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Closed-Formalism Approach to Antiproton-Nucleus Scattering (*).

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Summary. — Typical scattering data for $\bar{p}+{}^{12}C$, $\bar{p}+{}^{40}Ca$ and $\bar{p}+{}^{208}Pb$ are analysed using the closed-formalism or parametrized S-matrix approach which was successfully applied earlier by Frahn and his co-workers for the analysis of heavy-ion scattering data. The results indicate that the closed-formalism approach is also applicable for the analysis of antiproton-nucleus scattering data.

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1. – Introduction.

Closed-formalism (CF) or parametrized S-matrix approach (PSMA) is a well-formulated procedure for the analysis of elastic and inelastic scattering of heavy-ion collisions. In this approach the nuclear S-matrix is expressed in terms of several parameters incorporating both the wave mechanical as well as the semi-classical aspects of heavy-ion scattering [1-3]. The correlation of this approach to the conventional optical model [4, 5] has also been studied. In this paper, we demonstrate that the CF approach is also useful for the analysis of antiproton-nucleus ($\bar{p}$-A) scattering data which has some similarity with the heavy-ion scattering. The experimental results [6, 7] and the theoretical analysis of low-energy $\bar{p}$-A scattering [8-10] indicate several similarities between $\bar{p}$-A and nucleus-nucleus collisions. Both are predominantly surface-dominated phenomena and consequently the inner regions of the interaction potential are not uniquely determined. The cross-sections in both the cases correspond to the diffraction pattern associated with absorptive sphere. However, in $\bar{p}$-A scattering there is no Coulomb barrier and the surface dominance of the scattering is due to the large number of additional channels in $\bar{p}$-A system associated with the annihilation process. The nature of the effective potential of the $\bar{p}$-A system on the surface indicates a slow variation and hence the semi-classical WKB method is feasible for the analysis of $\bar{p}$-A scattering data [11]. In

(*) The authors of this paper have agreed to not receive the proofs for correction.

addition, the behaviour of the diffraction pattern in $\bar{p}$-A case is very similar to nucleus-nucleus case. In view of these, one expects that the CF approach is likely to be useful in the analysis of $\bar{p}$-A scattering. In the next section, we illustrate this for several cases of $\bar{p}$-A scattering.

2. – Results and discussion.

Two of the commonly used parametrizations of the S-matrix are: i) Ericson parametrization and ii) McIntyre parametrization. In the Ericson parametrization the nuclear S-matrix $S_N(\lambda)$ for l-th partial wave is represented as follows:

$$S_N(\lambda) = [1 + \exp[(\Lambda - \lambda)/\Delta]]^{-1}, \tag{1}$$

where Λ (complex) and Δ are the Ericson parameters and $\lambda = l + 1/2$. In this parametrization there are three real parameters, namely Δ, Re Λ and Im Λ. The expression for $S_N(\lambda)$ in the McIntyre parametrization is given by

$$S_N(\lambda) = \eta(\lambda) \exp[2i \operatorname{Re} \delta_N(\lambda)], \tag{2}$$

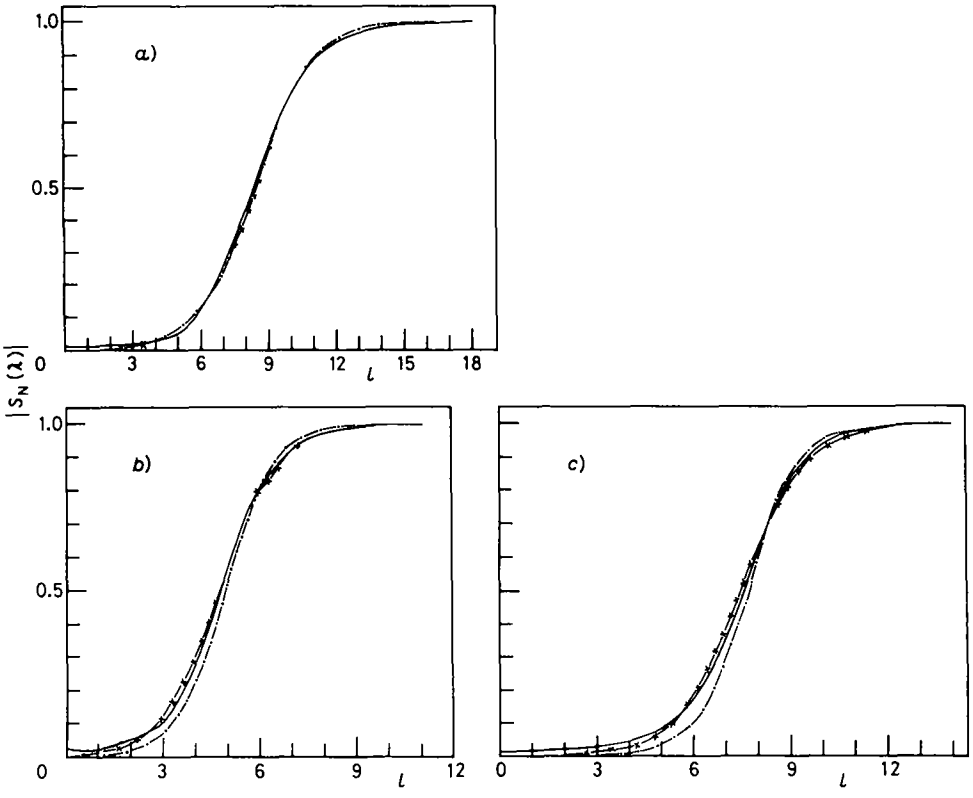

Fig. 1. – *a*) Reflection function ($|S_N(\lambda)|$) for $\bar{p} + {}^{12}C$ at $E_{lab} = 180$ MeV. The dash-cross-dashed (– × – × –), dash-dot-dashed (– · – · –) and solid (——) curves are the results of the McIntyre and Ericson parametrization and the OM calculation, respectively. *b*) Same as in *a*), but for $\bar{p} + {}^{12}C$ at $E_{lab} = 46.8$ MeV. *c*) Same as in *a*), but for $\bar{p} + {}^{40}Ca$ at $E_{lab} = 46.8$ MeV.

where

$$\eta(\lambda) = |S_N(\lambda)| = [1 + \exp[(\Lambda - \lambda)/\Delta]]^{-1}$$

and

$$\mathrm{Re}\,\delta_N(\lambda) = \delta_0(1 - \eta_P(\lambda)).$$

The form of $\eta_P(\lambda)$ is similar to that of $\eta(\lambda)$ with the parameters Λ_P and Δ_P. Λ and Δ are the McIntyre parameters for the reflection function ($|S_N(\lambda)|$) and δ_0, Λ_P and Δ_P are the McIntyre parameters for the phase shift. This parametrization is widely applied in the analysis of heavy-ion scattering[1]. It may be mentioned that in the conventional optical-model (OM) also, the total potential is generally parametrized in terms of 5-7 parameters including the Coulomb radius parameter r_C. It is to be noted that, in the CF adopted here, we restrict the parametrization of $S_N(\lambda)$ to 3 or 5 parameters. In this paper, we give the results of our calculation for $\bar{p}+{}^{12}C$, $\bar{p}+{}^{40}Ca$ and $\bar{p}+{}^{208}Pb$ at $E_{lab} = 46.8$ MeV and $\bar{p}+{}^{12}C$ at $E_{lab} = 180$ MeV within the framework of CF using both Ericson and McIntyre parametrizations. Typical sets of optical-model potential parameters which describe the $\bar{p}$-A cross-sections are listed in table I. In tables II and III we list the parameters of Ericson and McIntyre parametrizations, respectively, which generate the reflection functions and cross-sections similar to that obtained using OM calculation. The parameter Λ in both the cases corresponds to the partial wave for which the reflection function is close to 0.5. The parameter Δ is a measure of the variation of the reflection function from the region of full absorption ($|S_N(\lambda)| = 0$) to the case of no absorption ($|S_N(\lambda)| = 1$). Some results for $|S_N(\lambda)|$ and differential cross-section ($d\sigma/d\Omega$) obtained using some typical sets of parameters are shown in fig. 1*a*)-*c*) and fig. 2*a*), *b*), respectively.

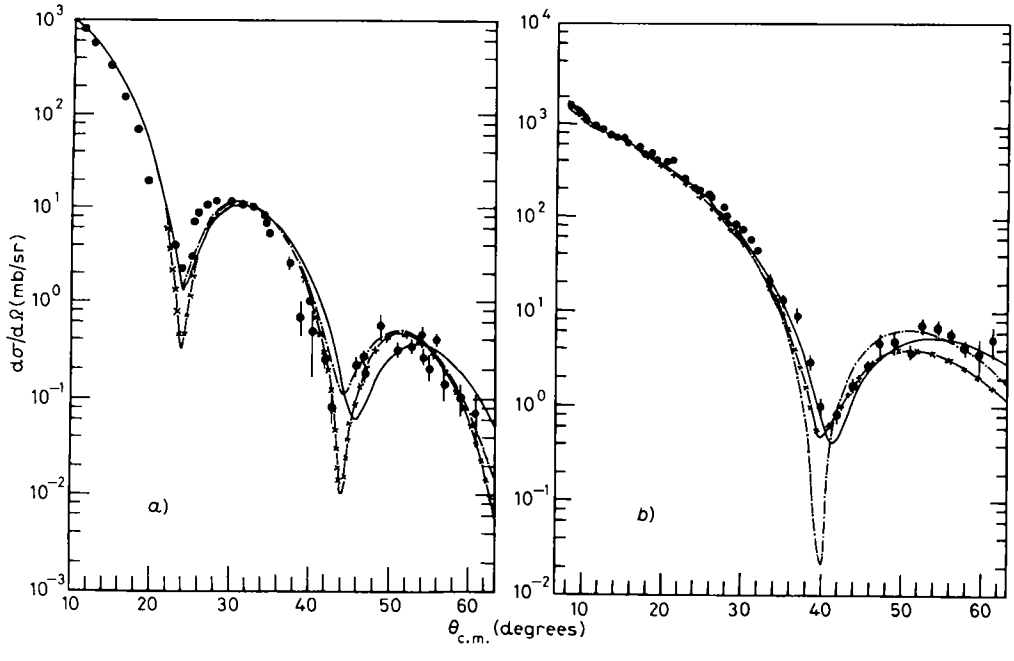

Fig. 2. – *a*) Comparison of differential cross-section ($d\sigma/d\Omega$) for $\bar{p}+{}^{12}C$ at $E_{lab} = 180$ MeV. Representations are same as that of fig. 1*a*). Experimental data (●) are taken from ref. [12]. *b*) Same as *a*), but for $\bar{p}+{}^{12}C$ at $E_{lab} = 46.8$ MeV.

TABLE I. – *Potential parameters used in the* OM *calculation for different systems.* V_0, r_r, a_r *are the potential depth, radius and surface diffuseness parameters for the real part of the* OM *potential in the ordinary Woods-Saxon form.* W_0, r_i, a_i *are the corresponding parameters for the imaginary part of the potential.* r_C *is the Coulomb radius parameter.*

System	E_{lab} (MeV)	V_0 (MeV)	r_r (fm)	a_r (fm)	W_0 (MeV)	r_i (fm)	a_i (fm)	r_C (fm)	Reference
$\bar{p}+^{12}C$	180	20.0	1.35	0.44	113.0	1.1	0.5	1.3	[9]
$\bar{p}+^{12}C$	46.8	140.0	0.421	0.743	120.9	0.928	0.636	1.3	[10]
$\bar{p}+^{40}Ca$	46.8	40.0	1.1	0.6	100.0	1.1	0.6	1.3	[9]
$\bar{p}+^{208}Pb$	46.8	20.0	1.1	0.65	140.0	1.1	0.65	1.3	[9]

TABLE II. – *Ericson parameters for different systems obtained to fit the elastic-scattering data.*

System	E_{lab} (MeV)	Re Λ	Im Λ	Δ	Remarks
$\bar{p}+^{12}C$	180	8.908	0.263	1.264	Fig. 1*a*) and 2*a*)
$\bar{p}+^{12}C$	46.8	5.383	0.171	0.761	Fig. 1*b*) and 2*b*)
$\bar{p}+^{40}Ca$	46.8	8.203	0.422	0.797	Fig. 1*c*)
$\bar{p}+^{208}Pb$	46.8	13.820	1.478	1.396	

TABLE III. – *McIntyre parameters for different systems obtained to fit the elastic-scattering data.*

System	E_{lab} (MeV)	Λ	Δ	δ_0 (rad)	Λ_P	Δ_P	Remarks
$\bar{p}+^{12}C$	180	8.902	1.254	2.6	− 0.64	1.697	Fig. 1*a*) and 2*a*)
$\bar{p}+^{12}C$	46.8	5.246	0.882	2.25	− 12.3	4.5	Fig. 1*b*) and 2*b*)
$\bar{p}+^{40}Ca$	46.8	7.974	0.987	0.75	0.5	1.45	Fig. 1*c*)
$\bar{p}+^{208}Pb$	46.8	13.980	1.301	− 0.735	12.733	1.174	

In fig. 1*a*)-*c*) we compare the reflection function obtained using Ericson (–·–·–) and McIntyre parametrizations (–×–×–) together with that obtained using (OM) (——) calculation for the systems $\bar{p}+^{12}C$ at E_{lab} = 180 MeV and $\bar{p}+^{12}C$ and $\bar{p}+^{40}Ca$ at E_{lab} = 46.8 MeV, respectively. These show that both these parametrizations of S-matrix developed for the analysis of heavy-ion scattering are equally useful in generating the reflection function for $\bar{p}$-A scattering also. In fig. 2*a*), *b*) we give two typical cases of differential cross-section, namely $\bar{p}+^{12}C$ at E_{lab} = 180 MeV and 46.8 MeV, respectively obtained using CF with that of the conventional OM calculation. The fits obtained for differential cross-section and reflection function for the systems $\bar{p}+^{40}Ca$ and $\bar{p}+^{208}Pb$ at E_{lab} = 46.8 MeV obtained using CF with the parameters given in tables II and III are comparable in quality to those obtained for $\bar{p}+^{12}C$ case. Hence, we have not given the figures for differential cross-section corresponding to $\bar{p}+^{40}Ca$ and $\bar{p}+^{208}Pb$ systems. These indicate that CF provides a simple procedure for the analysis of antiproton-nucleus scattering data. Our results along with that of Frahn *et al.* [1] establish the fact that in case of surface dominant

nuclear scattering showing semi-classical features, the CF or PSMA provides a simple method for the analysis of scattering data.

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