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Final Report

Investigation of the possibility of using Nuclear Magnetic Spin Alignment

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Background

A concept for "Gasdynamic Fusion Propulsion System for Space Exploration" (Reference 1) has been theoretically investigated at the University of Michigan for the Department of Energy. An experiment to determine the feasibility of this concept is currently being pursued at MSFC by Bill Emrich. The goal of this program is to develop a fusion propulsion system for a manned mission to the planet Mars. Several significant technological hurdles stand between this concept and flight hardware. Most, if not all, these hurdles for this concept stand on the problem of when the deuterium and tritium atoms under fusion, the resulting neutrons and alpha particles are emitted in random directions (isotropically). The probable direction of emission is equal for all directions. This results in most of the energy being wasted, massive shielding and cooling requirements, and serious problems with the physics of achieving fusion.

These problems could be alleviated if the atoms could be induced to undergo fusion and emit the neutrons and alpha particles with a preferential direction. The neutrons and alpha particles are always emitted in exactly opposite directions due to conservation of momentum. If the nuclear magnetic spin moments of the deuterium and tritium nuclei could be precisely aligned at the moment of fusion, the stream of emitted neutrons could be directed out the rear of the spacecraft for thrust and the alpha particles directed forward into an electromagnet to produce electricity to continue operating the fusion engine. This would result in the shielding and radiant cooling requirements being reduced to practically zero. The only thrust exhaust from the spacecraft would be electrically neutral neutrons, thus preventing charging of the spacecraft. Also, in this configuration, extraction of energy from the fusion process would be almost 100%.

Alignment of the nuclear magnetic spins of atoms occurs every day in hospitals around the world. The very useful diagnostic technique, NMR (Nuclear Magnetic Resonance) uses a magnetic field to precisely align the orientation of atomic nuclei in a patients body. The interaction of the magnetic field of the NMR machine and the nuclear magnetic spin of the nuclei causes the affected nuclei to align their spins in a precise direction. Radio frequency energy is applied, causing the spins of the nuclei to reverse orientation, or "flip". A sensor detects this spin flip and precisely locates the position of the atom whose spin has flipped.

The concept of using a magnetic field to align the nuclear magnetic spins of atoms is a common practice. A magnet with a magnetic field of the proper orientation could be located near the interaction region where the atoms undergo fusion in the spacecraft propulsion system. The nuclear magnetic spins of the deuterium and tritium nuclei would be oriented in the proper position to direct all the neutrons rearward as thrust and the alpha particles forward to generate electricity. Approximately 80% of the energy in fusion is released as the kinetic energy of the neutron, the other 20% of the energy is carried by the alpha particle. Less than 10% of this generated electrical power would be required to sustain continued operation of the fusion engine. If this technique could be applied to fusion propulsion, a manned mission to Mars could be a near-term possibility.

Introduction

In the gasdynamic fusion propulsion concept described in Reference 1, the 17.6 MeV of kinetic energy produced by the fusion of deuterium and tritium nuclei appears as a 14.1 MeV neutron and a 3.5 MeV alpha particle. Some of this energy manifests itself in the form of bremsstrahlung and synchrotron radiation, which eventually appears as heat and must be disposed of by a space radiator cooling system. The material mass of the required space radiator is estimated by dividing the total thermal power produced in the fusion engine by the power radiated per unit mass of the radiator. This is frequently assumed to be 5 MW/metric ton.

For a fusion system described in Reference 1 which utilizes a superconducting magnet with a total current density of 250 MA/m^2 , a deuterium and tritium plasma density of 10^{17} cm^{-3} at a temperature of 20 kev that exits through a 3 cm nozzle producing thrust, then the space radiator for such a spacecraft propulsion system would have a mass on the order of 21,000 metric tons. The wasted excess neutron power in this example is about 1725 MW/m^2 and the surface heat flux due to the bremsstrahlung and synchrotron radiation power is about 30 MW/m^2.

A concept for such an interplanetary space vehicle appears in Figure 1. This diagram clearly shows the massive size of the radiator required to eliminate excess heat produced when neutrons are emitted isotropically along the axis of the fusion propulsion engine.

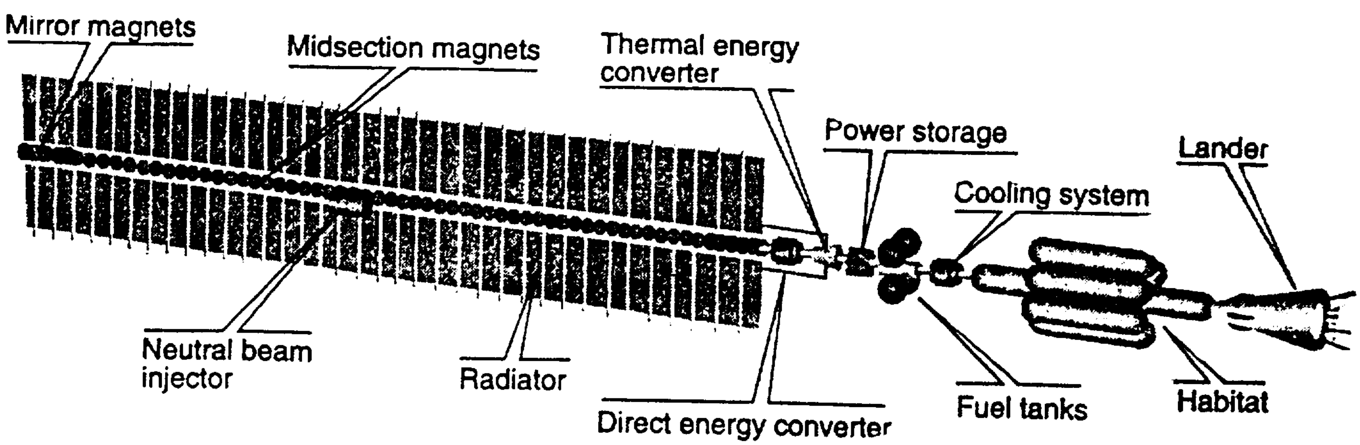

Figure 1. Interplanetary Space Vehicle Concept (Reference 2)

Nuclear Magnetic Moments and Spin Precession in a Magnetic Field

The nucleus of an atom has an angular momentum due to its spin. This angular momentum is quantified (Reference 3,4,5) by the nuclear spin quantum number **I** multiplied by Plank's constant **h** divided by 2π, or $\mathbf{I}\hbar$. In addition, the nucleus also possesses a magnetic moment. This nuclear magnetic moment is expressed in terms of a nuclear magneton **M** defined by the equation

$$M = \frac{e\hbar}{2 m_n}$$

in which **e** is the charge of the nucleus and $\mathbf{m}_n$ is the mass of the nucleus. The nuclear ***g*** factor relates the magnetic moment **G** of a nucleus to its spin angular momentum. The nuclear ***g*** factor is defined as the ratio of the nuclear magnetic moment, expressed in units of nuclear magnetons, to the spin angular momentum, expressed in units of **h** . Thus,

$$g = \frac{M}{I m_n}$$

And

$$M = g I m_n = g I \frac{e\hbar}{2 m_n}$$

When a nucleus of magnetic moment **G** is in a constant magnetic field of induction **B** , it will precess about the direction of **B** with a frequency given by Larmor's theorem

$$\nu = \frac{\mu B}{I h}$$

The magnetic moment **G** of a nucleus is thus determined by the Larmor frequency ν which the nucleus of spin quantum number **I** acquires in a known constant magnetic induction **B** .

The measured nuclear magnetic dipole moment **G** for a deuterium nucleus is + 0.8574376 nuclear magnetons with a spin of + 1 and for a tritium nucleus it is + 2.978962 nuclear magnetons with a spin of + ½.

When an accelerated beam of deuterons and tritons enter a region with a uniform external magnetic field, the spins of the nuclei are aligned with the magnetic field and precess about the magnetic field lines at the Larmor frequency. The evolution of the spin direction (References 6,7,8) and the orbital motion of a polarized beam in external magnetic fields is governed by the Thomas-BMT equation

$$\frac{d\vec{P}}{dt} = -\left(\frac{e}{\gamma m}\right)\left[G\gamma\,\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}\right] \times \vec{P}$$

and the Lorentz force equation:

$$\frac{d\vec{v}}{dt} = -\left(\frac{e}{\gamma m}\right)\left[\vec{B}_{\perp}\right] \times \vec{v}$$

where the polarization vector ***P*** is expressed in the frame that moves with the particle. From comparing these two equations it can readily be seen that, in a pure vertical field, the spin rotates $G\gamma$ times faster than the orbital motion. Here G is the nuclear magnetic moment of the deuteron or triton and gamma is the charge to mass ratio. In this case the factor $G\gamma$ then gives the number of full spin precessions for every full revolution, a number which is also called the spin tune frequency.

The acceleration of spin polarized beams of nuclei is complicated by the presence of numerous depolarizing resonances. During acceleration, a depolarizing resonance is crossed whenever the spin precession frequency equals the frequency with which spin-perturbing magnetic fields are encountered. There are two main types of depolarizing resonances corresponding to the possible sources of such fields: imperfection resonances, which are drive by magnet errors and misalignments, and intrinsic resonances, driven by the magnetic focusing fields.

By introducing a 180 degree magnetic spin rotator of the spin about the horizontal axis, the stable spin direction remains unperturbed at all times as long as the spin rotation form the 180 degree spin rotator is much larger than the spin rotation due to the resonance driving fields. Therefore the beam polarization, is preserved during acceleration. Such a magnetic spin rotator can be constructed by using either solenoidal magnets for low energy (less than 1 MeV) beams or a sequence of interleaved horizontal and vertical dipole magnets producing only a local orbit distortion for high energy beams.

Nuclear Spin Quantum Mechanics

In the absence of spin, the Hamiltonian for the motion of a deuteron or triton with a charge of +**e** in an electromagnetic field is (References 9,10,11)

$$\hat{H}_o = \frac{1}{2m}\left(\hat{P} - \frac{e}{c}\vec{A}\right)^2 + e\phi$$

where **A** is the vector potential and ϕ the Coulomb potential. Since the spin interacts with the magnetic field, the nucleon gains additional potential energy. The nuclear magnetic moment reads

$$\hat{m} = g\left(\frac{-|e|}{2mc}\right)\hat{S} = -\mu_B\,\hat{\sigma}$$

where μ_B = (**eh**/gmc) and the potential energy in the magnetic field is:

$$U = -\hat{m} \cdot B$$

The Hamiltonian of a nucleon with spin takes the following form:

$$\hat{H} = \hat{H}_o + \mu_B\,\hat{\sigma} \cdot B$$

Knowing the value of the Lande *g* factor, this Hamiltonian leads to the Schrodinger equation of a particle with spin, also known as the Pauli equation. This is the equation for a system of two coupled differential equations for spin wave functions describing the nuclei with the **z** component of their spin either up or down. Because of the form of the Pauli spin matrices, the spin system described by the Schrodinger equation is decoupled for the **z** component of the spin and only coupled by the **x** and **y** components. This Pauli equation is given by:

$$i\hbar \frac{\partial \psi}{\partial t} = \left[\frac{1}{2m}\left(\hat{p} - \frac{e}{c}\vec{A}\right)^2 + e\phi + \mu_B \hat{\sigma} \cdot B\right]\psi$$

To calculate the current density which results from the Pauli equation, the equation is rewritten in the form:

$$i\hbar \frac{\partial \psi}{\partial t} = \hat{H}_0 \psi + \mu_B \hat{\sigma} \cdot B \psi$$

The adjoint to this equation reads:

$$-i\hbar \frac{\partial \psi^+}{\partial t} = \hat{H}_0^* \psi^+ + \mu_B (\hat{\sigma} \cdot B \psi)^+$$

$$= \hat{H}_0^* \psi^+ + \mu_B \psi^+ \hat{\sigma} \cdot B$$

because $\hat{\sigma}$ is Hermitian and the magnetic field **B** is real. Rearranging and manipulating the Pauli equation and its adjoint yields the continuity equation

$$i\hbar \frac{\partial}{\partial t} \psi^+ \psi = -\frac{\hbar^2}{2m} \, div\left[\psi^+ \nabla \psi - (\nabla \psi^+)\psi\right] + \frac{i\hbar e}{mc} \, div(\vec{A} \psi^+ \psi)$$

in the form

$$\frac{\partial w}{\partial t} = -\operatorname{div} \vec{j}$$

where $w = \psi^{\dagger} \psi$ is the probability density and the current density of the nuclei is given by

$$\vec{j} = -\frac{i\hbar}{2m}\left[\psi^{\dagger} \nabla \psi - \left(\nabla \psi^{\dagger}\right) \psi\right] - \frac{e}{mc} \vec{A} \psi^{\dagger} \psi$$

With both components of the spin wave function (spin up and spin down) and their complex conjugates, the total current density equation is

$$\vec{j} = \frac{i\hbar}{2m}\left(\psi_1 \nabla \psi_1^{*} + \psi_2 \nabla \psi_2^{*} - \psi_1^{*} \nabla \psi_1 - \psi_2^{*} \nabla \psi_2\right)$$

$$- \frac{e}{mc} \vec{A}\left(\psi_1^{*} \psi_1 + \psi_2^{*} \psi_2\right)$$

or, rearranging,

$$\vec{j} = \frac{i\hbar}{2m}\left(\psi_1 \nabla \psi_1^{*} - \psi_1^{*} \nabla \psi_1\right) - \frac{e}{mc} \vec{A} \psi_1^{*} \psi_1$$

$$+ \frac{i\hbar}{2m}\left(\psi_2 \nabla \psi_2^{*} - \psi_2 \nabla \psi_2\right) - \frac{e}{mc} \vec{A} \psi_2^{*} \psi_2$$

The probability density and the current density are composed additively of the parts of the two different spin directions; multiplication of the nucleon current density j by the nuclear charge yields the electrical current density j_e.

The current density j_e does not contain the spin; rather it is the current density caused by the orbital motion of the nucleon, each with its own spin. However, the spin of a nucleon also causes a magnetic moments, which can be expressed by a corresponding current called the spin current density j_s. This current density cannot occur in a continuity equation in which the charge conservation is expressed by convection currents.

The spin current density can be calculated using Maxwell's equation for the curl of the magnetic field:

$$\mathrm{curl}\ B = \left(\frac{4\pi}{c}\right)\left(\vec{j}_e + c\ \mathrm{curl}\langle m\rangle\right)$$

In this case the magnetization $\langle m\rangle$ is replaced by the averaged density of the magnetic moment $\mathcal{M}$, where averaging is performed over the spin states. The nuclear magnetic dipole density is given by:

$$\langle m\rangle = \mu_B \Psi^{+} \hat{\sigma} \Psi$$

and thus

$$\mathrm{curl}\ B = \frac{4\pi}{c} j = \left(\frac{4\pi}{c}\right)\left(\vec{j}_e - c\mu_B\ \mathrm{curl}\ \Psi^{+}\hat{\sigma}\Psi\right)$$
$$= \left(\frac{4\pi}{c}\right)\left(\vec{j}_e + \vec{j}_s\right)$$

The contribution to the spin current density causing the magnetic moment of the nucleons is then described by:

$$\vec{j}_s = -c\,\mu_B \operatorname{curl} \psi^{+} + \vec{\sigma}\,\psi$$

Kinematics of Nuclear Reactions

When a deuteron and triton collide with sufficient energy, a nuclear reaction occurs similar to inelastic scattering where the incident and target nuclei are transformed into different nuclei or particles (a neutron and an alpha particle). Regardless of the circumstances of the reaction, four very important quantities (References 12 and 13) are observed to always be conserved; 1) mass-energy, 2) linear momentum, 3) angular momentum, and 4) spin. The last three are critical to the concept discussed in this report.

Conservation of linear momentum is a consequence of the invariance of the Hamiltonian function with respect to a translational shift of the origin of coordinates by which the position of the system as a whole is measured. Conservation of angular momentum results from the invariance of the Hamiltonian function of an isolated system with respect to the angular orientation of the coordinate system used to describe it.

Conservation of spin statistics asserts that the "spin character" of a closed system cannot change. That is, if a system consists of a number of particles of various spins, some integral and some half-integral, the total number of particles of half-integral spin must remain either even or odd. This conservation law is in some respects a consequence of the conservation of angular momentum, since orbital angular momentum can have only integral quantum numbers and there fore cannot "carry away" all of the intrinsic angular momentum of a particle.

Angular Distribution of Particles

During the process of nuclear fusion, a deuteron and triton combine or fuse to become a compound or excited nucleus. At some point shortly (10^{-15} to 10^{-12} seconds) after the fusion of the two nuclei, the nucleus separates into two distinct fragments, a neutron and an alpha particle with a total energy of 17.6 MeV.

These two particles separate along the nuclear symmetry axis (References 14,15). The quantum number K, which is the projection of the total vector angular momentum quantum number J on the nuclear symmetry axis, is a descriptive quantum number describing the passage of a nucleus from its excited transition state to the configuration of separated particles. The directional dependence of the separation particles resulting from a transition state with quantum numbers J, K, and spin quantum number M is uniquely determined.

The quantum numbers J and M (the spin projection of J on a space-fixed axis which is usually taken as the direction of motion of the incident particle in the center-of-mass coordinate system) are conserved in the entire particle separation process. Whereas J and M are fixed throughout the various extended shapes on the path to particle separation, no such restriction holds for the parameter K . In going from the original compound nucleus (with a shape which is the same as the of the ground state) to the saddle point or transition state, the nucleus suffers many vibration and changes in shape, and redistributes its energy and angular momentum in many ways. The K value (or values) of the transition nucleus are, therefore, unrelated to the initial K values of the compound nucleus. Once the nucleus reaches the transition state deformation, K is a good quantum number beyond this point of the particle separation process.

The angular momentum coupling scheme for a deformed nucleus and the relationship between J, M, and K is schematically illustrated in Figure 2.

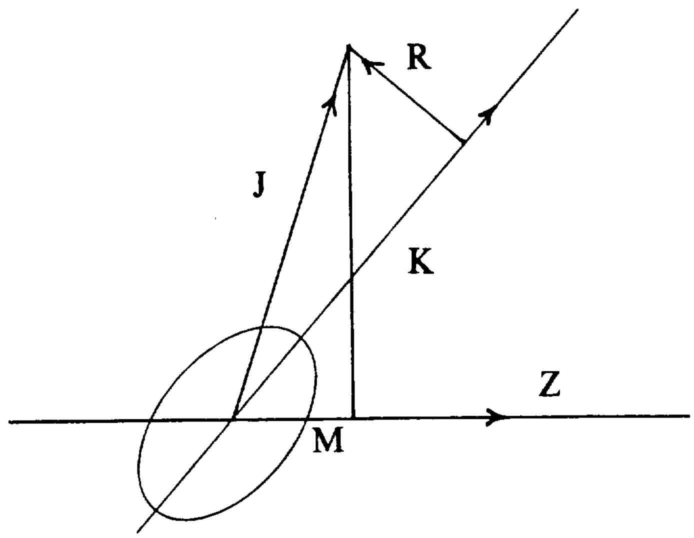

Figure 2. Angular Momentum Coupling Scheme

The vector J defines the total angular momentum. The quantity M is the spin component of the total angular momentum on the space-fixed Z axis, which is the direction of the incident particle velocity. The quantity K is the component of the total angular momentum along the nuclear symmetry axis. The collective rotational angular momentum R is perpendicular to the nuclear symmetry axis; thus, K is entirely a property of the intrinsic motion. The angle theta represents the angle between the nuclear symmetry axis an the space-fixed Z spin.

The probability of particles being emitted from a transition state with quantum numbers J, M, and K at an angle theta is given by:

$$P^J_{M,K}(\theta) = \left[(2J+1)/4\pi R^2\right] \left| d^J_{M,K}(\theta) \right|^2 2\pi R^2 \sin\theta \, d\theta$$

where $P^J_{M,K}(\theta)$ represents the probability of emitting particles at angle theta into the conical volume defined by the angular increment $d\theta$. The normalization is such that the probability integrates to unity for limits 0 and pi. The area of the annular ring on a sphere of radius R through which the particles are passing is given by the width of the strip $R \cdot d\theta$ times the circumference of the ring $2\pi R \sin\theta$, which is $2\pi R^2 \sin\theta \, d\theta$. This annular ring area must be divided by the total area of the sphere $4\pi R^2$ in order to give the probability as defined by the above equation.

The foregoing probability distribution depends on the $d^J_{M,K}(\theta)$ function and is universal in the sense that it is independent of the polar angle, the angle of rotation about the symmetry axis, and the moments of inertia. Hence the probability distribution depends only on the angle theta between the space-fixed and body-fixed axes. The $d^J_{M,K}(\theta)$ functions are defined by the following relation

$$d^J_{M,K}(\theta) = \left\{ (J+M)!(J-M)!(J+K)!(J-K)! \right\}^{1/2}$$
$$\times \sum_X \frac{(-1)^X \left[\sin\left(\frac{\theta}{2}\right)\right]^{K-M+2X} \left[\cos\left(\frac{\theta}{2}\right)\right]^{2J-K-2X}}{(J-K-X)!\,(J+M-X)!\,(X+K-M)!\,X!}$$

where the sum is over X = 0,1,2,3,... and contains all terms in which no negative value appears in the denominator of the sum for any one of the quantities in parentheses. There are a number of symmetry relationships among the d's, for example,

$$d^J_{M,K}(\theta) = (-1)^{M-K} d^J_{K,M}(\theta)$$

The angular distribution $W^J_{M,K}(\theta)$ is obtained by dividing the probability for emitting particles at angle theta as defined in the above equation by sin θ ,

$$W^J_{M,K}(\theta) = [(2J+1)/2]\,|d^J_{M,K}(\theta)|^2$$

The normalization of this equation is such that

$$\int_0^{\pi} W^J_{M,K}(\theta)\sin\theta\, d\theta = 1$$

The angular distribution function $W^J_{M,K}(\theta)$ is directly related to the differential particle cross section for a particular channel (J,π,K,M) at angle theta by the relation

$$\frac{d\sigma_f}{d\Omega}(J,\pi,K,M,\theta) = \frac{W^J_{M,K}(\theta)}{2\pi}\,\sigma_f(J,\pi,K,M)$$

where the differential particle cross section is to be expressed in the same units per steradian as the total fusion cross section. The factor 2 π appears instead of the usual 4 π due to the fact that two particles separated by 180 degrees arise from each fusion event.

The angular distribution of particles depends on two basic quantities: the angular momentum brought in the incident nucleus and the fraction of this angular momentum which is converted into orbital angular momentum between the neutron and alpha particle. This fraction is characterized through the parameter K, where K is defined as the projection of the angular momentum J on the nuclear symmetry axis. These are sufficient to describe the emitted particle angular distribution. This is based on the particles separating along the nuclear symmetry axis and that K is a good quantum number beyond the transition point. The distribution of the angular momenta resulting from the fusion system may be controlled by the proper choice of spin alignment.

The density of levels in the transition nucleus with spin J and projection of J on the nuclear symmetry axis equal to K is given by the approximate relation

$$\rho(J,K) \propto \exp\left[\left(E - E_{rot}^{J,K}\right)/t\right]$$

where K is the total energy, $E_{rot}^{J,K}$ is the energy tied up in rotation for transition state (J,K), and t is the thermodynamic temperature. The thermodynamic energy available to the nucleus is the quantity $E - E_{rot}^{J,K}$. The rotational energy of a nucleus in its saddle point deformation is

$$E_{rot}^{J,K} = \left(\hbar^2/2I_\perp\right)\left(J^2 - K^2\right) + \left(\hbar^2/2I_\parallel\right)K^2$$

where $I_\perp$ and $I_\parallel$ are nuclear moments of inertia about axes perpendicular and parallel to the symmetry axis, respectively. Substitution into the above equation yields

$$\rho(J,K) \propto \exp\left\{ \left(\frac{E}{t}\right) - \left(\frac{\hbar^2 J^2}{2 I_\perp t}\right) - \left(\frac{\hbar^2 K^2}{2 t}\right)\left[\frac{1}{I_\parallel} - \frac{1}{I_\perp}\right] \right.$$

For fixed values of E and t the number of transition levels ρ (J,K) depends on two quantities, $\frac{\hbar^2 J^2}{2 I_\perp t}$

and $\left(\hbar^2 K^2 / 2t\right)\left[\left(1/I_\parallel\right) - \left(1/I_\perp\right)\right]$

If in addition, J is fixed, then the distribution in K becomes

$$\rho(K) \propto \exp\left\{ -\left(\hbar^2 K^2 / 2t\right)\left[\left(1/I_\parallel\right) - \left(1/I_\perp\right)\right] \right.$$

This equation is equivalent to a Gaussian K distribution

$$\rho(K) \propto \exp\left(-K^2 / 2 K_0^2\right), \quad K \leq J$$

$$= 0 \qquad\qquad K > J$$

where $K_0^2 = \frac{t}{\hbar^2}\left[\left(1/I_\parallel\right) - \left(1/I_\perp\right)\right]$

If the quantity $\left[\left(1/I_\parallel\right) - \left(1/I_\perp\right)\right]$ is replaced by $1/I_{eff}$, then

$$K_0^2 = t\, I_{eff} / \hbar^2$$

For a Gaussian K distribution an exact expression for the particle angular distribution may be derived by proper weightings of J,M, and K. If the target and projectile spin are included, the exact equation for the angular distribution utilizing the proper statistical weights is

$$W(\theta) \propto \sum_{J=0}^{\infty} \sum_{M=-I_0+s}^{+I_0+s} \left\{ \sum_{\ell=0}^{\infty} \sum_{S=|I_0-s|}^{I_0+s} \sum_{\mu=-I_0}^{+I_0} \frac{(2\ell+1) T_\ell \left| C_{M,0,M}^{S,\ell,J} \right|^2 C_{\mu,M-\mu,M}^{I_0,s,S}}{\sum_{\ell=0}^{\infty} (2\ell+1) T_\ell} \right.$$

$$\times \sum_{K=-J}^{J} \frac{(2J+1) \left| d_{MK}^{J}(\theta) \right|^2 \exp(-K^2/2K_0^2)}{\sum_{K=-J}^{J} \exp(-K^2/2K_0^2)}$$

The quantities I_o, s, and S are the target spin, projectile spin, and the channel spin, respectively. The channel spin S is defined by the relation $\mathbf{S} = \mathbf{I_0} + \mathbf{s}$. The total angular momentum J is given by the sum of the channel spin and the orbital angular momentum, $\mathbf{J} = \mathbf{S} + \mathbf{l}$. The projection of $\mathbf{I_0}$ on the space-fixed axis is given by μ, whereas the projection of S (and J) on the space-fixed axis is M. The quantity in the bracket gives the weighting factor for a particular (J,M) combination. This value multiplies the angular dependent term for the allowable k states (K distribution is weighted also) of a particular J. This product is summed first over all M values for a particular J and finally over all J values. The $d_{MK}^{J}(\theta)$ function is defined in the saddle point deformation equation and the quantities $C_{M,0,M}^{S,\ell,J}$ and $C_{\mu,M-\mu,M}^{I_0,s,S}$ are Clebsch-Gordan coefficients.

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