy domain between 10 MeV/nucleon and, let's say, 500 MeV/nucleon. This is the energy region where we expect the transition from low energy mean field phenomena to high energy phenomena probably dominated by nucleon-nucleon interactions.

For orientation, Fig. 1 shows a "heavy ion reaction phase diagram" that was first introduced by Bondorf.[1] The coordinates of this schematic diagram are the projectile velocity and impact parameter. At low energies we have the well known processes of grazing collisions (generally associated with inelastic scattering and few nucleon

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Theory of Intermediate Energy Heavy Ion Collisions

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There are two problems in constructing a useful theory for collisions at intermediate energy. The first is to produce a framework of equations that is sufficiently flexible to describe the range of behavior possible in a heavy ion system. The parameters should be directly associated with the fundamental properties of the nuclear medium, such as the equation of state. As I will discuss, I think that there is an adequate framework fulfilling these conditions.

The other problem is the numerical solution of the equations, necessary if experiments are to actually measure the fundamental properties of the system. This phase of the theory is not yet in a good state; I will only be able to report on the results of calculations along one edge of the parameter space.

We take as our starting point Landau's kinetic equation for the single-nucleon phase space distribution function,

$$\frac{\partial f}{\partial t} + v \cdot \nabla f - \nabla U \cdot \nabla^{p} f = I \tag{1}$$

The dynamics is governed by the mean field U[f] and the collision integral I, which has the form,

$$\begin{aligned} I(p,r,t) = \frac{1}{(2\pi)^6} \int d^3p_2\, d^3p_3\, d^3p_4\, W(p_3 p_4 \to p p_2)\, \delta^3(\vec{p})\, \delta(E) \times \\ \left[\tilde{f}(p_3)\tilde{f}(p_4)(1-\tilde{f}(p))(1-\tilde{f}(p_2)) - \tilde{f}(p)\tilde{f}(p_2)(1-\tilde{f}(p_3))(1-\tilde{f}(p_4)) \right] . \end{aligned} \tag{2}$$

This is a classical equation, and has thrown away fluctuation phenomena and interference effects. Nevertheless, I believe it.

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THE MSU SUPERCONDUCTING CYCLOTRON PROJECT*

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The Cyclotron Laboratory at MSU is in the process of designing and constructing a large double cyclotron system for the purpose of providing high quality beams of heavy ions with energies up to 200 MeV per nucleon for lighter heavy ions such as calcium and up to 20 MeV per nucleon for the heaviest particles such as uranium. The 500 MeV first stage cyclotron is at present in the final year of its construction phase; funding for the second stage cyclotron and for a large expansion of experimental facilities and building is expected in fiscal year 1980. The project has been described in a number of previous publications.[1-13] In this paper we restrict ourselves to presenting a broad overview of the project in a brief form along with a statement of project status as of July 1979.

The long-range goals of the project are shown in Figure 1, which gives anticipated beam intensity as a function of energy per nucleon and projectile mass number. The operating range covers interesting new phenomenological regions corresponding to the expected onset of compressional waves in nuclei ("sound") and the expected region of coherent mesic phenomena and doubling of the nuclear density. Operation of the complete facility is expected in late 1983.

In the years 1980 to 1983, the first stage 500 MeV cyclotron will be used as an independent nuclear research instrument; expected intensity contours for operation in

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Conference Summary

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We have now almost come to the end of a very long, stimulating and enjoyable conference--stimulating for us all, enjoyable for you, and I can assure you at this point I would treat you to a long, rich and stimulating summary, except that I have a bus to catch at a quarter to one. I feel that this has been a successful conference, and is the first one that I have attended for quite some time that the talks have continued to interest me right up until the very last day. This was partly due to the lucidity of the presentations, partly due to the ordering of the talks by the clever organizers of the conference. It may also have something to do with the fact that I had to make the summary. As Oscar Wilde so aptly put it, "When a man is under sentence to be hanged, it concentrates the mind wonderfully."

Let me give some general impressions that I shall take away with me from this conference. The first concerns the general behaviour of heavy ion reactions in the region from 10 to a few hundred MeV/nucleon. They look like Fig. 1--you see a lot of junk. The illustrated analogy is profound because what you see here is a large massive projectile, skimming into the stratosphere and breaking up under very high temperature and high pressure conditions. There follows that terrible moment

PROCEEDINGS OF THE SYMPOSIUM ON HEAVY ION PHYSICS FROM 10 TO 200 MeV/AMU

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Subthreshold Pion Production with Heavy Ions

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Abstract

An experiment which measured pion production from 125 to 400 MeV/nucleon heavy ion collisions is described. It is shown that Coulomb effects in the π^- to π^+ ratio are very large and give some interesting insights into the reaction mechanism.

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FROM 10 TO 200 MeV/AMU

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A K = 800 High Resolution Heavy Ion Spectrograph

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This is a progress report on design considerations for a large heavy ion spectrograph to be used with MSU Phase II. A preliminary sketch indicating the position of the K = 800 spectrograph on the floor plan of the new heavy ion laboratory is shown in Fig. 1. Although the spectrograph design presented here is rather detailed, it is only intended to be suggestive and a focal point for discussion by the sponsors group and prospective users of the facility. We first outline the need for such a spectrograph and the choice of parameters such as energy and angular resolution, and then discuss the choice of optical mode for the system. Finally, a preliminary design of a particular beam transport-spectrograph combination is presented.

The collaborators in this work at MSU are Leigh Harwood and Edwin Kashy. Additional valuable input has been provided by K.L. Brown (SLAC), H.A. Enge (MIT), K. Halbach (LBL), S. Martin (Jülich), C. Morris (LASL), P. Roussel (Orsay), and H.A. Thiessen (LASL). The two existing large spectrographs which have been the seeds of our considerations are "Big Karl" at Jülich and the "High Resolution Spectrometer" (HRS) at LAMPF.

MSU Phase II will provide unique high quality heavy ion beams such as 200 MeV/amu ^{40}Ca. Because of the high energies of these beams (8 GeV in this case), a large spectrograph is

A Reaction Product Mass Spectrograph for Intermediate Energies*

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One of the major areas of use for any accelerator in the 10–200 MeV/nucleon energy range will be in production of new nuclei far from β-stability or in the "superheavy" mass region. A device which can measure the mass of these nuclei directly as they are emitted from the target would be extremely useful. During the past several months several designs for such a reaction product mass spectrograph (RPMS) to be used with the MSU superconducting cyclotrons have been studied. The following gives the details of the current plans of a system which appears potentially useful over a wide (1–200 MeV/nucleon) energy range. My collaborators at MSU are Jerry Nolen and Ed Kashy. H.A. Enge (MIT), Mike Nitschke (Berkeley), and Richard Pardo (MSU, ANL) have also been very helpful in the design.

Nuclear Spectroscopy

Lecture Notes of the Workshop
Held at Gull Lake, Michigan
August 27 – September 7, 1979

Chapter III

Nuclear Vibrations

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1. Introduction

In these lectures I will present some of the theoretical tools for the description of nuclear transitions. I first discuss the variables and the important operators, and find their matrix elements in Sect. 2. In Sect. 3 I derive sum rules which must be satisfied in any reasonable theory, based on the continuity equation and translational invariance. The only theory which is both guaranteed to satisfy the sum rules and is presently computible, is the RPA. I derive RPA from the time-dependent Hartree-Fock equations in Sect. 4, and make the connection with the various formulations that are given to the RPA. Of the various formulations, the coordinate-space representation best exhibits the consistency with sum rules. This representation also facilitates derivation of classical formulas for the frequencies of giant vibrations. The formulation as Landau theory, which emphasizes the properties of the interaction at the Fermi surface, is suited for compressional vibrations in large systems. The Green's function formulation is most useful for simplified interactions. A remarkably successful approximation uses a separable interaction whose form is determined by translational consistency. In the last section I compare the results of RPA with experiment, and discuss some open questions.

2. Operators and Matrix Elements

The most important operators we deal with are the density and the current, and we shall now derive their matrix elements in the Fock space representation, which was discussed in Chapter II.

2.1 Density Operator

The density operator is

$$\rho(\vec{r}) = a_r^{+} a_r \qquad (3\text{-}1)$$

$$= \sum_{\kappa\lambda} \phi_\kappa^{*}(r)\phi_\lambda(r) a_\kappa^{+} a_\lambda \qquad (3\text{-}2)$$

[†] Supported by the National Science Foundation under grant PHY-7620097.

IV. BALATON CONFERENCE
ON NUCLEAR PHYSICS

PROCEEDINGS
OF THE EPS TOPICAL CONFERENCE
ON
LARGE AMPLITUDE
COLLECTIVE NUCLEAR MOTIONS

KESZTHELY·HUNGARY
10–16. JUNE 1979

SEARCH FOR ISOVECTOR GIANT RESONANCES IN CHARGE-EXCHANGE REACTIONS*

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INTRODUCTION

Although the oldest known giant resonance, the giant (electric) dipole resonance, is an isovector resonance, the rebirth of giant-resonance studies since 1971 has focused on isoscalar resonances. Inelastic scattering, the major tool used in these studies, is so effective in exciting the broad isoscalar states that the isovector states are hard to find. It is for this reason that charge-exchange scattering such as (n,p), (p,n), (^{3}He,t), and (^{6}Li, ^{6}He), which can excite only the isovector states, may be better suited to finding isovector resonances.

GAMOW-TELLER RESONANCE

Following the discovery by Anderson and Wong of isobaric analog states[1] in (p,n) reactions (equivalent to superallowed or giant Fermi transitions in β decay) a giant Gamow-Teller (G-T), or spin-flip, transition in charge-exchange reactions was predicted.[2] Subsequently, a broad, structured peak in the ^{90}Zr(p,n)^{90}Nb reaction was interpreted as verifying the predicted transition,[3] a $0^+ \rightarrow 1^+$, $T=5 \rightarrow T=4$ transition from the ground state of ^{90}Zr to an excitation energy in ^{90}Nb centered at 8.4 MeV. Some of the neutron spectra of Doering et al.[4] are shown in Fig. 1. In each spectrum the isobaric analog

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Alpha Particle Emission in Peripheral Heavy Ion Reactions at 20 MeV/u

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ABSTRACT

The reaction ^{197}Au(^{16}O,HI) has been investigated at 310 MeV. The angular correlations of alpha particles measured in coincidence with projectile-like fragments are very strongly forward peaked; the reaction is dominated by large negative values of the three-body Q-value. Most of the observed alpha particles are emitted from projectile-like fragments. Within a factor of two, no anisotropy of emission in the center-of-mass frame of the coincident projectile residue and alpha particle was found.

1. INTRODUCTION

From the numerous recent experimental and theoretical studies of light particle emission in heavy-ion collisions, it has become clear that these particles are an important source of information on the time evolution of the reaction mechanism from low energies close to the Coulomb barrier up to the highest available relativistic energies. Over the whole energy domain, there is an increasing emphasis on coincidence measurements, which refine the global insights derived from the earlier single particle inclusive experiments. In this paper we discuss such coincidence measurements between alpha particles and projectile-like fragments in reactions induced by ^{16}O on ^{197}Au at 310 MeV. This energy lies in the transitional region between low and high energy heavy-ion phenomena.[1] Some initial results of the experiments were reported earlier.[2]

At low energies, less than 5 MeV/u above the Coulomb barrier, the interaction time of the two colliding nuclei is longer than, or comparable to, the nuclear relaxation time of typically 10^{-21} sec.[3-7] The dominant reaction mechanisms are established as deeply inelastic scattering or compound nucleus formation (see Refs. 3-7 and references therein). Here, the light particles are primarily emitted from the compound nucleus or from the fully accelerated and statistically equilibrated nuclei formed in deeply inelastic collisions.[8-11] Strictly speaking, these conclusions are based on studies of heavy colliding nuclei ($A \geq 40$). For lighter nuclei, there is already evidence for a component of preequilibrium emission of light particles, even at energies below 5 MeV/u.[12,13]

At higher energies, an increased, or even dominant, contribution is expected from preequilibrium processes, as established already in light-ion induced reactions.[14-18] The decrease in the reaction time allows the excitation of higher lying states, which subsequently decay by particle emission rather than propagate into more complicated configurations. This possibility is less likely in low energy heavy-ion collisions, where the energy loss in each step is too small to lead to significant preequilibrium emission.[19] There exists now a substantial body of data which demonstrate that non-equilibrium, light particle emission is an important aspect of heavy-ion collisions

HIGH ENERGY PROTON EMISSION IN REACTIONS INDUCED BY 315 MEV ^{16}O IONS

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Abstract:

Inclusive proton spectra have been measured for the reaction ^{197}Au(^{16}O,p)X at 315 MeV. The data, which are consistent with emission from a moving source, are compared with the fireball model and with models of preequilibrium emission.

In this letter we report the measurement of inclusive proton spectra from the reaction of 315 MeV ^{16}O ions on a ^{197}Au target. The motivation for this work was provided by the growth of interest in high energy proton emission accompanying heavy ion collisions. At low energies, ($E/A \leq 10$ MeV/nucleon) the emission of energetic light particles has been discussed in terms of break-up reactions,[1] cascade calculations,[2] preequilibrium models[3] and, more recently, hot spots[4] and jets.[5,6] At relativistic energies

OBSERVATION OF NEW NEUTRON-RICH ISOTOPES BY FRAGMENTATION OF 205 MeV/NUCLEON ^{40}Ar IONS*

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ABSTRACT

Yields of projectile fragments have been measured at 0° for the reaction of 205 MeV/nucleon ^{40}Ar ions on an 860 mg cm^{-2} carbon target. Mass resolution was achieved using a combination of magnetic analysis and energy loss measurements. The isotopes ^{28}Ne and ^{35}Al have been observed for the first time.

Heavy Ion Dynamics at Intermediate Energy

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As the energy of a heavy ion collision is raised above the Coulomb barrier, the nucleons will interpenetrate and momentarily produce a region of increased density. The relation between the density and the forces, summarized by the equation of state of nuclear matter, is an important objective in the study of heavy ion collisions. In particular, we would like to know whether there are any unusual phenomena, such as phase transitions, associated with high density nuclear matter. However, it is not yet clear how to extract this information from experiments. On the theoretical side, we need a mathematical description of the collision which is simple enough to solve on the computer, but also sufficiently general to encompass the range of behavior possible in a many-body system. Also, the experiments which are most sensitive to the underlying dynamics must be identified. It will be argued below that the experiments which measure as many particles as possible emerging from each collision are most relevant to the analysis of the important parameters of nuclear matter dynamics. But first we will trace the derivation of a manageable theory.

In Fig. 1 are displayed the various many-body theories and their relationships. The left-hand side are quantum theories and or the right are classical theories. On the most basic level at the top is the many-body Schrödinger equation which is intractable. The major soluble approximation is TDHF, discussed in detail by Koonin. There are two shortcomings of TDHF. Since there are no particle-particle collisions, it has limited validity at higher energy. This will be discussed in quantitative terms later. The second difficulty is that the representation, with all of the particles in the collision treated explicitly, makes calculations extremely slow for large systems. A useful approximation to TDHF is the RPA theory, which is valid in the limit of small amplitude oscillations. It is important to make the connection with RPA because most of our knowledge of nuclear dynamics is from nuclear structure physics, where the RPA is valid.

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PROCEEDINGS OF THE DARESBURY STUDY WEEKEND, MARCH 1979 (Edited by N.E. Sanderson)

"TUNING" FOR HIGH RESOLUTION

by

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A brief review will be given of some "tuning" methods where the goal is to optimise energy resolution of particle spectra in two-body reactions. The development of these methods began a few years ago with the work of Blosser et al(1) at Michigan State University and has since then been further pursued there(2-4). Similar work is now underway at the IPN with special emphasis on heavy-ions(5).

Given an accelerator, beam analyser, beam transport system and magnetic spectrograph, it is desired to test the system's potential for high resolution, identify its limitations, and optimise for highest possible resolution. This review will, 1) consider the physics of matching to the spectrograph; 2) discuss adjustments and diagnostics with the spectrograph at 0°; 3) look at some on-line tuning methods.

1. PHYSICS OF MATCHING

The characteristics required of the beam on target, so that following the nuclear reaction narrow peaks corresponding to nuclear states are obtained on the focal plane, have been reviewed by Hendrie(6). These requirements which involve target angle, kinematic energy spread and spectrograph characteristics can be calculated using the matrix formalism. Their incorporation into the code TRANSPORT(7) has been given by Reich et al(8). To appreciate what is required of particles leaving the target, in the usual situation where dispersion and scattering are in the same plane, fig.1 shows a central trajectory with momentum p_o leaving the focal plane region towards the target. Two other orbits, one (dashed line) with a momentum $p^+ = p_o(1 + \delta)$ and the other (dotted line) with $p^- = p_o(1 - \delta)$ where $\delta = \Delta p/p_o$ are shown. These arrive at the target position, displaced in both position and angle from the central trajectory. Both the displacement and angle depend on δ and are a property of the spectrograph. The beam preparation system, taking into account reaction kinematics, must reproduce the required correlation for particles leaving the target. In the figure, kinematic compensation in the spectrograph is done via focal plane motion. The lower part of the figure shows the focus position depending upon the value of the kinematical factor K, where $K = 1/p\ \partial p/\partial\theta$.

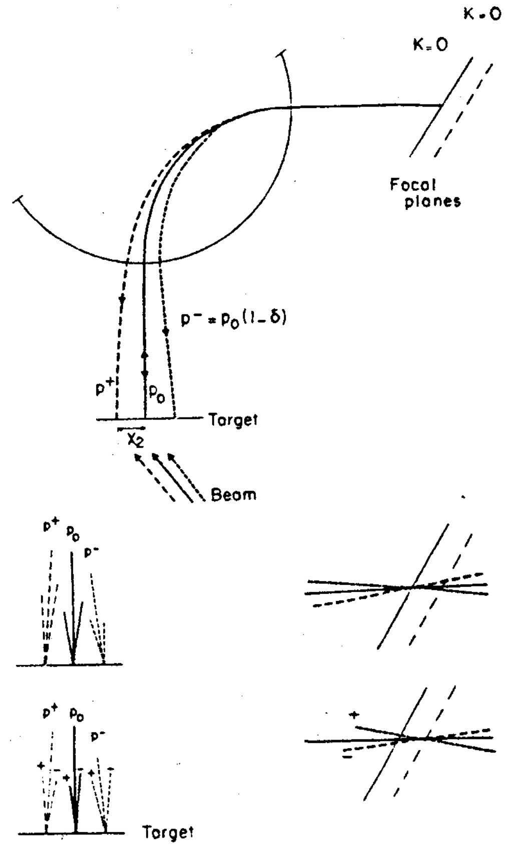

Fig.1 Three particle orbits chosen to demonstrate matching requirement in a spectrograph. Dispersion and scattering are in the same plane, and kinematic correction is made via focal plane motion.

A calculation which shows an example of required x-θ-δ correlations for the beam on target for the Bacchus spectrograph at IPN is shown in fig.2. The upper part shows a section of the phase space elliplipsoid inferred from recent measurements of the

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TRANSPORT DE FAISCEAU POUR SPECTROSCOPIE IONS LOURDS A HAUTE RESOLUTION.

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Beam-transport system for high-resolution heavy-ion spectroscopy :

A method is given to adjust a beam-transport system to the requirements of high energy-resolution heavy-ion spectroscopy. The results of a test experiment performed on a MP tandem with a ^{12}C beam are shown. A drastic improvement in energy resolution is obtained for a kinematical factor $K = \frac{1}{p}\, dp/d\theta \sim 0.12$.

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Atomic Masses and Fundamental Constants
6

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MASS OF $^9C^\dagger$

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ABSTRACT

A Q-value of -31.5762(30) MeV has been measured for the $^{12}C(^3He,^6He)^9C$ reaction. The mass of ^9C, when compared to its Coulomb analog levels in ^9B, ^9Be, and ^9Li, confirms a significant deviation from the quadratic form of the isobaric multiplet mass equation, with a cubic coefficient of d = 5.7 ± 1.5 keV.

I. INTRODUCTION

The properties of analog levels in nuclei have been of considerable interest in studies of microscopic and macroscopic nuclear properties. Examples are the mixing of $T_>$ levels with background $T_<$ levels in the first instance, and the determination of nuclear radii in the second. When three or more analog states are involved, it is expected[1] that the energies of the states in the various nuclei obey a quadratic relation, i.e., that the respective masses are described by the isobaric multiplet mass equation (IMME)

$$M(T_z) = a + bT_z + cT_z^2.$$

To test that relation, four or more masses must be measured, which is possible when the isospin T is greater than or equal to 3/2. . A recent review of experimental results for quartets and quintets of states showed that only for the A = 9 quartet is a highly significant deviation from the quadratic dependence observed.[2] The present measurement then represents an effort to reduce the chance of an experimental error as the source of the effect. Previous measurements yielding the ^9C mass include

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COMPARISON OF PRECISION MASS MEASUREMENTS OF LIGHT ISOTOPES

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This talk is a survey of the present status of precision mass measurements of isotopes below ^{19}F. The need for new precise mass measurements of certain stable as well as unstable light isotopes is presented. Three different techniques for precise mass measurements of unstable isotopes are briefly described and compared. These techniques are the ion source calibration technique currently being developed in Auckland, the rf time-of-flight technique used in Munich, and the kinematic calibration technique developed at Michigan State University. Four selected examples of recent measurements done here at MSU are discussed and compared with the results of other methods.

Despite the tremendous progress made in atomic mass measurements in the past 30 to 40 years there are still important reasons for improved measurements of several stable light isotopes. The important work done at Princeton with the precision rf mass spectrometer of Lincoln Smith has provided the masses of 11 light isotopes[1,2] (^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{13}C, ^{14}C, ^{14}N, ^{15}N, ^{16}O, and ^{19}F) relative to ^{12}C with precisions of better than 100 eV. Unfortunately, the remaining stable light isotopes (^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{17}O, and ^{18}O) still have mass uncertainties of about 1 keV, and in several cases these are the average of inconsistent experimental results. Fortunately, Smith's spectrometer has been moved to Delft by Koets and Wapstra and will soon be ready for new mass measurements.[3]

Mass measurements of ^{6}Li and ^{10}B with uncertainties of less than 100 eV are currently needed. The ^{6}Li mass is essential for a search for a parity and isospin violating component of

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Pole Terms and Absorption in the *P*-Wave Pion-Deuteron Interaction*

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We estimate the accuracy of the conventional ansatz of approximating the lowest order absorptive *P*-wave pion-deuteron interactions by pole term amplitudes. By comparing the matrix elements of the approximate pole term and complete absorptive reaction amplitudes for elastic πd scattering we find the pole term approximation to lead to better than 10% accuracy for both the P_{11} and P_{33} state interactions.

1. Introduction

The recent very successful predictions of low and intermediate energy pion-nucleus scattering data obtained with a local optical potential constructed from the pion-nucleon (πN) scattering amplitude [1] and expressed in terms of the local nucleon density operator suggest that the neglect of the nonlocal nature of the *P*-wave πN interaction is an excellent approximation. This nonlocality is due to the non-zero range of the Green's functions describing the inelastic nuclear intermediate state. The interactions which involve low lying inelastic intermediate states and for which the consequent nonlocality of the reaction amplitude could a priori be expected to be most significant are those involving the nucleon (P_{11}) and Δ_{33} resonance (P_{33}) intermediate states, illustrated in Figs. 1a and 1b.

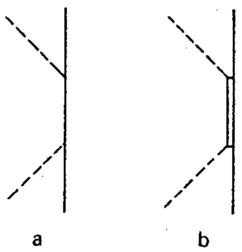

Fig. 1. a Nucleon intermediate state and **b** Δ_{33} intermediate state interaction

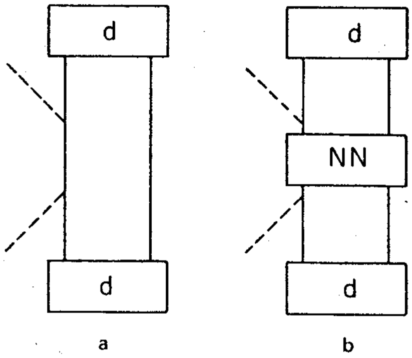

Fig. 2. a Nucleon pole term in πd-scattering, **b** corresponding absorptive contribution

The conceptual importance of the absorptive nature of these interactions becomes clear when effects of pion absorption are included in the scattering amplitude or optical potential. In this case the contribution of the nucleon pole term if included in the first order optical potential or impulse approximation amplitude overlaps with the absorptive contribution from the single nucleon pion absorption mechanism, as illustrated for the case of pion-deuteron (πd) scattering in Fig. 2. If double counting is to be avoided, one has the choice of either dropping the pole term (Fig. 2a) and including the absorptive contribution (Fig. 2b) or vice versa [2]. A completely similar problem arises at higher energies with the Δ_{33} intermediate state as illustrated in Fig. 3. Clearly every pole term in the πN amplitude in a nucleus repre-

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