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THE ROLE OF THE PYGMY RESONANCE IN THE SYNTHESIS OF HEAVY ELEMENTS WITH RADIOACTIVE BEAMS*

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ABSTRACT

It is suggested that the inclusion of the virtual excitation of the soft giant dipole (pygmy) resonance in the calculation of the cross-section for very neutron-rich radioactive beam-induced fusion reactions may enhance the formation probability of the heavy compound nucleus produced at low excitation energy.

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INTRODUCTION

Recently, it has been suggested[1] that the beams of neutron-rich radioactive nuclei offer a rather unique possibility for synthesizing both the superheavy nuclei lying around the magic neutron and proton numbers N = 184 and Z = 114 and the heavy isotopes with N ≥ 160 of new elements. Owing to the larger N/Z ratio of these exotic nuclei the effective Coulomb barrier is basically lowered, permitting the appreciable formation of not so excited compound nuclei at low energies. These cold compound nuclei have lower fission probability, thus increasing the possibility of observing them.

The theoretical calculation of the survival probability of heavy elements using radioactive neutron-rich beams has been done using the macroscopic model of extra-extra push of Swiatecki[2]. Substantial lowering of the effective fissility and, consequently a lower effective fission barrier is obtained. The degree of lowering of these physical parameters has, however, been recently questioned[3].

In the present paper, we address ourselves to another, dynamical effect involving neutron-rich nuclei. It has been theoretically established that nuclei in the neutron drip region exhibit appreciable collective at quite low excitation energies. In particular, the soft giant dipole resonance, in nuclei such as ^{11}Li, is predicted to be situated in the 1-2 MeV energy region, exhausting about 12% of the classical dipole sum rule and thus accounting for about 90%, of the observed fragmentation cross-section[4,5,6]. We shall demonstrate here that these "pygmy resonances" could enhance the fusion probability of neutron-rich nuclei by as much as %. We base our discussion on known facts about ^{11}Li and make reasonable extrapolations to the Fe isotopes induced fusion considered in reference 1).

2. THE PYGMY RESONANCE

In nuclei such as ^{11}Li, it has been suggested that the two neutrons in the $p_{1/2}$ level, form a "halo", and as such is very distanced from the ^{9}Li core. When discursing the collective dipole excitation of such a loosely bound system, one is bound to consider two types of such vibrations: the usual ($E^{*} \approx 20$ MeV) isovector proton vs. neutron vibration in the core, with the halo neutrons taken as were spectators, and the oscillation of the whole core nucleus agains the halo neutrons (the pygmy resonance). In this latter case the rather extended distribution of the halo results in a weak restoring force, and consequently a low excitation energy of the pygmy resonance (also known as the soft giant dipole resonance).

Recent microscopic calculation[4-6] of the structure of neutron-rich nuclei clearly confirmed the above qualitative picture. For the purpose of the present paper, however we shall use macroscopic, Steinwedel-Jensen, modeling guided with appropriate sum rule arguments to discuss the pygmy resonance in the Fe isotopes.

In a recent letter, Suzuki, Ikeda and Sato[7] predicted the following excitation energy of the pygmy resonance, using the S-J model

$$E^{*}_{pR} = \left[\frac{Z\,(N-N_{c})}{N\,(Z+N_{c})}\right]^{1/2} E^{*}_{GDR} \qquad (1)$$

where $\hbar\omega_{GDR}$ is the excitation energy of the usual giant dipole resonance $\left[\approx \frac{80}{A^{1/3}}\,\mathrm{MeV}\right]$ and N_c refers to the neutron number of the core. N and Z are the neutron and proton numbers of the whole nucleus. Thus for the ^{A}Fe isotopes with A = 56, ...70, we have: $E^{*}_{pR}(56) = 0$, $E^{*}_{pR}(70) = 0.38\,E^{*}_{GDR}$. This shows that in ^{70}Fe, the pygmy resonance occurs at ≈ 5 MeV. This value could well be lower ifthe separation energy of the excess neutron is small as e.g. the

case in ^{11}Li. The pygmy resonance in this latter nucleus is found to occur at ≈ 2 MeV[5,6].

A pure cluster model supplies slightly different results from those of reference 7). Within this model, the dipole strength is distributed according to[8]

$$\frac{dB(E1)}{dE^{*}} = \frac{3\hbar^{2}e^{2}}{\pi^{2}}\,\frac{Z^{2}\,\Delta N}{AA_{c}}\,\frac{\sqrt{\varepsilon}\,(E^{*}-\varepsilon)^{3/2}}{E^{*4}} \qquad (2)$$

when ΔN refers to the excess neutrons treated as a cluster and ε is the binding energy (separation energy) of this excess neutron clusters. The position of the maximum of $\frac{dB(E1)}{dE^{*}}$ is just the energy of the pygmy resonance and is easily calculated to be

$$E^{*}_{pR} = \frac{8}{5}\,\varepsilon, \qquad (3)$$

thus the smaller ε is the lower E_{pR} will be. In a nucleus such as ^{70}Fe, ε could very well be in the few keV region. Of course an ambiguity remains as to what should be the core. However, equations (1) and (2) should serve our purposes of supplying estimates.

From the above discussion one may safely assume that the pygmy resonance may occur in the 0.2-2 MeV excitation energy region in the Fe isotopes.

In discussing the energy weighted sum rule for neutron-rich nuclei one may consider the usual classical sum rule which reads

$$S(E1) = 14.8\,\frac{NZ}{A}\,[\mathrm{MeV\ fm^{2}e^{2}}] \qquad (4)$$

and the dipole cluster sum rule for the core plus excess neutron system[9]

$$S_c(E1) = S(E1) - S_{cluster}(E1) - S_{excess}(E1)$$

$$= 14.8 \left[\frac{NZ}{A} - \frac{N_c Z_c}{A_c}\right]\left[\text{MeV fm}^2 e^2\right] \qquad (5)$$

It is usually found that the pygmy resonance exhausts about 10% of the classical rule and 80% of t he cluster sum rule.

3. THE FUSION OF ^{A}FE + ^{208}PB

Aside from the static, barrier penetration effects considered in reference (1), there are dynamic effects arising from the virtual excitation of giant resonances. Here we consider the effects of the pygmy resonances. It has been shown in the last few years that the fusion cross section at low energies is appreciably increased over the static value, when channel coupling effects are taken into consideration[10]. The enhancement is largest when the Q-value of the non-elastic channel is lowest. We show below how the excitation of the pygmy resonance may help increase the fusion cross-section of the system ^{A}Fe+^{208}Pb. Although the theoretical description of coupled channels effect in the fusion of heavy ions is well developed we opt here for a simple two channel model that can be solved exactly. Calling H_0+V_0 the entrance channel Hamiltonian, $H_{pR}+V_{pR}$ the pygmy resonance channel Hamiltonian, V_c the coupling Hamiltonian and Q_{pR} the Q-value of the pygmy resonance channel, the two-channel Schrödinger equation then reads,

$$\begin{bmatrix} H_0 + V_0 & V_c \\ V_c & H_{pR}+V_{pR}+Q_{pR} \end{bmatrix} \psi = E\psi \qquad (6)$$

From the previous discussion we know that Q_{pR} is small

and we neglect it in what follows (the c.m. energy is much larger than Q_{pR}). Further $H_{pR}+V_{pR}$ describes the relative motion of the excited ^{A}Fe nucleus with respect to ^{208}Pb. We are safe in taking this Hamiltonian to be equal to H_0+V_0. We thus have

$$(H_0 + V_0 + V_c\sigma_x)\psi = E\psi \qquad (7)$$

where σ_x is a Pauli spin matrix which is introduced here for notational convenience. Fusion with no coupling is accounted for by the complex bare optical potential V_0. The corresponding cross-section is

$$\mathring{\sigma}_F = \frac{k}{E} \langle \mathring{\psi}_0^{(+)} | - \mathrm{Im}V_0 | \mathring{\psi}_0^{(+)} \rangle = \frac{\pi}{k^2} \sum \left(2\ell+1\right) \mathring{T}_\ell \qquad (8)$$

Taking into account the coupling interaction to all orders amounts to replacing $\mathring{\sigma}_F$ above by

$$\sigma_F = \frac{k}{E} \langle \psi^{(+)} | - \mathrm{Im}V_0 | \psi^{(+)} \rangle - \sigma_{pR} \qquad (9)$$

where $\psi^{(+)}$ is the spinor $\begin{pmatrix} \psi_0^{(+)} \\ \psi_{pR}^{(+)} \end{pmatrix}$ and σ_{pR} is the angle integrated inelastic cross-section for the direct transition $0 \longrightarrow pR$. The fusion cross-section σ_F can be written in closed form after performing a convenient transformation that diagonalizes σ_x. The result of σ_F is

$$\sigma_F = \frac{1}{2}\left[\sigma_R\left(V_c\right) + \sigma_R\left(-V_c\right)\right] \qquad (10)$$

where $\sigma_R(V_c)$ is the total reaction cross section obtained from the Hamiltonian $H_0+V_0+V_c$ and $\sigma_R(-V_c)$ from $H_0+V_0-V_c$. We should stress, that in all our discussion above we have disregarded the angular momentum (1) of the pygmy resonance, which is quite valid considering the great values of the orbital angular momentum involved. Equation (10) has been previously derived in a slightly different manner, by Lindsay and Rowley[11].

In calculating the enhancement of σ_F, we use the Wong formula[12], which reads

$$\overset{\bullet}{\sigma}_F \equiv \sigma_F(V_c=0) = \frac{\hbar\omega R_B^2}{2E}\, \ell n\left[1 + \exp\left(\frac{E - V_B}{\hbar\omega}\right)\right] \qquad (11)$$

where $\hbar\omega$ is measures the curvature of the Coulomb barrier and V_B is its height. Here the Coulomb barrier is obtained from $V_0(r)+\frac{\hbar^2\ell(\ell+1)}{2\mu r^2}$, and the Coulomb interaction is contained in V_0. We define the enhancement factor $\mathbb{E}(V_c)$ as

$$\mathbb{E}(V_c) = \frac{\sigma_F(V_c)}{\sigma_F(V_c=0)} = \frac{\ell n\left\{1+\exp\left[\left(\frac{E-V_B-V_c}{\hbar\omega}\right)\right]\right\} + \ell n\left\{1+\exp\left[\left(\frac{E-V_B+V_c}{\hbar\omega}\right)\right]\right\}}{2\ell n\left\{1+\exp\left[\left(\frac{E-V_B}{\hbar\omega}\right)\right]\right\}} \qquad (12)$$

At the barrier, $E = V_B$ one has

$$\mathbb{E}(V_c) = \frac{\ell n\left\{1+\exp\left(\frac{-V_c}{\hbar\omega}\right)\right\} + \ell n\left\{1+\exp\left(\frac{V_c}{\hbar\omega}\right)\right\}}{2\ell n2} \qquad (13)$$

Writing fully the structure of V_c (again ignoring the 1^- nature of the pygmy resonance), guided with the results for stable nuclei supplied by the collective model

$$V_c = C_1\left[B_{pR}(E1)\right]^{\frac{1}{2}} F(r) + V_c^{Coulomb} \qquad (14)$$

where C_1 in a strength which may be calculated within the Tassie model, $F(r)$ is the radial form factor given by $\int \frac{d}{dr'}\rho_{Fe}(r')\rho_{Pb}(r'-r)dr'$, and $V_c^{Coulomb}$ is the Coulomb piece of V_c which is also proportional to $(B_{pR}(E1))^{1/2}$. Thus

$$V_c = \mathbb{F}(r)(B_{pR}(E1))^{1/2} \qquad (15)$$

In Eqs. (14) and (15) $B_{pR}(E1)$ is the B(E1) value of the pygmy resonance, which in a cluster model (core + excess neutrons) can be written as[8] (by integrating Eq. (2) over E^*)

$$B_{pR}(E1) = \frac{3\hbar^2e^2}{16\pi}\left[\frac{Z^2\Delta N}{AA_c}\right]\frac{1}{\varepsilon} \qquad (16)$$

where ε is the binding energy of the excess neutron cluster with respect to the core. It is obvious that ε is the determining factor in the degree of enhancement of σ_{fusion}, thus, we obtain the final explicit form of the enhancement factor $\mathbb{E}$ (at $E_{c.m.} = V_B$) showing its dependence on the relevant physical parameters that characterize the exotic neutron-rich nucleus ^{A}Fe, with $A = A_c + \Delta N$, and using Eq. (3)

$$\mathbb{E} = \frac{1}{2\ell n2}\,\ell n\left\{2\left[1 + \cosh\left(\frac{\mathbb{F}(R_B)}{\hbar\omega}\,\frac{15\hbar^2e^2}{128\pi}\,\frac{Z^2\Delta N}{AA_c}\,\frac{1}{E^*_{pR}}\right)\right]\right\} \qquad (17)$$

where F(r) of Eq. (15) is evaluated at the barrier $r = R_B$. Since $\frac{Z^2}{A_c}$ is fixed once the core is decided upon, the quantity that varies as more neutrons, are added is $\frac{\Delta N}{AE^*_{pR}}$. The argument of the cosh could become very large for very neutron-rich isotopes such as ^{70}Fe, where E_{pR} is expected to be very small, rendering $\mathbb{E}$ to attain great values.

In fact if, as reference, we take for the factor $\chi \equiv \frac{\mathbb{E}(R_B)}{\hbar\omega}\,\frac{15\hbar^2e^2}{128\pi}\,\frac{Z^2\Delta N}{AA_c}$ the value $E^*_{GDR}(^{56}Fe) \cong 20$ MeV, and take $E^*_{pR}(^{56}Fe = E^*_{GDR}(^{56}Fe)$ then $\mathbb{E}(^{56}Fe) = 1$. With $E^*_{pR}(^{70}Fe)$ of about 0.2 MeV and ignoring the variation of χ with ΔN we get

$$\mathbb{E}(^{70}Fe) \cong \frac{100}{2\ell n2}$$

We should stress that the above value of $E(^{70}Fe)$ was obtained at $E = V_B$. At lower c.m. energies, one may obtain much larger enhancement.

Before presenting our concluding remarks, we warn the reader that our formula for E, equation (17) was derived in the sudden limit ($Q_{pR} = 0$) and using the cluster model for the pygmy resonance. The validity of the sudden approximation becomes suspect for small ΔN and one has to consider equation (17) as a great overestimation. In fact, in such cases, namely large values of E^*_{pR}, a more valid approximation is to simulate the excitation of the PR through an attractive local energy-independent polarization potential[13]. As far as the cluster model of the PR is concerned it has recently been demonstrated that this model overestimates the Coulomb fragmentation cross-section of $^{11}Li + ^{208}Pb$ at $E_{Lab} = 800$ MeV.A[8,14] and greatly overestimates the cross-section at lower energies[5]. However the analytic simplicity of the cluster model justifies its use here for the obtention of the simple estimate for E.

In conclusion, we have considered in this paper the influence of the excitation of the soft giant dipole resonance on the fusion of neutron-rich nuclei with heavy targets. The enhancement ones the static fusion calculation, exemplified by Eq. 17, shows clearly that the determining factor is the smallness of the excitation energy E^*_{pR} or, more precisely the large value of B(E1) as the number $\frac{N}{Z}$ is increased. Any static fusion calculation of the type discussed in reference 1 must be ammended by the multiplication with E of Eq. (17) or, even better, by a detailed coupled channel calculations.

Of course several questions have to be answered before a definite conclusion concerning the value of E can be reached. The most important of these questions is the precise value of $B_{pR}(E1)$ and F(r), which can only be settled through detailed measurement and analysis of the elastic scattering and break-up of these exotic neutron-rich nuclei.

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