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Measurement of the Electric Polarizability of the Deuteron

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The electric polarizability of the deuteron has been determined by measuring deviations from the Rutherford scattering formula for deuteron elastic scattering from ^{208}Pb at energies from 3.0 to 7.0 MeV. The measured value of the electric polarizability, $\alpha = 0.70 \pm 0.05$ fm^3, is in fair agreement with theoretical predictions.

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The scattering of projectiles from nuclei at energies far below the Coulomb barrier is described only approximately by the Rutherford expression. At sufficiently low energies residual nuclear effects resulting from the tail of the nuclear potential or from barrier penetration can be neglected, but in spite of this there can still be significant deviations from the Rutherford scattering law. From the point of view of nuclear physics, the most interesting effects are those which result from the internal degrees of freedom of the target or projectile—i.e., from real or virtual excitation of nuclear states.

The problem which we shall address here is that of deuteron scattering from heavy nuclei at very low energies. If the target nucleus has no low-lying collective states, it is essentially inert and may be thought of as a point charge.[1] In this case the deviations from Rutherford scattering result primarily from the electric polarization (i.e., stretching) of the deuterons in the Coulomb field of the nucleus.

If a deuteron is located at some position $\vec{r}$ relative to the target nucleus, the electric field of the target ($\vec{E}$) will polarize the deuteron, and consequently the electrostatic potential energy will be slightly smaller than Ze^2/r. If we keep only the dipole term, the change in the potential energy is simply $-\vec{P}\cdot\vec{E}$, where $\vec{P}$ is the induced electric dipole moment. Assuming that $\vec{P}$ is proportional to $\vec{E}$ one finds that the dipole correction to the potential energy can be written as $-\frac{1}{2}\alpha Z^2 e^2/r^4$, where the constant α is the electric polarizability of the deuteron. For deuteron scattering at very low energies the dipole stretching potential is weak enough to be treated as a perturbation, and it follows that the deviations from Rutherford scattering are essentially proportional to α. This suggests[1] that it might be possible to determine α by obtaining accurate measurements of the cross section for deuteron elastic scattering at low energies.

The primary reason for our interest in measuring α is simply that the deuteron electric polarizability is a fundamental property of the n-p bound state which, up until now, has not been measured. A measurement of the electric polarization is also of importance because Coulomb stretching of the deuteron is closely related to the more general issue of the role of deuteron stretching and breakup in nuclear reactions. This is a topic of considerable interest for sub-Coulomb energies and for higher energies as well.

Calculations of the electric polarizability of the deuteron have been reported by a number of authors,[2-7] and a variety of calculational methods have been employed. While values of α ranging from 0.21 to 0.64 fm^3 have been reported, it appears that the best calculations give values close to 0.60 fm^3.

In the present Letter we report the first empirical determination of α. Measurements of the cross section have been obtained for deuteron elastic scattering from ^{208}Pb at energies from 3 to 7 MeV. (The Coulomb barrier for ^{208}Pb is approximately 11 MeV.) Since the expected deviations from Rutherford scattering are typically only a few tenths of one percent, the experiment must be done with great care. Rather than attempting to obtain absolute cross-section measurements we have measured only ratios of cross sections. The quantity which we determine is

$$R = \frac{\sigma(E_1,\theta_1)/\sigma(E_1,\theta_2)}{\sigma(E_2,\theta_1)/\sigma(E_2,\theta_2)}, \quad (1)$$

where E_1 and E_2 are two bombarding energies and θ_1 and θ_2 are two scattering angles. (In our experiment θ_1 is a forward angle, θ_2 is a back angle, and $E_1 < E_2$.) To determine R we measure the

Radiative Width of Molecular-Cluster States

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Molecular states are characterized by enhanced electromagnetic deexcitations of many different multipolarities. The expected enhancement of $E1$, $E2$, and $E3$ transitions is examined by deriving molecular sum rules for radiative deexcitation widths and via a dimensionality approach. The enhancement of the $E1$ transitions is the most striking.

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The single-particle shell model and the collective (quadrupole) degrees of freedom are clearly evident in the low-lying level structure of nuclei. In 1960 it was suggested[1] that high-lying resonance states in $^{12}C+^{12}C$ correspond to quadrupole vibration-rotation excitations of dinuclear molecular states in the composite nucleus ^{24}Mg. Recently,[2] it was suggested that "diatomic nuclear molecular" states arise from excitation of a new degree of freedom—a dipole degree of freedom—described by the relative separation vector connecting the centers of the two clusters. The existence of such a collective degree of freedom can be deduced from several observations.

One such observation is the spin and parity of members of an apparent rotational band built on a fixed intrinsic molecular state. When the two nuclear clusters involved are not identical, rotation by 180° around an axis perpendicular to the symmetry axis is not a symmetry operation so that both even and odd spins are allowed in the $K=0$ band. However, reflection in a plane containing the symmetry axis is still a symmetry, leading to a connection between parity and spin.[3] Thus, a $K=0$ molecular band will contain the states 0^+, 1^-, 2^+, 3^-, ... in an alternating parity sequence.

Another observation indicative of a molecular structure is that of enhanced $E1$ transitions (within a rotational band).[2] This is possible only when the ratio of the charges of the two clusters is different from that of their masses; under these conditions the center of charge does not coincide with the center of mass,[4] resulting in a nonvanishing *intrinsic* dipole moment. While $E1$ transitions are expected to be enhanced in such a situation, the $B(E1)$ may still be only a few percent of the single-particle estimate. A central goal of this paper has been to find new measures for such molecular radiative decay widths. To this end we have derived a molecular dipole sum rule to be discussed below.

A third indication of a molecular cluster may be found in the cluster decay width and its relation to the Wigner sum rule. The two sum rules of decay widths can be used simultaneously to yield measures of the probable existence of a molecular structure. For light nuclei, cluster decay widths are readily available as some of the higher-lying states in a proposed band may be observed as scattering resonances.

Recently,[5] a very similar cluster approach has been suggested for heavy ($Z>82$) nuclei. In this case, cluster widths are deduced from the ground-state α-particle decay widths, and from relative hindrance factors for decay to excited states. These have long been known to be small for the low-lying 1^- states in the Ra isotopes.[6]

Recent experimental investigation suggests the existence of an $\alpha+^{14}C$ molecular band in the light nucleus ^{18}O,[7] as well as an $\alpha+^{214}Rn$ one in the heavy nucleus ^{218}Ra.[8] In particular, in ^{18}O the proposed cluster band involves a 0^+, 1^-, 2^+, 3^- sequence based on the four-particle, two-hole (4p-2h) 0^+ state at 3.63 MeV. Enhanced $E1$ transitions [$B(E1)\sim10^{-2}$ Weisskopf unit (W.u.)] and $E2$ crossover transitions [$B(E2)\sim20$ W.u.] were also found,[7] as shown in Fig. 1.

A first rough estimate of the $E1$ decay rate can be obtained, in the spirit of Gell-Mann and Telegdi,[4] by replacing the nuclear radius in the definition of the Weisskopf unit with the equilibrium displacement of the center of charge from the center of mass. In this way a new "molecular Weisskopf unit" (m.W.u.) for $E1$ transitions is obtained. For example, for $\alpha+^{14}C$ states in ^{18}O

ENERGY DEPENDENCE OF NUCLEAR MATTER DISASSEMBLY IN HEAVY ION COLLISIONS

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Measurements of light charged particle spectra from ^{20}Ne + Au at 100 and 156 MeV/nucleon are compared with results for similar systems at 9, 13, 19, 43, 241, 393, and 800 MeV/nucleon. Spectra at each energy are fitted with a moving source model to extract the temperatures, cross sections and source velocities for protons and light nuclei in the intermediate rapidity region. The ^{4}He/p production ratio decreases drastically with incident energy, whereas the d/p and t/p ratios are almost constant.

An important concept in relativistic nuclear collisions concerns the formation of an excited, localized region of participant nucleons moving with a velocity intermediate between those of the projectile and target [1,2]. In this letter we present a new approach to the study of this region over a wide range of incident energies through its disassembly into nucleons and light composite nuclei. The relative abundance of these emitted fragments as a function of temperature in the zone is characteristic of the detailed mechanism of its disassembly [3–5]. Within a thermodynamic model, temperature and relative numbers of nucleons and light nuclei are predicted to vary smoothly with incident energy, whereas a hydrodynamical model [6] incorporating compression, could lead to a discontinuity in the temperature and a sudden decrease in the production of light composite nuclei as a function of incident energy. We report new measurements of p, d, t, and ^{4}He energy spectra and angular distributions from ^{20}Ne-induced reactions on a Au target at incident energies of 100 and 156 MeV/nucleon. Our results for production cross sections and temperatures, when combined with those extracted from previous measurements for ^{16}O or ^{20}Ne-induced reactions on heavy targets, give a consistent picture of an intermediate velocity source with a temperature that varies smoothly with incident energy. We also observe that the deuteron to proton ratio (d/p) is almost independent of energy whereas the ^{4}He to proton ratio (^{4}He/p) varies from 1.9 at 9 MeV/nucleon to 0.05 to 800 MeV/nucleon. These observations lend support to models that describe these reactions in terms of a localized, thermalized, expanding interaction zone [3–5].

THE EFFECTIVE QUADRUPOLE FORCE BETWEEN LIKE IBA-BOSONS

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It is shown that an effective quadrupole interaction between like bosons in the Interacting Boson Model (IBM) arises from the neutron–proton quadrupole force as a consequence of the truncation of the full shell-model space to the S–D subspace. The strength of this effective interaction vanishes in the SU(5) limit of IBM but is appreciable in the SU(3) and O(6) limits and thus can give rise to the occurrence of an SU(3) symmetry.

In the Interacting Boson Approximation [1] (IBA) model the structure of even–even nuclei is described in terms of a system of interacting s- and d-bosons. A boson is regarded as a collective pair of two neutrons or two protons. From the spectra of semi-closed shell nuclei there is strong evidence that there is no, or at most a very weak quadrupole force between like particles [2] and consequently no quadrupole force between like bosons. It is the strong neutron–proton quadrupole–quadrupole force that gives rise to the collective features of the spectra of medium heavy and heavy nuclei that have both valence neutrons and protons. In a recent paper, however, Dieperink and Bijker [3], give strong evidence, on phenomenologic grounds, for a strong quadrupole force between like bosons in nuclei where the SU(3) or O(6) limits of the IBA model apply. In this letter it will be shown that this paradox can be resolved by considering the effective interaction which arises from the truncation of the full shell model space to the S–D pair subspace [4] which corresponds to the IBA boson space.

The consequence of the space truncation has been considered by Sage and Barrett [5], where the effects of the G-pair are studied in a perturbative approach. The G-pair state is a collective $v = 2, J = 4$ state and is obviously outside the S–D fermion pair space. A parameter of the IBA-model that has been considered in ref. [5] is ϵ_d, the energy difference between tne s- and d-boson. Phenomenologic calculations [6] indicate that ϵ_d decreases when adding both neutron and proton pairs to the closed shell. To explain this decrease in ϵ_d essentially the diagram shown in fig. 1 was considered, where $V^Q_{\pi\nu}$ is the proton–neutron quadrupole –quadrupole interaction.

The dominant part in the shell model neutron–proton interaction is the quadrupole term,

$$V_{\pi\nu} = F_2 Q^F_\pi \cdot Q^F_\nu , \tag{1}$$

where the superscript F denotes an operator working in the fermion space. In general Q^F_ρ can be written in terms of operators working on a boson space as

$$Q^F_\rho \to \kappa_\rho Q_\rho + \kappa'_\rho Q'_\rho + Q''_\rho , \quad \rho = \pi, \nu, \tag{2}$$

where

$$Q_\rho = (s^\dagger \tilde{d} + d^\dagger s)^{(2)}_\rho + \chi_\rho (d^\dagger \tilde{d})^{(2)}_\rho \tag{3}$$

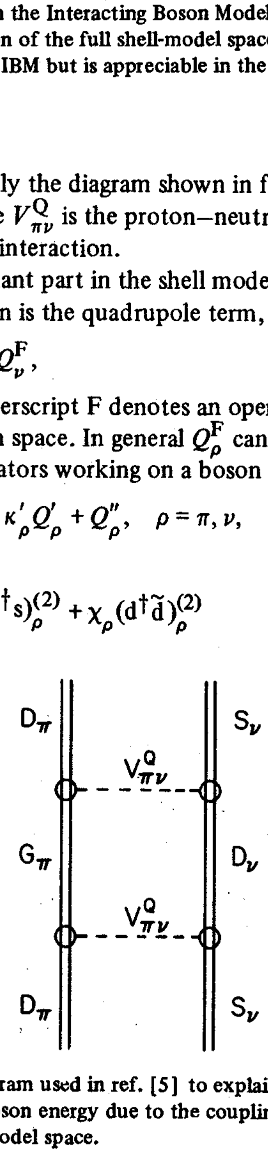

Fig. 1. The diagram used in ref. [5] to explain the renormalization of the d-boson energy due to the couplings to states outside the S–D model space.

ISOSPIN DEPENDENCE OF PION ABSORPTION BY NUCLEON PAIRS IN THE He ISOTOPES

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We calculate the relative absorption ratio of a pion by $T = 0$ and $T = 1$ nucleon pairs in the He isotopes measured recently by Ashery et al. Standard theory based on Δ–isobar intermediate excitations agrees with the experimental observation that for energies around the resonance, pion absorption by a $T = 1$ nucleon pair is strongly suppressed.

Very recently Ashery et al. [1] performed the $(\pi^+, 2p)$ and (π^-, pn) measurements on ^3He and ^4He at pion kinetic energy of $T_\pi = 165$ MeV in order to obtain information on the cross sections for pion absorption by $T = 0$ and $T = 1$ nucleon pairs. They found surprisingly large ratios for $d\sigma(\pi^+, pp)/d\sigma(\pi^-, pn)$, on the order of ~100. By counting the numbers of initial nucleon pairs with the isospin $T = 0$ and $T = 1$ in those nuclei, these ratios were expressed in terms of the isospin of initial nucleon pairs. It was then found that $R \equiv d\sigma(T = 0)/d\sigma(T = 1) \approx 50$ [1]. If one estimates this ratio in terms of the isospin geometry for the formation of Δ isobars, one finds $R = 2$ [1,2].

In this short note, we would like to demonstrate that our current understanding of the pion nucleon interaction and the Δ isobar formation provides a natural explanation for the observed large value of this ratio.

In recent years, there have been a number of theoretical derivations of the pion–nucleus optical potential parameters from the pion–nuclear many body theory [3–11]. In particular, the imaginary part of the two body optical potential has a direct relationship to pion absorption. The S-wave and P-wave pion absorption mechanisms seem to provide a microscopic understanding of the optical parameters derived from pionic atoms and pion–nucleus elastic scattering cross sections [12]. The S-wave pion absorption mechanism accounts for the experimental fall off of the $\pi d \to pp$ cross section with increasing pion energy and becomes negligibly small above $T_\pi \approx 50$ MeV. On the other hand, the P-wave pion absorption mechanism, in particular through the Δ isobar intermediate excitation, becomes dominant above $T_\pi \approx 100$ MeV.

Since our interest is in pion absorption in the resonance energy region, we concentrate on the P-wave absorption process through the Δ isobar intermediate excitation alone, as depicted in fig. 1. The wavy lines denote the spin–isospin dependent interaction which is usually described in terms of the pion and rho meson exchanges [13]. The T-matrix for pion absorption by the pion exchange mechanism is obtained by the Feynman graph technique in momentum space;

$$
\begin{aligned}
T(\boldsymbol{k}_1, \boldsymbol{k}_2; \boldsymbol{k}) = {} & [f(k_1)/\mu](\boldsymbol{\sigma}_1 \cdot \boldsymbol{k}_1)\boldsymbol{\tau}_1 \cdot D_\pi(\boldsymbol{k}_1) \\
& \times [f^*(k_1)/\mu](\boldsymbol{S}_2^+ \cdot \boldsymbol{k}_1) \cdot \boldsymbol{T}_2^+ G_D(\boldsymbol{P}_\Delta)[f(k)/\mu]\, \boldsymbol{S}_2 \cdot \boldsymbol{k} T_{2\lambda} \\
& + [f(k_1)/\mu](\boldsymbol{\sigma}_1 \cdot \boldsymbol{k}_1)\boldsymbol{\tau}_1 \cdot D_\pi(\boldsymbol{k}_1) \\
& \times [f^*(k_1)/\mu](\boldsymbol{S}_2 \cdot \boldsymbol{k}_1) \cdot \boldsymbol{T}_2 G_C(\boldsymbol{P}_\Delta) \\
& \times [f(k)/\mu]\, \boldsymbol{S}_2^+ \cdot \boldsymbol{k} T_{2\lambda} + (1 \rightleftharpoons 2).
\end{aligned}
\qquad (1)
$$

Here $\boldsymbol{k}$ is the incoming pion momentum in the laboratory frame, which after absorption gets distributed as $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ among the two nucleons 1 and 2 involved in the process. $\boldsymbol{\sigma}, \boldsymbol{\tau}$ are the spin, isospin Pauli matrices and $\boldsymbol{S}, \boldsymbol{T}$ the corresponding transition operators between a nucleon and a Δ isobar. The $\pi N\Delta$ coupling

MICROSCOPIC CALCULATION OF THE PARAMETERS OF THE INTERACTING BOSE–FERMI APPROXIMATION FOR NONDEGENERATE ORBITS

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Microscopic calculations of the parameters of the quadrupole operator of the Interacting Bose–Fermi Approximation are reported for the realistic case in which the valence orbits are nondegenerate. The results of these exact calculations are compared with those of an approximate formalism and in general reasonable agreement is found.

In this letter, we present the resu'ts of a fully microscopic calculation of the parameters of the Interacting Bose–Fermi Approximation (IBFA) [1] model for the realistic case in which the valence nucleons occupy nondegenerate single-particle orbitals. We focus on the quadrupole operator, which plays a central role in the model. In both the Interacting Boson Approximation (IBA) [2] model of even–even nuclei and the IBFA model of odd-A nuclei, the strength and structure of the quadrupole–quadrupole interaction dictate whether the nucleus is spherical, axially symmetric deformed or γ-unstable. In previous approaches to determine the form of the quadrupole operator for odd-A nuclei [3], the nondegeneracy of the valence nucleon orbits was treated approximately, using the Number Operator Approximation (NOA) [4] of Otsuka and Arima. In our calculations, the nondegeneracy of the valence orbits is treated exactly and our results are then compared with those of the earlier approximate treatment. We find that the approximate formalism leads to results in fairly close agreement with our exact results.

The procedure we use is closely related to earlier work on the IBA [5]. As in that work we use a multinomial expansion to relate the matrix elements of the multi-orbit problem to matrix elements for individual orbits. We have, however, simplified the earlier formalism to facilitate its extension to the higher generalized seniority matrix elements required in the IBFA.

The IBFA model of odd-A nuclei is an approximation to the nuclear shell model. The states of the model are built up out of s and d boson creation operators and single fermion creation operators. The s and d boson creation operators correspond to the fermion operators S and D which create the energetically lowest pairs of like nucleons. The fermion pair creation operators can be expressed in terms of single-fermion creation operators c_j^+ according to

$$S^+ = \sum_j \alpha_j(\Omega_j/2)^{1/2}(c_j^+ c_j^+)^{(0)} \tag{1}$$

$$D^+ = \sum_{j_1 \leq j_2} \beta_{j_1 j_2}(1+\delta_{j_1 j_2})^{-1/2}(c_{j_1}^+ c_{j_2}^+)^{(2)}, \tag{2}$$

where

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ANOMALONS AS PINEUTS BOUND TO NUCLEAR FRAGMENTS: A POSSIBLE EXPLANATION

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We suggest that the properties of anomalons, the highly reactive heavy-ion reaction fragments observed in emulsions, can be explained by considering them to be "pineuts", i.e., a π^- bound hadronically to a neutron cloud extending out from the nuclear fragment.

"Anomalons" is the name given to certain relativistic projectile fragments from high-energy heavy-ion collisions – those fragments that have anomalously short reaction mean free paths (mfp's) immediately following their formation [1,2]. These were first postulated in 1954 from cosmic-ray evidence [3] and were seen subsequently by other groups scanning cosmic-ray emulsions [4–8]. Because of limited statistics and possible systematic uncertainties in and among the various experiments, these cosmic-ray results never attracted overmuch attention. With the advent of accelerator-produced relativistic heavy-ion beams, however, it has become possible to perform experiments that are more nicely controlled and have much greater statistics. Three more or less independent groups [1,2; 9; 10] have already reported positive results on observing anomalons, and many experiments, both with emulsions and with counters, are in progress by other groups [11].

The properties of anomalons can be summarized basically as follows (using numbers from ref. [2], although refs. [2], [9] and [10] are in essential agreement): When a high-energy ($\sim 1-2A$ GeV) heavy-ion beam (e.g., ^{16}O, ^{56}Fe) impinges on an emulsion, the primary heavy ions exhibit "normal" reaction mfp's, but, following a reaction star, the secondary and later generation projectile fragments do not. During the first few cm after their production, the mean free path for reactions is abnormally small. The results are consistent with there being a small ($\sim 6\%$) component having an anomalously short mfp (~ 2.5 cm). This reduction in interaction mfp implies a correspondingly large increase in the reaction cross section. Such an effect has not been observed for heavy-ion beams at lower energies, although extensive searches for anomalons produced below 1 A GeV have not been made. By the time some 5 cm has been traversed, the mfp's again agree with those of the primary projectiles. This implies that the anomalons either have all interacted or are decaying with a lifetime of $\gtrsim 10^{-10}$ s. No "observable" decay particles appear to have been emitted along the track, from which it can be inferred that the decay proceeds by "neutral" emission, if any. The charges of the anomalons were determined by standard methods of nuclear emulsion research, and they were found to lie between 3 and 26, with the fractional effect on the cross section greatest for the lower charge values, falling off until essentially normal behavior is reached at charge 26. (Recent results [12] indicate no anomalon effect for $Z = 2$, and this also appears to be true for $Z = 1$, although other investigators [1,11] have shown inconclusive results for these low charges.) Finally, the anomalon tendency persists from generation to generation; i.e., tertiary and later generations of fragments produced by the interactions of anomalous secondaries show an even greater tendency toward

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LIQUID–GAS PHASE INSTABILITIES IN NUCLEAR SYSTEMS

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The conventional approach to composite fragment production in heavy ion collisions from a single gaseous phase may require modification at temperatures below 20 MeV due to the onset of a liquid–gas phase instability. Clusters heavier than the α-particle are necessary for an unambiguous experimental signature.

In high energy nuclear collisions, a localized zone of participant nucleons can be created at excitation energies greater than the binding energy of the nucleons. The disassembly of the hot transient system into many different final channels is a problem of current interest [1]. Thermodynamic models have been developed to account for the emission of light composite fragments by treating the participant zone as a single gaseous phase in thermal and chemical equilibrium. However, under certain combinations of density and temperature the system may develop an instability toward division into liquid and gas phases which could influence the production of composite fragments. In this paper we discuss the conditions for this instability to develop and we suggest how this effect might be observed experimentally.

To derive the condition for a liquid–gas instability, we start from the relation [2]

$$\rho = \frac{4}{(2\pi)^3} \int d^3k\, [1 + \exp(k^2/2m - \mu)/T]^{-1},$$

from which the chemical potential, μ, is determined as a function of the density ρ and the temperature T. The thermal contribution to the internal energy is given by

$$\frac{E_T}{V} = \frac{4}{(2\pi)^3} \int d^3k\, \frac{k^2}{2m}\, [1 + \exp(k^2/2m - \mu)/T]^{-1},$$

using the calculated values of μ. The pressure due to the thermal motion is then $2E_T/3V$ corresponding to a zero point pressure of $\frac{2}{5}\epsilon_F(\rho)$ where ϵ_F is the Fermi energy. The total pressure is the sum of the thermal pressure and the pressure, P_v due to the interaction among the constituents of the system. To derive P_v we express the energy per nucleon in the form [3] obtained from a Skyrme type interaction, ignoring the effective mass contribution,

$$E_v/A = -A\rho + B\rho^{\sigma+1},$$

where A and B are constants determined by the constraint $E/A = -16$ MeV (for nuclear matter) when $\rho = \rho_0$ together with the further condition for stability of normal density nuclear matter, $\partial(E/A)/\partial\rho = 0$.

Solving for A and B with $\epsilon\ (\rho = \rho_0) = 38$ MeV and $\sigma = 2/3$ we find $A\rho_0 = 74.2$ and $B\rho_0^{5/3} = 35.4$ MeV. In general A and B have some temperature dependence but here we assume that the thermal and interaction energies and pressures are separable. The pressure due to the interaction (at $T = 0$) is $\rho^2\partial(E/A)/\partial\rho$, resulting in

$$P_v/\rho = -A\rho + \tfrac{5}{3}B\rho^{5/3}.$$

The total pressure as a function of density for constant temperature is plotted in fig. 1, which shows that the equation of state has the form typical of a Van der Waal's system with liquid and gaseous phases. For the unphysical region (shown only for $T = 15$ MeV) where the slope is negative (implying a negative incompressibility) a maxwellian construction is employed, along which the liquid and gas phases coexist.

AN INTERACTING BOSON–FERMION MODEL CALCULATION FOR THE ODD-MASS PROMETHIUM ISOTOPES

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A calculation in the framework of the interacting boson–fermion model for the excitation energy and spectroscopic factors for the negative parity levels in the odd-mass promethium isotopes is presented. The parameters are compared with those obtained from an earlier calculation of the europium isotopes.

In the Interacting Boson–Fermion Model [1] (IBFM) the spectra of odd–even nuclei are described by coupling the degrees of freedom of the odd particle to the even–even core, which is described in terms of the Interacting Boson Model [2] (IBM). The model has been applied with much success to many odd-A nuclei in different regions of the periodic table. In this work we will focus our attention on the promethium (Pm) isotopes ($Z = 61$) which are adjacent to the europium (Eu) isotopes ($Z = 63$). An extensive study of the Eu isotopes has already been published [3]. This allows us to determine the variation of the IBFM parameters, not only as a function of neutron number but also as a function of the number of protons.

The hamiltonian can in general be written as

$$H = H_B + H_F + V_{BF},$$

where H_B is the IBM hamiltonian that describes the even–even core, H_F contains the single-particle energies and V_{BF} describes the boson–fermion interaction. As is discussed in ref. [1], V_{BF} can be written as a sum of three terms, a quadrupole–quadrupole interaction with a strength Γ_0, an exchange force with strength Λ_0, and a monopole interaction with strength A. The occupancies v_j^2 of the different spherical single-particle (sp) orbits also enter into the interaction.

The odd-mass Pm isotopes are described in the model by coupling the degrees of freedom of the odd proton to the neodynium (Nd) core with the same neutron number. For the Nd isotopes there exists a calculation in the IBM [4]. To calculate the negative parity levels, which are the subject of this paper, it is sufficient to consider only the $h_{11/2}$ proton orbit. In the case of an unique orbit for the odd particle, only two of the three parameters (Γ_0, Λ_0 and v^2) enter as linear independent parameters in the calculation of excitation energies. For each isotope therefore the value of v^2 has been kept fixed to the value indicated by single-particle spectroscopic factors while Γ_0 and Λ_0 have been adjusted so as to give a best agreement for the excitation energies. The strength of the monopole force, A_0, has been taken to be the same as for the Eu isotopes: $A_0 = -0.1$ MeV. In fig. 1 the calculated excitation energies are compared with experiment. There is a clear transition in the type of spectra. For the lighter isotopes the spectrum is typical for a particle vibrator model in which the $h_{11/2}$ sp states are lowest and higher in the spectrum a multiplet of levels can be found arising from the coupling of the $h_{11/2}$ to the 2_1^+ in the core. In ^{153}Pm on the other hand, clear rotation bands have developed as is expected in a Nilsson picture. The partial occupancy of the spherical $h_{11/2}$ orbit gives rise to the fact that here the $5/2_1^-$ is the lowest negative parity level.

THE N = 82 ISOTONES IN THE GENERALIZED SENIORITY SCHEME

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A calculation for the N = 82 isotones in the generalized seniority scheme is presented and compared with a shell model calculation.

As has been emphasized by Talmi [1], the generalized seniority scheme provides for semi-closed shell nuclei a good basis to label the states. The advantage of working directly in a generalized seniority basis is therefore that without losing any of the important physics, one can work in a much smaller basis than what is necessary in the shell-model. In this article we will show this by comparing a calculation in the generalized seniority scheme for the N = 82 isotones with a shell-model calculation.

The generalized seniority scheme as it was introduced by Talmi [1] is a generalization of the usual seniority concept [2,3] to the case of several non-degenerate single particle (s.p.) orbits. The seniority quantum number v counts the number of particles not pairwise coupled to angular momentum $J = 0$. Mathematically seniority is introduced via the operators

$$S_{+j} = (2J+1)^{1/2}(a_j^\dagger a_j^\dagger)^{(0)} , \tag{1a}$$

$$S_{-j} = (2J+1)^{1/2}(\tilde{a}_j\tilde{a}_j)^{(0)} , \tag{1b}$$

$$S_{0j} = \tfrac{1}{2}[S_{+j}, S_{-j}] = \tfrac{1}{2}[\hat{n}_j - \tfrac{1}{2}(2J+1)] , \tag{1c}$$

where $\hat{n}_j$ is the fermion number operator. It can easily be verified that these three operators form the generators of a quasi-spin [3] [SU(2)] algebra. The representations of this group are labeled by v and an n-particle state can be written as

$$|j^n, v, \alpha, J\rangle = S_{+j}^{(n-v)/2}|j^v, v, \alpha, J\rangle , \tag{2}$$

where α denotes the other quantum numbers necessary to label the state uniquely.

To generalize the seniority concept from the case of a single j shell to that of many orbits, one introduces the operators

$$S_+ = \sum_j \alpha_j S_{+j} , \tag{3a}$$

$$S_- = \sum_j \alpha_j S_{-j} . \tag{3b}$$

It can be shown [4] that it is possible to form from these operators (by introducing a proper S_0) a quasi-spin algebra if $\alpha_j^2 = 1$. This case corresponds to the case of degenerate s.p. levels. Similar to the case of normal seniority, the states with generalized seniority w are written as

$$|\tilde{j}^n, w, \alpha, J\rangle = S_+^{(n-w)/2}|\tilde{j}^w, w, \alpha, J\rangle , \tag{4}$$

where the ~ indicates that the particles are distributed over more than one j orbit, and furthermore

$$S_-|\tilde{j}^w, w, \alpha, J\rangle = 0 . \tag{5}$$

The definition of the generalized seniority basis as it is given here makes it very similar to that of the Broken Pair model [5].

While in the normal seniority scheme, it is relatively simple to calculate the matrix elements of an operator, it is much more complicated in the generalized seniority scheme. Recently however analytic formulas have been derived [6] to calculate matrix elements for states in the generalized seniority scheme.

The calculations presented here are done in a basis

NUCLEAR FRAGMENTATION

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We consider the conditions under which nuclei will fragment into smaller pieces. We argue that fragmentation will occur when the nuclear matter has expanded adiabatically to the onset of hydrodynamic instability, $\partial P/\partial V|_S = 0$. We discuss the conditions of initial heating and/or compression which lead to fragmentation, and argue that the resulting fragmented matter will be composed mainly of alpha-particles and nucleons.

When enough energy is brought into a nucleus, it will break up into smaller pieces. This process is an important part of the cross section for reactions induced by high energy protons [1,2]. It is also seen in heavy ion collisions at projectile energies of the order of 20 MeV per nucleon and higher [3,4]. However, there has been little theoretical work to date on the breakup process itself in the region of its threshold. Our present understanding of fragmentation is quite limited, being guided primarily by the numerical results of time-dependent Hartree–Fock theory.

In this note we analyze the bulk dynamics of nuclear matter under various conditions of density and internal energy, as a theoretical framework for describing the onset of fragmentation. We begin with the relation between the energy per particle of nuclear matter, E, the particle number density n, and the excitation energy per particle I,

$$E = f(n) + I . \qquad (1)$$

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We call this the equation of state, although purists would reserve that designation for eq. (4) below. A typical example of an equation of state is given by the Skyrme parametrization,

$$E = 22.5(n/n_0)^{2/3} - 62(n/n_0)^2 + 23.5(n/n_0)^3 + I \text{ MeV}. \qquad (2)$$

This is graphed in fig. 1. The parameters have been adjusted to reproduce the binding energy of nuclear matter, $E = -16$ MeV when $n = n_0 \sim 0.16/\text{fm}^3$. The only additional information we need for the dynamics is the dependence of E on n at fixed entropy. In a non-interacting Fermi gas, the excitation energy behaves exactly the same way as does the total kinetic energy, i.e. it varies as the 2/3 power of the density under isentropic changes in state.

$$I(s,n) = I(s,n')(n/n')^{2/3} . \qquad (3)$$

In this respect, there is no difference between a Fermi gas and a classical Maxwell–Boltzmann gas of monoatomic particles. Some isentropes in the (n, E) plane are shown as dashed lines in fig. 1. The Skyrme interaction would modify the excitation energy of eq. (3) with an extra factor m/m^*, where m^* is the density-dependent effective mass. We suppose that $m \approx m^*$

Linear momentum transfer in nonrelativistic nucleus-nucleus collisions

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The systematic behavior of linear momentum transfer from projectile to target in nonrelativistic nucleus-nucleus collisions has been studied using the results of fission-fragment angular-correlation measurements on uranium target nuclei. Data for ^{4}He, ^{12}C, ^{16}O, and ^{20}Ne projectiles have been analyzed over an energy range which extends well above the interaction barrier. The data illustrate the division of the total reaction cross section into two primary components: one associated with $\sim$ 90 percent or greater linear momentum transfer and the other involving much smaller amounts of linear momentum transfer. The former is attributed to fusionlike collisions and the latter to peripheral collisions. The minimum between these two components corresponds to a linear momentum transfer of about 50 percent. It is observed that the ratio of fusionlike collisions to the total reaction cross section decreases regularly as a function of both increasing bombarding energy and projectile mass. From comparison of the experimental fission-fragment angular correlation functions with the predictions of complete fusion kinematics, it is shown that above 10 MeV/nucleon, the experimental definition of complete fusion is complicated by the increasing probability for large, but incomplete, linear momentum transfer collisions. Estimates of critical angular momenta derived from these data do not show any major disagreement with rotating-liquid-drop predictions.

NUCLEAR REACTIONS, FISSION Studied systematics of fission-fragment angular correlation measurements from uranium target nuclei. Deduced linear momentum transfer distributions, fusionlike collision and complete fusion probabilities, and critical angular momenta.

I. INTRODUCTION

A useful overview of the global features of nonrelativistic nucleus-nucleus collisions can be obtained from studies of the linear-momentum-transfer distribution which characterizes the target-projectile interaction. For reactions involving highly fissionable target nuclei, where essentially the total reaction cross section is accompanied by fission, information of this type is provided by measurements of the angular correlation between binary fission fragments.[1-8]

As illustrated schematically in Fig. 1, the separation angle between coincident fission fragment pairs, θ_{AB}, serves as an indicator of the linear momentum transferred from the incident projectile to the struck nucleus—thereby contributing to the understanding of the salient mechanisms which describe a given reaction. In the limit of complete linear momentum transfer, processes such as complete fusion yield fission fragments which are emitted with a unique separation angle $\theta_{AB}°$, defined by the momenta of the projectile and the primary fragments. At the opposite extreme, inelastic scattering

$M1$ strength in zirconium isotopes by proton inelastic scattering

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A broad resonance has been observed by inelastic scattering of 200 MeV protons from ^{90}Zr, ^{92}Zr, ^{94}Zr, and ^{96}Zr. This resonance has a sharply forward peaked angular distribution and an excitation energy and strength which strongly suggest that it is the $M1$ giant resonance. Microscopic distorted wave impulse approximation calculations match the shape of the angular distribution reasonably well. The strength, however, is only about 30% of that predicted.

[NUCLEAR REACTIONS ^{90,92,94,96}Zr(p,p'), $E=200$ MeV, measured $\sigma(\theta)$, DWBA analysis, enriched targets, deduced levels, resolution 70 keV.]

I. INTRODUCTION

The study of $M1$ states in nuclei allows the exploration of the nuclear spin degrees of freedom, which is interesting for a number of reasons.[1] The shell model predicts that there should be $M1$ states (1^+ in even-even nuclei) made when the spin of a particle in a j-unsaturated shell is flipped, i.e., $j=1+1/2 \rightarrow j=1-1/2$. The $M1$ strength is therefore a measure of the extent to which unsaturated spin-orbit-partner orbits are occupied in the nuclear ground state. Secondly, the $M1$ strength gives a check on the renormalization (due to core polarization and mesonic effects) of the magnetic charge (effective g factors).[2] This renormalization, until now, has been determined mainly from the study of magnetic moments. Thirdly, in scattering experiments the $M1$ strength allows, in principle, the determination of the spin-dependent components of the effective interaction between the nucleons in the projectile and the target. At small angles and at bombarding energies above 100 MeV/nucleon, where the $V_{\sigma\tau}$ component is dominant,[3,4] the strength should be particularly sensitive to this one component. Finally, since the one pion exchange potential involves spin and isospin transfer of one, and since the $V_{\sigma\tau}$ operator involves spin flip and isospin flip, the magnitude of this operator at large momentum transfers is important in determining the pionic interactions with nuclei and in particular whether or not a phase transition to a pion condensed phase can take place.[5,6]

Various shell model estimates give little variation in the predicted excitation energy of the $M1$ state,[1,7] but searches to locate it in targets having $A \geq 60$ using both inelastic electron[8,9] and inelastic proton[10,11] scattering have, until recently, proven unsuccessful. Recent observations,[12–14] in intermediate-energy (p,n) reactions on a number of targets, of a broad peak which has been identified as the giant Gamow-Teller (GT) state (in which $J^\pi=1^+$) have provided a clue for the search for the $M1$ transition in the parent nucleus. The fact that the GT state was more prominent at $E_p \geq 120$ MeV than at 45 MeV (Ref. 15) implied that the $V_{\sigma\tau}$ component of the effective interaction had increased relative to the other components, as is also suggested by the energy dependence of the nucleon-nucleon interaction.[4] This implies that the 1^+, $M1$ state, which is excited by means of this same component of the effective interaction, might also be more strongly excited at higher bombarding energies. Since the orbital angular momentum transfers involved in this $0^+ \rightarrow 1^+$ transition are zero and two, the cross section for the state should be peaked at 0° and fall off rapidly with angle. These considerations suggested a search for the $M1$ transition using inelastic scattering of high energy ($E>100$ MeV)

Gamow-Teller strength at high excitations

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A perturbative calculation is reported for the mixing of Gamow-Teller strength with two-particle two-hole configurations at high excitation energies. We find that roughly 50% of the Gamow-Teller strength is shifted into the region of 10–45 MeV excitation for the nucleus ^{90}Zr. This would explain a substantial part of the continuum background seen in the 200 MeV (p,n) reaction.

[NUCLEAR STRUCTURE ^{90}Zr, Gamow-Teller strength function, $E_{ex}=10$–45 MeV, theory.]

The recent elucidation of the giant Gamow-Teller state in heavy nuclei by the (p,n) reactions presents a paradox. There is a well-defined peak whose energetics is reproduced by the Tamm-Dancoff approximation (TDA) shell model theory,[1] but the strength is apparently less than half of the predicted value.[2,3] Part of the suppression can be ascribed to the Δ-isobar admixtures in the nuclear wave functions,[4–6] but part is undoubtedly due to conventional nuclear mixing.[6,7] For example in the case of ^{41}Sc, Towner and Khanna[6] found that more strength was depleted by ordinary nuclear configuration mixing than by the Δ amplitudes in the wave functions.

In this article, we will examine in some detail the distribution of the strength that is lost to the Gamow-Teller peak due to configuration mixing. Our motivation is the presence of excitation strength in the (p,n) reaction at 0°, for excitation energies ranging up to ~ 50 MeV above the Gamow-Teller peak.[3] We anticipate that much of this excitation strength is due to Gamow-Teller strength for the following reasons. The main other possibilities are multistep excitation, and excitation by operators with orbital dependence, e.g., $[Y_L(r)\sigma\tau_-]_J$. Multistep reaction cross sections characteristically rise with increasing excitation energy, due to the greater number of intermediate states possible for higher energy losses. However, the (p,n) reaction cross section falls with energy loss up to excitation energies beyond 50 MeV. This is clearly seen in the data of Gaarde *et al.*,[3] which we reproduce in Fig. 1. Furthermore, explicit calculation of multistep reaction cross sections indicates that single step should dominate at forward angles when the excitation energy is less than half the beam energy.[8] Concerning the possibility of single-step excitation with $L\neq 0$, we note that distorted-wave impulse approximation (DWIA) calculations of angular distributions predict that the 200 MeV (p,n) cross section increases with angle for all multipoles but $L=0$. The experimental angular distribution in the continuum region[9] is flat near 0°, indicating that $L\neq 0$ cannot dominate the 0° cross section. A model calculation of the continuum cross section which assumed no Gamow-Teller strength in this region, failed to reproduce the 0° continuum cross section by a factor of 3, while agreeing at larger angles.[10] In contrast to the (p,n) results, the model fit the angular distribution of the (p,p') reaction quite well, down to the lowest angles measured. More microscopic calculations of the continuum region have been made by Osterfeld,[11] who also finds that $L\neq 0$ multipoles are insufficient to explain the 0° cross section. The angular distribution[8] between 0° and 10° can be well fit as a sum of $L=0$, 1 and 2 multipoles.[12] According to the fit, roughly half of the 0° cross section for ^{90}Zr(p,n) at 30 MeV excitation energy is due to $L=0$.

Our calculation of the Gamow-Teller strength in the continuum will be based on second-order pertur-

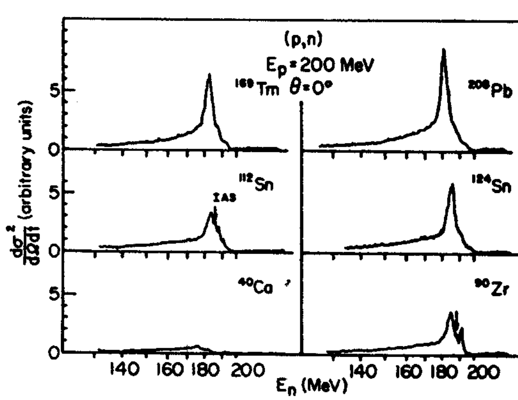

FIG. 1. Differential cross section for the (p,n) reaction at 200 MeV and 0° scattering angle, from Gaarde *et al.* (Ref. 3). Note the long tail at excitation energies above the Gamow-Teller peak, which is present only in the nuclei with neutron excesses.

Low energy particles produced in heavy ion reactions

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A model is presented for the low energy spectrum of nucleons produced in small impact parameter heavy ion reactions. Special attention is paid to the effects of the Coulomb force which not only gives rise to an energy shift but also to a sideward focusing. Calculated angular distributions are compared with high multiplicity selected events in the Ne on U reaction at 393 MeV/nucleon.

[NUCLEAR REACTIONS U(Ne,x) at 400 MeV/nucleon, calculated $\sigma(\theta)$ for emitted neutrons and protons at energies < 50 MeV.]

Considerable attention has recently been focused on the reaction Ne on U at 400 MeV/nucleon[1]; in particular, it has been suggested that the high multiplicity selected data might show some evidence for collective phenomena. These arguments are based primarily on the angular distributions of protons at low energies. However, Coulomb forces and source velocities influence the proton spectra significantly in this energy regime. It is the purpose of this Communication to show that the high multiplicity selected data now available, including side-peak features and neutron-proton ratios, is consistent with a schematic model that involves little more than conservation laws, the long range Coulomb force, and a simple geometry based on two sources. We find that the spectra of the lowest energy protons places strong constraints on the mass, velocity, and excitation energy of the portion of the system from which they come.

Our assumptions concerning the collision geometry are based on the following observations: For high multiplicity selected events the most probable impact parameter is one for which all the nucleons in the projectile can collide with target nucleons, i.e., $b_0 \simeq R_T - R_P$ where R_T and R_P are the target and projectile radii. For the case of Ne on U this amounts to $b_0 \simeq 4$ fm. Smaller impact parameters will contribute less to the total cross section for geometrical reasons, whereas for larger impact parameters the multiplicity of the event will decrease. We shall consider here only collisions of a small projectile with a much larger target nucleus. Collisions of this kind at the impact parameter b_0 will involve on the order of half the target nucleons directly.

Our model is therefore to assume two portions in the excited system, roughly though not literally, associated with the traditional participant-spectator division. Both parts are moving in the laboratory and both parts are excited. It is envisioned that the part directly involved (referred to as hot) is excited to high excitation energy in the early stages of the collision. The remaining part (referred to as cold) acquires both its momentum and excitation from energetic nucleons coming from the hot portion. The final spectra, especially those at low energies, are then obtained as a sum of the particles coming from these two sources, taking the acceleration and deflection by the Coulomb field into account.

The number of particles in the hot part will, in general, be larger than in a purely participant-spectator approach since during the initial stages of the collision process nucleons will scatter away from the beam direction, thereby involving more nucleons of the target than those on the path of the initial projectile. For this reason, this number has been kept as a free parameter in the model. A sharp boundary is assumed between the cold and the hot part. In order to avoid introducing additional parameters the boundary is taken to be a plane. It is assumed that in the initial stage of the collision all the kinetic energy of the projectile is shared by all the nucleons in the hot part and that the cold part is affected in a secondary manner. To describe this the plane boundary between the two parts is taken to be tilted by an angle β with respect to the beam axis (see Fig. 1). For $\beta = 0$ the cold part is not involved. In our approach

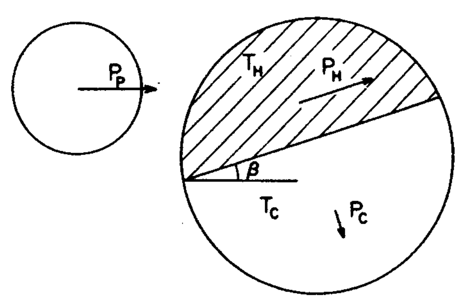

FIG. 1. Sketch of the geometry used, as explained in the text.

Comparison of alpha spectroscopic factors on ^{24,26}Mg: The (^{14}N, ^{10}B) reaction

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Cross sections for states populated in the ^{24}Mg(^{14}N, ^{10}B)^{28}Si and ^{26}Mg(^{14}N, ^{10}B)^{30}Si reactions at 83 MeV were measured. Equal strengths for population of ^{28}Si and ^{30}Si ground states were observed, in contrast to (^{16}O, ^{12}C) and (^{12}C, ^{8}Be) reactions, but in agreement with (^{6}Li, d) results and with theoretical predictions.

[NUCLEAR REACTIONS ^{24}Mg (^{14}N,^{10}B), ^{26}Mg (^{14}N,^{10}B), $E = 83$ MeV; measured $\sigma(\theta)$.]

I. INTRODUCTION

Several measurements of alpha-spectroscopic factors between the ground states of ^{24}Mg-^{28}Si and ^{26}Mg-^{30}Si have been carried out in the past few years with widely varying results. Measurements of the ratio of spectroscopic factors via the $(\alpha,2\alpha)$ reaction[1] are in good agreement with shell model predictions,[2] but in poor agreement with (^{12}C, ^{8}Be) (Ref. 3) and (^{16}O,^{12}C) (Ref. 4) reactions. Unpublished results[5] for ^{26}Mg(^{6}Li,d)^{30}Si at $E_{\rm Li}=36$ MeV observe the ground state spectroscopic factor (and peak cross section) to be nearly equal to that from the ^{24}Mg(^{6}Li,d)^{28}Si reaction at the same incident energy[6] — a result which is in good agreement with the shell model predictions. In order to try to pin down this discrepancy and, in particular, to look for substantive problems in the description of the different reactions as one-step direct alpha transfer, we have investigated the relative ground-state yields to ^{28}Si and ^{30}Si via the (^{14}N,^{10}B) reaction on ^{24,26}Mg. The ^{26}Mg(^{14}N,^{10}B)^{30}Si reaction has been shown[7] to be adequately described by distorted wave Born approximation (DWBA) calculations at 70 MeV, giving an indication that the reaction mechanism is direct. An earlier study of the relative ground state yields for the two reactions at 70 MeV proved inconclusive due to insufficient statistics.[8]

II. EXPERIMENTAL PROCEDURE AND RESULTS

Beam currents of up to 1.5 μA of 83 MeV ^{14}N were obtained from the Texas A&M 88 inch cyclotron and were used to bombard ~ 100 μg/cm^2 targets of isotopically enriched ($>99\%$) ^{24}Mg and ^{26}Mg on thin carbon backings. Reaction products were observed in the focal plane of an Enge split-pole spectrograph using a 1.2 m detector[9] with mass and charge identification derived from energy loss information and particle rigidity. Transfer reaction cross sections were measured at 8°, 9°, and 10°. The ^{12}C(^{14}N,^{10}B)^{16}O reaction[10] was used for calibration. The backing on the Mg targets provided reference peaks since the cross sections are a factor of 10 larger than for either Mg isotope. Unfortunately, the mass resolution was insufficient to completely resolve ^{10}B from ^{11}B. This did not prove a problem with the ^{24}Mg target, where the ^{11}B yields were less than half those for ^{10}B. However, this introduced large backgrounds with the ^{26}Mg target which produced ^{11}B's at a rate ten times that of the ^{10}B's. The large leak-through of ^{11}B's resulted in considerable uncertainty in yields for the ^{26}Mg target and prohibited extraction of yields for ^{30}Si excited states.

Relative cross sections were obtained by using the dead time corrected charge integration. Repeated runs showed a reproducibility of better than 3%. The products of target thickness and solid angle needed for calculating absolute cross sections were obtained by measuring elastic scattering cross sections and simultaneously fitting the normalization and the optical model parameters with the code ECIS.[11] Different parameter sets[7,12] were compared to establish the uncertainties of the procedure. The overall normalization is estimated to have an uncer-

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Theoretical interpretation of the Gamow-Teller strength in the $^{42}Ca(p,n)^{42}Sc$ reaction

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We have calculated the Gamow-Teller strength of the $^{42}Ca(p,n)^{42}Sc(1^+)$ reaction using the Kuo-Brown wave function. This shell model calculation together with the Δ isobar quenching mechanism accounts for the Gamow-Teller strength.

[NUCLEAR STRUCTURE Shell model, reaction matrix, GT strength, Δ isobar polarization.]

Recently, Goodman *et al.* have performed a (p,n) experiment on ^{42}Ca with the proton energy $E_p = 160$ MeV.[1] In their neutron forward angle spectrum ($\theta = 0°$) they found a strong peak at the excitation energy $E_x = 0.6$ MeV and very weak strengths at higher excitation energy. All these peaks were identified as $J^\pi = 1^+$ states due to the strong preference of spin-isospin excitation of high energy proton.[2,3] This data has to be contrasted with the 0° neutron spectrum of the $^{48}Ca(p,n)^{48}Sc$ reaction, where most of the Gamow-Teller (GT) strength is found in the region between $E_x = 5$–10 MeV and only $\sim 20\%$ of that is seen at the lowest 1^+ state.[4] All heavier nuclei studied so far show the same features in the Gamow-Teller strength function as is seen in ^{48}Sc.

In order to understand this result on ^{42}Sc, Goodman *et al.* suggest that the ground state of ^{42}Ca might be more nearly characterized by $L = 0$, $S = 0$, and $T = 1$ [U(4) symmetry] than is implied by $(f_{7/2})^2 J = 0$.[1] This is because the operation of the Gamow-Teller operator, $\sum \sigma\tau_-$, on the U(4) symmetry state yields only the $L = 0$, $S = 1$, and $T = 0$ state and nothing else, as is found in the experiment. It is true that the eigenfunction taking into account the realistic aspects of shell model such as the large spin-orbit splitting between the $f_{5/2}$ and $f_{7/2}$ states do show the tendency to the U(4) symmetry.[5] However, this happens only at a qualitative level.[5] Therefore, we have asked if this conventional shell-model approach can provide a reasonable explanation for the concentration of the GT strength in the lowest 1^+ state.

For this purpose, we take the wave functions calculated by Kuo and Brown (KB) for the $0f$-$1p$ shell nuclei.[6] These wave functions are derived from a Hamiltonian based on the Brueckner G matrix derived from the nucleon-nucleon interaction, and have demonstrated a satisfactory description of these nuclei. Reference 6 derived the G matrix from the Hamada-Johnson potential, but the use of more recent potentials such as the Reid or Paris potentials does not change the G-matrix elements appreciably.[7,8] Furthermore, the core polarization graph is taken into account for the open shell effective interaction as the most important correction to the bare reaction matrices. We prefer these KB matrix elements over the interaction[9] which is used in Ref. 1.

Let us first look at the ground state wave function of ^{42}Ca. (See Table 2 in Ref. 6.) Out of the five configurations in the model space spanned by $f_{7/2}, f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2}$, the $(f_{7/2})^2$ configuration is dominating ($\sim 86\%$) and the $(f_{5/2})^2$ configuration is about 4% sharing about the same probabilities with the others. Therefore, the wave function is far from that of $L = 0$, $S = 0$, and $T = 1$, which demands about equal amplitudes for $(f_{7/2})^2$ and $(f_{5/2})^2$; i.e., 57% and 43%, respectively.

Coming to the 1^+ states, we have seven states for $T = 0$ and three states for $T = 1$. Kuo and Brown do not tabulate all their wave functions, so we have reconstructed them by diagonalizing the Hamiltonian constructed from the interaction matrix elements given in Appendix 3 of Ref. 6. We find the Gamow-Teller strength to be distributed over the eigenstates as shown in Table I. The lowest 1^+ state takes almost the full strength among the $T = 0$ states. The rest is distributed among four states with $T = 0$ distributed between $E_x = 4$–9 MeV. Hence, as far as $T = 0$ states are concerned, the Kuo-Brown wave functions provide correct features as to the concentration of the GT strength to the lowest 1^+ state. The use of the interaction employed in Ref. 1 gives essentially the same result. If we take overlap between this lowest 1^+ state with the U(4) symmetry state, it comes out $|\langle (L = 0, S = 1)J = 1 | \text{lowest } 1^+ \rangle|^2 = 0.64$. It means even if the ^{42}Ca ground state had the U(4) symmetry, about 36% of the GT strength would be distributed among higher 1^+ states. In fact, the $T = 1$ states carry the GT strength of 0.84, which is shared by two very close states at 9.5 MeV. Note that the sum of the GT strengths does

Cross section of the capture reaction $^3He(\alpha,\gamma)^7Be$

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The cross sections for the astrophysically significant reactions $^3He(\alpha,\gamma)^7Be$ and $^4He(^3He,\gamma)^7Be$ have been measured near 900 keV in the center of mass by measuring the activity of ^7Be produced in a gas cell. The results imply a zero-energy cross-section factor $S(0)$ of 0.63(4) keV b, consistent with the larger of previous measurements. Extant values of $S(0)$ are reviewed and a recommended value for use in stellar evolution calculations is presented.

NUCLEAR REACTIONS $^3He(\alpha,\gamma)^7Be$, $^4He(^3He,\gamma)^7Be$, $E_{c.m.}=897$ keV, measured σ, deduced astrophysical capture cross section.

I. INTRODUCTION

The reaction $^3He(\alpha,\gamma)^7Be$ is a link in the chain of reactions leading to ^8B in the interior of the sun and other hydrogen-burning stars.[1] Since ^8B is responsible for most of the neutrinos observable in the experiment of Davis,[2] there is great interest in the recent experiment of Kräwinkel *et al.*,[3] who reported cross sections for $^3He(\alpha,\gamma)^7Be$ almost a factor of 2 lower than those found in previous work.[4,5] Adopting their value significantly reduces, but does not entirely remove, the discrepancy between the predicted neutrino flux[1] and the experimental result.[2]

It appears that there is no significant disagreement about the energy dependence of the cross section and that it is only the normalization that is in question. In an effort to resolve the discrepancy, we have undertaken a measurement at a single energy (900 keV in the center of mass) using a method well suited to a reliable determination of the absolute cross section. A cell containing ^3He (^4He) is bombarded with ^4He (^3He) for a known integrated flux and the resulting ^7Be is assayed with a detector of known absolute efficiency. The technique is independent of the angular distribution of capture radiation and of its disposition between cascade paths. Furthermore, an accurate determination of the target thickness is easier than it is for windowless gas targets.

II. EXPERIMENT METHOD

Three identical gas cells were used: one was filled with ^3He and bombarded with ^4He; the second was filled with ^4He and bombarded with ^3He; the third was filled with ^4He and bombarded with ^4He. This last cell was used for beam tuning and to check the radiochemical purity of the construction materials. The cells were mounted on a post having rotational and up-down translational freedom in a scattering chamber. The beam entered the chamber through a 4-jaw slit located 56.2 cm from the center of the cell, and was in every irradiation limited to 240 nA ($^3He^+$ or $^4He^+$) in order to avoid damage to the Ni entrance windows of the cells. The beam spot size was set to 0.28 by 0.28 cm at the slit, and care was taken to illuminate the slit aperture uniformly to avoid destructive localized heating of the entrance windows. Figure 1 shows a schematic drawing of the gas cell.

The energy of the beam delivered by the vertical Van de Graaff accelerator at the Los Alamos National Laboratory was determined by magnetic analysis. In a test run immediately prior to the experiments reported herein, the calibration of the analyzing magnet was checked against the 3.046-MeV resonance[6] in $^{16}O(\alpha,\alpha)^{16}O$ and was found to be accurate to within the 10 keV uncertainty of the measurement.

The number of beam particles incident on the target was determined by elastic scattering from a gold foil placed 0.48 cm in front of the entrance window of the cell. Elastically scattered particles were detected in a Si surface barrier detector mounted in an extension tube connected to the vacuum chamber. A tantalum collimator 0.638 cm in diameter defined the solid angle subtended by this detector to be $1.310(5)\times 10^{-4}$ sr. The distance from the gold foil

Multiplicity selection in high-energy heavy-ion collisions

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The effect of multiplicity selection on coincident single-particle distributions has been simulated for a "2π" multiplicity detector for several well-defined hypothetical events. It is shown that, in some instances, the single-particle distributions may be significantly distorted by the phase-space constraints of the multiplicity selection. The reaction ^{20}Ne + U at $E/A=400$ MeV has been simulated using a full fireball calculation which incorporates the kinematic effects of multiplicity selection. The calculation does not reproduce the recently observed enhanced sidewards emission of light particles.

NUCLEAR REACTIONS ^{20}Ne+U at $E/A=400$ MeV; Monte Carlo simulation of detection process, fireball model, multiplicity selection.

I. INTRODUCTION

The current experimental direction in the study of relativistic nuclear collisions is increasingly toward multiparticle coincidence measurements. This is largely due to the fact that single-particle inclusive cross sections are dominated by phase-space effects and are, as a consequence, rather insensitive to more detailed assumptions of various models. Coincidence studies are expected to provide more specific information about the structure of the final state and to discriminate between conflicting models. It is hoped that the coincidence requirement will emphasize some dynamic aspect of the final state without being dominated by kinematic phase-space restrictions. In order to interpret coincidence results meaningfully, it is therefore important to be aware of the kinematic constraints imposed by the coincidence requirement.

We have investigated the kinematic effects which can arise for particle multiplicity-selected events detected by a multiplicity detector of large solid angle. The response of a "2π" charged-particle multiplicity detector[1,2] has been simulated for several hypothetical types of high-energy nuclear events, including the fireball model[3,4] for the case of ^{20}Ne+U at $E/A=400$ MeV, which has been investigated experimentally by Stock *et al.*[1]

In Sec. II we describe the details of the model and the detector arrangement used in the present simulation. In Sec. III the results of the full fireball model simulation are presented, as well as results illustrating the effect of multiplicity selection on several simplified types of events. Our conclusions are presented in Sec. IV.

II. DETAILS OF THE CALCULATION

A. Kinematical and dynamical correlations

We wish to consider the n-particle decay of a system of A_0 nucleons with total charge Z_0, momentum $\vec{P}_0$, and excitation energy E_0. We characterize an event by the variables a_i, z_i, and $\vec{p}_i$ $(i=1,n)$ which refer to the baryon number, charge, and momentum of each of the n particles in the decaying system. If we assume that the single-particle distributions are independent with no dynamic correlations, but are subject only to the constraints of conservation of energy, momentum, charge, and baryon number, then the n-particle distribution function can be written as

$$F(\{a_i,z_i,\vec{p}_i\})=\prod_{i=1}^{n} f(a_i,z_i,\vec{p}_i) \times\delta(E-E_0)\delta(\vec{P}-\vec{P}_0) \times\delta_{AA_0}\delta_{ZZ_0}\,, \quad (1)$$

where $f(a_i,z_i,\vec{p}_i)$ is the single-particle distribution function for a particle of momentum $\vec{p}_i$, charge z_i, and baryon number a_i. The δ functions ensure the conservation requirements with

Strengths of transitions between 0^+ and 1^+ states and their relationship to inelastic electron scattering form factors: Example of ^{24}Mg

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The strengths of transitions in $A=24$ between $J^{\pi}=1^+$, $T=1$ states and the lowest $J^{\pi}=0^+$ states of $T=0$ and 2 are calculated from shell-model wave functions constructed in the full eight-particle $0d_{5/2}$-$1s_{1/2}$-$0d_{3/2}$ configuration space. The model Hamiltonian is an empirical interaction which yields a good accounting of the energies of intra-*sd*-shell states throughout the $A=17-39$ region. With these same wave functions the (e,e') form factors for the magnetic dipole excitation of ^{24}Mg to its lowest five states of $J^{\pi}=1^+$, $T=1$ are calculated in the plane-wave Born approximation. The predicted form factors and the associated predictions for $B(M1)$ and B (Gamow-Teller) are compared to existing experimental values.

NUCLEAR STRUCTURE Predicted strengths of isospin-changing $M1$, Gamow-Teller, and (p,n) transitions between $J=0^+$ and 1^+ states in ^{24}Mg and form factors for ^{24}Mg(e,e'); shell-model wave functions, complete *sd*-shell basis space, universal *sd*-shell Hamiltonian.

INTRODUCTION

Inelastic electron scattering measured at 180° yields definitive information about the fundamental $M1$ mode of nuclear excitations.[1,2] The excitation energy of the $M1$, or the related Gamow-Teller, "giant resonance" provides basic constraints upon the form of the effective interaction between nucleons in the nucleus. This has motivated extensive experimental work directed towards mapping this phenomena across the periodic table. While $M1$ strength in heavier nuclei has proved difficult to detect,[3] strong $M1$ transitions have been observed in most even-mass *sd*-shell nuclei.[4–9] Recently, the magnitudes of these excitations have become of increasing interest as constituting possible evidence for the participation of the nucleon-isobar mode in ostensibly nuclear excitations.[10–12] In attempting to isolate the effects of such an "unconventional" mechanism in distinction from the possible effects of several other more conventional processes, all of which can alter the observed total $M1$ excitation strength from the simplest theoretical expectations, it is essential that the conventional processes be examined with the greatest possible precision.

Our aim is to delineate as completely as possible the effects of configuration mixing within the orbitals of a single major shell upon the $M1$ excitation process. To this end we examine the case of ^{24}Mg. This example is advantageous in several respects. The shell-model wave functions for this region of nuclei have been checked to confirm that they reproduce the complete range of spectroscopic features with good accuracy. Since the selection rules for $M1$ excitation confine the transition amplitudes to lie within the *sd*-shell space, the present full-space wave functions can encompass the complete giant resonance strength. The density of states is low enough that the dominant portion of the strength is concentrated into the lowest few 1^+ levels, which facilitates both calculation and comparison to experiment. From the aspect of experimental knowledge, there are measurements of gamma and beta decay strengths involving these states and of their excitation probabilities via the (e,e') and (p,n) (proceeding to the isobaric analog states in ^{24}Al) reactions. Correlations between these data make possible detailed analysis of the structure of the transitions and of the validity of the shell-model wave functions with which we attempt to model them. Finally, the location of ^{24}Mg within the *sd*-shell is such that the system can serve as a paradigm for heavier systems, so that our conclusions may have some implications for the general case of $M1$ excitation. We shall examine the sensitivity of the predicted features of $M1$ excitation to the details of the shell-model wave

Gamow-Teller strength in the continuum

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We present the results of a decomposition of the angular distribution of the continuum observed in the ^{90}Zr(p,n) reaction at 200 MeV into different angular momentum transfers. We found significant amounts of $L=0$ strength over a wide range of excitation energies in the continuum, which sums up to more than half of the missing Gamow-Teller strength.

[NUCLEAR REACTIONS Continuum Gamow-Teller strength in (p,n) reaction.]

Recently a simple model has been proposed[1] for the continuum part of the spectra as observed in medium energy proton scattering. This model, which considers the quasielastic scattering from the nuclear surface, is in good quantitative agreement with the data for 800 MeV (p,p').[2] For 200 MeV (p,n) on ^{90}Zr (Ref. 3) the same model calculation underpredicts the cross section at forward angles by about 2.0 mb/sr MeV at an excitation energy of 30 MeV. At larger angles ($\theta > 15°$) the calculation agrees with experiment. This discrepancy at forward angles might imply that the continuum contains a considerable amount of $L=0$ transfer strength in addition to a real "background" due to quasielastic scattering. Since only about 30–40% of the Gamow-Teller (GT) strength (about 55% if all the cross sections under the GT peak are included[4]) is identified in the peak region,[5] the remaining fraction could be hidden in the background. In this Brief Report we will present an empirical estimate of the continuum strength, based on the measured angular distribution in the continuum.

In order to be more quantitative we have made a decomposition of the experimental angular distribution into several angular momentum transfer components, using the distorted-wave Born approximation (DWBA) angular distributions for individual L transfers. The optical model parameters were taken from Ref. 6, and we used as a form factor the derivative of a real Woods-Saxon potential with $V=10$ MeV, $R_0=1.15$ fm, and $a=0.16$ fm. At the momentum transfers ($q \leq 70$ MeV/c) in which we are interested, we can neglect the tensor force in the direct channel. The strength of the tensor force in the exchange channel is, however, highly uncertain. A strength comparable to that taken in Ref. 7 does not significantly alter the shape of the angular distributions. Since our results do not depend on an overall normalization factor, we have neglected the tensor force altogether. Because only $L=0$ peaks at 0° the unfolding procedure works reasonably well for assigning the $L=0$ strength.

We have made two different fits to the data. In the first we have fitted the excess cross section over the predicted quasielastic background at $E_x=30$ MeV with a sum of $L=0$, 1, and 2 angular distributions. As is shown in Fig. 1, this fit reproduces the data at all angles. In the second approach we fitted the experimental cross section as a sum of $L=0$, 1, and 2 but disregarded the quasielastic background. Since the $L=2$ angular distribution falls off sharply beyond $\theta=10°$, we considered only the data at $\theta < 10°$ in our fit. Both procedures resulted in the same amount of $L=0$ cross section, which is about 40% of the total cross section at $\theta=0°$. Since the latter method is independent of the model of the background, we repeated the same analysis also at $E_x=15$ and 45 MeV. We found almost the same $L=0$ spectroscopic strength at these energies, although the actual $L=0$ cross section at 0° is falling sharply with increasing excitation energy. We should note here that the extraction of the $L=0$ strength at higher energies

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NUCLEON SCATTERING FROM LIGHT NUCLEI
(I). The targets ^{6}Li and ^{7}Li *

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Abstract: New data for the elastic and inelastic scattering of 24.4 MeV protons from ^{6,7}Li are presented and a summary of all the available data for the elastic, inelastic, and charge exchange scattering of 24–50 MeV protons from these same targets is given. The cross-section data for $E_p \simeq 25$ and 50 MeV are examined theoretically within the framework of the microscopic folding model and the distorted-wave approximation. Standard p-shell wave functions, supplemented by renormalization factors deduced from electromagnetic and β-decay data, are used to describe the target nuclei in these calculations. Results obtained using a phenomenological 1 fm range Yukawa interaction illustrate the information on proton-neutron differences contained in the data for quadrupole transitions in ^{7}Li and differences in the energy dependence of the spin-flip and non-spin-flip isovector central components of the effective interaction contained in the data for the (p, n) reaction on this same target. Results obtained with the more realistic G-matrix interaction of Bertsch *et al.* give a reasonable description of the overall features of the experimental data after 20–60 % reductions in the strengths of its varous components are made. The calculations fail to provide a consistent picture of the energy dependence of the optical potential and the quadrupole transition potentials. Some difficulties are also encountered in describing the cross sections for scattering to the 0^+, $T = 1$ level in the mass-6 systems.

1. Introduction

Although many studies of the (p, p), (p, p′) and (p, n) reactions on p-shell nuclei with $E_p \lesssim 50$ MeV were reported in the late 1960's and early 1970's, the available experimental data are still incomplete and no consistent theoretical analysis of the existing data has been carried out. In view of the current interest in heavy-ion

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LIGHT PARTICLE CORRELATIONS IN INTERMEDIATE ENERGY HEAVY ION COLLISIONS

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Abstract: Various light particle coincidence techniques will be reviewed that were employed to study the emission of energetic light particles in nucleus-nucleus collisions at energies above 10 MeV/nucleon. Several reaction mechanisms have been shown to contribute to the emission of energetic light particles, ranging from the sequential statistical decay of excited projectile residues, direct breakup and knock-out reactions, to multistep emission processes that can be rather well described in terms of the concept of local thermal equilibrium.

1. Introduction

Nucleus-nucleus collisions at energies significantly above the Coulomb barrier are generally accompanied with the dissipation of large amounts of the incident kinetic energy into more complex degrees of freedom. As a consequence, the emerging nuclei are highly excited and decay by the emission of light particles and γ-rays or by fission. At low energies, the emission of light particles occurs predominantly after full statistical equilibrium of the intrinsic degrees of freedom has been attained by the primary reaction products. With increasing energy, particle emission prior to the attainment of full statistical equilibrium is expected to become important.

Some of the characteristics of light particle energy spectra observed at beam energies above 10 MeV per nucleon are illustrated in Fig. 1. Part a of the figure

Emission of Energetic Light Particles: Energy Dependence of Spectral Shapes

Moving Source Parameterization

$$\frac{Ed^2\sigma}{p^2 dp d\Omega} = N_o \gamma(E-\beta p\cos\theta)\exp[-\gamma(E-\beta p\cos\theta)/T]$$

$$E = (p^2+m^2)^{1/2}$$

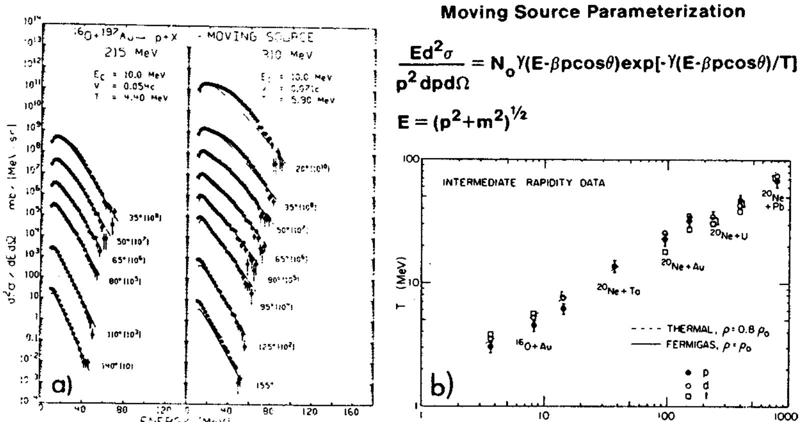

FIG. 1. a) Proton cross sections measured[1]) for the reaction $^{197}Au(^{16}O,p)$ at 215 and 310 MeV. The solid lines correspond to thermal emission from a moving source. b) Energy dependence of moving source temperatures[2]) extracted from single-particle inclusive cross sections.

Nuclear Physics A388 (1982) 1–18

SYSTEMATICS OF THE EXCITATION OF M1 RESONANCES IN MEDIUM HEAVY NUCLEI BY 200 MeV PROTON INELASTIC SCATTERING

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Abstract: In a series of seventeen nuclei ranging from ^{51}V to ^{140}Ce, broad resonance structures are observed at energies between 8 and 10 MeV, nearly mass independent. These resonances have very forward peaked angular distributions which imply that they are populated by an angular momentum transfer of zero. This together with the observed excitation energies suggests an M1 character for these resonances. In ^{51}V, ^{58}Ni, ^{60}Ni, ^{62}Ni, a sharp peak located at an excitation energy above the threshold for neutron emission is interpreted as a part of the T_0+1 component of the M1 resonance. Cross sections are given for all the M1 resonances. For ^{58}Ni, ^{90}Zr, ^{92}Mo, ^{120}Sn and ^{140}Ce, an "attenuation" factor for the cross sections is extracted in a DWIA calculation assuming simple shell-model structures for these resonances.

E | NUCLEAR REACTIONS ^{51}V, ^{58,60,62}Ni, ^{68}Zn, ^{90,92,94,96}Zr, ^{92,94,96,98,100}Mo, ^{120,124}Sn, ^{140}Ce(p, p'), $E = 200$ MeV; measured $\sigma(\theta)$. ^{51}V, ^{58,60,62}Ni, ^{68}Zn, ^{90,92,94,96}Zr, ^{92,94,96,98,100}Mo, ^{120,124}Sn, ^{140}Ce deduced resonances, Γ, T, M1 character. DWIA calculations.

1. Introduction

Although M1 states are well known in light nuclei [1]), there has been doubt as to their distribution in medium and heavy nuclei. In ^{90}Zr and ^{140}Ce, for example, where strong resonances were observed around 9 MeV in electron inelastic scattering [2,3]), more recent work [4,5]), with better energy resolution, has revealed much M2 strength but only a few narrow M1 states. In contrast, charge exchange (p, n) reactions performed on many targets ranging from ^{40}Ca to ^{208}Pb [refs. [6,7])] show the excitation of the giant Gamow-Teller resonance, which is the antianalog of the M1 resonance; in some nuclei, the analog of the M1 transition could be separated. The experiments performed with

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PROTON EXCITATION OF THE M1 RESONANCES IN THE Ni ISOTOPES

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Abstract : The giant M1 excitation has been studied by inelastic scattering of 200 MeV protons from the four isotopes ^{58,60,62,64}Ni. In all the isotopes, structures assigned to the T_0 and the T_0+1 components of the M1 resonance are excited ; their relative strengths are compared with those obtained in (ee') and (γγ') experiments when available. The strength of the isovector part of the M1 resonance in ^{58}Ni is compared to theoretical predictions.

1. Introduction

The recent studies of spin excitations in nuclei[1]) through Gamow-Teller transitions in charge-exchange reactions, in inelastic scattering and resonant scattering experiments have proved to be extremely interesting. By comparing results obtained with different probes one can expect to get information on the interactions and on the nuclear models.

The 200 MeV proton beam of the Orsay synchrocyclotron and the experimental set up, which allows measurements at extremely forward angles, are particularly suited to the study of M1 resonances[2,3,4]). We report here new results obtained on the excitations of the M1 resonance in the four isotopes ^{58,60,62,64}Ni performed with better energy resolution and better statistics than in ref.3. The experimental set up and data analysis method have been given elsewhere[3,5]).

2. Experimental results and discussion

The Ni targets were all isotopically enriched to more than 95%. The excitation energies ranging from 3 to 19 MeV were studied at 4 and 6° for ^{58,60,62}Ni and at 3, 4, 5, 6, 7 and 9° for ^{64}Ni. The experimental spectra taken at 4° for the four Ni isotopes are given in fig.1.

In all isotopes, a broad and very fragmented structure is observed, located between 6 and 9.5 MeV in ^{58}Ni and between 6 and 11 MeV in ^{60,62,64}Ni. Some peaks are clearly seen in the energy range from 10 to 15 MeV, but their number decreases with increasing A ; in the four Ni isotopes a very sharp peak is excited with an energy increasing with A but with an intensity decreasing with increasing A.

The bumps located between 6 and about 10 MeV show clearly resolved peaks, as well as some structures which are the superposition of two or three unresolved peaks and broad structures which cannot be decomposed. The contribution of the underlying continuum has been obtained by giving to the well resolved peaks the shape of the elastic peak measured under the same experimental conditions. Some peaks (8.66 MeV in ^{58}Ni, 9.05,9.40,9.80 in ^{60}Ni) have a differential cross section decreasing more rapidly with angle than the theoretical differential cross section for a $\Delta L = 0$ transition; they do however decrease in agreement with a curve computed for the coulomb excitation of an E1 transition[3]) . In the low energy region some peaks have a cross section increasing with angle, corresponding to angular momentum transfers greater than zero ; these peaks were subtracted from the cross sections reported.

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AN EFFECTIVE INTERACTION FOR INELASTIC SCATTERING DERIVED FROM THE PARIS POTENTIAL

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Abstract: An effective interaction for inelastic scattering of nucleons from nuclei is derived by fitting oscillator G-matrix elements of the Paris nucleon-nucleon potential to the matrix elements of a sum of Yukawa terms. Except for the singlet-odd channel, these G-matrix elements do not differ in any significant respect from those obtained from the Reid soft-core potential, and give similar results for inelastic proton scattering.

1. Introduction

Some years ago, effective interactions for inelastic scattering of nucleons from nuclei were derived by Bertsch *et al.* [1]) from the phenomenological nucleon-nucleon (NN) potentials of Hamada and Johnston [2]) and Reid [3]). The derivation proceeded in two stages: the G-matrix elements of these potentials in an oscillator basis were first obtained, and then fitted to a sum of Yukawa terms. The effective interactions thus calculated were appropriate for use in nucleon scattering codes and have been applied to several inelastic nucleon scattering studies at bombarding energies up to about 65 MeV [refs. [4–6])]. A particular choice of the interaction which has come to be known [4]) as M3Y has been especially popular.

The purpose of the present paper is to describe a similarly motivated effective interaction derived from the Paris NN potential [7]), an analytic form for which has recently been published [8]). The medium- and long-range parts of this potential are based upon a meson theory of nuclear forces, while the short-range part is fitted phenomenologically. The Paris potential is thus based on a more fundamental theory of the NN interaction than the earlier potentials. Moreover, new NN scattering data obtained in the 1970's went into the development of this potential. The Reid soft-core potential is based on earlier and partially erroneous phase-shift data in the singlet-odd, triplet-even and spin-orbit-even channels [9]); and it has a much stronger tensor part than the Paris potential [10]). It is of interest to study whether these differences in the basic NN potential lead to any significant changes in the effective interaction.

The G-matrix elements that we obtain in the course of the derivation of the

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ENTROPY AND COMPOSITE PARTICLE PRODUCTION

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Abstract: The application of entropy to composite particle production in nucleus-nucleus collisions is reviewed. More entropy is generated in high energy nuclear collisions than is predicted from bulk dynamics, due to the surfaces which are effectively quite thick. The measured production of deuteron-like clusters agrees with theory based on independent nucleon dynamics. The entropy concept may also be useful at low energies to help characterize the breakup of nuclei. We find the region of instability of nuclear matter as a function of energy and density. We suggest that the unstable region is reached in nuclear reactions by an isentropic expansion of overstressed nuclear matter.

One of the important observable processes in collisions between nuclei is the equilibration of the combined system. We can ask whether the system comes to a local equilibrium, and if it does, we can try to characterize the properties of that equilibrium. If an equilibrium is established, the venerable principles of statistical mechanics are at our disposal for describing the equilibrium. At a qualitative level, it is clear what happens in a high energy heavy ion collision. As the nuclei interpenetrate, the collisions between particles cause the combined system to fly apart. Initially there would be a large random component to the particles' velocities, which we would describe by a temperature. As the particles move outward, their velocity vectors become more and more oriented in the radial direction with a reduced random component. In thermodynamic terms, the nuclear gas cools, with thermal energy converted to collective flow energy in the radial direction. This behavior is depicted in fig. 1, showing schematically the temperature and volume of the system as a function of time. At some point, marked by the dashed line in the figure, collisions between the particles cease. The measurable characteristics of the system become frozen at this point. I drew fig. 1 to emphasize that a thermodynamic analysis of the system in terms of temperature and volume is not easy, because both these variables change rapidly with time.

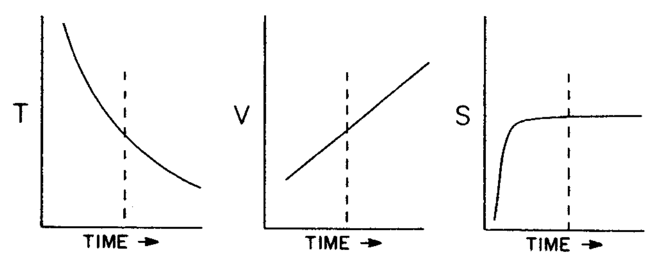

Fig. 1

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NEW RESULTS AT INTERMEDIATE ENERGIES

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Abstract: Recent experimental results on light particle emission from intermediate energy nucleus-nucleus collisions are reviewed. Present, mostly single particle inclusive measurements are consistent with the concept of thermalization of a subset of nucleons. The measurement of thermally produced composite light particles is hoped to provide more specific information about the decay properties of hot nuclear matter and a possible liquid gas phase transition.

I. Introduction

Over the last few decades, nuclear physics had its major focus on detailed spectroscopic studies of nuclei at low excitation energies, generally not exceeding a few tens of MeV. The availability of nuclear projectiles covering a large range of mass and energy provides a unique opportunity to explore the statistical and dynamical properties of strongly interacting many body systems at considerably higher excitation energies. Efforts to investigate the global properties of hot and dense nuclear matter present a marked deviation from the more traditional field of nuclear spectroscopy. It has become clear, by now, that this exciting task will be quite difficult - both from the experimental and the theoretical points of view.

Little is known about the thermodynamic properties of nuclear matter, except for the binding energy ($E_B \simeq 16$ MeV) and incompressibility ($K \approx 210$ MeV) at normal nuclear density ($\rho_0 \approx 0.15$ fm^{-3}). Experiments in the laboratory are confined to small ensembles of nucleons ($A \leq 500$). Even if highly excited states of statistical equilibrium can be achieved for such ensembles, they would immediately decay by particle emission due to the large surface area. Inferences about the thermodynamic properties of nuclear matter, therefore, have to rely on a solid understanding of these decay processes.

Up to now, the decay of statistical nuclear ensembles by particle emission has mainly been treated in two extremes. For low energy nuclear reactions, the decay of the compound nucleus can be quantitatively understood in terms of the Hauser-Feshbach theory[1]). This theory corresponds to particle evaporation from the liquid phase of nuclear matter. Thermodynamic approaches at higher energies[2-4]), on the other hand, have been based on the assumption of an expanding gas of nuclear matter in thermodynamic equilibrium. The equilibrium distribution of this hot nuclear gas is then assumed to be "frozen" out, once the density has decreased to the freeze-out density ρ_f, below which collisions between the gas constituents become negligible.

It is only recently, that the possible coexistence of the gas

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PROSPECTS OF INTERMEDIATE ENERGY NUCLEAR COLLISIONS

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Abstract: We focus on central nuclear collisions--"multifragmentation events"--in the energy range 20-400 MeV/n. They seem well suited to study bulk properties of nuclear matter at moderate entropies. Various ways of extracting information on the produced entropy are discussed. We emphasize the importance of medium mass fragment production for this goal. The consequences of a first order liquid-vapor phase transition at low densities $\rho<\rho_0$ are pointed out--the release of latent heat results in an increase of the entropy at energies $E_{LAB} \lesssim 200$ MeV/n. It is pointed out that a minimum in the mass distribution is indicative of the onset of condensation. Such a minimum has indeed been observed in multifragmentation events. The medium energy reactions also provide an enhanced sensitivity to the stiffness of the nuclear equation of state at high densities $\rho>\rho_0$. This is discovered in a 4π exclusive energy flow analysis performed on the basis of the nuclear fluid dynamical model. A strong bombarding energy dependence of the flow effects is predicted, which is not found in cascade simulations. The flow analysis can also be used to reveal the presence of a high density abnormal state via a characteristic change of the flow pattern at a critical bombarding energy.

The availability of the 84 MeV/n ^{12}C-beam at CERN and heavier beams at LBL have only recently enabled first exploratory experiments[1-14]) on nuclear collisions at intermediate energies. One of the most challenging motivations for doing these experiments is the opportunity to study nuclear matter at other than ground state densities and at moderate temperatures and entropies[6,15-18]). Over this medium energy regime, we expect a transition from the mean field phenomena typical of low energy reactions to two (and more) nucleon collisions for high energy reactions[6,15-18]). Fig. 1 shows the reaction dynamics as predicted by a quantal, mean field TDHF calculation[16]) compared to the semiclassical, macroscopic nuclear fluid dynamical model[15,16]). The latter assumes that the incident nucleons

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MULTIBODY FINAL STATES OF THE ^{6}Li+^{6}Li REACTION AT 97 MeV†

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Absolute coincidence cross sections were measured for the reactions ^{6}Li+^{6}Li → 3α, ^{6}Li(^{6}Li, 2α), and ^{6}Li(^{6}Li, 2d), where the latter two represent N-body ($N \geqq 4$) final states. Broad peaks from the ^{6}Li(^{6}Li, 2α) reaction are well described by a double spectator pole (DSP) model utilizing a Hulthén wave function, whereas near 40 MeV the DSP peaks are much narrower than predicted. A broad peak in the 3α final-state spectrum, attributed to a single-spectator pole (SSP) process, is well described with the same wave function. The SSP is the principal mechanism for the 3α reaction, in contrast to data near 40 MeV which show that sequential decay from ^{8}Be levels is dominant.

E | NUCLEAR REACTIONS ^{6}Li+^{6}Li → 3α, ^{6}Li(^{6}Li, 2α), ^{6}Li(^{6}Li, 2d), $E = 97.5$ MeV; measured $\sigma(\theta_1, \theta_2, E_1, E_2)$; deduced reaction mechanisms. Single, double spectator pole models.

1. Introduction

There have been several investigations of the ^{6}Li+^{6}Li reaction producing either the 3α final state, or four-or-more-body final states, at bombarding energies up to 50 MeV. Not only do these studies fail to give us a unified picture of these different multibody final states, and whether they are populated by similar reaction mechanisms; they do not even determine unambiguously the mechanisms responsible for the individual reactions.

For example, studies [1]) of ^{6}Li+^{6}Li → 3α at 2 to 13 MeV were interpreted as showing that the reaction proceeds by a single-spectator pole (SSP) process

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The charge and matter distributions of ^{208}Pb

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Abstract. The best available data on the charge and matter distributions of ^{208}Pb are analysed using (*a*) a Woods–Saxon potential, (*b*) a Hartree–Fock potential based on Skyrme interactions and (*c*) a combination of the two, Woods–Saxon for the surface region and Skyrme–Hartree–Fock for the interior. The single-particle energies and tail densities (or RMS radii) of the valence orbitals are also analysed. The agreement between experiment and theory obtained with potential (*c*) is much better than with (*a*) or (*b*).

1. Introduction

The charge distribution of ^{208}Pb is of particular interest because experimentally it has one of the most accurately measured form factors and because of the doubly magic and spherical nature of this nucleus which makes the theoretical calculations comparatively easy. Moreover there is considerable experimental information from hadron scattering related to the matter (the sum of the point proton and point neutron) densities and from sub-Coulomb one-nucleon transfer reactions related to the properties of the tail densities of the valence orbitals.

We are still a long way from understanding these data starting from first principles, that is from a many-body theory in which the only inputs are the interactions between the nuclear constituents. However, much can be understood qualitatively from phenomenological models which attempt to make predictions for and relationships between observables based on a few underlying parameters. With the models presently available there are several features which have not been well understood. The single-particle potential derived from a realistic finite-ranged nucleon–nucleon interaction should be non-local or, equivalently, energy dependent. The experimental single-particle energy levels, on the other hand, are much closer to what is expected for a simple local potential. Also the charge density is expected to exhibit oscillations due to the shell structure associated with the magic number 82, whereas the experimental charge density shows much less structure.

The goal of this work is limited to the study of what refinements, if any, can be made to

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High-resolution measurements of isotope shifts and hyperfine structure in stable and radioactive lead isotopes

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Abstract. We present new measurements of isotopic shifts and hyperfine structure in the lead resonance line for a total of 15 isotopes. The experimental accuracy is of order 4 MHz. Using independent measurements of the nuclear parameter λ for the stable isotopes we have derived λ for all measured isotopes. The derived values of λ are compared with various theoretical predictions for the lead nuclei. We also give values for the nuclear magnetic dipole and electric quadrupole moments deduced from our measurements.

1. Introduction

Optical spectra are a source of information on the properties of the atomic nucleus, and have historically been very important in our understanding of the nucleus. Optical isotope shift measurements are used to study changes of nuclear size, while the hyperfine splitting of spectral lines is used to determine nuclear moments. One great advantage which optical methods have over others is their great sensitivity. Whereas, for example, scattering experiments typically call for milligram samples of enriched isotopes, optical methods require much smaller quantities, and can thus be extended to radioactive isotopes of which only minute quantities can be prepared. We have used a laser spectroscopic method to study a series of stable and unstable lead isotopes. Lead has been of particular interest in isotope shifts studies since the early days of spectroscopy (e.g. Kopfermann 1932) and recent work has included two-photon measurements (Lindgren *et al* 1981), atomic beam laser spectroscopy (Hüffer 1982) and absorption studies of some radioactive species (Moscatelli *et al* 1982). There is a long chain of lead isotopes which can be studied by off-line techniques and this gives information on changes of nuclear mean-square charge radii as well as on nuclear moments. Several independent measurements of the charge radii of the stable isotopes are available for calibration of the isotope shift data. The variation of the charge radii in lead is of particular interest because it enables us to test critically theoretical models in the region of a double shell closure (^{208}Pb), where calculations are physically very instructive. For comparison with the experimental results one can either adopt a microscopic approach in order to calculate the nuclear densities, or use a macroscopic approach such as the droplet model (Myers 1977).

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PHYSICAL REVIEW C

NUCLEAR PHYSICS

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Proton capture to excited states of ^{16}O: $M1$, $E1$, and Gamow-Teller transitions and shell model calculations

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We have measured excitation functions of the γ rays resulting from the bombardment of ^{15}N by polarized and unpolarized protons in the energy range $E_p = 2.5-9.5$ MeV with emphasis on identifying dipole decays to the first (0^+) and second (3^-) excited states in ^{16}O. Resonances in γ_{12} are observed at $E_x = 16.21$, 16.45, 16.82, 17.12, 18.03, 18.98, 19.90, and 20.41 MeV. The 16.21 and 17.12 MeV resonances in γ_{12} are identified as $M1$ decays of the 1^+ $T=1$ states to the 6.05 MeV 0^+ state in ^{16}O. The measured ratio of reduced strengths $B(M1,\gamma_1)/B(M1,\gamma_0)$ is 0.48 ± 0.03 for decays from the 16.21 MeV state and 0.55 ± 0.04 for decays from the 17.12 MeV state. The 18.03 MeV resonance is due to a 3^- $T=1$ state in ^{16}O with a strength $\Gamma_p \Gamma_{\gamma_2}/\Gamma = (1.96 \pm 0.27)$ eV and the 18.98 MeV resonance is due to the 4^- $T=1$ stretched particle-hole state with a strength of (0.85 ± 0.10) eV. We determine absolute particle and γ widths for these states. The $M1$ γ_2 width of the 18.98 MeV state, (7.1 ± 3.1) eV, is in agreement with a shell-model calculation. Resonances in γ_3 are observed at 16.82 and 17.27 MeV and in γ_4 at 17.88 MeV. The excitation energies and widths of these levels as well as the strengths of the γ transitions suggest a $T=1$ character for all of the resonances for which capture γ rays are observed. Correspondences of our resonances to levels in ^{16}N are given. Strong α_1 branches for many of these states indicate isospin impurities. We compare γ widths, including ground-state $M1$ decays, and allowed β transition rates in $A=16$ nuclei with shell model calculations and obtain rough agreement with the experimental results. Additional shell model calculations for $M1$ and Gamow-Teller decays in the $A=14$, 15, 17, and 18 nuclei are presented, which indicate that Gamow-Teller matrix elements are quenched by $\sim 20\%$ relative to shell model predictions and also relative to the spin part of the $M1$ matrix elements.

NUCLEAR REACTIONS $^{15}N(p,\gamma)^{16}O$, $^{15}N(p,p'\gamma)^{15}N$, $^{15}N(p,\alpha_1\gamma)^{12}C$, $E=2.5-9.5$ MeV, measured capture γ rays to $E_x = 6.05$, 6.13, 6.92, and 7.12 MeV final states. Measured $\sigma(90°)$, $A_y(90°)$, $\sigma(\theta)$. Deduced $M1$ and $E1$ resonance strengths. Performed shell model calculations and compared with these and other $M1$ and Gamow-Teller strengths in nuclei near $A=16$. Deduced average inhibition of GT matrix elements relative to shell model and to the spin part of $M1$ matrix elements.

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THE PULSE-HEIGHT CORRECTION TECHNIQUE FOR IMPROVING γ-RAY SPECTRA FROM COAXIAL Ge DETECTORS

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We demonstrate that the pulse-height correction technique can be used for coaxial as well as planar Ge γ-ray detectors. Pulses from the detectors are analyzed according to their rise-times, and an improved spectrum is obtained by correcting the incompleteness of charge collection, using the relation between rise-time and pulse-height defect. Geometrical effects in coaxial detectors require at least a three-parameter correlation, in which the rise-times of the pulses are analyzed for two time segments. We have been able to improve the energy resolution of neutron-damaged Ge detectors by more than 50% and their peak-to-Compton ratios by almost as much, all without significant loss in detector efficiency.

1. Introduction

The pulse-height correction (PHC) technique [1] is a means by which one can improve both the energy resolution and the peak-to-Compton ratios of γ-ray spectra taken by Ge detectors. To do so, one performs a detailed analysis of the rise-times of the pulses coming from the detectors. In general, the pulses having slower rise-times are associated with damaged or defective portions of the detector; consequently, these pulses suffer from incomplete charge collection. Thus, merely by "throwing away" such slower rise-time pulses, one can immediately improve the resolution, albeit with a significant loss in detector efficiency.

With PHC one can circumvent this loss in efficiency in the following manner: the spectra can be sorted into bins or slices as a function of the pulse rise-time. If a correlation can be found between the rise-time and the degree of incompleteness of charge collection, then a correction can be made to compensate for the incompleteness of charge collection. Each bin or slice can be corrected in turn, and many or most of the corrected slices can be reassembled to produce an improved spectrum characteristic of a superior detector. And this can be done without any significant loss in detector efficiency.

As might be expected, the PHC method produces its most dramatic results with Ge or Ge(Li) detectors whose resolution has deteriorated, most often because of neutron damage. For such detectors we have obtained resolutions improved by 40–50% – and this was done more or less routinely, using electronics that are available in most nuclear science or counting laboratories. For pristine, state-of-the-art, highest-resolution intrinsic Ge detectors, results from the PHC technique are much less dramatic – indeed, they can become marginal to the point that it is not worth the bother of applying the technique. However, most laboratories have γ-ray detectors that are no longer of the highest quality, yet which are too good to discard or to send back for refurbishing. Since the PHC technique is basically a straightforward process, it can be quite useful in improving the quality of the spectra obtainable from these middle-quality detectors.

In our initial paper [1] we applied the PHC technique primarily to spectra obtained with planar detectors. Most planar detectors tend to be rather small, and in planar detectors the electric field is basically uniform; therefore, essentially all the variation in rise-time of a pulse of given energy can be attributed to traps or inhomogeneous portions of the detector. As a result, the correlation between rise-time and pulse-height defect is linear, and a simple one-parameter correction is sufficient to correct the spectra.

In this paper we extend our procedures to spectra produced by coaxial detectors. In coaxial and trapezoidal detectors (or detectors of more complex geometry) the rise-time of the pulse is affected strongly by the position where the electron–hole pair is created, much more so than in a small planar detector. This variation in rise-time is geometrical in origin and can occur even with

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ON THE FEASIBILITY OF AXIAL INJECTION IN SUPERCONDUCTING CYCLOTRONS *

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In connection with the superconducting cyclotron program at MSU a feasibility study of axial injection, aimed mainly at the K-800 cyclotron, has been carried out.

The results encompass all major aspects of a working system, i.e. center region, injection trajectories and phase space matching. It is shown that axial injection is indeed feasible, although problems exist not ordinarily encountered in conventional AVF cyclotrons.

The possible solutions and limitations are presented and discussed in detail.

1. Introduction

A large amount of research and development has been carried out recently in various laboratories, concerning new types of heavy ion sources for accelerators. Noteworthy results have already been reported for EBIS [1] and ECR [2] sources. Both of these sources, although using quite different physical principles, aim at producing high charge states for light–medium, and more in perspective, very heavy ions.

Even though a substantial development work must still be carried out, the results so far obtained are very encouraging. In particular, it looks like the ECR source is already at the stage where high charge states of ions up to mass ≈ 40 can be produced with reasonable intensities. This fact has enticed several laboratories with AVF cyclotrons [3–7] to provide themselves with such sources which will be used via an axial injection system.

In connection with the superconducting cyclotron program at MSU, we have undertaken a feasibility study of axial injection into superconducting cyclotrons. Axial injection at moderate injection voltages (tens of kV at most) seems in fact the most practical way to use these sources also in superconducting cyclotrons. The advantages of such source with respect to the conventional PIG sources seem, on paper, impressive enough in terms of either intensities or high charge states to warrant such a study.

The goal of the present investigation was not to produce a detailed design of an actual axial injection system, but rather to identify the main physical problems and find out realistic solutions. The peculiar characteristics of superconducting cyclotrons, like the very high magnetic fields, limited clearances in the center etc., suggest in fact that problems may be more complex than those already solved in conventional AVF cyclotrons.

In the process we have obtained results which do have a general validity and should therefore hold for any superconducting cyclotron where axial injection is attempted. It is the purpose of this paper to present them in some detail.

* This material is based upon work supported by USDOE, under contract DE-ACO2-80ER10579.

2. General outline

This study has been mostly connencted with the K-800 cyclotron, whose design parameters are extensively reported elsewhere [8]. For the sake of clarity, fig. 1 shows the operating diagram of the cyclotron in the (B_0, q/A) plane, B_0 being the center field value and q/A the charge to mass ratio of the ion accelerated. In this context we have chosen the following two representative ions:

- a fully stripped light ion, $q/A = 0.5$, with a center field B_0 of 34.6 kG, which corresponds to an energy of 200 MeV/n;
- a high charge state (46^+) uranium ion, at a center field B_0 of 47.5 kG, with a final energy of 45 MeV/n.

As will be apparent later, the analysis of these two cases encompasses, at least from the point of view of magnetic field properties, most of the machine operating range.

The axial injection scheme is presented in fig. 2 just to show the physical dimensions involved. Since a detailed analysis of the single components and their pur-

Damping of nuclear excitations

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The authors review the theory and the empirical evidence of damping of simple nuclear excitations. The excitations considered are the particle states and vibrational states. The particle damping phenomena include the fragmentation of single-particle levels, the systematics of neutron strength functions, and the optical absorption of elastic scattering. Information on the known collective vibrational states is summarized and compared with theory. A theoretical model that has found considerable success is based on a damping mechanism in which the simple excitations mix with the surface vibrations. This implies that the surface damping dominates for excitation energies below about 15 MeV. There is a close relation between the single-particle damping and the damping of collective vibrations. However, the vibrational damping is strongly suppressed by the coherence between the particle and the hole. While the model reproduces many of the observed features of the data rather well, it tends to underpredict the spreading width by as much as a factor of 2. Thus other degrees of freedom, not well understood at present, may play a role in the damping.

CONTENTS

I. INTRODUCTION

Nuclear structure physics aims at an understanding of the damping of simple nuclear excitations such as that found in single-particle states and collective vibrations. The subject is an old one, beginning with Bohr's picture of the nucleus as a highly overdamped system, the compound nucleus (Bohr, 1936). Later, elastic neutron scattering experiments showed that single-particle motion could persist across the diameter of the nucleus; this led to the first quantitative description of damping, the optical model. By now we have a thorough knowledge of the single-particle motion, not only from elastic scattering but also from spectroscopic studies with transfer reactions, and to some extent from inelastic scattering reactions. The study of nuclear vibrations also had an early beginning, dating from the discovery of the giant dipole resonance in the photoabsorption cross section. In recent years inelastic scattering experiments have unveiled a rich variety of vibrations of different types. All these vibrational modes are characterized by the quantum numbers of orbital angular momentum, spin angular momentum, and isospin. The vibrations are observed as peaks in the energy distribution of inelastic scattering, peaks from which the mean energy, the strength, and the damping width are extracted.

The properties of a nuclear excitation can be most conveniently discussed in terms of its strength function, defined as

$$S(E)=\sum_i \langle i \mid \mathcal{O} \mid o \rangle^2 \delta(E-E_i)\ . \quad (1)$$

Here $\langle i \mid \mathcal{O} \mid o \rangle$ is the matrix element of the operator

The Nuclear Response Function

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These lectures present the theory of the nuclear response in the Random Phase Approximation (RPA). In the first lecture, various relations are derived between densities and currents which give rise to the well-known sum rules. Then RPA is derived via the time-dependent Hartree theory. The various formulations of RPA are shown: the configuration space representation, the coordinate space representation, the Landau theory of infinite systems and the RPA for separable interactions constrained by consistency. The remarkable success of RPA in describing the collective density oscillations of closed shell nuclei is illustrated with a few examples. In the final lecture, the $\sigma\tau$ response is discussed with the application of simple theoretical considerations to the empirical data. Finally, we point out several problems which remain in the response theory.

§ 1. Introduction

These lectures will present the theory of the nuclear response function, aimed toward students learning the techniques for calculating the vibrational properties of nuclei. The response function measures how the one-body observables for the nucleus change in the presence of external fields. We define the response function in terms of the external field V and the one-body operator O to be measured as

$$R(V, O, \omega) = -\sum_i \left(\frac{\langle 0|O|i\rangle\langle i|V|0\rangle}{E_i-\omega} + \frac{\langle 0|O|i\rangle\langle i|V|0\rangle}{E_i+\omega} \right). \quad (1)$$

Here we label the eigenstates of the nucleus by i, with energies E_i. The energy transferred by the external field is ω. In principle, $R(\omega)$ contains all the information one needs about the vibrational energies and the transition strengths. The theory which has proven to be the most useful for calculational purposes is RPA.*) This has many formulations, which are more or less convenient depending on the application. In the general theory of the response, sum rules play an important role, because they provide a firm point of knowledge about the response function. In the first lecture I will discuss

*) The name Random Phase Approximation (RPA) was coined by Pines and Bohm.[1]

Noncompound Light Particle Emission in Nucleus–Nucleus Collisions

Present experimental results of noncompound light particle emission are consistent with the concept of statistical equilibrium for a subset of nucleons. By studying the energy dependence of composite light particle emission, one may eventually obtain information about the transition between the liquid and gas phases of nuclear matter.

INTRODUCTION

Over the last few decades, nuclear physics research has been primarily focused on detailed spectroscopic studies of nuclei at low excitation energies, generally not exceeding a few tens of MeV. Still, few facts about the global properties of nuclear matter have been established beyond its binding energy ($E_B \simeq 16$ MeV) and incompressibility ($K \simeq$ 210 MeV) at normal density ($\rho_0 \simeq 0.15\ \mathrm{fm}^{-3}$). Efforts to study strongly interacting many body systems at considerably higher excitation energies and to obtain information about the properties of hot and dense nuclear matter present a marked deviation from the more traditional field of nuclear spectroscopy. Experiments in the laboratory are confined to small ensembles of nucleons ($A < 500$). Even if highly excited states of statistical equilibrium can be prepared in the laboratory, they would immediately decay by particle emission because of the large surface area of such small ensembles. Inferences about thermodynamic properties of nuclear matter therefore must rely on a solid understanding of these decay processes.

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Dynamics of Medium Energy Nuclear Collisions

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Abstract

Recent theoretical attempts to study high energy heavy ion reactions are reviewed. Special emphasis is given to the description of the dynamical evolution and to the production of pions and light fragments in the collision. Evidence for a collective quasi-hydrodynamic flow behaviour of compressed nuclear matter is presented. We show that the pion yield is sensitive to the nuclear equation of state and to the viscosity in hot dense nuclear matter. A 4π exclusive flow analysis of intermediate energy nuclear collisions can be used to reveal the compressibility coefficient of nuclear matter.

1. Introduction

The interest in central high energy heavy ion reactions is based on the unique opportunity to form and investigate large pieces of nuclear matter at high density and temperature. Topics of interest include the nuclear compressibility and sound velocity, the nuclear equation of state and possible phase transitions at high densities, $\rho \gtrsim 3\rho_0$ (pion condensation, density isomers, quark matter) and at low densities, $\rho \lesssim 5\rho_0$ (the liquid gas phase transition from the strongly interacting nuclear fluid into the observed free gas of light nuclear fragments). Ab initio calculations for these complex reactions are not feasible up to date; hence we will discuss various theoretical models developed to describe such collisions, which are presented in the first section. The production of pions and light fragments is discussed in the second chapter together with measurements of the temperature and entropy. In the third part of the paper the results of microscopic and macroscopic calculations are compared and confronted with recent data. The last chapter focuses on event-by-event analysis of collisions in 4π geometry. Kinetic flow, sphericity and flatness are discussed.

2. Theoretical models for the dynamics of the collision

2.1. *The time-dependence Hartree–Fock (TDHF) method*

This microscopic quantal theory neglects the collisions between individual nucleons – the nucleon wave functions collide with the average nuclear potential only, i.e., with the self-consistent mean field. This model is appropriate for the description of nuclear collisions at low and intermediate energies, $E_{\mathrm{LAB}} \lesssim 100$ MeV/n, but it breaks down at higher energies, where the Pauli principle loses it's importance.

Figure 1 shows a TDHF-calculation [1] of the reaction $^{12}\mathrm{C} + {}^{197}\mathrm{Au}$ at $E_{\mathrm{LAB}} = 30$ MeV/n.

The different impact parameters exhibit different reaction mechanisms: In the central collision, $b = 1$ fm (left hand side of the figure) we observe the emission of Fermi-jets or PEP's [2] with a broad spread in the velocity of the outgoing nucleons. The intermediate impact parameter shows in addition to the forward emitted PEP's a large projectile residue being captured by the target nucleons. These are typical "incomplete fusion" or "massive transfer" events as discussed intensively at this meeting. At the higher energies, $E_{\mathrm{LAB}} \sim 80$–100 MeV/n, our TDHF-calculations [1,3] yield a complete shattering and fast

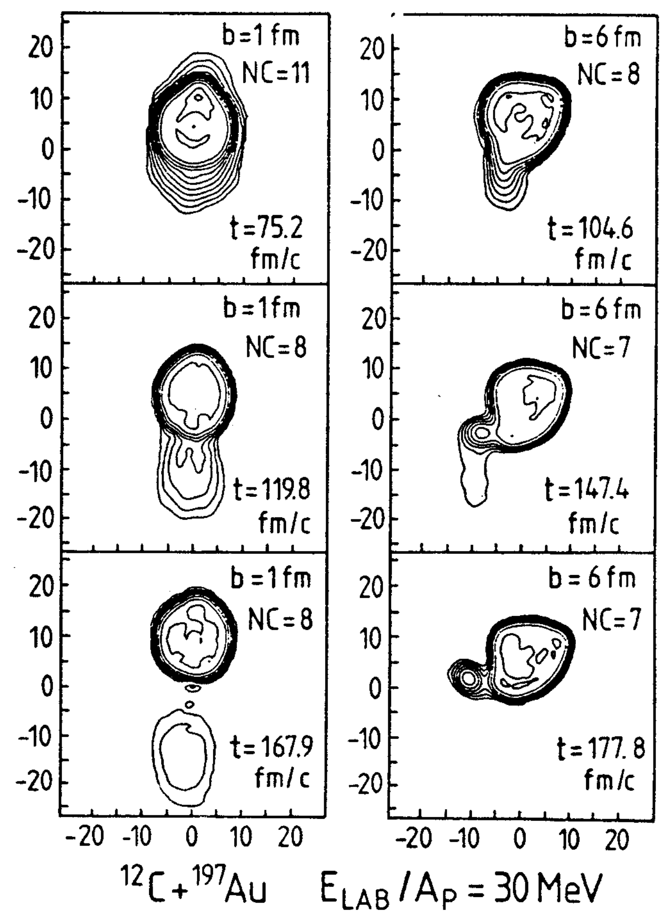

Fig. 1.

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Collective Phenomena in Relativistic Nucleus-Nucleus Collisions*

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Abstract

Recent theoretical attempts to study high energy heavy ion reactions are reviewed. Special emphasis is given to the description of the dynamical evolution and to the production of pions and light fragments in the collision. Evidence for a collective quasi-hydrodynamic flow behaviour of compressed nuclear matter is presented. We show that the pion yield is sensitive to the nuclear equation of state and to the viscosity in hot dense nuclear matter. A 4π exclusive flow analysis of intermediate energy nuclear collisions can be used to reveal the compressibility coefficient of nuclear matter.

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Energy Dependence of Light Particle Emission from Intermediate Energy Heavy Ion Collisions

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Abstract

High energy nucleus-nucleus collisions can provide a unique method of studying nuclear matter at densities and excitations far from the normal ground state. In these collisions a source can be identified with a velocity intermediate between the projectile and target velocities as well as sources that can be associated with decay of excited projectile and target nuclei. The study of light particle spectra (p, d, t and alpha) associated with this intermediate source can provide information on the equation of state of nuclear matter. Results are presented for O and Ne induced reactions on heavy targets ranging in energy from 9 to 800 MeV/nucleon. Analysis of these light particle data in terms of a single moving source model leads to a consistent description of a system in thermodynamic and chemical equilibrium. Extracted d/p and t/p ratios are almost independent of incident energy while the alpha/proton ratio increases dramatically at low bombarding energies.

An important concept in high energy nucleus–nucleus collisions is the formation of a highly excited, localized region of participant nucleons moving with a velocity intermediate between the projectile and target velocities. The study of this zone as a function of incident projectile energy can provide information about the behavior of nuclear matter at densities and excitations far from the normal ground state. Specifically one can study the equation of state of nuclear matter and perhaps observe phenomena such as phase transitions and flash temperatures.

In Fig. 1 two different visualizations are shown for the interaction of two high energy nuclei. In the fireball model [1] it is assumed that the interaction of the two nuclei occurs on a sufficiently short time scale that the reaction is localized to the overlapping volume of the nuclei. One further assumes that the two overlapping regions undergo a completely inelastic collision in which the kinetic energy of the projectile volume is completely transformed into internal excitation forming a highly excited and compressed system of nuclear matter. In the hydrodynamic model [2], as the projectile approaches the target nucleus, pressure is built up in the interaction region until the projectile bounces off at an angle leaving behind an intermediate, excited region and an excited target remnant. In both cases there is an identifiable intermediate velocity source. This intermediate source is the subject of this paper.

An obvious property of this intermediate region, which can be systematically studied, is its disassembly into pions, nucleons, and light nuclei. In a thermodynamic description assuming both thermal and chemical equilibrium [3] in the intermediate system, the temperatures and relative abundances of the emitted fragments are predicted to vary smoothly with incident energy. If one introduces an equation of state incorporating compression, a discontinuity in the temperature and a sudden increase in the production of nucleons relative to light nuclei can be predicted to occur near a critical temperature termed the flash temperature [4]. Thus by studying a wide range of incident energies and resulting temperatures one can possibly observe properties of the nuclear matter equation of state.

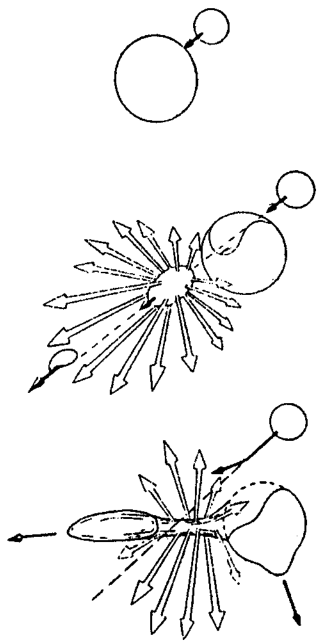

Fig. 1. Two different models for high energy nucleus–nucleus reactions. The fireball model is depicted in (a) [1] and the hydrodynamical model is depicted in (b) [2].

The range of interesting incident projectile energies reaches from 9 MeV/nucleon up to 800 MeV/nucleon. This range spans energies from just above the coulomb barrier up to energies where pion production becomes significant. Velocities range from far below the fermi velocity up to relativistic velocities many times the speed of sound in nuclear matter. Until recently, a gap has existed in the available data above the energies of current cyclotrons (approx. 30 MeV/nucleon) and below the lowest easily available energies at the Bevalac (approx. 200 MeV/nucleon). Presently this region is being studied at the CERN Synchrocyclotron (SC), at SARA, and at the Bevalac Low Energy Beam Line. In the near future, heavy ion induced measurements in this energy range will be available from GANIL, the MSU K500 Cyclotron, and Saturne II. The data considered here are double differential cross-sections for p, d, t, and alphas emitted in the reactions of O + Au at 9, 13, and 20 MeV/nucleon [5], Ne + Ta at 43 MeV/nucleon [6], Ne + Au at 100 amd 156 MeV/nucleon [7], Ne + U at 241 and 393 MeV/nucleon [8], and Ne + Pb at 800 MeV/nucleon [9].

The first question that must be answered in the study of this intermediate zone is its isolation from contributions resulting

SECTION IV

THESIS TITLES

(JULY 1, 1982 TO JUNE 30, 1983)

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Finck, Joseph E.	A Study of ^{206}Pb by Inelastic Scattering of 35 MeV Protons
Ledebuhr, Arno George	Experimental Studies of Isobaric Quintets
Narayanaswamy, Janaki	A Study of the Gamow Teller Strength in $^{40,42,44,48}Ca$ from the (p,n) Reaction at 120 MeV
Radhi, Raad Abdul-Karim	Calculations of Elastic and Inelastic Electron Scattering in Light Nuclei with Shell-Model Wave Functions

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M.S. Thesis

Angius, Silvana P.	Fast Fragment Emission in Nuclear Collisions

Department of Chemistry

M.S. Thesis

Wernig, Sue	Masters by course work