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Coupled-channel Treatment of Isobaric Analog Resonances in (p,p′) Capture Processes

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With the advent of nuclear reactions on unstable isotopes, there has been a renewed interest in using isobaric analogue resonances (IAR) as a tool for probing the nuclear structure. The position and width of isobaric analogue resonances in nucleon-nucleus scattering are accurate and detailed indicators of the positions of resonances and bound states with good single-particle characters. We report on implementation within our coupled-channels code FRESCO of the charge-exchange interaction term that transforms an incident proton into a neutron. Isobaric analog resonances are seen as peaks in γ-ray spectrum when the proton is transformed into a neutron at an energy near a neutron bound state. The Lane coupled-channels formalism was extended to follow the non-orthogonality of this neutron channel with that configuration of an inelastic outgoing proton, and the target being left in a particle-hole excited state. This is tested for ^{208}Pb, for which good (p,p'γ) coincidence data exists.

I. INTRODUCTION

The position and width of isobaric analogue resonances in nucleon-nucleus scattering are accurate and detailed indicators of the positions of resonances and bound states with good single-particle characters [1, 2]. Since determining the positions of shells and shell gaps has often been the objective of experiments with unstable isotopes, measuring isobaric analogue resonances (IAR) should be modeled as well as possible by theorists in relation to proposed experiments. These IAR have the great virtue that *neutron* bound states, both occupied and unoccupied, can be determined in experiments that react *protons* on nuclei. Proton targets can be made with hydrogen, but neutron targets are not feasible. The best information about levels is determined by (p,p′γ) coincidence experiments [3]. The displacement energies of IAR also depend critically on neutron-proton density differences, so can be used to probe those densities in the surface. Experiments such as [4, 5] show the methods are also useful for light neutron-rich nuclei for which the Coulomb displacement energy is sufficiently low that the IAR could be observed in inverse kinematics at energies accessible presently.

We therefore implemented within our coupled-channels code FRESCO [6] the main Lane coupling term [7]: the interaction that couples an incident proton to a neutron at a lower energy, such as a sub-threshold energy near an unoccupied single-particle state. We see doorway resonances when the neutron energy is near a bound state energy. At the same time, a target neutron must have changed to a proton, so it must have been in an occupied neutron state with quantum numbers such that a proton with those parameters is not Pauli blocked. We therefore extended the Lane coupled-channels formalism to follow the non-orthogonality of this neutron channel with that configuration of an inelastic outgoing proton, and the target being left in a particle-hole excited state. This is tested for ^{208}Pb, for which good (p,p′γ) coincidence data exists [3]. Further mechanisms are indicated which can contribute coherently to an non-resonant background, and the multiple steps of which mechanisms may be included more satisfactorily within a coupled-channel rather than a one-step computational framework.

II. ISOBARIC COUPLING

The usual formulation of nucleon-nucleus optical potential is as $V(R) = V_0(R) + 2t_z(N-Z)/AV_1(R)$, where $V_0(R)$ is the isoscalar form factor, and $V_1(R)$ is the isovector form factor. The nucleonic isospin $t_z = 1/2$ for neutrons and $-1/2$ for protons. If we define the target isospin as $T_z = (N-Z)/2$, then $V(R) = V_0(R) + \frac{2}{A}t_zT_zV_1(R)$. Lane [7] then generalizes this expression as $t_zT_z \to \mathbf{t}\cdot\mathbf{T}$, to yield a form which is invariant under 'rotations' in isospin space. This new form has off-diagonal couplings between neutron and proton channels, as $\mathbf{t}\cdot\mathbf{T} = t_+T_- + t_-T_+ + t_zT_z$, where $t_\pm$ and $T_\pm$ are the projectile and target isospin-raising and -lowering operators. The effects of these $t_\pm$ terms is to directly couple proton and neutron isobaric-analog channels. That is, a p+(N,Z) incident channel is coupled by a form factor proportional

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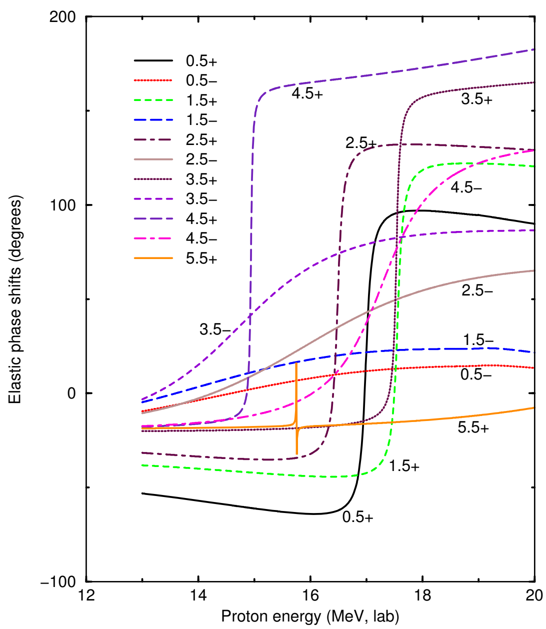

FIG. 1. Phase shifts in p + ^{208}Pb scattering for the various partial waves indicated, taking into account Lane couplings to neutron isobaric-analog channels. Optical potentials with only real components were used.

to $V_1(R)$ to the n+$(N-1, Z+1)$ analog channel. This describes a Fermi transition, in which the initial and final partial waves of respectively the proton and neutron are the same: there are no spin-flip terms in the Lane coupling term.

The resulting coupled-channel equations for proton and neutron scattering together are

$$\begin{aligned}[T_p + V_p - E_p]\psi_p(R) + V_{pn}(R)\psi_n(R) &= 0 \\ [T_n + V_n - Q - E_p]\psi_n(R) + V_{pn}(R)\psi_p(R) &= 0, \quad (1)\end{aligned}$$

where the coupling $V_{pn}(R) = -2\sqrt{2T}\ V_1(R)$, and Q is the energy released in a (p,n) reaction. The energy $-Q$ is called the Coulomb displacement energy, denoted by E_d^{TOT} in [1, section 5].

Consider for example the ^{208}Pb(p,n)^{208}Bi reaction at low energies. Here the Coulomb displacement energy is 18.9 MeV. That is, the neutron has much less energy than the incident proton, and may hence be trapped below threshold. If the trapped neutron is near an unoccupied bound state, the coupled-channel system shows resonances in the proton scattering. These are called Isobaric Analog Resonances (IAR). Many of these resonances are narrow, and hence are only visible in calculations if there is little energy averaging, or, what is equivalent, the imaginary parts of the proton and neutron optical potentials are sufficiently reduced. If only a real optical potential is used for the proton, we see the phase shifts drawn in Fig. 1.

The energies of particular resonances in Fig. 1, once $-Q = 18.9$ MeV is subtracted, may be seen to correspond almost exactly with the energies of single-particle neutron states in ^{208}Pb. Table I, from Rademacher et al. [3], shows these energies in the left-hand column, relative to the $3p_{1/2}$ Fermi surface at 7.3755 MeV below the breakup threshold. Individual neutron spins and parities are identifiable from the resonances in the same spin and parity partial wave for proton scattering, for these Fermi transitions. If such proton resonances could be observed, therefore, then neutron single-particle states could be determined. This would be of great use in probing exotic beams of short-lived isotopes, if such measurements of these narrow resonances were possible.

III. GAMMA-RAY PRODUCTION FROM ISOBARIC ANALOG RESONANCES

The IAR peaks are not in fact visible in proton elastic scattering, because elastic optical potentials have too much imaginary strength to see such narrow resonances. Putting this in another way, there is too much spreading of resonances into the compound-nucleus set of resonances to allow individual peaks to be discerned. The only way of seeing them is in coincidence experiments, where there might be a γ-ray emission from the resonant configuration.

The IAR 'decay' to the elastic channel is what gives the resonance phase shifts, though it is difficult to measure proton phase shifts accurately at the required energies (14–18 MeV) This mechanism is the trapped neutron charge-exchanging back to the elastic proton. The needed γ-ray emission occurs, however, if *other* neutrons change back into protons. They can do this as long as they are in spatial orbitals *not* occupied by protons. From Table I, we see that all of the neutrons in the orbitals $1h_{9/2}$ to $3p_{1/2}$ are thus allowed to charge-exchange back to continuum protons. Such transitions leave the nucleus with a weakly-bound neutron (eg $4s_{1/2}$) and a hole at or below the Fermi level (eg $3p_{1/2}$): a particle-hole inelastic excitation, which will eventually γ-decay. The outgoing proton has its energy reduced by the particle-hole energy difference, so this results in an inelastic (p,p′) reaction. Experimentally, therefore, the task is to measure inelastic protons and gamma decays in coincidence.

TABLE I. Neutron single-particle levels around ^{208}Pb, relative to the $3p_{1/2}$ Fermi surface at 7.3755 MeV below the breakup threshold. Data are from Rademacher et al. [3].

Unoccupied levels		Occupied levels	
Orbital	Energy (MeV)	Orbital	Energy (MeV)
$3d_{3/2}$	5.93	$3p_{1/2}$	0
$2g_{7/2}$	5.88	$2f_{5/2}$	−0.57
$4s_{1/2}$	5.44	$2f_{5/2}$	−0.57
$3d_{5/2}$	4.97	$3p_{3/2}$	−0.90
$1j_{15/2}$	4.82	$1i_{13/2}$	−1.64
$1i_{11/2}$	4.18	$2f_{7/2}$	−2.35
$2g_{9/2}$	3.41	$1h_{9/2}$	−3.47

TABLE II. The four relevant partitions for the ^{208}Pb(p,p$'\gamma$) reaction in the vicinity of the $4s_{1/2}$ resonance. The K.E. column shows the kinetic energy, which is negative for sub-threshold states.

Partition	Partition	K.E.	Neutron state
1.	p + ^{208}Pb$_{gs}$	17 MeV	in $3p_{1/2}$ in ^{208}Pb$_{gs}$
2.	p' + ^{208}Pb$_{ph}$	12 MeV	in $4s_{1/2}$ on ^{207}Pb
3.	n + ^{208}Bi	−2 MeV	in $4s_{1/2}$ as projectile
4.	d + ^{207}Pb	12 MeV	in deuteron

IV. COUPLED-CHANNEL TREATMENT

We now implement a coupled channels treatment of these charge-exchange mechanisms in the code FRESCO [6]. This code expands the system wave function in two-body partitions. In the reaction ^{208}Pb(p,p$'\gamma$) in the vicinity of the $4s_{1/2}$ resonance, there are conceptually the four different partitions listed in Table II.

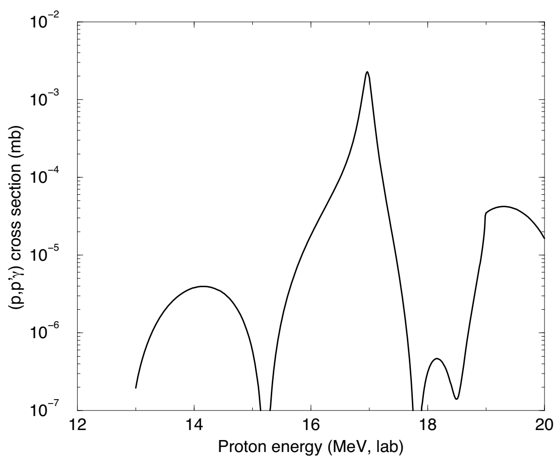

FIG. 2. Calculated inelastic cross sections for the ^{208}Pb(p,p$'\gamma$) reaction to the $(4s_{1/2})(3p_{1/2})^{-1}$ particle-hole state in ^{208}Pb*.

Since the partitions 2 and 3 are not orthogonal, we define new overlap form in FRESCO to take this into account when solving the coupled equations using an orthonormal expansion on R-matrix basis states. The resulting calculated cross sections are shown in Fig. 2.

There are (at least) two other direct contributions to the ^{208}Pb(p,p$'\gamma$) reaction that are not resonant, but still need to be taken into account since their amplitudes interfere coherently with the charge-exchange mechanism. This makes a coupled-channel formulation of the problem particularly fruitful, since then additional mechanism may be easily included. These other mechanisms, for the (p,p$'\gamma$) reaction to the $(4s_{1/2})(3p_{1/2})^{-1}$ particle-hole state, are:

1. an inelastic n* excitation outside a ^{207}Pb$_{1/2^-}$ core: ^{208}Pb$_{3p1/2}$(p,p$'$) ^{208}Pb$_{4s1/2}$, and/or
2. a two-step neutron transfer reaction via an intermediate deuteron state: ^{208}Pb$_{3p1/2}$+p $\rightarrow$ d+^{207}Pb$_{1/2^-}$ $\rightarrow$ p$'$ + ^{208}Pb$_{4s1/2}$

These additional mechanisms will be included in future calculations.

V. CONCLUSIONS

This work demonstrates the feasibility of a 'valence nucleon' account of isobaric analog resonances. In the longer-term, full structure-model calculations of widths would be preferable, but for the immediate calculation of cross sections the present coupled-channel framework should be rather useful. There is still a need for verification of absolute magnitudes for all peaks, and of choosing the correct energy-averaging interval, since the IARs are too narrow for optical-model averaging. As stated, experiments thus need (p,p$'\gamma$) coincidences to see the IARs among the compound-nucleus decays. Related to this is the question of energy-dependences in the needed optical potentials, which is particularly relevant for transitions from 20 MeV to sub-threshold, as here.

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